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Atlas Breached Waste Package and Drip Shield Experiments: Breached Drip Shield Tests

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EXECUTIVE SUMMARY

The Engineered Barrier System (EBS) represents one system in the performance of the Yucca Mountain high-level radioactive waste (HLW) repository to isolate and prevent the transport of radionuclides from the site to the accessible environment. Breached Waste Package and Drip Shield Experiments (BWPDSE) were performed at the Department of Energy's National Nuclear Security Administration Nevada Support Facility in North Las Vegas, NV in the A-1 lowbay between May 2, 2002 and July 25, 2002. Data collected from the BWPDSE will be used to support the flux splitting model used in Analysis and Modeling Report ANL-WIS-PA-000001 REV 00 ICN 03 *EBS Radionuclide Transport Abstraction* (BSC 2001a). Tests were conducted by dripping water from heights representing the drift crown or wall on a full-scale section of a drip shield with both smooth and rough surfaces. The drip shields had machined square breaches that represent the general corrosion breaches or nodes in the *WAPDEG Analysis of Waste Package and Drip Shield Degradation* AMR (CRWMS M&O 2000d). Tests conducted during the BWPDSE included: initial tests to determine the splash radius distances and spread factor from the line of drip impact, single patch tests to determine the amount of water collected in target breaches from splashing or rivulet flow, multiple patch tests to determine the amount of water collected in several breaches from both splashing and rivulet flow, and bounding flow rate tests. Supplemental data were collected to provide additional information for rivulet spread, pan evaporation in the test chamber, and water temperatures of the input water and drip shield surface water. The primary flow mechanism observed on both smooth and rough surfaces was rivulet flow, not film flow. Lateral rivulet spread distances were, in general, wider on the smooth drip shield surface than on the rough drip shield surface. There were substantial differences between the mechanisms of rivulet formation and movement on smooth and rough drip shield surfaces. Water collected in breaches was a function of the location of drip impact upstream from the target breach, i.e., impact breaches must be directly above or slightly to the side of the breaches in order for a substantial volume of water to collect in breaches. Splash droplets contributed a small portion of the water collected in breaches. Mass balances showed that evaporation from the drip shield was a large component of water loss. This was particularly manifested during low flow runs of the bounding flow rate tests where test duration was around five hours.

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ACRONYMS

AMR	analysis model report
AP	administrative procedure
BWPDSE	Breached Waste Package and Drip Shield Experiments
CRWMS	Civilian Radioactive Waste Management System
DOE	Department of Energy
DI	deionized
DS	drip shield
DTN	data tracking number
EBS	Engineered Barrier System
HLW	high-level radioactive waste
HMP	humidity moisture probe
M&TE	measuring and test equipment
QA	quality assurance
QARD	quality assurance requirements and description
RH	relative humidity
RTD	resistance temperature device
TCO	YMP Test Coordination Office
TDMS	Technical Data Management System
WP	waste package

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1. INTRODUCTION

1.1 PURPOSE AND SCOPE

Data collected from the Breached Waste Package and Drip Shield Experiments (BWPDSE) will be used to support the flux splitting model used in future revisions of the Analysis and Modeling Report (AMR) ANL-WIS-PA-000001, *EBS Radionuclide Transport Abstraction* (BSC 2001a). The purpose of the BWPDSE was to collect information on water flow paths and penetration through breaches on drip shield surfaces so that the flux splitting model can be both validated and made more complete with respect to water mass losses caused by splashing and evaporation.

The scope of this report is to document the BWPDSE by:

- Presenting test configurations and operating conditions
- Summarizing test data and providing data submittal tracking numbers
- Presenting test results

Both waste package (WP) and drip shield (DS) geometries are applicable to the flux splitting model and data generated in these tests will be used to describe seepage flux entering breaches through both DSs and WPs. A DS surface was used in these tests for simplification, and future testing to support the EBS radionuclide transport abstraction may include tests performed on WP surfaces if it is determined that such data are required.

1.2 BACKGROUND

The Engineered Barrier System (EBS) represents one system in the performance of the Yucca Mountain high-level radioactive waste (HLW) repository to isolate and prevent the transport of radionuclides from the site to the accessible environment. The primary transport mechanism for radionuclides is liquid water that may penetrate the EBS through breaches in the drip shields (DS) and waste packages (WP), which make up the components of the EBS. Water flux (represented by the letter "q") can enter the breaches via three different mechanisms: q(direct), a droplet falls directly through the patch (hole); q(film) liquid enters a breach by film or rivulet flow and; q(splash) liquid enters a breach as a result of liquid being pushed or lofted from a point of drip impact on the DS. A patch is a modeling term for a breach in the DS or WP. The flux splitting model (BSC 2001a) is conservatively based on the following assumptions:

1. Drip impact occurs without a loss of water mass from splattering and evaporation.

2. Dripping flux falls exactly at the crown of the DS. This limits the zone of impact to the horizontal surface across the DS crown and does not include the curved surface that would cause droplets to be deflected from the DS.

3. The flux passing through a DS patch is proportional to the ratio of the length of the penetration in the axial direction to the total axial length of the DS. In this assumption

all fluid that drips and flows from the DS crown toward a penetration will be collected if the axial locations of the source and patch coincide (BSC 2001a).

The current model does not consider drop mass loss and splash radius following impact. The water droplets projected during impact, in reality, may land on the DS surface in another location or be completely thrown off of the DS. Because natural processes were in effect, these experiments represented effects not considered in the current models, which were not capable of incorporating the random processes inherent in water dripping onto both dry and wetted surfaces.

Test controls included the drip seepage rate, drip impact location, breach location, and breach size. General corrosion breaches were the only breaches considered in these tests and were based on the nodes or square patches of area 0.072144 m^2 (0.2685963-m square) from the *WAPDEG Analysis of Waste Package and Drip Shield Degradation* AMR (CRWMS M&O 2000d). For testing purposes the patch size in the BWPDSE was rounded to 0.270-m square in place of the patch size (0.2685963-m square) used in CRWMS M&O 2000d. The drip shield length was constructed to 10 patch lengths, or 2.7 m. In CRWMS M&O 2000d, general corrosion patches did not appear on DSs before 10,000 years after placement, while manufacturing defects were predicted to appear after 1000 years.

Environmental conditions of interest in the BWPDSE were temperature and relative humidity (RH). The test was performed in an enclosed insulated chamber where the RH was elevated above 80%. It is important to note that these tests did not consider the effects of elevated temperature. It was not the intent to maintain test environment conditions, i.e., temperature and RH, at the expected repository environment, but conditions were maintained to provide accurate water collection.

1.3 QUALITY ASSURANCE

This technical report was prepared in accordance with Administrative Procedure (AP)-3.11Q, *Technical Reports.* The technical work plan (TWP) that governed the work for the BWPDSE was TWP-MGR-MD-000015 Rev. 2, *Technical Work Plan For: Engineered Barrier System Department Modeling and Testing FY 02 Work Activities* (BSC 2002a), which was prepared in accordance with AP-2.27Q, Rev. 0, *Quality Determination and Planning for Scientific, Engineering, and Regulatory Compliance Activities*. Specific activities for the BWPDSE, including the writing of this report, are described in *The Test Plan for: Atlas Breached Waste Package and Drip Shield Experiments,* SITP-02-EBS-005 (BSC 2002b). This activity was subject to the Quality Assurance Requirements and Description (DOE 2003) requirements.

Other quality assurance features of this testing program include:

The Field Work Package (FWP)-EBS –02-001, Engineered Barrier Systems – *Breached Waste Package and Drip Shield Testing* (YMP 2002) which defines the execution plan, facility requirements, and health and safety guidelines of the BWPDSE.

