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8D EQUIPMENT SURVIVABILITY ANALYSIS

The purpose of this appendix is to present the equipment survivability analysis for the ESBWR. Equipment survivability is evaluated to demonstrate that necessary components and instrumentation will be functional in the severe accident environment so that the plant may be placed in a controlled, stable state. In this appendix, equipment necessary to achieve this goal is identified and its capabilities are evaluated with respect to the environmental conditions predicted in a severe accident.

By definition, a severe accident is an event that progresses beyond the postulates of a design basis event. The capability to place the plant in a controlled, stable state even after the occurrence of a severe accident provides an additional measure of risk reduction. To evaluate this capability, a four-step process has been implemented:

(1) Identify the functional requirements needed to place the plant in a controlled, stable configuration after a severe accident,

(2) Identify the plant equipment necessary to implement these functional requirements,

(3) Establish the severe accident environment, and

(4) Evaluate equipment capability in the severe accident environment.

Broadly speaking, the functions necessary to place the plant in a stable configuration are those that are required to terminate the severe accident progression, thus limiting the potential challenge to the containment as the final environmental barrier. The resultant plant condition must be monitored to allow appropriate accident management. Section 8D.1 identifies the specific severe accident mitigating functions that are required to achieve a stable plant configuration given a severe accident.

After the severe accident mitigating functions have been established, the equipment necessary to achieve these functions must be identified. The term “equipment” is applied to structures, components and instrumentation necessary to achieve the function. Section 8D.2 identifies severe accident mitigating equipment required to implement the functions identified in Section 8D.1.

The severe accident environment must then be established to provide the framework in which equipment survivability must be evaluated. The severe accident environment is established by considering the spectrum of severe accidents identified in the PRA as well as a hypothetical scenario in which 100% of the clad surrounding the fuel is reacted. Section 8D.3 discusses the severe accident environment considered in this analysis.

Finally, Section 8D.4 summarizes ESBWR equipment capabilities in terms of the severe accident environment. As discussed in References 8D-1 and 8D-1, there must be “reasonable assurance” that mitigating features will operate in the severe accident environment and over the time span in which they are needed. Section 8D.4 provides the basis for concluding that equipment necessary to place the plant in a stable configuration after a severe accident will survive in a severe accident environment.

8D.2 FUNCTIONAL REQUIREMENTS DURING SEVERE ACCIDENT

Evaluation of the ESBWR severe accident functional requirements was considerably simplified by the initial assumption that all severe accident scenarios result in RPV failure. This evaluation approach is based on the conservative assumption that recovery of failed equipment is not credited. That is, if equipment is failed or unavailable at any time during the accident sequence, it will not be repaired or made available. It is from this perspective that the mitigating functions necessary to place the ESBWR in a stable, controlled configuration have been considered. Table 8D.1-1 summarizes these functions and their role in the ESBWR survivability evaluation.

8D.2.1 Severe Accident Initial Conditions

Core damage defines the assumed initial conditions of a severe accident in the ESBWR PRA. That is, all core damage mitigation functions have been insufficient in providing core cooling, and RPV pressure is either low (depressurization was successful) or depressurization has been attempted and has failed. As recovery of failed equipment is not credited in the severe accident analysis, in-vessel core melt is assumed to proceed until RPV failure occurs and the corium exits the vessel.

8D.2.2 Reactivity Control

The severe accident progression is assumed to lead to core relocation onto the drywell floor. After RPV failure, the corium cannot be credibly postulated to form a critical, ex-vessel configuration. Therefore, reactivity control methods are not required for severe accident mitigation and no reactivity control equipment is considered in the severe accident survivability evaluation.

8D.2.3 RPV Depressurization

According to the severe accident initial conditions provided in Section D8.1.1, depressurization has either occurred or been attempted and failed by the time the severe accident conditions may be present. As such, RPV depressurization is not required for severe accident mitigation and is not considered in the severe accident survivability evaluation.

8D.2.4 In-Vessel Core Cooling

Severe accidents are defined as beginning at core damage. Core damage does not occur until all in-vessel core cooling systems have failed and no equipment failure recovery is credited in the severe accident analysis. As a result, no in-vessel core cooling systems are considered in the severe accident survivability evaluation.

8D.2.5 Cooling of Corium Debris Bed (Lower Drywell)

Once a severe accident, defined by core damage, is initiated, no equipment recovery to arrest the melt in-vessel is credited. As a result, a corium debris bed will form in the lower drywell following RPV failure. The debris bed, if not cooled, will interact with the containment concrete resulting in non-condensable gas generation, which would eventually overpressurize the containment. Cooling the debris bed would limit this core-concrete interaction, which is necessary to prevent ultimate containment overpressurization. Debris bed cooling is accomplished by flooding the lower drywell with a pool of water immediately following RPV failure.

Heat transfer from the corium debris bed to the lower drywell water pool also prevents the containment temperature rise that would occur due to heat radiated from an uncovered debris bed. In this manner, potential high temperature challenges to mitigating equipment and containment pressure boundary components such as penetrations seals are limited.

Thus, the function of lower drywell debris bed cooling will be evaluated in a severe accident environment as a means of limiting core-concrete interaction and high containment temperatures.

8D.2.6 Cooling of Corium Debris (Upper Drywell)

If the severe accident is not terminated by successful core cooling, and the RPV has not been depressurized, the RPV will ultimately fail at high pressure. In such a scenario, there is the potential for ejection of core material at high pressure, with several potential mechanisms for containment challenge. Section 21 demonstrated the capability of the containment to withstand the DCH impulse loads and postulates that the amount of corium deposited in the upper drywell would be minimal. Two mechanisms remain to be evaluated to determine the need for upper drywell debris cooling function in a severe accident.

- Dispersal of material into the upper drywell could result in a debris bed that would cause a core-concrete interaction (CCI) and generate non-condensable gases, which would threaten to overpressurize the containment. However, an upper drywell debris bed would be of insufficient depth to cause significant gas generation because the limited amount of debris transported to the upper drywell and its dispersal would be likely be adequate to prevent the sustained CCI associated with a lower drywell debris bed.
- Debris distributed to the upper drywell could potentially contribute to the containment heat load in proportion to the amount of dispersed material. However, giving no credit for drywell spray, corium debris in the upper drywell does not contribute to a significantly elevated upper drywell temperature transient. This phenomenon is shown in Figure 8B-4k.

Thus, the function of upper drywell debris cooling will be evaluated as the capability of the containment (including penetrations) to withstand the severe accident environment.

