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TESTING CRITERIA

FOR

BYPASS LEAKAGE TESTING

OF

DRYWELL-TO-WETWELL INTERFACE

FOR

ESBWR NUCLEAR POWER PLANTS

ILRT INC.
PALM HARBOR, FLORIDA

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TECHNICAL REPORT

TESTING CRITERIA FOR BYPASS LEAKAGE TESTING OF DRYWELL-TO-WETWELL INTERFACE FOR ESBWR NUCLEAR POWER PLANTS

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1.0 INTRODUCTION

The ESBWR designed by General Electric-Hitachi uses a passive design in response to a loss-of-coolant (LOCA) accident. This requires that no operator action is needed for 72 hours after a LOCA. The PCCS operates by natural circulation. Its operation is initiated by the difference in pressure between the drywell and the wetwell, which are the two primary contained volumes of the ESBWR pressure suppression type containment system. The drywell and wetwell vacuum breakers serve to allow controlled communication between these volumes. They must fully close after each demand to support the PCCS operation. If a vacuum breaker does not close when required, a backup isolation valve will close.

The design incorporates three (3) vacuum breakers between the wetwell and the drywell. During normal plant operation, the inerted wetwell and the drywell volumes remain at a pressure slightly above atmospheric conditions. However, certain events could lead to a depressurization transient that can produce a negative pressure differential in the containment. A drywell depressurization results in a negative pressure differential across the drywell walls, vent wall, and diaphragm floor. A negative pressure differential across the drywell and wetwell walls means that the RB pressure is greater than the drywell and wetwell pressures, and a negative pressure differential across the diaphragm floor and vent wall means that the wetwell pressure is greater than the drywell pressure. If not mitigated, the negative pressure differential can damage the containment steel liner. The ESBWR design provides the vacuum relief function necessary to limit these negative pressure differentials within design values.

The concept of the pressure suppression reactor containment is that any steam released from a pipe rupture in the primary system is condensed by the wetwell, and thus, does not produce a significant pressurization effect on the containment. This is accomplished by channeling the steam into the wetwell water volume through a vent system. If a leakage path were to exist between the drywell and the wetwell gas space, the leaking steam would produce undesirable pressurization of the containment. The analytical limit for testing drywell to wetwell bypass leakage assumes a bypass leakage area of 2 cm^2 (2.15 E-03 ft^2), ($A/\sqrt{k}$). Thus, it is extremely important that the vacuum breakers remain leak tight to prevent bypass of steam into the wetwell that would result in exceeding the containment design pressure.

2.0 DRYWELL-TO-WETWELL BYPASS TESTING METHODOLOGY

2.1 Regulatory Requirements

NUREG-0800, Standard Review Plan 6.2.1.1.C, “Pressure-Suppression Type BWR Containments,” Appendix A requires that pre-operational and periodic leakage tests be conducted to detect leakage in the drywell to suppression chamber vent piping, penetration downcomers, vacuum breakers, floor seals, vent seals, and the diaphragm. This test should be performed at each refueling outage at a differential pressure corresponding to approximately the submergence of the vents.
The capability for steam bypass for small primary system breaks in the Mark I, II, and III containment design are as follows: the Mark I design is of the order of 18.6 cm^2 (0.02 ft^2), the capability of the Mark II containment is approximately 46.5 cm^2 (.05 ft^2), and the Mark III design has a capability of $A/\sqrt{k}$ = 929 cm^2 (1 ft^2).

The Mark II and Mark III acceptance criteria for both the high and low pressure leakage tests shall be a measured bypass leakage which is less than 10% of the capability of the containment. For Mark I containment the acceptance criterion is that the measured leakage is not greater than the leakage that could result from a 2.54 cm (one inch) diameter opening. In comparison to the design capability for Mark I containments, this is an acceptance criteria for measured bypass leakage that is 27.2% of the design.

2.2 Historical Test Practices

The current test methodologies used include monitoring pressure drop in the drywell or pressure rise in the suppression pool, determining $A/\sqrt{k}$ based on volumetric flow and flow velocity, and measuring makeup flow to the drywell to maintain the required differential pressure between the drywell and containment (Mark III).

Monitoring the pressure drop or pressure rise is the most commonly used method. This method does not actually determine the value of $A/\sqrt{k}$ but compares the pressure drop or pressure rise to a curve based on the allowable $A/\sqrt{k}$ value. It requires that assumptions be made based on temperature in the drywell or suppression pool. Test durations typically range from ten (10) minutes to four hours. This method is used by Mark I and some Mark II and Mark III containments.

Determining $A/\sqrt{k}$ based on volumetric flow and flow velocity is most commonly used in conjunction with the Integrated Leakage Rate Test. Using the already installed pressure, drybulb temperature, and relative humidity instrumentation, the volumetric flow rate and flow velocity into the suppression pool is determined and used to calculate $A/\sqrt{k}$ based on volumetric flow and flow velocity. No assumptions are required concerning temperature, since drywell and suppression pool temperature are measured. Test durations are typically two (2) hours, after a one hour stabilization. This method is primarily used by some Mark II containments.

At least two Mark III containments perform a flow makeup test. The acceptable $A/\sqrt{k}$ value is used to determine an acceptable flow rate based on a measured or assumed temperature in the drywell. Test duration is approximately two (2) to four (4) hours and requires using portable rented air compressors to supply the makeup flow.