Details of the test configuration and records of the test execution were documented in scientific notebook numbers SN-M&O-SCI-043-V1, SN-M&O-SCI-043-V2, and SN-M&O-SCI-043-V3, per AP-SIII.1Q, *Scientific Notebooks* (Howard 2002a, Howard 2002b, and Howard 2002c).

All instruments were calibrated in the Bechtel Nevada calibration laboratory and calibrations were documented in scientific notebook SN-M&O-SCI-043-V1 (Howard 2002a, pp. 24-34) and SN-M&O-043-V2 (Howard 2002b, pp. 223-240).

All data were entered manually into the scientific notebook, and then entered manually into MS Word documents for submittal to the TDMS. Data were reviewed and verified in accordance with AP-2.14Q prior to being submitted to the TDMS. Because the data were entered manually into the scientific notebook and then submitted to the TDMS via MS Word documents, the only AP-SV.1Q controls listed in the TWP that applied were those outlining personal computer security and a regular back up of test files. These controls were in place during the BWPDSE.

The only software utilized during the BWPDSE was MS Excel '97 for performing calculations and making data plots. All formulas, inputs and outputs are documented and this software is, therefore, exempt from the requirements of AP-SI.1Q per AP-3.11Q Sec. 5.1.3e.

During the BWPDSE, BSC QA conducted a surveillance (Krisha 2002) and found the testing to be programmatically compliant. No conditions adverse to quality were identified.

1.4 EBS BREACHED DRIP SHIELD TEST DESCRIPTION

The BWPDSE was conducted at the Department of Energy's National Nuclear Security Administration Nevada Support Facility in North Las Vegas, NV in the A-1 lowbay between May 2, 2002 and July 25, 2002. Testing was performed by dripping water on smooth and rough DS surfaces with cut square breaches (0.270-m square). Water was dripped on the DS surfaces at nominal rates of 2 m^3/yr (3.8 g/min), 0.2 m^3/yr (0.38 g/min), and 20 m^3/yr (38 g/min) and allowed to collect in breaches or gutters placed on the DS boundaries. Following each test, the collected water was weighed at each station and a mass balance performed. Before tests were conducted, initial tests were performed to determine splash distances after drop impact and lateral rivulet spread from the line of impact. In some of the initial tests Blue #1 food coloring was used in the drip water in order to make rivulets and splashes more visible on the drip shield surface. This practice was used sparingly during the initial tests and was not used during the formal testing because the food coloring stained the DS surface, making it necessary to thoroughly clean the DS surface before the next test run. The measurements taken during the initial tests were used to select drip impact locations for formal tests. All tests were performed at full-scale with respect to drop distance and DS curvature.

2. TEST CONFIGURATION

2.1 TEST DESIGN CRITERIA

The following criteria applied to the test design:

1. DS breaches represent square general corrosion patches of area 0.072144 m^2 (0.2685963 by 0.2685963 m), based on the AMR ANL-EBS-PA-000001 REV 00 ICN 01 WAPDEG *Analysis of Waste Package and Drip Shield Degradation* (CRWMS M&O 2000d). Actual breaches used in the BWPDSE were machined (or cut) into the DS with dimensions of 0.270 by 0.270 m.

2. The WP diameter (1.564 m) used in the BWPDSE represents those of the 21 PWR WP (CRWMS M&O 2000b). The WP diameter is the WP footprint beneath the DS and represents the seepage area over the DS as illustrated in Figure 1.

3. The dripping distance was based on AMR design parameters, and thus drip velocity was represented on a full scale. The EBS/repository design parameters and values used in the BWPDSE, including reference to full DS dimensions, are listed in Table 1. Based on the values listed in Table 1, the distance from the top of the drift to the crown of the DS is 2.173 m. Drip impact locations were positioned along lateral lines at the crown, 33^o along the DS curvature, and 16.5^o along the DS curvature (see Figure 1).

4. The nominal seepage drip rate was based on an average of the seepage flux rates expected in the repository (BSC 2001b). It is assumed that the DS will intercept all seepage flux entering the drift and for the purposes of these tests, seepage flux was represented as drips per unit time per unit area of DS above the waste package (WP) footprint. A nominal seepage rate of 2 m^3/yr was used in the q(splash) and q(film) tests, while bounding rates of 0.2m^3/yr and 20m^3/yr were used during the bounding flow rate tests.

5. The condition of DS surfaces during the time they are not expected to fail (i.e., 1000 years for manufacturing defects and 10,000 years for general corrosion) was difficult to predict and replicate. Two different surfaces were tested: a standard machined stainless steel surface (the most conservative condition), and a rough surface that only approximated DS conditions expected to exist during DS failure. Both surface conditioning processes can be replicated.

6. The tests were conducted in an environment that would minimize evaporation, but not necessarily simulate repository conditions. This was achieved by conducting the tests in an insulated test chamber. During formal testing (not including all initial tests), the relative humidity (RH) in the chamber was maintained above 80%. The test chamber temperature was not directly controlled during testing, but was monitored.

2.2 DRIP SHIELD MATERIALS AND SURFACE CONDITIONS

The DS was constructed of ¼ inch stainless steel and supported by an aluminum frame. For purposes of the BWPDSE, a full-scale section of DS was used in place of a complete DS. The DS section design was based on the full DS dimensions outlined in Table 1. The DS was 2.7-m long, 1.27-m wide, and 1.62-m high. A diagram of the drip shield with dimensions and patch (breach) locations is shown in Figure 2 and a picture of the DS and frame can be viewed in Figure 3 (Howard 2002a, p. 14 and p. 16). The smooth DS surface was formed by polishing the stock stainless steel with 60-grit sandpaper on a circular sander. A close-up photograph of the stainless steal DS surface is shown in Figure 4. The rough surface was formed by covering the stainless steel DS surface with a silica anti-slip coating (Howard 2002b, p. 70). A picture of the rough DS can be viewed in Figure 5 and a picture of the texture can be viewed in Figure 6.

2.3 TEST CHAMBER DESIGN AND INSTRUMENTATION

The test chamber was constructed from standard metal framing material and plywood. The chamber was insulated with R-5.7 rated insulation all sides and ceiling (Howard 2002c, p. 113). The test chamber dimensions were 3.66-m long, 2.74-m wide, and 2.44-m high (Figure 7). Water vapor was introduced into the chamber with the use of commercial humidifiers. Initially two humidifiers were used. A third humidifier was added before the q(film) tests (see Section 2.1.6) on the smooth DS for the purpose of increasing the RH at a faster rate and maintaining a higher RH in the chamber. During testing the RH was maintained at 80% or higher. A ventilation fan was used during testing to circulate air around the test chamber. Figure 7 shows a diagram of the test chamber with locations of humidifiers, the ventilation fan, and monitoring instrumentation. Test chamber instrumentation is listed with all testing M&TE in Appendix A. The test chamber ceiling had three slots positioned along the length of the chamber ceiling to allow water drips to fall on the DS crown, the 16.5° line, and the 33° line. The slots were covered during testing with a 1.5-in styrofoam sheet, except for one of the many pre-cut access holes where the drip tower (see Section 2.4.1) was located. The test chamber environment data were collected before and after each test and recorded by hand on data collection sheets that were entered into the scientific notebook.