8D.2.7 Containment Isolation

Containment isolation is required to establish the containment as a fission product boundary to the environment. By design, containment isolation is established early in an accident sequence with the function being implemented within the design basis environment. Thus, in this survivability evaluation, the containment isolation function is considered in terms of maintaining the containment pressure boundary, rather than establishing a boundary in a severe accident environment. The containment isolation function applies to the containment structure and penetrations as well as containment isolation valves and other isolation barriers.

8D.2.8 Containment Pressure Control

In a severe accident, assuming successful containment isolation, the containment pressure retaining capability can be challenged by steam or non-condensable gas generation. Two functions are considered in the severe accident environment to mitigate these challenges.

8D.2.8.1 Containment Heat Removal

Containment heat removal is required to prevent eventual containment overpressure due to energy added from decay heat and potential exothermic chemical reactions associated with a severe accident. In the ESBWR, the containment heat removal function requires that accident-generated energy be transferred to coolant water in the lower drywell after RPV failure. This energy, in turn, may be transferred to the suppression pool or PCCS pools. Containment heat removal may be initiated at any stage of a postulated severe accident prior to containment failure. Thus, survivability is evaluated in terms of initiating heat removal and continued functionality in a severe accident environment.

8D.2.8.2 Containment Venting

Containment venting is available as an emergency action in the event that the containment pressure rise in a severe accident threatens to exceed the containment ultimate strength. Containment venting is applicable to situations in which non-condensable gas generation has not been prevented or containment heat removal is unavailable. Venting requires operator action from the main control room to open a pathway from the containment to the environment. The source term evaluation discussed in Section 9 does not credit closure of the vent path. Thus, survivability is evaluated in terms of the capability to open the controlled vent path for a single use.

8D.2.9 Combustible Gas Control

Combustible gas control is required to prevent containment challenges due to the effects of deflagration or detonation. The ESBWR containment is inerted during power operation and thus, a combustible environment is not credible. The potential for hydrogen and oxygen generation during a severe accident introduces the possibility that a combustible gas mixture could develop. However, as indicated in Section 8.1, oxygen generation during a severe accident is insufficient to produce a combustible atmosphere within containment for at least 24 hours following a severe accident. Thus, combustible gas control is present at the start of a potential accident sequence due to the inerted containment and survivability is evaluated from the perspective of the containment isolation system maintaining a leak-tight containment environment.

8D.2.10 Post-Accident Monitoring

Monitoring of plant conditions after a severe accident is important to assess the plant condition and determine the need for additional mitigating measures. The specific parameters that need to be monitored can be derived from several sources.

Reference 8D-3 explicitly cites the need for monitoring

- Containment pressure,
- Containment water level,
- Containment hydrogen concentration,
- Containment radiation intensity and
- Noble gas effluents at potential release points.

Reference 8D-3 also makes the general requirement that instrumentation be provided "for monitoring plant conditions following an accident that includes core damage."

Instrumentation necessary to support emergency planning and response actions should be included in the survivability evaluation. Once established, the ESBWR Emergency Procedure Guidelines (EPGs) and Severe Accident Guidelines (SAGs) will define strategies for RPV and containment control in a severe accident. These strategies will require information on key plant parameters to determine guideline entry points and the need for operator actions defined by the guidelines. When available, these requirements will be taken into consideration in the severe accident equipment survivability analysis.

Finally, post-accident monitoring is required for the parameters needed to implement the functional requirements identified in the preceding sections.

There is significant overlap in the requirements identified by these sources, but consideration of the monitoring requirements from all of these sources provides assurance that all of the necessary post-accident monitoring functions have been identified.

Table 8D.1-1

Severe Accident Mitigating Functions

Function	Functional response in severe accident environment
Reactivity Control	Not required because in-vessel arrest is not credited. Ex-vessel sequences do not result in a critical configuration.
RPV Depressurization	Not required because in-vessel arrest is not credited; thus, depressurization not required to permit core cooling.
In-Vessel Core Cooling	Not required because in-vessel arrest is not credited
Cooling of Corium Debris Bed (Lower Drywell)	Lower drywell debris cooling terminates core-concrete interaction, thus eliminating possibility of basemat melt-through and containment overpressurization due to CCI. Lower drywell debris cooling also limits containment temperature rise.
Cooling of Corium Debris Bed (Upper Drywell)	Active cooling of upper drywell corium is not required in the analysis because the amount of corium relocated to the upper drywell is insufficient to cause significant CCI; the PCCS limits drywell temperature rise.
Containment Isolation	Containment isolation must be maintained to provide a barrier to radionuclide release to the environment.
Containment Pressure Control: Heat Removal	Containment pressure control via heat removal is required to prevent containment overpressurization due to steam generation and/or exothermic chemical reactions.
Containment Pressure Control: Venting	Containment pressure control via venting is required to prevent containment overpressurization due to non-condensable gas generation.
Combustible Gas Control	Combustible gas control is shown to be successful in Section 8.1 as long as the containment is leak-tight. Therefore, an inerted condition is assured by successful containment isolation.
Post-Accident Monitoring	Post-accident monitoring provides information to allow post-accident response and evaluation of RPV and containment conditions.

8D.3 EQUIPMENT REQUIRED FOR SEVERE ACCIDENT MITIGATION

The prior section established the functional requirements for mitigating a postulated severe accident and placing the plant is a stable state. Implementation of the identified functions requires a successful response of plant equipment, including structures, support components and associated instrumentation. This section addresses the plant equipment that must survive in the severe accident environment to implement each severe accident mitigating function. Key to the evaluation is the location of the required equipment, i.e., only those components within the containment boundary are subject to the severe accident environment.

It should be noted that the ESBWR design provides the flexibility to achieve mitigating functions with equipment other than that discussed here. For example, in addition to the Passive Containment Cooling System (PCCS) discussed here, the Fuel and Auxiliary Pool Cooling System (FAPCS) could provide containment cooling. As indicated in Reference 8D-2 (Section I.L), the survivability evaluation must demonstrate that there is reasonable assurance that systems and equipment will perform the intended function in a severe accident environment; the redundancy and diversity requirements of 10CFR50 are not applicable. Thus, the equipment included in this evaluation has been selected based on considerations such whether the equipment can function passively or has been explicitly designed for severe accident conditions; such factors simplify the survivability evaluation. Additional redundant or diverse equipment may also be available to mitigate a severe accident, but is not explicitly evaluated here.

The following sections address the equipment associated with each required mitigating function, as identified in Section 8D.1.