For existing Mark I containments, the bypass test frequency is once per refueling or once per operating cycle. The low differential pressures allow some Mark I containments to perform the bypass test on-line by using the drywell inerting pressure. The Mark I containment vacuum breakers are not capable of being individually local leakage rate tested.

For existing Mark II containments, most plants have received Technical Specification changes to allow the bypass test to be conducted on the same frequency as the Integrated Leakage Rate Test (ILRT), which is currently once per 10 years (120 months). The vacuum breakers are then individually locally leakage rate tested every refueling outage (24 months).

For existing Mark III containment, most plants have received Technical Specification changes to allow the bypass test to be conducted on the same frequency as the Integrated Leakage Rate Test (ILRT), which is currently once per 10 years (120 months). There are no vacuum breakers associated with Mark III containments.

2.3 ESBWR Bypass Test Procedure

Based on the experience of ILRT Inc., the recommended test approach for the ESBWR bypass test should be based on determining $A/\sqrt{k}$ using volumetric flow and flow velocity on a frequency coincident with the ILRT. This approach is recommended based on:

- Using the calibrated instrumentation already in place for the ILRT
- Ability to measure the drywell and wetwell pressures, humidities, and drybulb temperatures
- Calculating the mass transfer across the drywell to wetwell diaphragm floor
- Reporting the results at the 95% upper confidence limit

Current industry practice for drywell to wetwell bypass testing is to perform the testing coincident with the Integrated Leakage Rate Test (ILRT). The current regulatory frequency for the ILRT is once every 120 months (10 years). However, there is a current industry initiative, headed by the Nuclear Energy Institute (NEI), to extend this interval to once per 180 months (15 years). The ESBWR Bypass test frequency should coincide with the ILRT frequency. In addition, individual local leakage rate testing of the drywell to wetwell vacuum breakers is conducted every 24 months (refueling outage).

The analytical limit for testing drywell to wetwell bypass leakage assumes a bypass area of 2 cm^2 (2.15E-03 ft^2), ($A/\sqrt{k}$). The proposed acceptance criteria for the drywell to wetwell bypass test is an $A/\sqrt{k}$ of 1.0 cm^2 (1.076E-03 ft^2), which is 50% of the design value.

NUREG-0800, Standard Review Plan Section 6.2.1.1.c, Appendix A, requires a test $A/\sqrt{k}$ value that is 10% of the design $A/\sqrt{k}$ value for Mark I and Mark II containments and a test $A/\sqrt{k}$ value that is 27.2% for Mark I containments. However, due to the limited number of drywell to wetwell penetrations through the diaphragm floor and the most credible leakage paths being through the vacuum breakers, General Electric-Hitachi is proposing a test $A/\sqrt{k}$ that is 50% of the design value.

The proposed acceptance criterion for the total leakage through the vacuum breaker/vacuum breaker isolation valve pairs is a leakage rate equivalent to 35% of the leakage through analytical testing bypass area ($A/\sqrt{k}$) of 2.0 cm^2 or 70% of the leakage through the allowable bypass area ($A/\sqrt{k}$) of 1.0 cm^2. The total leakage rate will be determined by summing the maximum pathway leakage from each pair of vacuum breaker and vacuum breaker isolation valves. Maximum pathway leakage is defined in ANSI/ANS 56.8-1994 (reference 7.4).

This provides a margin of 65% to the analytical bypass area and a margin of 30% to the Technical Specification limit for the allowable bypass area. This provides a large, conservative margin to accommodate the remaining potential leakage area through the passive structural components. Mark II containment drywell-to-suppression chamber bypass test data (refer to Section 4.1) indicates that the bypass leakage through the passive structural components will be much less than the 65% margin. The combined vacuum breaker/vacuum breaker isolation valve leakage limit, with the negligible passive structural leakage area, ensures that the drywell-to-wetwell bypass leakage limit is met for those outages for which the drywell-to-wetwell chamber bypass test is not scheduled.

The proposed acceptance criterion for the individual leakage of each vacuum breaker and each vacuum breaker isolation valve is leakage rate equivalent to 15% of the design bypass area ($A/\sqrt{k}$) of 2.0 cm^2 or 30% of the allowable bypass area ($A/\sqrt{k}$) of 1.0 cm^2. This criterion is stipulated to identify vacuum breakers or vacuum breaker isolation valves with a higher leakage area.

The bypass test frequency coincident with the ILRT has been approved by the NRC for Columbia Generating Station, Nine Mile Point Unit 2, Susquehanna Steam Electric Station Units 1 and 2, and Limerick Generating Station Units 1 and 2. (References 7.6 – 7.10)

The ESBWR vacuum breakers are capable of being individually local leakage rate tested. Existing 10CFR50 Appendix J instrumentation and methodology can be used to perform these tests at a refueling outage interval.

The ESBWR drywell-to-wetwell bypass test is performed in much the same manner as in existing BWR Mark II containments with the bypass test conducted in conjunction with the Integrated Leakage Rate Test (ILRT).

For the conduct of the ILRT, systems penetrating containment are aligned per the requirements of 10CFR50, Appendix J with communication established between the drywell and wetwell air spaces. The containment structure is then pressurized to the calculated peak containment accident pressure and the ILRT is conducted. To prevent the drywell and wetwell from communicating during the Bypass Test, the PCCS vent line spectacle flanges must be rotated to the closed position and the Isolation Condenser vent line block valves must be closed. Since the spectacle flanges are located inside the wetwell, they must be rotated to the closed position prior to the start of pressurization for the ILRT.