2.4 WATER INJECTION AND COLLECTION SYSTEMS

2.4.1 Water Injection

Water drips were introduced into the test environment by injecting water through an aquarium diffuser using a metering pump. The aquarium diffuser is a porous medium that allows water drops to collect slowly and fall after enough mass has collected to break the surface tension. A test performed to measure the droplet mass from an aquarium diffuser resulted in a mean mass of 0.141 grams (Howard 2002b, pp. 4-6). This method was used because it is similar to the processes that occur when water droplets collect and fall from the drift crown. The diffuser was mounted in a clear PVC tube (drip tower) and was adjusted to three different heights during the tests, which represent the drip distances between the DS surface at the crown, 16.5°, and 33° and the corresponding position on the drift wall (see Figure 1). Figure 8 presents a photograph of the drip tower showing the three possible drip positions at 2.17-m (crown), 2.22-m (16.5°), and 2.31-m (33°) (Howard 2002a, p. 36). The drip tower was movable and was positioned over the designated impact location through the one of the three slots in the test chamber ceiling.

The input water rate was measured by weighing the initial and final water masses over the test time duration. Test duration times were measured with a stopwatch from the time the first drop impacted the drip shield to the time when the metering pump was shut off.

2.4.2 Water Collection System

Water that was dripped over the DS surface was collected at various stations that constituted water passing through breaches, water passing around breaches and running off the DS, water splashing over the edge of the DS boundary, and residual water that adhered to the DS surface. Water that ran into breaches was collected in pans that were mounted on the inside of the DS. Paper towels were placed inside the collection pans to prevent water from splashing out of the pan and to direct water into the pan from the breach inside edges. Water that passed by breaches and off the DS surface collected in gutters mounted to the front and back of the DS. Water that splashed off the front, back, and sides of the DS was caught and directed into the same collection gutters used to collect runoff. Residual water that remained on the DS surface was wiped up with pre-weighed lint-less paper towels. Diagrams of the gutters and splash shields mounted on the DS are shown in Figure 9. Six breaches and four gutters were used during the tests. The numbering system for the breaches is shown in Figure 4 and the numbering system for the gutters and splash shields is shown in Figure 9.

Water was collected from the gutters and splash shields in the same manner as it was collected from the DS surface. Water was wiped up with pre-weighed lint-less paper towels from gutters and splash shields, then weighed to determine the net moisture picked up by the towels. Water mass collected through breaches was determined by pre-weighing the collection pans then weighing them again following each test. The water masses collected at each station (i.e., breaches 1-6, gutters 1-4, and splash shields 1-4) were recorded by hand on data sheets then attached in the scientific notebook.

In the course of the testing it became evident that exposed towels could exchange moisture mass with the test chamber air for a net mass gain or loss. In order to provide data on the possible mass change for exposed towels, a reference towel was used in tests starting with the single patch tests for the rough DS surface. These data were applied only to the towels used to prevent splashing in the breach collection pans because the towels used to swab water from the DS, gutters, and splash shields were either weighed shortly before use or placed in pre-weighed sealed containers before and after use.

2.5 SUPPORTING MEASUREMENTS

Supporting measurements were those additional measurements that did not contribute directly to the collection of water, but provided additional data to add to the understanding of water pathways, in the form of rivulet flow and evaporation from the DS surface. These additional measurements include pan evaporation, water temperature, and rivulet spread. These measurements were not taken during every test, but enough measurements were taken to provide sufficient data to understand these processes.

2.5.1 Pan Evaporation Measurements

Evaporation in the test chamber was measured during tests with a 20.3-cm by 20.3-cm square plastic pan. The procedure used was to fill the pan with enough water to just cover the bottom then weigh the pan and water before and after the test. The pan was weighed without water to get a tare weight of 67.7 grams (Howard 2002a, p. 70). The evaporation pan data is not a direct representation of evaporation from the DS surface because of the differences between the exposed water surface area on the DS surface and the pan. The evaporation pan data is used as a general reference for the evaporation potential inherent under chamber conditions.

2.5.2 Rivulet Spread Measurements

Rivulet spread measurements were taken as a part of the initial tests on the smooth and rough DS surfaces to provide data for determining the impact locations for the formal testing. The practice of measuring the maximum and minimum rivulet spread was made a part of the data collection routine during the single patch q(film) tests on the smooth DS surface. Measurements were performed with a commercial ruler or tape measure from the axial line of drip impact down the face of the DS. The convention for measurement direction was positive to the DS right and negative to the DS left when facing the DS front. Measurements were recorded to the nearest 0.5-cm.

2.5.3 Water Temperature Measurements

Water temperature measurements were taken during the final week of bounding flow rate tests on the rough DS. The four types of temperature measurements taken were input water, DS beaker water, DS surface water, and air temperature. Descriptions of these measurements are provided in Table 3. The primary objective of these measurements was to collect water temperature data to aid in the understanding of water evaporation from the DS surface.

2.6 INSTRUMENT ACCURACY AND ERROR

Instrument accuracies for the BWPDSE are listed in Table 2 and are stated in the initial entry of the scientific notebook SN-M&O-SCI-043-V1 (Howard 2002a, p. 5). Instrument unique identifiers and their calibration status can be found in the scientific notebook and in Appendix A of this report.

There were two different analytical balance models used during the tests, each model having a different specification for accuracy. The model used to weigh input water was the same or less accurate than the balance used to weigh collection water. In this scenario, the mass balances test data (see Appendix B) are limited in accuracy by the less accurate model (or input mass). Because of this limitation, the accuracy for the less accurate model was used as the standard for water masses during the test and the mass balance data reported in Appendix B of this report has been truncated to reflect this.

3. TEST MATRIX

The tests conducted during the BWPDSE on both smooth and rough DS surfaces include initial (or preliminary) splash radius (drip splash) and spread factor, single patch q(splash), single patch q(film), and multiple patch tests. The test descriptions and geometries are presented in the following sections. A list of the tests conducted for the BWPDSE is provided in Table 4.

3.1 INITIAL TESTS

3.1.1 Initial Splash Radius Tests on the Smooth DS Surface

The objective of the splash radius tests was to determine the splash distance from the point of drip impact. The two measurements of interest from the splash radius tests are: 1) the radius of the bulk or cluster of splash droplets that accumulate around the impact point, and 2) the farthest drip splash thrown from the impact point which is referred to as the fringe. The data in these tests were used to set the impact point distance from the patch (breach) center in the single patch q(splash) tests. Two splash radius tests were conducted on the smooth DS surface.

3.1.1.1 Splash Radius Test #1 – Smooth DS

Splash radius test #1 was performed by dripping deionized (DI) water on the DS crown at a location of 27 cm from the DS centerline as illustrated in Figure 10 (The DS centerline is centered on Patch 6). The drops were counted and the drip radius measurements were taken at regular intervals during the test. Drip measurements were taken along three axes at 0°, 90°, and 180° (see Figure 10). The distance from the drip injection point to the impact point was 2.17 m. The patch located at the crown was covered to prevent water from entering. Relative humidity, temperature, and barometric pressure were measured inside and outside of the test chamber before and after the test.

3.1.1.2 Splash Radius Test #2 – Smooth DS

Splash radius test #2 was performed by dripping DI water with Blue #1 food coloring on the DS centerline at 33° from the crown as illustrated in Figure 11. The drops were counted and the drip radius measurements were taken at regular intervals during the test. Measurements were reported to the nearest whole cm. Drip measurements were taken along three axes at 0, 180, and 270 degrees (see Figure 11). The distance from the drip injection point to the impact point was 2.31 m. Patch #2 was covered to prevent water from entering. Relative humidity, temperature, and barometric pressure were measured inside and outside of the test chamber before and after the test.

3.1.2 Initial Spread Factor Tests on the Smooth DS Surface

The objective of the spread factor tests was to determine the lateral rivulet spread distance from the drip impact point. The data collected in these tests was used to set the impact point distance from the patch (breach) center in the single patch q(film) tests.