8D.3.1 Cooling of Debris (Lower Drywell)

Cooling of the debris bed in the lower drywell can be accomplished in a severe accident by flooding the area. The GDCS, operating in the deluge mode, is the primary means for lower drywell flooding and requires no motive power. The GDCS deluge system injects water as described in Sections 8.2.1.3.5 and 8A.2.2. The water is distributed through the BiMAC system, described in Section 21. System instrumentation, squib valve circuitry, and deluge actuation are all powered by the stand-alone GDCS deluge electrical system.

8D.3.2 Cooling of Debris (Upper Drywell)

Debris in the upper drywell is postulated only if the RPV fails at high pressure. The amount of debris that would deposit in the upper drywell is relatively small. No active system is credited in the ESBWR PRA for upper drywell debris cooling; the containment structure is able to withstand the upper drywell heating associated with the postulated corium relocation.

8D.3.3 Containment Isolation

Containment isolation actuates early in an accident sequence by design of the ESBWR Leak Detection and Isolation System (LD&IS). The LD&IS is designed to NRC requirements, including post-TMI requirements. The system includes redundant isolation barriers; the control system is designed such that resetting of the isolation signal does not result in automatic reopening of the containment isolation valves. The containment isolation event trees described in Section 8.2 do not credit that containment isolation can be established after the start of the severe accident; only LD&IS success at the start of the accident, within the design basis environment, is considered as success. Thus, in this survivability evaluation, the containment isolation function is considered in terms of maintaining closure of the containment isolation barriers and the integrity of the containment structure and penetrations. The inboard containment isolation valve, containment structure, and penetrations are subject to the severe accident environment.

8D.3.4 Containment Pressure Control

As discussed in Section 8D.1.7, containment pressure control can be accomplished by removing the heat energy accumulating within containment during a severe accident or venting to reduce pressure.

8D.3.4.1 Containment Heat Removal

The Passive Containment Cooling System (PCCS) can accomplish containment heat removal. The PCCS does not require active components, instrumentation or power to initiate or control. The system is part of the containment boundary. The PCCS heat exchanger and piping are subject to the severe accident environment.

The PCCS operates by natural circulation. Its operation is initiated by the difference in pressure between the drywell and wetwell, which are subject to the severe accident environment. To maintain this pressure difference, the normally closed vacuum breakers between the wetwell and drywell are required to be closed during the severe accident.

8D.3.4.2 Containment Venting

In the event that the severe accident generates pressure that threatens containment integrity, the ESBWR design includes a controlled vent path through the Containment Inerting System to terminate the pressure rise. The vent path takes suction from the suppression pool airspace and is only analyzed for a one-time actuation to open. This vent point forces the escaping fission products through the suppression pool, which provides significant fission product scrubbing prior to release. The vent valve is outside the containment, so only the valve internals are subject to the wetwell conditions.

8D.3.5 Combustible Gas Control

Combustible gas control is achieved in the ESBWR by maintaining an inert containment atmosphere. The containment is inerted during normal operation; thus, there are no active system requirements necessary to achieve combustible gas control during a severe accident. As indicated in Section 8D.1.8, a combustible gas environment will not be generated within 24 hours of accident initiation. Thus, the only requirement for combustible gas control is that the containment pressure boundary be maintained, i.e., there are no additional components that must be evaluated in the survivability evaluation than are considered for containment isolation.

8D.3.6 Post Accident Monitoring

As discussed in Section 8D.1.9, monitoring of plant conditions is necessary to place the plant in a stable configuration. Consideration of regulatory requirements and the ESBWR severe accident functional response evaluation (including EPG/SAG requirements), Table 8D.2-1 identifies variables that provide the necessary information to monitor the plant condition after a severe accident:

Table 8D.2-2 summarizes the plant systems needed to carry out the severe accident functions. The table also lists the system components that are located within the containment pressure boundary and thus, subject to the severe accident environment.

Table 8D.2-1

Function vs. Monitored Variable

Function	Monitored Variable
Cooling of Debris Bed (Lower Drywell)	Lower Drywell Temperature Deluge Valve Status Indication Drywell Air Temperature GDCS Tank Water Level Drywell Sump Level
Cooling of Debris Bed (Upper Drywell)	Drywell Air Temperature
Containment Isolation	Drywell pressure Isolation valve position
Containment Pressure Control: Heat Removal	Drywell pressure Wetwell pressure Drywell Air Temperature
Containment Pressure Control: Venting	Drywell pressure Wetwell pressure
Combustible Gas Control	Drywell/Wetwell H^2 concentration Drywell/Wetwell O^2 concentration
Containment water level	Suppression Pool Level Drywell Sump Level
Containment radiation intensity	Containment area radiation monitoring
Noble gas effluents at potential release points.	Environs release point monitoring

Table 8D.2-2

Equipment Associated with Severe Accident Mitigating Functions

Function	System	Components within Containment
Cooling of Corium Debris (Lower Drywell)	Deluge Mode of GDCS	GDCS tanks Squib valves for GDCS deluge Associated Instrumentation (Thermocouples for detection) Associated Control Wiring
Cooling of Corium Debris (Upper Drywell)	Containment	Containment structure Containment penetrations Inboard containment isolation valves
Containment Isolation	Containment Isolation System	Containment structure Containment penetrations Inboard containment isolation valves
Containment Pressure Control: Heat Removal	▪ PCCS ▪ VB ▪ Containment	PCCS heat exchanger PCCS piping Vacuum Breakers
Containment Pressure Control: Venting	Containment Inerting System	None
Combustible Gas Control	Containment Inerting System	Same as Containment Isolation System
Post-Accident Monitoring	▪ Safety System Logic and Control System ▪ Containment Monitoring System ▪ Leak Detection and Isolation System ▪ Radiation Monitoring Systems	GDCS Tank Level Sensor GDCS Deluge Valve Status Indicator Drywell pressure taps Wetwell pressure taps Drywell Air Temperature Suppression Pool Water Level Sensors Suppression Pool Water Temperature Sensors Lower Drywell Water Level Containment Isolation Valve Status Indicator Containment air sample taps (for H2/O2 concentration) Containment area radiation detectors

8D.4 SEVERE ACCIDENT ENVIRONMENT

References 8D-1 through 8D-3 provide the equipment survivability requirements that an applicant must address for postulated severe accidents. References 8D-1 and 8D-2 require that "credible" severe accidents be considered in a survivability evaluation. Reference 8D-3 requires that equipment survivability should consider an accident with the release of hydrogen generated by the equivalent of a 100 percent fuel-clad metal-water reaction. In this section, the ESBWR severe accident environment to be considered in the equipment survivability evaluation is established. The approach used to establish the severe accident environment was to develop bounding pressure, temperature and radiation conditions from the severe accident spectrum required by References 8D-1 through 8D-3. As defined in 8D.1.1, in-vessel recovery after a severe accident has begun would require equipment recovery, which is not credited in the ESBWR PRA. Thus, an in-vessel recovery sequence is not required to evaluate the survivability of equipment that may be used this type of severe accident.