Following completion of the ILRT, the containment is depressurized to ≥ 2.0 psig and the communication path used during the ILRT from the drywell to the wetwell is isolated. The maximum pressure is influenced by the wetwell water level. With a wetwell level of 5.45 m [17.88 ft], the maximum differential pressure is 15.69 kPa [2.27 psid]. With a wetwell level of 5.5 m [18.04ft], the maximum differential pressure is 16.18 kPa [2.35 psid]. The wetwell water level needs to be maintained constant during the Bypass test. In order to maximize the differential pressure between the two containment volumes (while avoiding uncovering the top horizontal vent), for ease of testing, the wetwell water level should be established high in the allowable band.

The wetwell air space is then depressurized to 0 psig and the wetwell depressurization pathway is isolated. If required, an ILRT air compressor may be re-started to maintain ≥ 2.0 psig in the drywell while the wetwell is depressurized to 0 psig.

When the wetwell reaches 0 psig, the ILRT air compressor, if used to maintain drywell pressure, is isolated. The pressurization line is isolated and vented to prevent makeup flow to the drywell. The drywell pressure and wetwell pressure are recorded to calculate the differential pressure and verify that it is within the required range.

The wetwell water level is recorded and monitored periodically to verify that it is remaining constant. Since the wetwell water level also affects the ILRT, makeup and drains from the wetwell will have been isolated and no change in wetwell water level is expected during the Bypass test.

The drywell and wetwell ambient conditions are allowed to stabilize for approximately one hour. After one hour, using instruments installed for the ILRT, drywell pressure, temperature, and relative humidity and wetwell pressure, temperature, and relative humidity measurements are taken for a minimum of two hours, with a minimum of 30 data points for statistical analysis (reference 7.4). A computer program analyzes the data and calculates a bypass area. Following completion of the Bypass Test, the wetwell is depressurized to 0 psig.

3.0 DRYELL TO WETWELL BYPASS TEST INSTRUMENTATION

The ESBWR containment should be instrumented with precision pressure, drybulb temperature and relative humidity sensors that meet the following instrumentation accuracy, resolution, and repeatability requirements of ANSI/ANS 56.8-1994, "Containment System Leakage Testing Requirements."

Absolute Pressure

Accuracy	± 0.02 psi (± 0.1379 kPa)
Resolution	± 0.001 psi (± 0.0069 kPa)
Repeatability	± 0.005 psi (± 0.0345 kPa)

Drybulb Temperature

Accuracy	± 1.0°F (± 0.55°C)
Resolution	± 0.03°F (± 0.017°C)
Repeatability	± 0.2°F (± 0.11°C)

Relative Humidity

Accuracy	± 3.5% RH
Resolution	± 0.5% RH
Repeatability	± 1.0 %RH

For an ESBWR containment, ILRT Inc. recommends that at least 2 precision pressure gauges, twenty-four (24) drybulb temperature sensors, and twelve (12) humidity sensors be used in the following arrangement:

- One (1) precision pressure gauge is attached to the drywell free air space
- One (1) precision pressure gauge is attached to the wetwell free air space
- Eighteen (18) drybulb temperature sensors in the drywell free air space
- Six (6) drybulb temperature sensors in the wetwell free air space
- Nine (9) relative humidity sensors in the drywell free air space
- Three (3) relative humidity sensors in the wetwell free air space

Temperature sensors and relative humidity sensors are volume weighted according to their assigned free volume.

The instrumentation will be calibrated traceable to the National Institute of Standards and Technology (NIST) not more than six months prior to use or in accordance with the facility's measuring and test equipment (M&TE) control program.

4.0 ANALYSIS METHODS

4.1 Historical Perspective

Due to the passive design of the ESBWR as discussed previously, the analytical steam bypass capability $A/\sqrt{k}$ is 2.0 cm^2 (2.15E-03 ft^2). Although this value is much smaller than those used for existing Mark II containments at 46.5 cm^2 (.05 ft^2), recent historical data for Mark II containments, as shown in the table below, measured bypass areas much smaller than that used for the ESBWR.

Plant	Unit	Year	Calculated Bypass Area (cm^2)	Calculated Bypass Area (ft^2)
Plant A	1	1998	0.0692	0.000075
Plant A	2	1999	0.0114	0.000012
Plant B	1	2006	0.0455	0.000049
Plant B	2	2007	0.0997	0.000107

This indicates that the existing test methodology and test instrumentation are sufficient to determine $A/\sqrt{k}$ values of the magnitude proposed for the ESBWR.

To get an appreciation for the magnitude of the leakage through an allowable bypass area of 1.0 cm^2, it may be beneficial to compare it to allowable 10CFR50 Appendix J leakage rate values for primary containment leakage (ILRT) and for containment isolation valves and penetrations (LLRT).