3.1.2.1 Spread Factor Test #1 – Smooth DS

Spread factor test #1 was performed by dripping DI water on the DS Crown at a location of 27 cm from the DS centerline as illustrated in Figure 12. The drops were counted and rivulet spread measurements were taken at regular intervals during the test. The pump was stopped to take measurements. The distances from the line of impact on the DS surface to the rivulets were measured at 33°, the transition between the vertical and curved sections, and at the top of the patches on the vertical section. The distance from the drip injection point to the impact point was 2.17 m. The breaches located at the crown (breach 6) and at the vertical center position (breach 2) were covered to prevent water from entering (see Figure 12). Relative humidity, temperature, and barometric pressure were measured inside and outside of the test chamber before and after the test.

3.1.2.2 Spread Factor Test #2 – Smooth DS

Spread factor test #2 was performed by dripping DI water with Blue #1 food coloring on the DS crown at a location of 27 cm from the DS centerline. The test geometry and method used to measure rivulet spread was the same as spread factor test #1 (see Figure 12).

3.1.2.3 Spread Factor Test #3 – Smooth DS

Spread factor test #3 was performed by dripping DI water with Blue #1 food coloring on the DS crown at a location of 27 cm from the DS centerline. The drops were allowed to accumulate on the DS surface and form rivulets without stopping the pump. After a period of time when several rivulets had formed, the pump was shut off and the rivulet spread was measured for each rivulet that remained on the DS. The measurement convention was positive for rivulets to the right of the drip impact center and negative for rivulets to the left. The distances from the line of impact to the rivulets were measured at 33°, the transition between the vertical and curved sections, and at the top of the patches on the vertical section. The distance from the drip injection point to the impact point was 2.17 m. The breaches located at the crown (breach 6) and at the vertical center position (breach 2) were covered to prevent water from entering. The geometry was the same as that used in spread factor test #1 (see Figure 12). Relative humidity, temperature, and barometric pressure were measured inside and outside of the test chamber before and after the test.

3.1.2.4 Spread Factor Test #4 – Smooth DS

Spread Factor Test #4 was performed by dripping DI water with blue #1 food coloring on the DS centerline at 33° as illustrated in Figure 13. The method used to collect measurements was the same as spread factor test #3. The distance from the drip injection point to the impact point was 2.31 m. The breaches located at the crown (breach 6) and at the vertical center position (breach 2) were covered to prevent water from entering (see Figure 13). Relative humidity, temperature, and barometric pressure were measured inside and outside of the test chamber before and after the test.

3.1.3 Initial Splash Radius Tests on the Rough DS Surface

Splash radius tests were conducted on the rough DS surface with the same method as those conducted on the smooth DS surface, however, the test matrix was modified to provide more data that represents characteristics of the rough surface. Three test drip impact locations were tested on the rough DS surface at the crown, 16.5°, and 33°. Because the rough DS surface reacted differently than the smooth surface, three replicate tests were performed at the crown drip impact location. The data in these tests were used to set the impact point distance from the patch (breach) center in the single patch q(splash) tests.

3.1.3.1 Splash Radius Tests #1 - #3 – Rough DS

Splash radius tests #1 through #3 on the rough DS surface were performed in the same manner as splash radius test #1 conducted on the smooth DS surface. DI water was dripped on the DS crown at a location of 27 cm left of the DS centerline as illustrated. The methods and geometry were the same as splash radius test #1 on the smooth DS surface, with the exception that the drip impact location was located to the left of DS center instead of the right as illustrated in Figure 9.

3.1.3.2 Splash Radius Tests #4 and #5 – Rough DS

Splash radius tests #4 and #5 on the rough DS surface were performed by dripping DI water at a location of 27 cm from the DS centerline at 33° and 16.5°, respectively. The method was the same as that used in splash radius tests #1 - #3. The geometry for tests #4 and #5 differ with drip impact points located at 33° (2.31-m drop distance) and 16.5° (2.22-m drop distance).

3.1.4 Initial Spread Factor Tests on the Rough DS Surface

Spread factor tests were conducted on the rough DS surface with the same method as those conducted on the smooth DS surface. Three drip impact locations were tested on the rough DS surface at the crown, 16.5°, and 33°. Spread factor tests #1, #2, and #3 on the rough DS surface were performed by dripping DI water at a location of 27 cm left of the DS centerline at 16.5°, 33°, and the crown, respectively. The drops were allowed to accumulate on the DS surface and form rivulets without stopping the pump. After a period of time when several rivulets had formed, the pump was shut off and the rivulet spread was measured for each rivulet that remained on the DS. The measurement convention was positive for rivulets to the right of the drip impact center and negative for rivulets to the left. The distances from the line of impact to the rivulets were measured at 33°, the transition between the vertical and curved sections, and at the top of the patches on the vertical section.

3.2 SINGLE PATCH q(SPLASH) TESTS

The objective of the single patch q(splash) tests was to collect splash droplets only (excluding rivulets flow) that entered target breaches 4, 5, and 6 while water was dripped onto the DS section at a impact point within the bulk radius of splash determined in the splash radius tests. The single patch q(splash) tests were performed by dripping DI water on the DS at a locations determined during the initial splash radius tests for a period long enough to allow a sufficient collection of water in the breaches of interest. Breach 2 was covered to prevent water entry (see Figures 14 and 15). Relative humidity, temperature, and barometric pressure were measured inside and outside of the test chamber before and after the tests.

3.2.1 Single Patch q(splash)Tests on the Smooth DS Surface

The drip impact locations for the single patch q(splash) tests conducted on the smooth DS surface are listed in Table 5 and test geometry is illustrated in Figure 14.

3.2.2 Single Patch q(splash) Tests on the Rough DS Surface

The drip impact locations for the single patch q(splash) tests conducted on the rough DS surface are listed in Table 6 and test geometry is illustrated in Figure 15. It was evident during q(splash) tests on the smooth surface that the splash area patterns resulting from some drip locations did not meet the test objective to allow only splashes (excluding rivulet flow) to enter target breaches 4, 5, and 6 (see Section 3.2). For this reason, the number of drip locations was reduced for the single patch q(splash) tests on the rough DS based on observation and test results from the q(splash) tests on the smooth DS.

3.3 SINGLE PATCH q(FILM) TESTS

The objective of the Single Patch q(film) tests was to collect rivulet flows that entered patches 2, 4, and 5 while water was dripped onto the DS section at an impact point within the rivulet spread range determined in the spread factor tests. The single patch q(film) tests were performed by dripping DI water on the DS at locations determined during the initial spread factor tests for a period long enough to allow a sufficient collection of water in the patches of interest. Breaches 1, 3, and 6 were covered to prevent water entry during the smooth DS tests (see Figure 16). No breaches were covered during tests performed on the rough DS surface because the collection of water in the additional breaches did not interfere with target breach collection and additional splash data could be obtained in breach 6 (see Figure 17). Relative humidity, temperature, and barometric pressure were measured inside and outside of the test chamber before and after the test. The single patch q(film) tests were also referred to as rivulet flow tests.

3.3.1 Single Patch q(film) Tests on the Smooth DS Surface

The drip impact locations for the single patch q(film) tests conducted on the smooth DS surface are listed in Table 7 and test geometry is illustrated in Figure 16.

3.3.1 Single Patch q(film) Tests on the Rough DS Surface

The drip impact locations for the single patch q(film) tests conducted on the rough DS surface are listed in Table 8 and test geometry is illustrated in Figure 17.

3.4 MULTIPLE PATCH TESTS

The objective of the multiple patch tests was to collect both splash and rivulet flows that entered all affected patches while water was dripped onto the DS section at regular impact points along the DS axis. Multiple patch tests on the smooth and rough DS surfaces were performed by dripping DI water on the DS at locations shown listed in Table 9 and shown in Figure 18. The drip impact locations in Table 9 and Figure 18 apply to tests on the smooth and rough DS surfaces.