The ESBWR PRA results discussed in Section 7.2 demonstrate that sequences in which the RPV fails at high and low pressure are both important contributors to overall core damage frequency. As such, both cases will be evaluated for in-containment equipment survivability.

Section 7.2 indicates that LOCA sequences inside of containment contribute about 9% of the core damage frequency. A large steam break in Feedwater Line B is the most significant contributor by frequency. However, the FDW line break results in an assumed containment failure (see Section 8.2). Therefore the equipment survivability is evaluated using the next largest contributor. The medium liquid LOCA is the second most significant LOCA contributor, and is analyzed in Section 8D.3.3. Loss-of-coolant accidents may provide a different challenge to equipment survivability than transient sequences because the core energy is initially deposited directly to the drywell rather than to the suppression pool through the SRVs. Thus, a LOCA sequence is included in the survivability evaluation.

Sequences with RPV failure at high pressure pose potentially more demanding in-containment conditions than those with RPV failure at low pressure. The only credible accident sequence with RPV failure at high pressure involves core damage and subsequent success of containment heat removal. The case used is identical to the T_nDP_nIN_TSL sequence shown in Section 8 and Appendix 8B.

As indicated earlier, consideration of a potential severe accident with the release of hydrogen generated by the equivalent of a 100% fuel-clad metal-water reaction is required by regulation. There is not a credible scenario in which all of the cladding is reacted, thus, a calculation was performed to estimate the maximum temperature and pressure produced by this postulated condition.

In summary, four sequences were selected to establish the severe accident environment for the ESBWR equipment survivability evaluation:

- T_nIN_TSL: The sequence is initiated by a transient and is accompanied by no core injection. The end state is defined by successful containment function and release due only to allowed Technical Specifications Leakage (TSL).

- T_nDP_nIN_TSL: The sequence is initiated by a transient, but differs from T_nIN in that RPV depressurization fails. The RPV eventually fails at high pressure, resulting in more challenging in-containment conditions compared to the low-pressure RPV failure. The end state is defined by successful containment function and release due only to allowed Technical Specifications Leakage (TSL).
- MLi_nIN_TSL: The sequence is initiated by a medium LOCA in a liquid line and is accompanied by no core injection. It depicts core energy input that is initially directed to the drywell rather than to the suppression pool. The end state is defined by successful containment function and release due only to allowed Technical Specifications Leakage (TSL).
- LLS_nIN_TSL_mcad: The sequence is initiated by a main steam line break. However, the peak containment pressure and temperature were statically calculated using MATHCAD to illustrate the effect of 100% fuel-clad metal-water reaction as required by Reference 8D-3.

As discussed in Section 8.3, ESBWR severe accident sequences are simulated with the MAAP code. A MAAP simulation was developed for the first three representative sequences; conditions for the fourth sequence were calculated using conservative, simplifying assumptions. Then, to evaluate equipment survivability, composite curves of containment pressure and temperature over a 24-hour period were developed to represent bounding severe accident conditions. Radiation levels after a severe accident were estimated using a simplified one-compartment model. It was assumed that releases of 100% of the core noble gases and 50% of the core halogens were instantaneous at the start of the accident. All the noble gases and halogens were assumed airborne for the full calculation time period with no credit taken for suppression pool scrubbing or other removal processes either natural or otherwise (leakage or purging).

References to the sequence results are provided in Table 8D.3-1. The bounding conditions are presented in Section 8D.3.5.

8D.4.1 Low Pressure Representative Sequence

The sequence "T_nIN_TSL" is initiated by a transient and is followed a failure of core injection. In T_nIN_TSL, the ADS functions to depressurize the RPV. Isolation condenser operation is not credited. The sequence represents Accident Class I, which provides approximately 46% of the ESBWR core damage frequency. Examples of sequences represented by T_nIN_TSL include the transients with loss-of-offsite power and transients with loss-of-feedwater, as discussed in Section 7.2.1

As indicated in Table 8.3-2, the probability of the sequence being accompanied by loss-of-containment heat removal is exceedingly small; thus, the PCCS is assumed available. Similarly, Table 8.3-2 shows that failure of the GDCS deluge and BiMAC function is physically remote. The resultant ex-vessel sequence, T_nIN_TSL, is evaluated in Section 8.3 and the results can be found in the figures referenced in Table 8D.3-1.

As indicated in the figures, drywell pressure approaches an asymptotic value of about 0.7 MPa, much less than the ultimate containment strength discussed in Reference 8D-5. Wetwell pressure is less than the drywell pressure. Due to hot gases passing through the DPVs, the upper drywell temperature significantly exceeds that in the lower drywell until RPV failure, at which point the corium debris melts into the lower drywell. At that time, the upper and drywell temperatures move closer together. The drywell temperature peaks at about 550 °K and is then reduced due to GDCS actuation; the upper temperature equalizes at about 450 °K.

8D.4.2 High Pressure Representative Sequence

The sequence "T_nDP_nIN_TSL" is initiated by a transient and is defined by a failure of to depressurize the RPV and a failure of high-pressure injection. By definition, the ICS is failed or the RPV pressure would be reduced to low pressure. This sequence represents Accident Class III, which contributes approximately 37% of the ESBWR core damage frequency.

As indicated in Table 8.3-2, the probability of a Class III sequence being accompanied by a failure of containment heat removal is exceedingly small; thus, PCCS is assumed available. Similarly, Table 8.3-2 shows that failure of the GDCS deluge and BiMAC function is physically remote. The resultant sequence, T_nDP_nIN_TSL, is evaluated in Section 8.3 and the results can be found in the figures referenced in Table 8D.3-1.

8D.4.3 LOCA Sequences

The dominant in-containment LOCA is a steam break in Feedwater Line B. However, as discussed in Section 8D.3, this case is not analyzed because an ex-vessel explosion containment failure is assumed to occur.

The sequence MLi_nIN_TSL is initiated by a medium LOCA in the GDCS injection line. No core injection is provided which results in an ex-vessel severe accident sequence. As discussed in Section 7.2, LOCA sequences inside of containment contribute approximately 9% to the core damage frequency. The probability of such a sequence being accompanied by a loss-of-containment heat removal is exceedingly small based on insights from Sections 8 and 21. Thus, the sequence is modeled with PCCS, GDCS deluge and BiMAC availability.