At normal water level in the wetwell, the ESBWR has a containment free air volume (drywell plus wetwell) of approximately 12764 cubic meters (450,760 cubic feet). Assuming a design basis accident pressure of 45 psig and a maximum allowable leakage rate (L_a) of 0.5% by weight per day, the maximum allowable leakage rate is equivalent to approximately 6.3 scfm. For the Integrated Leakage Rate Test (ILRT), the maximum allowable leakage rate is limited to 0.75L_a or approximately 4.7 scfm. This would correspond to a leakage area of approximately 0.034 cm^2 (0.0052 in^2). This is a much smaller leakage area than proposed test bypass leakage area of 1.0 cm^2 (0.155 in^2). Current ILRT testing instrumentation and testing methodology have been able to measure containment leakage rates much lower than these values. Therefore, the testing methodology and test equipment/instrumentation used on the current BWR generation plants is applicable for the ESBWR drywell to wetwell bypass test.

For local leakage rate testing of all containment isolation valves and penetrations subject to 10 CFR 50, Appendix J, the allowable combined total leakage must be less than or equal 0.6 La or approximately 3.8 scfm (approx 107,900 sccm). For an ESBWR drywell to wetwell bypass test with an allowable $A/\sqrt{k}$ of 1.0 cm^2, and a pressure differential of 2.2 psid, the equivalent flow rate would be approximately 35.72 scfm or 1,011,483 sccm.

The bypass leakage from an effective area of 1.0 cm^2 is more than nine times larger than combined allowable leakage rate from all containment isolation valves and penetrations subject to 10 CFR 50, Appendix J. Therefore, the testing methodology and test equipment/instrumentation used on the current BWR generation plants is applicable for local leakage rate testing of the ESBWR drywell to wetwell vacuum breaker.

At normal water level in the suppression pool, the ESBWR has a containment free air volume (drywell plus wetwell) of approximately 450,760 cubic feet.

Assuming a design basis accident pressure of 45 psig and a maximum allowable leakage rate (L_a) of 0.5% by weight per day, the weight of air in containment can be calculated using the ideal gas law:

$$W = \frac{P\,V\,(144)}{R\,T} = \frac{(45+14.7)\,(450{,}760)\,(144)}{(53.35)\,(70+460)} = 137{,}047.7\ \text{lbm}$$

The mass leakage equivalent to the maximum allowable leakage rate of L_a can be calculated:

$$L_a = \left(\frac{0.005}{\text{day}}\right)(137{,}047.7\ \text{lbm}) = 685.2385\ \text{lbm/day} = 28.55\ \text{lbm/hr} = 0.476\ \text{lbm/min}$$

To calculate the leakage rate in standard volume units, divide by the standard density of air:

$$L_a = \frac{0.476\,\frac{\text{lbm}}{\text{min}}}{0.075\,\frac{\text{lbm}}{\text{scf}}} = 6.35\ \text{scfm}$$

For the Integrated Leakage Rate Test (ILRT), the maximum allowable leakage rate is limited to $0.75L_a$ or approximately 4.76 scfm.

For local leakage rate testing of all containment isolation valves and penetrations subject to 10 CFR 50, Appendix J, the allowable combined total leakage must be less than or equal 0.6La or approximately 3.81 scfm. Converting to sccm:

$$0.6L_a = \left(\frac{3.81\,\text{scf}}{\text{min}}\right)\left(\frac{28317\ \text{scc}}{\text{scf}}\right) = 107{,}888\ \text{sccm}$$

For an ESBWR drywell to wetwell bypass test with an allowable $A/\sqrt{k}$ of 1.0 cm^2, and a pressure differential of 2.2 psid, the equivalent flow rate can be calculated from the following equation (Reference 7.5):

$$M = \frac{A}{\sqrt{k}}\sqrt{(2g_c\,(144)\,dP/\nu)}$$

where:

M = mass flow in lbm/sec

$A/\sqrt{k}$ = effective flow area in square feet

g_c = gravitational constant (32.17 lbm-ft/lbf-s^2)

ΔP = drywell to wetwell differential pressure (lbf/in^2)

For:

$A/\sqrt{k}$ = 1.0 cm^2 = 0.155 in^2 = 0.001076 ft^2

ΔP = 2.2 psig

υ @ 80°F & 16.9 psia = 11.8385 ft^3/lbm for air

$$M = (0.00108)\sqrt{\frac{2\,(32.17)(144)(2.2)}{11.8385}} = 0.04465 \text{ pounds mass per second}$$

$$M = 0.04465\frac{\text{lbm}}{\text{s}}\ \text{x}\ \frac{60\ \text{s}}{\text{m}} = 2.679\ \text{lbm/min}$$

This is the mass rate at a density of 0.08447 lbm/ft^3. To obtain flow rate in standard units, divide by the density of air at standard conditions (0.075 lbm/ft^3)

$$q = \frac{2.679\ \text{lbm/min}}{0.075\ \text{lbm/ft}^3} = 35.72\ \text{scfm x}\ \frac{28317\ \text{scc}}{\text{scf}} = 1{,}011{,}483\ \text{sccm}$$

The bypass leakage from an effective area of 1.0 cm^2 is over nine times larger than combined allowable leakage rate from all containment isolation valves and penetrations subject to 10 CFR 50, Appendix J. Thus, the testing methodology and test equipment/instrumentation used on the current BWR generation plants is still applicable for the ESBWR.

For the total vacuum breaker local leakage rate testing criteria, the bypass area would be an effective area of 0.70 cm^2, and the approximate leakage rate would be 25.01 scfm or 708,200 sccm.

For the individual vacuum breaker local leakage rate testing criteria, the bypass area would be an effective area of 0.30 cm^2, and the approximate leakage rate would be 10.72 scfm or 303,560 sccm.