3.5 BOUNDING FLOW RATE TESTS

The objective of these tests was to provide data for the extreme drift seepage conditions to compare with test data performed at the nominal 2.0 m^3/yr rate during the single and multiple patch tests. The bounding flow rate tests were carried out at seepage rates of 0.2 m^3/yr and 20 m^3/yr. The bounding flow rate tests on the smooth and rough DS surfaces were performed by dripping DI water on the DS at locations listed in Table 10, which represent nine of the drip impact locations used in the multiple patch tests (see Figure 18). The low flow rate (0.2 m^3/yr – nominal) tests were performed for approximately five hours for each location, while the high flow rate (20 m^3/yr – nominal) were performed for approximately10 minutes. The drip impact locations in Table 10 apply to tests on the smooth and rough DS surfaces.

4. TEST DATA

4.1 BWPDSE TEST DATA TRACKING NUMBERS

Data submittals outlined in this section represent data generated during the BWPDSE and logged in the scientific notebooks (Howard 2002a and Howard 2002b). Test data tracking numbers (DTNs) and titles for the BWPDSE are listed below:

Atlas Breached Waste Package and Drip Shield Experiments: Initial Tests for Rough Drip Shield Surface, DTN: MO0207EBSATBWP.021
Period: 6/26/2002 to 6/28/2002

Atlas Breached Waste Package and Drip Shield Experiments: Initial Tests for Smooth Drip Shield Surface, DTN: MO0207EBSATBWP.022
Period: 5/13/2002 to 5/15/2002

Atlas Breached Waste Package and Drip Shield Experiments: Single Patch q(splash) and q(film) Tests on the Smooth Drip Shield Surface, DTN: MO0207EBSATBWP.023
Period: 5/16/2002 to 6/1/2002

Atlas Breached Waste Package and Drip Shield Experiments: Multiple Patch Tests for Smooth Drip Shield Surface, DTN: MO0207EBSATBWP.024
Period: 6/3/2002 to 6/14/2002

Atlas Breached Waste Package and Drip Shield Experiments: Bounding Flow Rate Tests on the Smooth Drip Shield Surface, DTN: MO0207EBSATBWP.025
Period: 6/14/2002 to 6/24/2002

Atlas Breached Waste Package and Drip Shield Experiments: Single Patch q(splash) and q(film) Tests on the Rough Drip Shield Surface, DTN: MO0208EBSATBWP.026
Period: 7/11/2002 to 7/16/2002

Atlas Breached Waste Package and Drip Shield Experiments: Multiple Patch Tests on the Rough Drip Shield Surface, DTN: MO0208EBSATBWP.027
Period: 6/28/2002 to 7/25/2002

Atlas Breached Waste Package and Drip Shield Experiments: Bounding Flow Rate Tests on the Rough Drip Shield Surface, DTN: MO0208EBSATBWP.028
Period: 7/16/2002

4.2 BWPDSE TEST OBSERVATIONS AND DATA ANALYSIS

4.2.1 Initial Test Observations

The purpose of this section is to summarize the observations of the initial tests performed on the smooth and rough DS surfaces. Observations were particularly made with respect to droplet formation and rivulet spread in the splash radius and spread factor tests. Droplet formation for the smooth and rough DS surfaces was documented in photos for some of the initial tests. (Howard 2002a and Howard 2002b).

4.2.1.1 Observations during Initial Tests Performed on the Smooth DS Surface

An example of water droplet formation is presented in a photograph from splash radius test #1 in Figure 19. 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. Droplet splashing was observed on the crown as well as the curved drip shield surface within the tested seepage area (above the 33^{o} line). No film flow was observed during tests on the smooth DS surface.

The maximum lateral splash radius observed in splash radius test #1 was 72.5 cm after 60 drops. As a comparison, the longest lateral splash distance observed in spread factor test #2 was 71.0 cm after 478 drops. To determine the distance to be used in the q(splash) tests, a value of 70.0 cm was multiplied by 0.25 for a final distance of 17.5 cm, which falls within the cluster values observed in the splash test observations after sufficient mass had been deposited on the DS surface to allow regular splashing from impact on water droplets.

When water was dripped at the crown, the rivulet flow area spreads out in a delta formation, meaning maximum spread was located on the vertical section of the DS and the minimum spread was located at the point of impact. The delta formation spread was less for drip impact locations on the 33^{o} line. Spread distances, distance from the patch/breach center, used during the single patch q(film) tests for breaches 2, 4, and 5 were based on spread distances measured during impact on the crown. The spread distances used for the single patch tests on the smooth DS surface were: breach 2, 15 cm from patch center; breach 4, 8.0 cm from patch center; and breach 5, 4.0 cm from patch center.

4.2.1.2 Observations during Initial Tests Performed on the Rough DS Surface

On the rough DS surface water beads formed from splashing would lead to the formation of small pools with constant dripping. A large pool would form around the drip impact center and spread. A photograph showing water pooling around the impact center is provided in Figure 20. Rivulet flow began much later on the rough DS surface after the pools grew large enough to reach the DS slope, causing the pools to drain down the DS face. As observed on the smooth drip shield surface, droplet splashing occurred on the curved section within the tested seepage area (above the 33^{o} line). Film flow was not observed during the tests on the rough DS surface.

The maximum lateral (0^{o} or right) bulk splash radius was observed in splash test #1 at 48.0 cm after 203 drops. The distance used in the q(splash) tests was determined by multiplying a value of 40.0 cm by 0.5 for a final distance of 20 cm. This final distance falls within the cluster values observed in the splash test observations after sufficient mass had been deposited on the DS surface to allow regular splashing from impact on water droplets. The splash radius on the rough DS was less than on the smooth DS surface. The outer splashes on the fringe tended to be smaller and less frequent than the fringe splashes on the smooth DS surface.

The spread factor distances used in the q(film) flow tests were designed to allow either all or a portion of the rivulets formed up gradient to enter at breaches 2, 4, and 5. The rivulet spread distances from the drip centerline were much less on the rough DS surface than on the smooth DS. In many cases, rivulets flowed straight down the face of the drip shield with little lateral deviation. In addition, established flow paths were maintained, meaning there was a continuous flow of water in some rivulets. The impact points for the rough DS tests were set at 13.5 cm from the patch centers, or along the edge, for Patches 2, 3, and 4.

4.2.2 Test Data Analysis

Data from the single patch tests, multiple patch tests, and bounding flow rate tests were analyzed by performing a mass balance. As a part of the analysis the percentages were determined for water collected in each station as a function of the total input. Seepage rate, pan evaporation, and reference towel data were included as references. These data are listed in Appendix B with the test chamber environment conditions. A complete representation of the data is found in the TDMS submittals (see Section 4.1). The values listed in Appendix B have been truncated to the number of significant figures representing the instrument error of the weighing balance (see Section 2.6). Losses determined in the mass balances ranged from around 7% to the mid 50% range. The highest losses were observed during the low flow runs of the bounding flow rate tests. Most of the losses ranged from around 10% to 30%. Losses in the mass balance can be attributed mainly to evaporation of water droplets from the DS surface and other collection surfaces (gutters and splash shields) with some loss attributed to the limitation of the collection procedure, i.e., collecting water by swabbing the DS and collection surfaces. In general, more losses were observed on the rough DS surface over the smooth DS surface. The water collection process, i.e., swabbing water from the DS surface, may have had a greater impact on experimental error than the weighing process. The greater losses observed on the rough DS surface can most likely be attributed to the added difficulty of swabbing water from the roughened texture.