Figure 8D.3.3-1 illustrates drywell pressure for 24 hours. As indicated in the figure, pressure approaches an asymptotic value of about 0.7 MPa, much less than the ultimate containment strength discussed in Appendix B.8. Wetwell pressure is less than the drywell pressure. Figure 8D.3.3-2 illustrates temperature in the upper and lower drywell. Due to hot gases passing through the DPVs, the upper drywell temperature significantly exceeds that in the lower drywell until RPV failure, when time corium debris melts into the lower drywell. At that time, the upper and drywell temperatures move closer together. The drywell temperature has a brief, sharp peak to about 650 °K and is then reduced due to GDCS actuation; the upper temperature equalizes at about 480 °K.

8D.4.4 100% Metal-Water Reaction

The 100% metal water reaction was calculated non-mechanistically because of modeling limitations with the MAAP code. The result of the calculation was the maximum drywell pressure reached in the theoretical accident scenario. Realistically, this scenario would require limited coolant flow to support the metal-water reaction; thus, this would not serve as the most challenging scenario from a drywell temperature standpoint because the core is retained in-vessel.

8D.4.5 Bounding Severe Accident Conditions

The bounding pressure curve is shown in Figure 8D.3.2-1; Figure 8D.3.2-2 provides the bounding drywell area temperature history. The figure indicates that upper drywell peak temperature does not exceed approximately 644K during the representative accident scenarios. As will be shown in 8D.4.2, this indicates reasonable assurance that the integrity of the upper drywell electrical penetrations will be maintained.

The bounding radiation environment will be provided in the next revision to this document. It is anticipated that the integrated radiation dose within 24 hours associated with severe accident conditions will not exceed equipment design bases. This is readily apparent for equipment that is designed for severe accident conditions, such as the GDCS deluge system, but will also be demonstrated for any required equipment that is not specifically designed for severe accident conditions.

Table 8D.3-1

References for Representative Sequence Results

Case	Description	Figures
T_nIN_TSL	Low pressure RPV failure	F8.3-1 (a-e), F8B-1 (a-n)
T_nDP_nIN_TSL	High pressure RPV failure	F8.3-4 (a-b), F8B-4 (a-p)
MLi_nIN_TSL	Medium LOCA – GDCS Injection Line	F8D.3.1-1, F8D.3.1-2