4.2 ESBWR Bypass Test Computations

The effective bypass area ($A/\sqrt{k}$) is calculated dividing Q, the volumetric flow rate (ft^3/min) by v, the flow velocity (ft/min) $A/\sqrt{k} = \frac{144\,Q}{v}$.

Since the pressure drops during the bypass test are extremely small, there are only small changes in the air density. Due to the small changes in density, the hydraulic formulas applicable to incompressible flow may be used. [Reference: 7.5]

The symbols used in this section are defined as follows:

$\frac{A}{\sqrt{k}}$	- equivalent drywell to wetwell bypass area (in^2)
Q	- volumetric flow rate (ft^3/min)
V	- flow velocity (ft/min)
$\dot{m}$	- mass flow (lbm/min)
ΔW	- change in mass (lbm)
Vs	- wetwell free air volume (ft^3)
Ps	- wetwell total atmospheric pressure (psia)
PVs	- wetwell atmospheric water vapor pressure (psia)
Pd	- drywell total atmospheric pressure (psia)
PVd	- drywell atmospheric water vapor pressure (psia)
Ts	- wetwell atmosphere temperature (^{o}R)
Td	- drywell atmosphere temperature (^{o}R)
t	- test duration (min.)
gc	- dimensional constant = 32.174 $\frac{lbm - ft}{lbf - s^2}$
ρ	- density of air-vapor mixture (lbm/ft^3)
R	- Universal gas constant for air = 53.35 $\frac{lbf - ft}{lbm - {}^{o}R}$

The equations used to calculate $A/\sqrt{k}$ are as follows:

By definition, volumetric flow rate is:

$$Q = \frac{\dot{m}}{\rho} = \frac{\Delta W}{t\,\rho}$$

$$\Delta W = \left[\frac{(Ps2 - PVs2)\,Vs}{R_g\,Ts2} - \frac{(Ps1 - PVs1)\,Vs}{R_g\,Ts1}\right]$$

$$\rho = \frac{W}{Vs} = \frac{\dfrac{Vs\left[(Ps1 - PVs1) + (Ps2 - PVs2)\right]}{R_g\,(Ts1 + Ts2)}}{Vs} = \frac{(Ps1 - PVs1) + (Ps2 - PVs2)}{R_g\,(Ts1 + Ts2)}$$

$$Q = \frac{Vs}{t\,R_g}\;\frac{\left[\dfrac{(Ps2 - PVs2)}{Ts2} - \dfrac{(Ps1 - PVs1)}{Ts1}\right]}{\dfrac{(Ps1 - PVs1) + (Ps2 - PVs2)}{R_g\,(Ts1 + Ts2)}}$$

$$Q = \frac{Vs}{t}\left[\left(\frac{(Ps2 - PVs2)}{Ts2} - \frac{(Ps1 - PVs1)}{Ts1}\right)\left(\frac{(Ts1 + Ts2)}{(Ps1 - PVs1) + (Ps2 - PVs2)}\right)\right]$$

The flow velocity is computed from the following based on the Bernoulli Equation:

$$v = \left[2\,gc\,(144)\left(\frac{\Delta P}{\rho}\right)\right]^{0.5}$$ where $\Delta P = PD - PS$ and

$$PD = \frac{Pd1 + Pd2}{2},\; PS = \frac{Ps1 + Ps2}{2}$$

$$v = \left[2\,gc\,(144)\left(\frac{Pd1 + Pd2}{2} - \frac{Ps1 + Ps2}{2}\right)/\rho\right]^{0.5}$$

$$v = \left[gc\,(144)\left(\frac{(Pd1 + Pd2) - (Ps1 + Ps2)}{\rho}\right)\right]^{0.5}$$

where $gc = 32.174 \dfrac{\text{lbm - ft}}{\text{lbf - sec}^2}$

$$v = \left[32.174 \text{ x } 144 \text{ in}^2/\text{ft}^2 \left(\frac{(\text{Pd1} + \text{Pd2}) - (\text{Ps1} + \text{Ps2})}{\rho} \right) \right]^{0.5}$$

$$v = 68 \left[\frac{(\text{Pd1} + \text{Pd2}) - (\text{Ps1} + \text{Ps2})}{\rho} \right]^{0.5} \text{ x } 60 \text{ sec/min}$$

$$v = 4080 \left[\frac{(\text{Pd1} + \text{Pd2}) - (\text{Ps1} + \text{Ps2})}{\rho} \right]^{0.5}$$

The density is computed using the ideal gas law

$$\rho = \rho_{da} + \rho_{wv}$$

ρ = total air density

ρ_{da} = dry air density

ρ_{wv} = water vapor density

$$\rho = \frac{(\text{PD - PVD})144}{R_g \text{ TD}} + \frac{\text{PVD}\,144}{R_V \text{ TD}}$$