4.2.3 Rivulet Spread Data

The rivulet spread from the impact centerline was measured for a number of tests (see Section 2.5.2). These data are listed in Appendix C. Rivulet spread ranged from 0 to around 45 cm from the drip impact line. In general the smooth DS surface produced a wider spread over the rough DS surface. In many cases on the rough DS, surface rivulet flow would start in a few main rivulets then maintain flow through those rivulets through the duration of the test. The smooth DS surface produced several variable flow paths during the single test.

4.2.4 Water Temperature Data

Water temperature data were collected for the input water and the DS surface water during the last week of testing (see Section 2.5.3). These data are listed in Appendix D. The primary objective of these data was to aid in the understanding of evaporation from the DS surface. The DS surface water temperatures matched the air temperature (within tenths of a ^{o}C) and the DS beaker and input waters were generally lower than the air and DS surface water temperatures.

5. CONCLUSIONS

The purpose of the BWPDSE was to provide data to support the validation and further development of the flux splitting model used in the *EBS Radionuclide Transport Abstraction* (BSC 2001a). The data gathered in these tests represent the possible flow paths that affect the entry of water through corrosion breaches on both smooth and rough DS surfaces. These data were limited by the instrument error information provided in Section 2.6. Uncertainties in the data were based primarily on limitations of the collection process, which was performed by swabbing up water from the DS surfaces, gutters, and splash shields. The differences in the water mass collection and seepage input (see Appendix B) can be attributed primarily to evaporation from the DS and other collection surfaces. The evaporation process from beaded water droplets on flat surfaces was much greater than the measured pan evaporation. It was evident from the bounding flow rate data that evaporation losses were greater when the test time was lengthened. Evaporation processes played a substantial role in water losses during the BWPDSE and should be investigated further. The following items summarize the conclusions of the BWPDSE:

- The primary flow mechanism on both smooth and rough surfaces was rivulet flow, not film flow.
- Lateral rivulet spread distances were, in general, wider on the smooth DS surface than on the rough DS surface.
- There were substantial differences between the mechanisms of rivulet formation and movement on smooth and rough DS surfaces.
- Water collected in breaches was a function of the location of drip impact upstream from the target breach, i.e., impact location must be directly above or slightly to the side of the breach in order for a substantial volume of water to collect in breach.
- Splash droplets contribute a small portion of the water collected in breaches.
- Mass balances showed that evaporation from the DS was a large component of water loss. This was particularly manifested during low flow runs of the bounding flow rate tests where test duration was around 5 hours.
- Mass balances were affected to some degree by the water collection process. This was manifested in the losses observed between tests conducted on the smooth and rough DS surfaces.

6. AKNOWLEDGMENTS

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7.3 OUTPUT DATA

MO0207EBSATBWP.021. *Atlas Breached Waste Package and Drip Shield Experiments: Initial Tests for Rough Drip Shield Surface.* Submittal date: July 31, 2002.

MO0207EBSATBWP.022. *Atlas Breached Waste Package and Drip Shield Experiments: Initial Tests for Smooth Drip Shield Surface*. Submittal data: July 31, 2002

MO0207EBSATBWP.023. *Atlas Breached Waste Package and Drip Shield Experiments: Single Patch q(splash) and q(film) Tests on the Smooth Drip Shield Surface*. Submittal data: July 31, 2002.

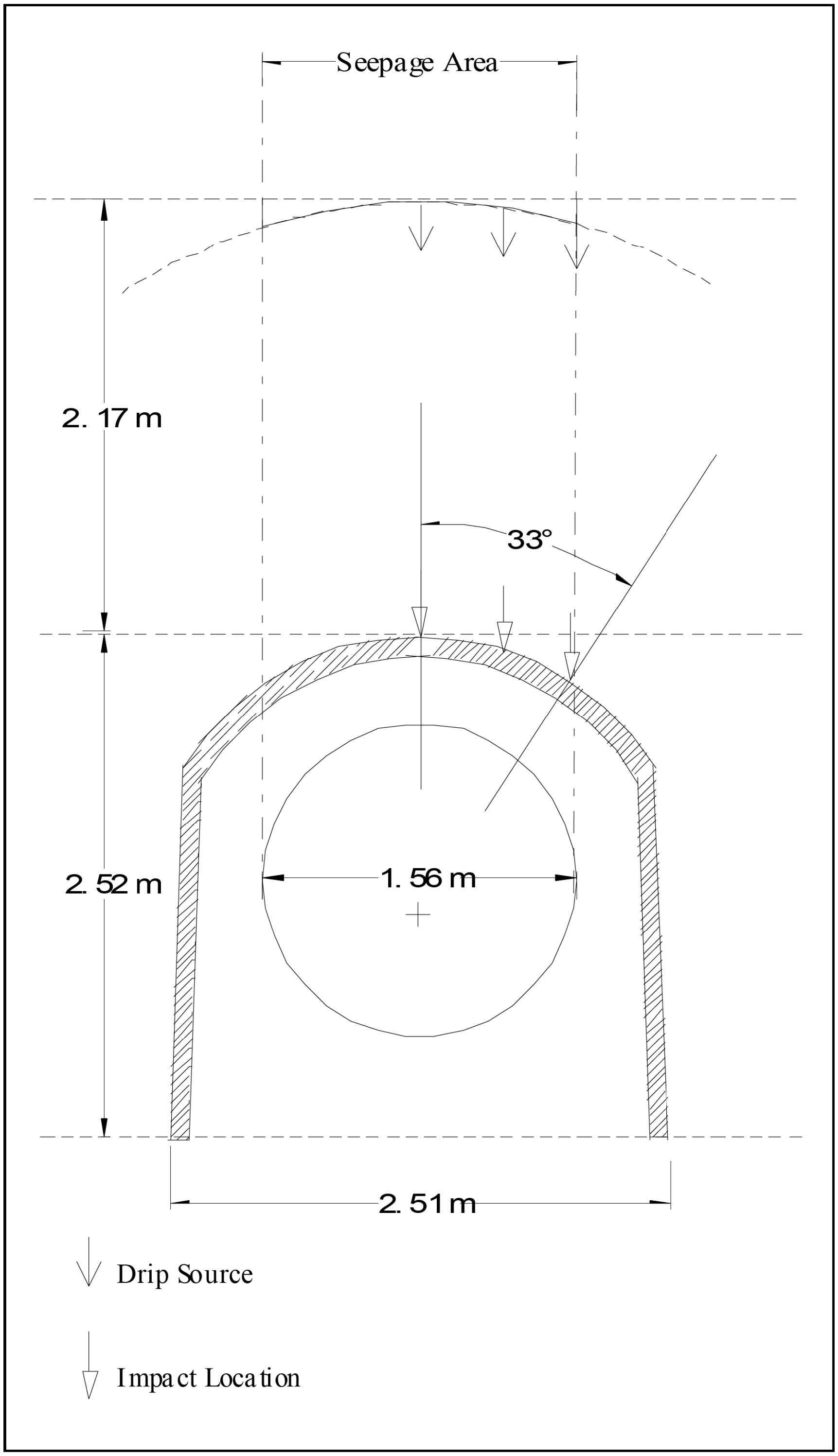
MO0207EBSATBWP.024. *Atlas Breached Waste Package and Drip Shield Experiments: Multiple Patch Tests for Smooth Drip Shield Surface*. Submittal data: July 31, 2002.

MO0207EBSATBWP.025. *Atlas Breached Waste Package and Drip Shield Experiments: Bounding Flow Rate Tests on the Smooth Drip Shield Surface*. Submittal data: July 31, 2002.

MO0208EBSATBWP.026. *Atlas Breached Waste Package and Drip Shield Experiments: Single Patch q(splash) and q(film) Tests on the Rough Drip Shield Surface*. Submittal data: August 13, 2002.