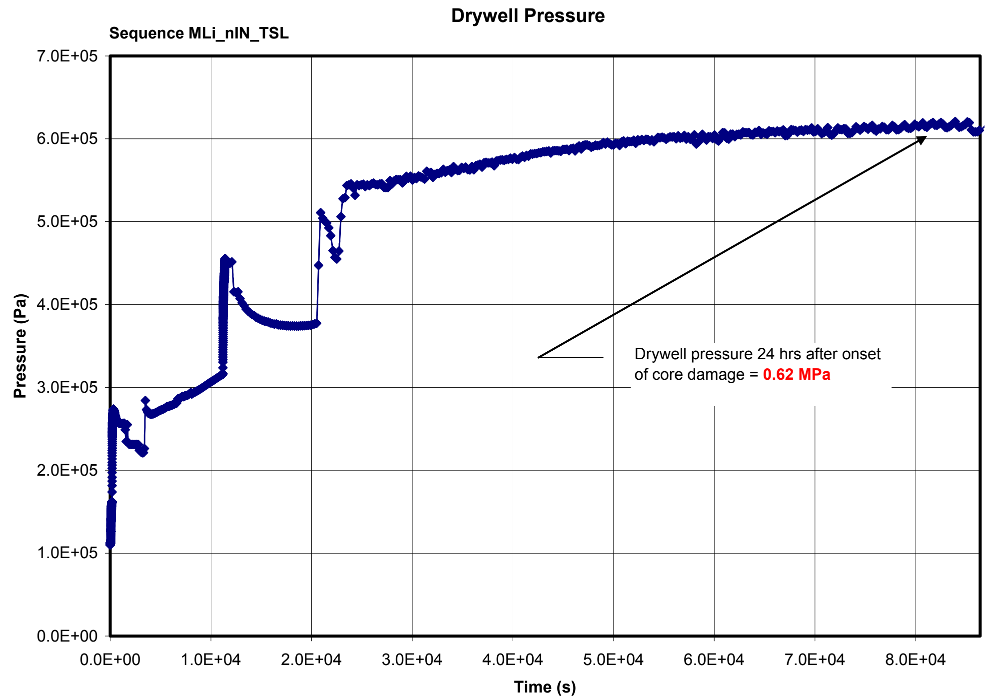

Figure 8D.3.1-1. Containment Pressure, Sequence MLi_nIN_TSL

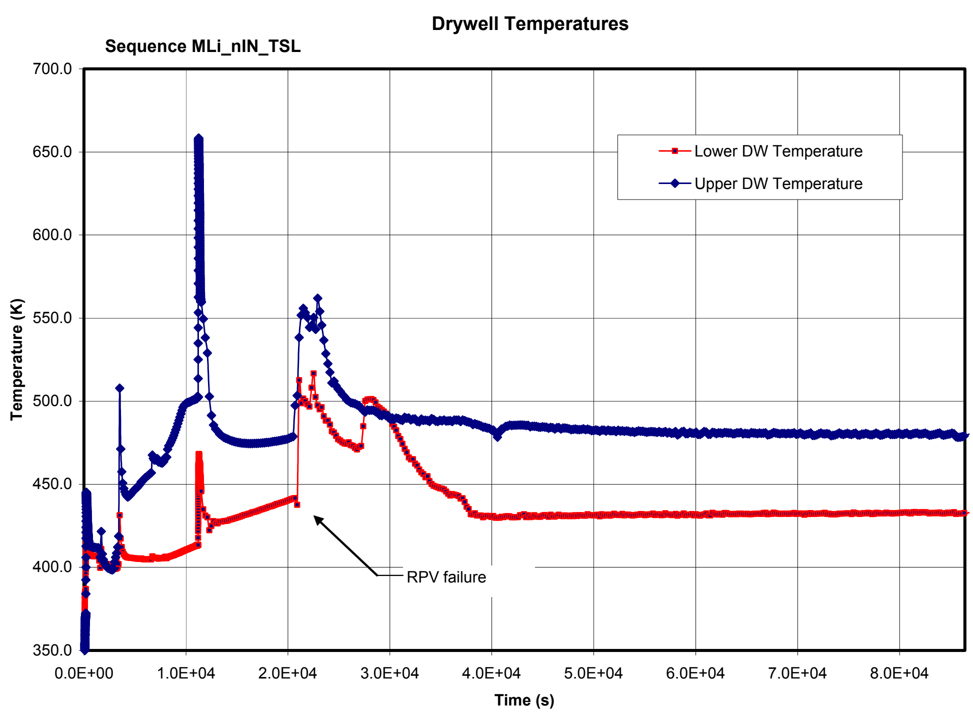

Figure 8D.3.1-2. Drywell Temperatures, Sequence MLi_nIN_TSL

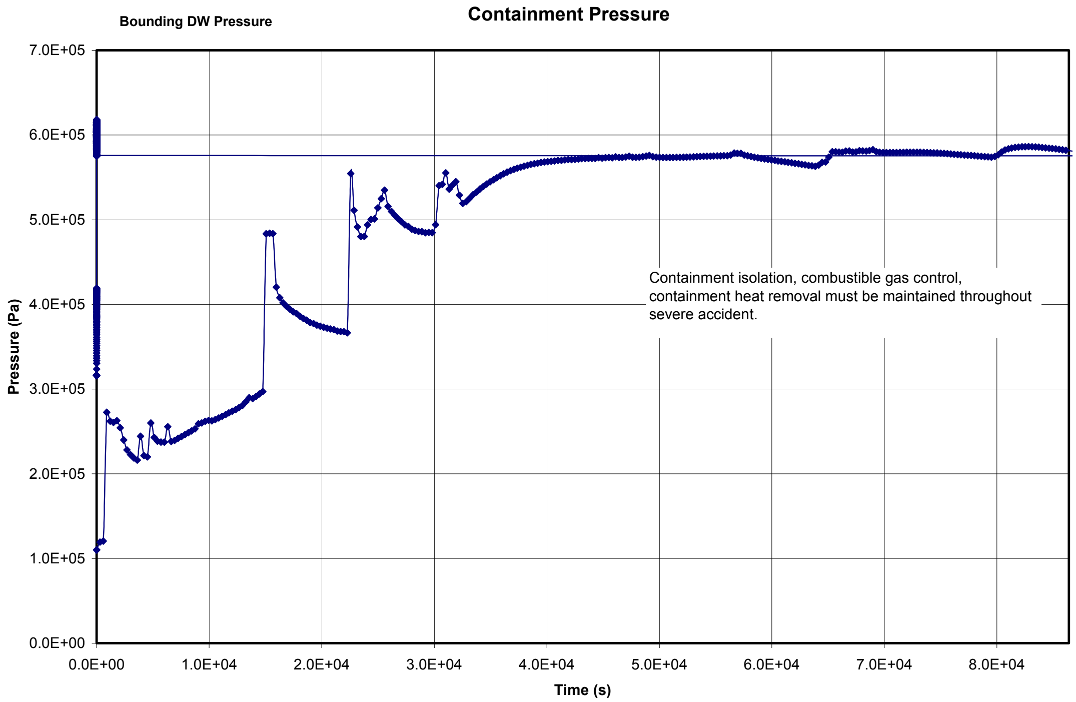

Figure 8D.3.2-1. Containment Pressure, Bounding Pressure Profile

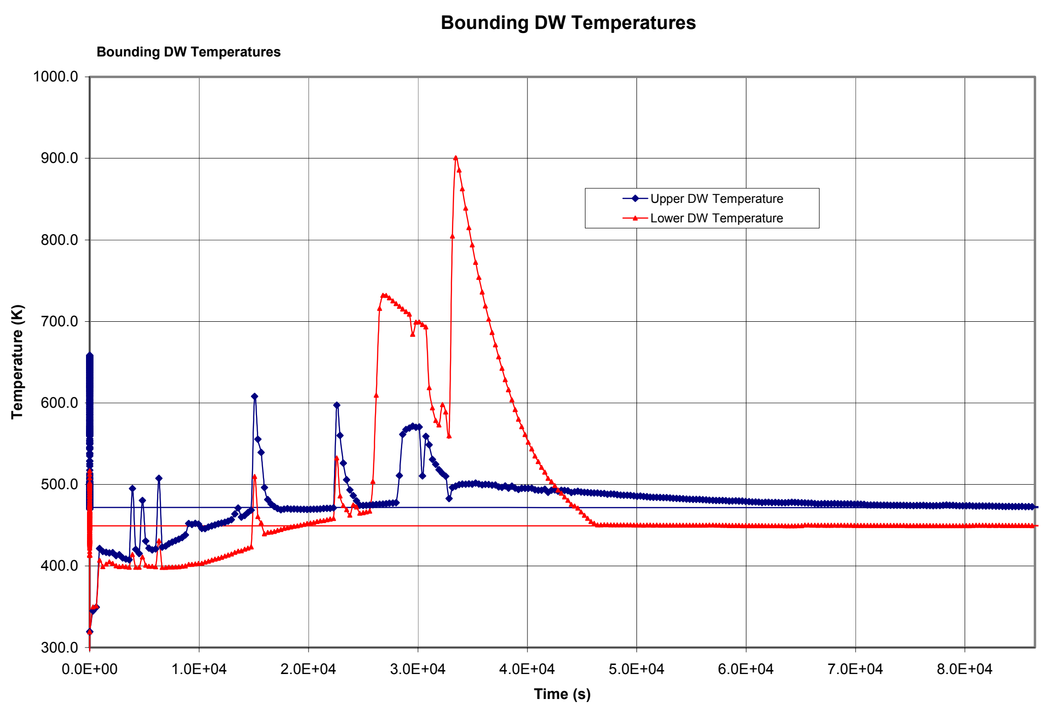

Figure 8D.3.2-2. Drywell Temperatures, Bounding Temperature Profiles

8D.5 EQUIPMENT CAPABILITY

Section 8D.1 identified the functions that must be achieved to place the plant in a stable configuration after a severe accident. Section 8D.2 identified the systems and equipment that can be used to implement each function. Section 8D.3 provides a bounding severe accident environment used to evaluate equipment survivability. In this section, the bases are developed for concluding that equipment required to place the plant in a stable configuration will survive in the severe accident environment.

As indicated in References 8D-1 and 8D-2, the requirements for "equipment survivability" differ from those that are applied to "equipment qualification", a term which is generally applied to design-basis accidents. Specifically, the references indicate that the environmental qualification requirements of 10CFR50.49, the quality assurance requirements of 10CFR50 (Appendix B) and the redundancy/diversity requirements of 10CFR50.50 (Appendix A) need not be applied to features provided for severe accident protection. This conclusion is justified because of the significant differences in the likelihood of severe accidents in comparison to design basis accidents. Instead, there must be "reasonable assurance" that severe accident mitigation equipment will operate in the severe accident environment over the time span in which it is needed.