R_g = gas constant for air = 53.35 lbf-ft^2/lbm-^{0}R

R_v = gas constant for water vapor = 85.8 lbf-ft^2/lbm-^{0}R

$$\rho = \frac{144}{\text{TD}} \left[\frac{(\text{PD - PVD})}{53.35} + \frac{\text{PVD}}{85.8} \right] = \frac{144}{\text{TD}} \left[\frac{\text{PD}}{53.35} - \frac{\text{PVD}}{53.35} + \frac{\text{PVD}}{85.8} \right]$$

$$\rho = \frac{144}{\text{TD}} \left[\frac{\text{PD}}{53.35} - \frac{\text{PVD}}{53.35} + \frac{\text{PVD}}{85.8} \right] = \frac{144}{\text{TD}} \left[\frac{\text{PD}}{53.35} - \frac{\text{PVD}}{53.35} + \frac{0.622\text{PVD}}{53.35} \right]$$

$$\rho = \frac{144}{(53.35)\text{TD}} \left[\text{P}D - 0.378\text{PVD} \right]$$

where $\text{PD} = \dfrac{\text{Pd1} + \text{Pd2}}{2}$, $\text{PVD} = \dfrac{\text{PVd1} + \text{PVd2}}{2}$, $\text{TD} = \dfrac{\text{Td1} + \text{Td2}}{2}$, $R = 53.35 \dfrac{\text{ft - lbf}}{\text{lbm°R}}$

$$\rho = \frac{\left[\left(\frac{Pd1 + Pd2}{2}\right) - 0.3783\left(\frac{PVd1 + PVd2}{2}\right)\right] \quad 144in^2 / ft^2}{53.35\left(\frac{Td1 + Td2}{2}\right)}$$

$$\rho = \frac{(Pd1 + Pd2) - 0.3783\,(PVd1 + PVd2)}{0.37\,(Td1 + Td2)}$$

Final Formulas

$$Q = \frac{Vs}{t}\left[\left(\frac{(Ps2 - PVs2)}{Ts2} - \frac{(Ps1 - PVs1)}{Ts1}\right)\left(\frac{(Ts1 + Ts2)}{(Ps1 - PVs1) + (Ps2 - PVs2)}\right)\right]$$

$$v = 4080\left[\frac{(Pd1 + Pd2) - (Ps1 + PS2)}{\rho}\right]^{0.5}$$

$$\rho = \frac{(Pd1 + Pd2) - 0.3783\,(PVd1 + PVd2)}{0.37\,(Td1 + Td2)}$$

$$\frac{A}{\sqrt{k}} = \frac{144Q}{v}$$

A measured bypass area is calculated using the above equations using the initial data point and the latest obtained data point as follows:

A_1 = measured bypass area based on time 0 and time 1

A_2 = measured bypass area based on time 0 and time 2

A_3 = measured bypass area based on time 0 and time 3

A_i = measured bypass area based on time 0 and time t_i

4.3 ESBWR Bypass Test Analysis

The data is analyzed using the Total Time method in a manner similar to that described for primary containment leakage rate testing in Bechtel Topical Report BN-TOP-1, Revision 1.

Since it is assumed that the bypass area is constant during the testing, a plot of the measured bypass area versus time would ideally yield a straight line. However, sampling techniques and test conditions are not perfect and as a result, the values of the measured bypass area deviate from an ideal straight line.

The method of least squares is a statistical procedure for finding the "best fitting" straight line and is commonly called a regression line. This method places a straight line to the measured data such that the sum of the squares of the deviations from the straight line is minimized.

The calculated bypass area ($\hat{A}$) would then be determined from the least squares fit equation:

$$\hat{A} = mx + b$$

Where:

$$m = \frac{n(\Sigma tiAi) - (\Sigma t * \Sigma Ai)}{n(\Sigma ti^2) - (\Sigma ti)^2} \qquad \text{(slope of least squares fit line)}$$

and

$$b = \frac{(\Sigma Ai)(\Sigma ti^2) - (\Sigma ti)(\Sigma tiAi)}{n(\Sigma ti^2) - (\Sigma ti)^2} \qquad \text{(intercept of least squares fit line)}$$

4.4 ESBWR Bypass Test Error Accountability

The effects of random errors for the bypass test are inherently accounted for in the least squares fit analysis under the assumption that the bypass area is essentially constant. The effects of instrumentation errors are accounted for by using instrumentation that meets the ANSI/ANS 56.8-1994 accuracy, resolution, and repeatability requirements and by reporting the final calculated bypass area at the 95% upper confidence limit. The 95% UCL is defined by the following equation:

$$\mathrm{UCL} = \hat{\mathrm{A}} + \mathrm{t}_{0.95}\,\sigma$$

where:

$\hat{\mathrm{A}} =$ calculated bypass area

$\mathrm{t}_{0.95} =$ student's t distribution at the single sided 95$^{\mathrm{th}}$ percentile

$$\mathrm{t}_{0.95} = \frac{1.6449\,\mathrm{D_F} + 3.5283 + 0.85602/\mathrm{D_F}}{\mathrm{D_F} + 1.2209 - 1.5162/\mathrm{D_F}} \quad \text{[ANSI/ANS 56.8-1994 Appendix B]}$$

where $\mathrm{D_F}$ = number of degrees of freedom [For bypass testing, $\mathrm{D_F}$ = (n-2) where n is the number of data points]