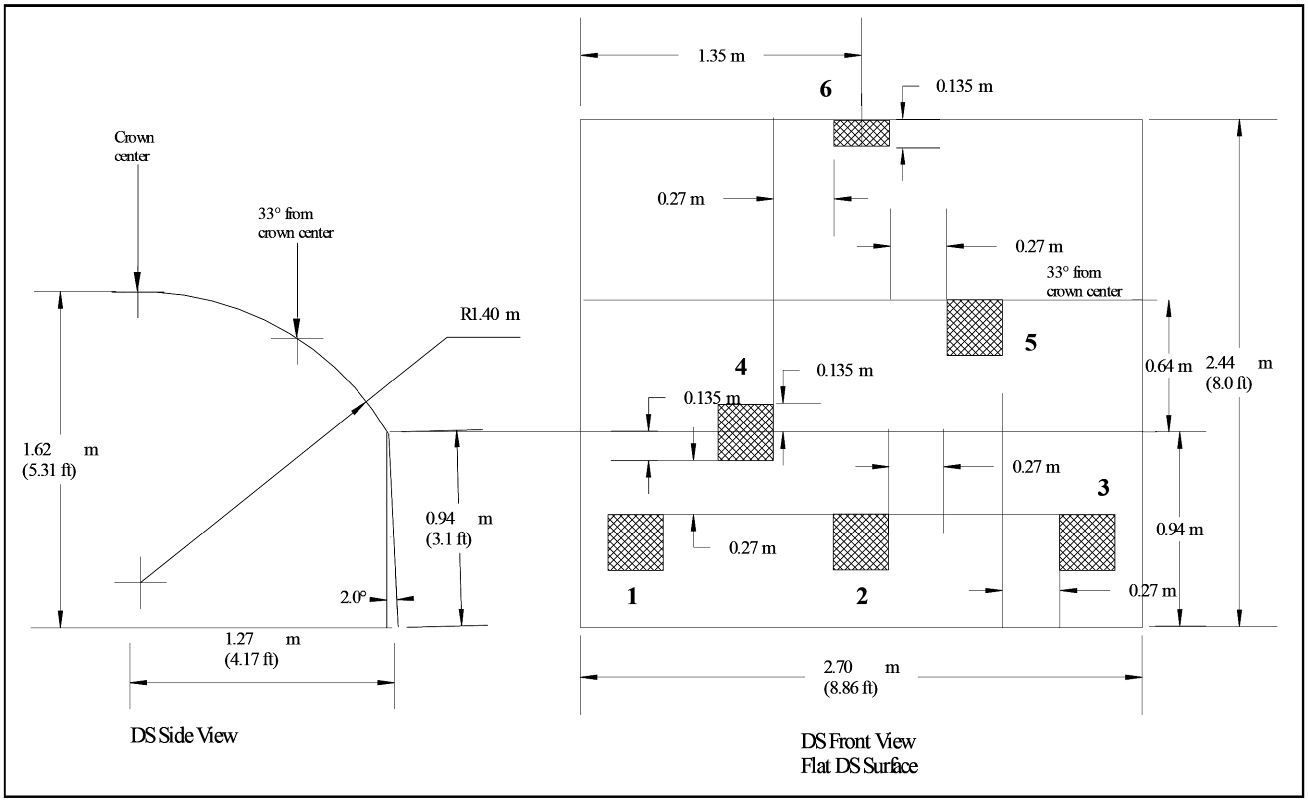
MO0208EBSATBWP.027. *Atlas Breached Waste Package and Drip Shield Experiments: Multiple Patch Tests on the Rough Drip Shield Surface*. Submittal data: August 13, 2002.

MO0208EBSATBWP.028. *Atlas Breached Waste Package and Drip Shield Experiments: Bounding Flow Rate Tests on the Rough Drip Shield Surface*. Submittal data: August 13, 2002.



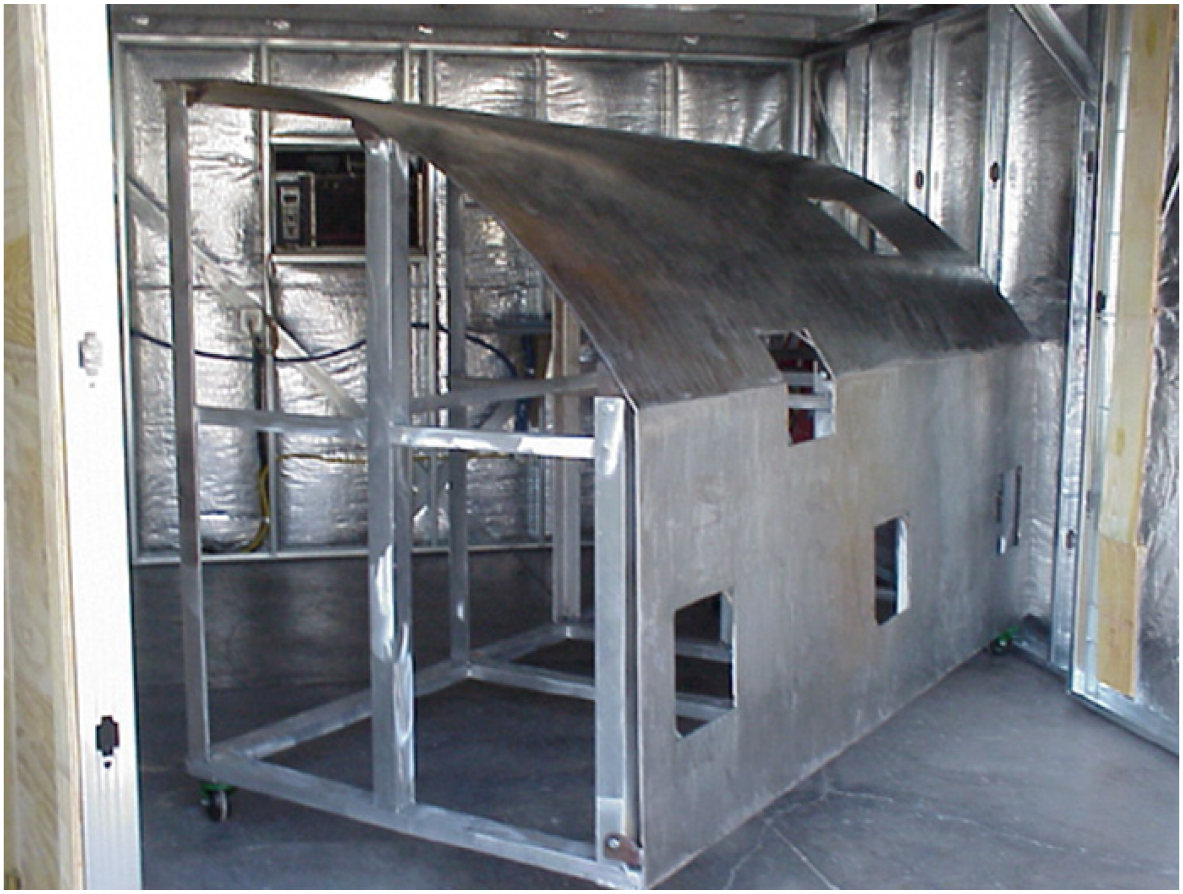
Source: Howard 2002c, p. 111.