To evaluate the ESBWR equipment capability in a severe accident environment, and to demonstrate reasonable assurance of operability, several considerations were made:

(1) Equipment physical location. The evaluation considers whether required equipment is exposed to the severe accident environment. Exposure occurs if the equipment is physically located in the primary containment. A specific location within containment may not be subject to the most severe conditions postulated in the accident, e.g., wetwell airspace conditions would be more benign than lower drywell conditions.

(2) The equipment design or qualification in comparison to the severe accident environment. The evaluation considers whether the severe accident environment exceeds equipment design and, if so, the significance of the equipment exposure to the severe accident environment.

(3) The timing of the required equipment function. The evaluation considers when the equipment function is required, notably if the equipment performs its function before its design bases are exceeded.

(4) The nature of the required equipment function. The evaluation considers whether the equipment must change state ("active" component) within the severe accident environment, or must simply maintain ("passive" component) its position to achieve its mitigation function.

(5) The duration of the severe accident condition. The evaluation considers whether the severe accident effect on equipment is transitory or consistent over a long duration.

(6) Equipment material properties. The evaluation considers fundamental material properties such as yield strength of steel in relation to conditions predicted during a severe accident.

The evaluation considers mechanical and electrical components, including associated instrumentation, for a 24-hour period after onset of core damage. The following sections summarize the equipment evaluation in terms of the required severe accident mitigating functions identified in Section 8D.1.

8D.5.1 Cooling of Debris (Lower Drywell)

Lower drywell debris cooling is accomplished by actuation of the GDCS deluge subsystem. The flow of GDCS coolant from the tanks is initiated by firing the squib-actuated deluge valves. All components associated with the deluge function are designed to function in severe accident conditions. Water drains by gravity feed to the BiMAC system, which distributes water through the lower drywell basemat and corium debris bed. The BiMAC is a feature in the ESBWR that is explicitly designed to mitigate severe accidents, as discussed in Section 21. The deluge valve squibs are actuated by a combination of thermocouples in the lower drywell floor and passive temperature permissive switches in the LDW airspace. Both types of equipment are intended to sense conditions associated with a severe accident. Once opened, the squib-actuated valves are designed to remain permanently open. Squib valves and associated instrumentation are powered by a stand-alone, deluge-specific electrical system, and the pyrotechnic charge is qualified for a severe accident environment. Control wiring to the squib initiators is designed to withstand the severe accident environment.

All equipment associated with the GDCS deluge mode is either explicitly designed to function in a severe accident environment or is constructed with materials able to withstand severe accident conditions. Thus, there is reasonable assurance that components required for lower drywell debris cooling will function in a severe accident environment.

8D.5.2 Cooling of Debris (Upper Drywell)

The only mechanism for debris dispersal to the upper drywell is a high-pressure melt ejection. No systems are credited for debris cooling in the upper drywell; instead, the containment isolation function is analyzed to determine its ability to maintain a leak-tight boundary. Figures 8B-4a and 8B-4k show drywell pressure and upper drywell temperature, respectively. As shown, the drywell pressure does not approach containment ultimate strength, and the temperature does not exceed the criteria set forth in Reference AJ.9-32 of Reference 8D-4, shown in Table 8D.4-1.

8D.5.3 Containment Isolation

Containment isolation initiated by the safety-related Leak Detection and Isolation System (LD&IS). Isolation boundary configurations follow the requirements of the General Design Criteria (GDC) such as the requirements for redundancy and location (inside/outside containment pressure boundary). Containment isolation is required early in the progression of a potential accident when conditions are within the actuation system and component design envelopes and remain closed for the duration of the event. As illustrated in the containment event trees provided in Appendix 8A Figures 8A-1 through 8A-7, there is no credit in the PRA for containment isolation success if isolation is not initially successful. Thus, closure of open isolation boundaries in the severe accident environment is not considered in the survivability evaluation.

The pressure capability of the containment's limiting component is higher than the pressure that results from assuming 100% fuel clad-coolant reaction. As discussed in Section 6.2.4, containment isolation valve design is consistent with applicable General Design Criteria, Regulatory Guide 1.11, ASME Boiler and Pressure Vessel Code and seismic design criteria.

Additionally, the analyses presented in 8D.3 show that containment ultimate strength is never reached in a credible severe accident scenario.

Containment isolation is achieved early in a potential accident sequence when components are functioning within their design bases. In the severe accident, isolation boundaries must only maintain their isolation configuration. Containment isolation boundary design criteria and redundancy provide reasonable assurance that components required for containment isolation will function in a severe accident environment.

8D.5.4 Containment Pressure Control

As discussed in Section 8D.1.7, containment pressure control can be accomplished by removing the heat energy accumulating within containment during a severe accident or venting to reduce pressure.

8D.5.4.1 Containment Heat Removal

Containment heat removal is accomplished with the PCCS. The PCCS requires no active components for actuation, control or motive force and is an extension of the containment boundary. The PCCS is designed for conditions that meet or exceed the upper limits of containment reference severe accident capability.

The vacuum breakers between the DW and WW are self-actuating, similar to a check valve. The passive, process-actuated nature of the vacuum relief function will not be affected by severe accident conditions.

The pressure differential between the drywell and wetwell is continuously monitored to give indication of any potential vacuum breaker leakage. If leakage is detected, a back-up valve automatically isolates the leakage path to ensure that PCCS function is maintained. Further, the likelihood of a severe accident in conjunction with vacuum breaker failure is beyond the scope of a credible accident, as shown in Table 8.3-2. As such, back-up isolation valve function is not considered in the survivability analysis.

Containment heat removal is performed by the PCCS, which is designed for conditions associated with a severe accident. The PCCS requires no active components for actuation, control or motive force. The pressure suppression capability of containment requires that the vacuum breakers remain closed during a severe accident; WW to DW vacuum-relief requires the vacuum breakers to open periodically. All vacuum breaker operation is passive and process-driven. Thus, there is reasonable assurance that equipment required for containment heat removal will function in a severe accident environment.

8D.5.4.2 Containment Venting

Containment venting is achieved by operator action to open venting valves in the Containment Inerting System to connect the suppression pool airspace to the Reactor Building HVAC. All components in the Containment Inerting System are located outside of the primary containment and, as such, are not subject to severe accident conditions.

8D.5.5 Combustible Gas Control

The ESBWR containment is inerted and as discussed in Section 8D.2.8, a combustible gas environment will not be generated during within 24 hours of accident initiation. Thus, the equipment requirements for combustible gas control are the same as those for maintaining containment isolation.