$\sigma =$ standard deviation

$$\sigma = \mathrm{s}\left[1 + \frac{1}{\mathrm{n}} + \frac{\left(\mathrm{t_p} - \bar{\mathrm{t}}\right)^2}{\Sigma\left(\mathrm{t_i} - \bar{\mathrm{t}}\right)^2}\right]^{0.5}$$

$$\mathrm{s}^2 = \frac{\Sigma\left(\mathrm{A_i} - \hat{\mathrm{A}}\right)^2}{\mathrm{n} - 2}$$

where:

$$\bar{\mathrm{t}} = \frac{\Sigma\,\mathrm{t_i}}{\mathrm{n}}$$

$\mathrm{t_p}$ = time after start of test

n = number of $\mathrm{A_i}$, $\mathrm{t_i}$ pairs

$\mathrm{A_i}$ = measured bypass area

$\hat{\mathrm{A}}$ = calculated bypass area (bypass area on least squares fit line)

5.0 VACUUM BREAKER TESTING METHODOLOGY

5.1 Regulatory Requirements

Although not specifically addressed in NUREG-0800, Standard Review Plan 6.2.1.1.C, Appendix A, local leakage rate testing of the vacuum breaker and the vacuum breaker isolation valve is proposed as part of the Technical Specifications for those outages in which an ILRT is not performed. As the only credible leakage path between the drywell air space and the wetwell air space, local leakage rate testing on a 24 month frequency will provide assurance that the bypass leakage is not substantially increased over the life of the plant.

5.2 Vacuum Breaker Local Leakage Rate Testing Procedure

The ESBWR vacuum breaker and vacuum breaker isolation valve local leakage rate tests (LLRT) are performed in much the same manner as 10CFR50 Appendix J local leakage rate testing. The testing will be conducted during plant outages on a 24 month frequency.

Local leakage rate testing of the ESBWR vacuum breaker and the vacuum breaker isolation valve with air or nitrogen will be performed using the flow make-up method as described in ANSI/ANS 56.8-1994. Due to the small test volume, it is recommended that the flow make-up method be used.

With the plant in shutdown and access to the vacuum breaker available, calibrated local leakage test equipment is obtained. A source of pressurizing air or nitrogen (instrument air system connection or nitrogen bottle) is connected to the local leakage rate test equipment. A Foreign Material Exclusion Zone should be established around the vacuum breaker to prevent debris from entering the valve when the outlet screens are removed.

The four (4) outlet screens from the vacuum breaker are removed and three (3) blind flanges with gaskets are installed. On the remaining port, a test flange is installed.

The outlet of the leakage rate test equipment is connected to the test flange. The tubing should be at least 3/8 inch in diameter and the length should be minimized to reduce the pressure drop between the leakage rate test equipment and the valve. The vacuum breaker isolation valve is opened to provide a vent path.

The vacuum breaker will be pressurized and maintained at a pressure of at least 2.0 psig, using a LLRT test equipment pressure regulator. The makeup flow to maintain test pressure shall be used as the leakage rate of the vacuum breaker. No minimum test duration is required; however, test data shall be obtained during stable conditions. Due to the small volumes involved, the test duration should be approximately fifteen minutes. Pressures higher than 2.4 psig should not be used as the higher pressure may result in increased sealing of the valve. The leakage rate of the vacuum breaker is recorded in sccm from the readout of the LLRT test equipment. The test volume is depressurized and the vacuum breaker is opened.

Lift the vacuum breaker off its seat, close the vacuum breaker isolation valve and then pressurize the vacuum breaker isolation valve. Maintain a pressure of at least 2.0 psig, using a LLRT test equipment pressure regulator. The makeup flow to maintain test pressure shall be used as the leakage rate of the vacuum breaker isolation valve. No minimum test duration is required; however, test data shall be obtained during stable conditions. Due to the small volumes involved, the test duration should be approximately fifteen minutes. Pressures higher than 2.4 psig should not be used as the higher pressure may result in increased sealing of the valve. The leakage rate of the vacuum breaker isolation valve is recorded in sccm from the readout of the LLRT test equipment.

The test volume is depressurized, the vacuum breaker is returned to its seat and the vacuum breaker isolation valve is opened. The LLRT test equipment is disconnected from the test flange. The four flanges are removed and replaced with the outlet screens.

5.3 Vacuum Breaker Local Leakage Rate Test Equipment

Local leakage rate test equipment consists of either a commercially purchased unit with mass flowmeters or a plant fabricated unit with rotameters. The mass flowmeter unit does not require correction for pressure or temperature since it measures mass flow directly (based on a temperature change) and converts the reading to standard volume units. The unit using rotameters would require correction since it measures volume flow and the rotameters are calibrated for a specific pressure and temperature.

A description and specifications for a commercially available mass flow local leakage rate unit is as follows:

The Local Leakage Rate Testing System is a compact, light weight and rugged instrument used for performing flow make-up or pressure decay Type B and C tests on valves, flanges, airlocks and other containment barriers. This state-of-the-art unit utilizes all digital flow instrumentation. The microprocessor based laminar flow elements may be relied upon to accurately and repeatedly measure air or nitrogen flow. The user may custom specify the three ranges desired, from 500 sccm to 100 SLM full scale.

The monitor is powered by 12 VDC. This may be supplied by either the included rechargeable battery pack or by the power adapter/re-charger with wall plug. Up to 40 hours of operation may be expected on a single three hour charge.

A high accuracy digital pressure gauge is used to measure the test volume's pressure. The pressure gauge may be any full scale desired. The standard accuracy rating is 0.25% FS this may be increased at no additional cost to 0.05% FS. The pressure sensor may be subjected to up to 5X overpressure with no effect upon calibration. Flow rates are direct reading in units switchable between *scfh* or *sccm*. Either air or nitrogen may be used. Pressure and temperature effects are automatically compensated for, no correction factors are ever required.