Figure 1. Seepage Area Represented in the BWPDSE



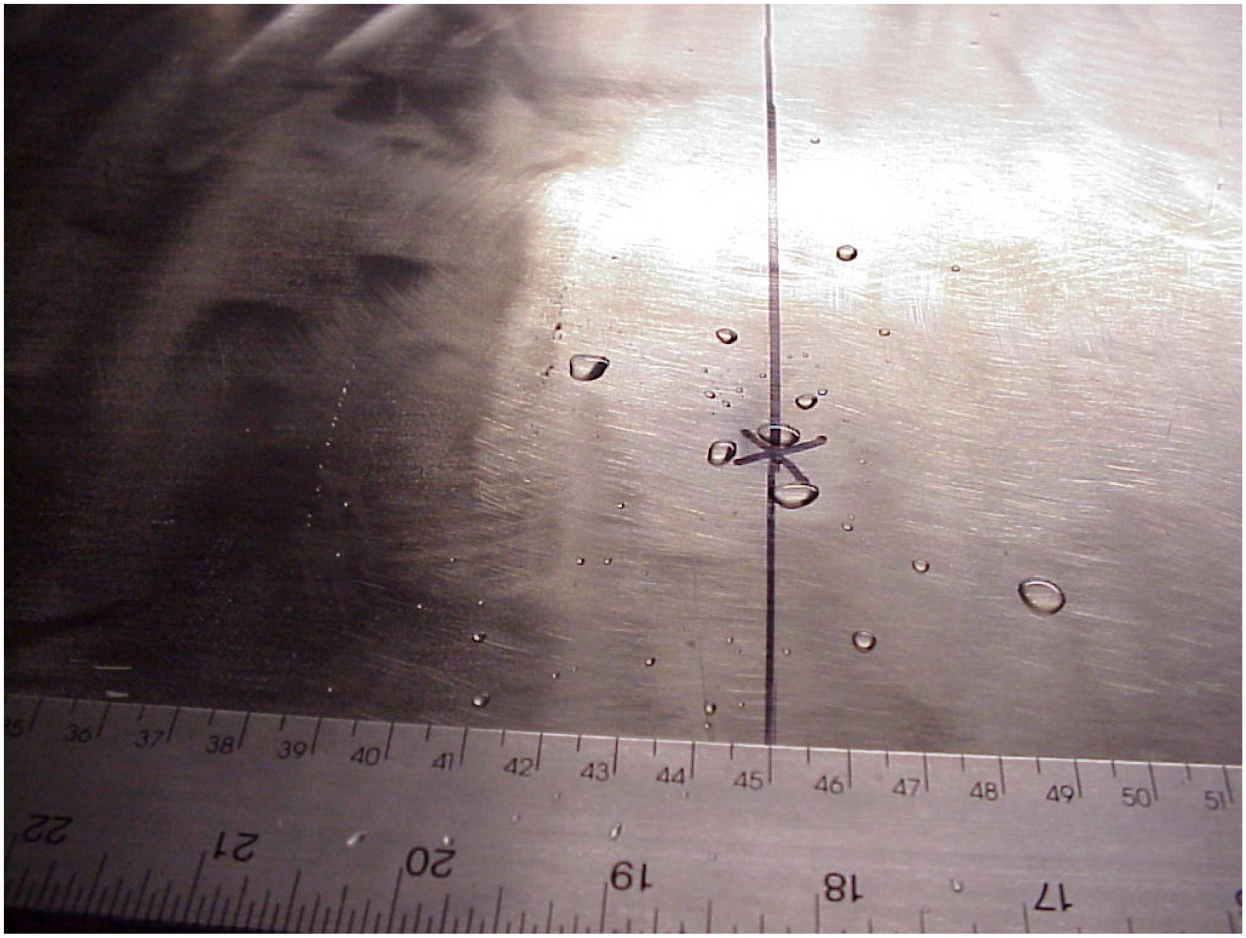
Source: Howard 2002a, p. 14.

Figure 2. BWPDSE Drip Shield Dimensions and Patch Locations



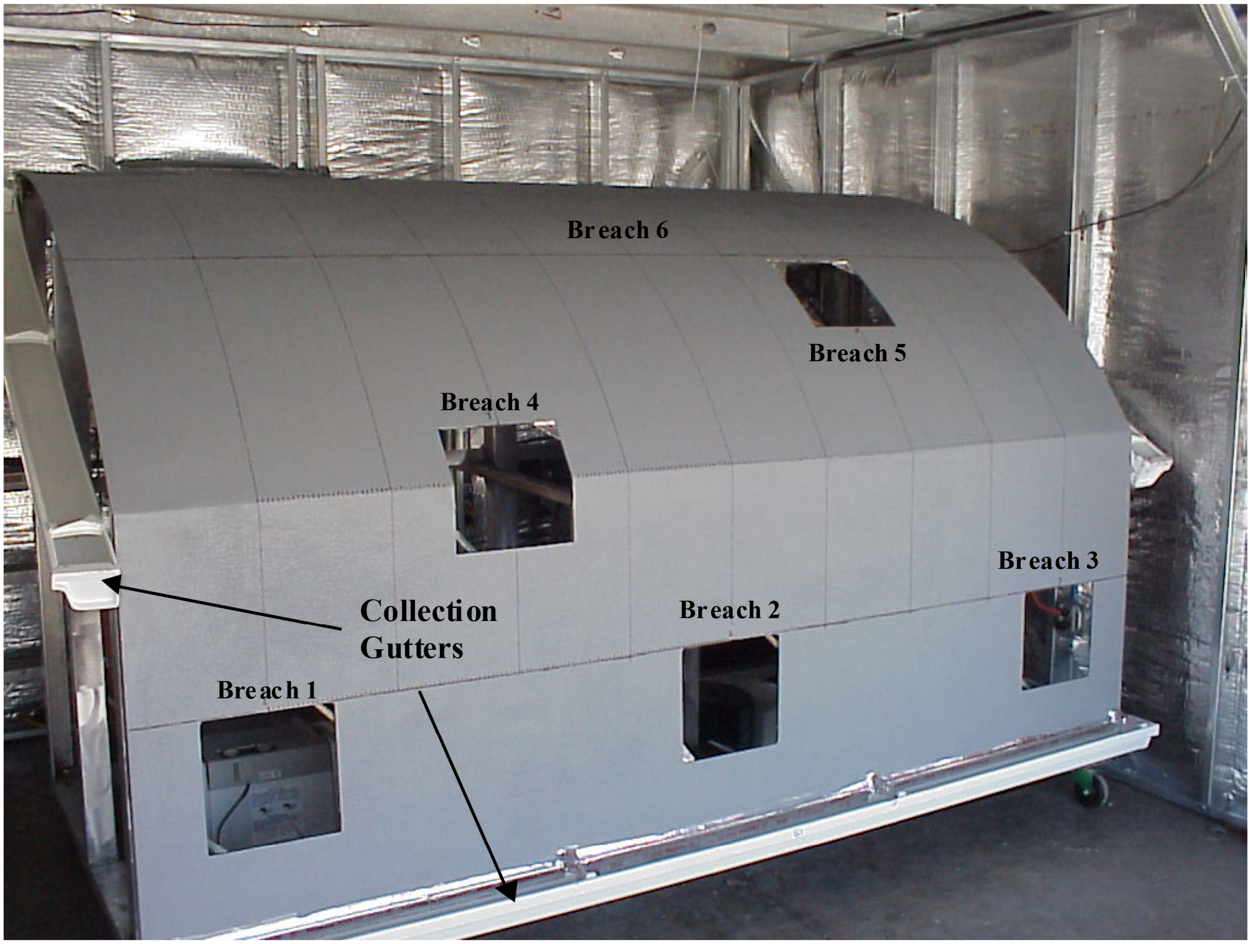
Source: Howard 2002a, p. 16.

Figure 3. Stainless Steel Drip Shield Section



Source: Howard 2002a, p. 42.

Figure 4. Polished Stainless Steel Drip Shield Surface (Splash Radius Test #1 - 2 Drops)



Source: Howard 2002c, p. 112.

Figure 5. Rough Drip Shield Surface with Collection Gutters