Spot checks of the flowmeters accuracy may be performed using the monitor's built-in flow check nozzles. Each nozzle is sized to flow approx. 75% of its meter's full scale flow at test pressure. The expected flow at test pressure may then be compared against the flow rate displayed. A 1% calibration may be performed by a simple panel adjustment of each meter's span pot. A more accurate calibration may be performed by using the included PC calibration software and downloading a breakpoint table directly into the monitor's nonvolatile memory.

Specifications

Weight: Approx 15 Lbs.
Power: 12 VDC From Included Battery Pack or DC Adaptor
Serial Output: RS-232 or RS-485 8/N/1 9600 baud
Calibration Interval: One year
Pressure Regulator: Venting or non-venting, user specified
Outlet Pressure Range: 0.5 to 90 psig, user specified
Maximum Inlet Pressure: 120 psig
Inlet And Outlet: 1/4" or 3/8" Compression Fittings
Flow Check Nozzles: One nozzle for each range

Pressure:

Range: 0 to 100 psig, (or user specify other range)
Accuracy: 0.25% Full Scale
Resolution: 0.02 psi
Repeatability: 0.1 psi
Calibration Interval 10 years

Flow: Laminar Flow Elements:

Fluid: Air or Nitrogen
Accuracy: 1% of Full Scale
Repeatability: 0.5% of Full Scale
Ambient Temperature: 32° to 122° F
Ranges: Three User Specified Ranges

The pressure, temperature, and flow instrumentation will meet the following accuracy, resolution, and repeatability requirements of ANSI/ANS 56.8-1994. Temperature in not required for LLRT units using mass flowmeters.

Temperature – (as required)

Accuracy	± 2.0°F (± 1.1°C)
Resolution	± 1.0°F (± 0.55°C)
Repeatability	± 1.0°F (± 0.55°C)

Pressure

Accuracy	± 2% of test pressure
Resolution	± 1% of full scale
Repeatability	± 1% of full scale

Flow

Accuracy	± 2% of full scale

Instrumentation used shall be calibrated traceable to National Institute of Technology (NIST) not more than six months prior to use or in accordance with the facility's measuring and test equipment (M&TE) control program.

6.0 CONCLUSIONS

The ESBWR drywell-to-wetwell bypass test should be performed in conjunction with the Integrated Leakage Rate Test (ILRT) and on the same frequency. Based on the experience of ILRT Inc., the recommended test approach for the ESBWR bypass test should be based on determining $A/\sqrt{k}$ using volumetric flow and flow velocity on a frequency coincident with the ILRT. This method has been successfully used on Mark II containments and the existing test methodology and test instrumentation are sufficient to determine $A/\sqrt{k}$ values of the magnitude proposed for the ESBWR.

As in Mark II containments, the ESBWR vacuum breakers are capable of being individually local leakage rate tested. The vacuum breakers and vacuum breaker isolation valves should be individually local leak rate tested on a 24 month frequency. Existing 10CFR50 Appendix J instrumentation and methodology can be used to perform these tests at a refueling outage interval.

The proposed acceptance criterion for the combined leakage of the three vacuum breakers and the three vacuum breaker isolation valves provides a large, conservative margin to accommodate the remaining potential leakage area through the passive structural components. The combined vacuum breaker/vacuum breaker isolation valve leakage limit, with the negligible passive structural leakage area, ensures that the drywell-to-wetwell bypass leakage limit is met for those outages for which the drywell-to-wetwell chamber bypass test is not scheduled.

Thus, the testing methodology and test equipment/instrumentation used on the current BWR generation plants is still applicable for the ESBWR.

7.0 REFERENCES

7.1 NUREG-0800, Standard Review Plan 6.2.1.1.C, "Pressure-Suppression Type BWR Containments," Appendix A, Revision 7, March 2007

7.2 Crane Technical Paper No. 410, Eighteenth Printing 1979

7.3 BN-TOP-1, Revision 1, Testing Criteria for Integrated Leakage Rate Testing of Primary Containment Structures for Nuclear Power Plants, November 1972

7.4 ANSI/ANS-56.8-1994, Containment System Leakage Testing Requirements

7.5 GE Document 22A3759AL, Revision 2, Sheet 50, Containment and NSSS Interface, March 29, 1991

7.6 Columbia Generating Station - Issuance of Amendment Re: Suppression Chamber-To-Drywell Vacuum Breakers And Drywell-To-Suppression Chamber Bypass Leakage Test (TAC No. MD1225), February 9, 2007 (ADAMS Accession Number ML070300021)

7.7 Issuance of Amendment for Nine Mile Point Nuclear Station, Unit 2 (TAC No. M95083), August 27, 1996 (ADAMS Accession Number ML011140033)

7.8 Susquehanna Steam Electric Station, Units 1 And 2 (TAC Nos. M94922 and M94923, September 6, 1996 (ADAMS Accession Number ML010110174)

7.9 Limerick Generating Station, Units 1 And 2 (TAC Nos. M92613 And M92614), January 25, 1996 (ADAMS Accession Number ML011560200)

7.10 Suppression Pool Bypass Leak Test Units 1 And 2 (TAC Nos. M88332 And Limerick Generating Station, M88333), February 17, 1994 (Adams Accession Number Ml011550083)