8D.5.6 Post-Accident Monitoring

Instrumentation, power and control components associated with severe accident monitored variables are located outside of the containment pressure boundary. Thus, the only components needed to monitor the plant conditions that are subject to the severe accident environment are local area sensors, taps and wiring. Instrumentation lines penetrating the containment follow the recommendations of Regulatory Guide 1.11. Much of the instrumentation is safety-related and meets the requirements of Category 1 components per Regulatory Guide 1.97. Category 1 and 2 instruments whose ranges are required to extend beyond those ranges calculated in the most severe design basis accident event are qualified using the guidance provided in ANS-4.5. If instruments not explicitly qualified for severe accident environment, much of instrument designed to LOCA conditions. All post-accident monitoring instrumentation is designed in accordance with the Regulatory Guides listed in Section 7.5.1.3.1.4.

<u>Valve position sensors:</u>

- Containment isolation is credited only if it is successful within the design envelope, so isolation valve position indication is not required during severe accident conditions.
- All instrumentation associated with the GDCS deluge system, including valve position indication, is designed for operation in a severe accident environment. As a result, deluge indication is reasonably assured.

<u>Temperature sensors:</u>

- Thermocouples in the lower drywell protective layer, which are used to actuate GDCS deluge, are qualified for severe accident conditions.
- The Containment Inerting System uses twelve temperature sensors at various locations inside the drywell to measure air temperature. All components in the Containment Inerting System are designed to withstand LOCA conditions. The bounding severe accident environment in the drywell airspace presented in Section 8D.3.5 does not significantly exceed the LOCA environment as indicated by comparison to the conditions presented in Section 8D.3.3. The high degree of redundancy among temperature sensors and their capability to withstand LOCA conditions with design margin indicates that there is reasonable assurance of successful drywell temperature monitoring during a severe accident.

<u>Water Level</u>

- Lower drywell water level will always reach a high level immediately after RPV rupture due to GDCS deluge system actuation. During a severe accident, the water itself will provide substantial thermal and radiation shielding. Therefore, there is reasonable assurance that water level instrumentation will be functional in a severe accident environment.

- GDCS tank level instrumentation is located high in the drywell in the GDCS tanks, well separated from the most severe conditions in the lower drywell. The instruments are explicitly designed to withstand a design basis LOCA and are located under the surface of the GDCS pools. The underwater environment, in conjunction with their upper drywell location, provides reasonable assurance that GDCS pool level indication will function in a severe accident environment. The instruments are safety-related and meet the requirements of Category 1 components per Regulatory Guide 1.97.
- Suppression pool (SP) level instruments are located under the surface of the suppression pool in the wetwell. The severe accident environment within the wetwell is much less harsh than that in the drywell because all accident-generated gases in the wetwell are forced through the SP water. The ability of the SP level instrumentation to function with margin in a design basis LOCA, combined with the less severe wetwell conditions, provides reasonable assurance that SP level monitoring will function in a severe accident. The instruments are safety-related and meet the requirements of Category 1 components per Regulatory Guide 1.97.

<u>Containment Pressure Indication</u>: Containment pressure indication is available from several instrumentation systems with redundant and diverse components. Pressure taps transducers are generally qualified beyond intended measurement bandwidth.

Per DCD 7.5.2.3, containment monitoring instrumentation will be qualified for accident conditions.

<u>Containment Area Radiation:</u> The Area Radiation Monitoring System (ARMS) is a non-safety related system that detects containment radiation levels. Containment area radiation can also be sampled by containment air sampling if area monitors fail; that is, containment monitoring system piping connections permit the Post-Accident Sampling subsystem to extract a periodic gas sample for laboratory analysis. The ability of these diverse, redundant systems to perform with margin in a design basis LOCA, combined with the existence of multiple available systems for radiation monitoring, provides reasonable assurance that the function will be available during a severe accident.

<u>Combustible Gas Concentration:</u>

Combustible gas concentrations can be determined by extracting periodic gas samples if area monitors fail. Sampling equipment is not exposed to the severe accident environment. Thus, there is reasonable assurance that combustible gas concentrations can be monitored in a severe accident environment.

Table 8D.4-2 summarizes the evaluation of severe accident equipment capability.

Table 8D.4-1 Electrical Penetration Survivability Criteria*	
Criterion	**Value**
Temperature	644 K
Pressure	1.025 MPa

*Reference 8D-4

Table 8D.4-2

Bases for Equipment Severe Accident Survivability

Function	Required Equipment Subject to Severe Accident Environment	Bases
Cooling of Corium Debris Bed (Lower Drywell)	GDCS tanks GDCS deluge piping GDCS deluge valves BiMAC Actuation Instrumentation Control Wiring DC power	The components required for lower drywell debris cooling consist of piping, actuation instrumentation, water sources, GDCS deluge valves, BiMAC piping, and control wiring. This equipment is either explicitly designed to function in a severe accident environment or is constructed with materials able to withstand severe accident conditions. Thus, here is reasonable assurance that components required for lower drywell debris cooling will function in a severe accident environment.
Cooling of Corium Debris Bed (Upper Drywell)	See "Containment Isolation"	Cooling of corium debris in the upper drywell is not credited, instead the containment itself passively mitigates this phenomenon by providing a consistently leak-tight structure. See "Containment Isolation".
Containment Isolation	Containment isolation valves Containment penetrations Containment structure	Containment isolation is achieved early in a potential accident sequence when components are functioning within their design bases. In the severe accident, only the maintenance of a leak-tight containment boundary is required. See 8D.4.3 for specific basis regarding design criteria.
Containment Pressure Control: Heat Removal	PCCS components Vacuum breakers	Containment heat removal requires is achieved with the PCCS, which is designed for conditions associated with a severe accident. The PCCS requires no active components for actuation, control or motive force. The pressure suppression capability of containment requires that the vacuum breakers remain closed during a severe accident. A severe accident combined with vacuum breaker failure is not considered credible, as explained in 8D.4.4.1. Thus, there is reasonable assurance that equipment required for containment heat removal will function in a severe accident environment.
Containment Pressure Control: Venting	Vent valve and Controls HPNSS	No components required for the containment venting function are inside the primary containment, thus, there is reasonable assurance of venting function.

Table 8D.4-2

Bases for Equipment Severe Accident Survivability

Function	Required Equipment Subject to Severe Accident Environment	Bases
Combustible Gas Control	See "Containment Isolation"	Section 8.1 demonstrates that a combustible containment atmosphere is physically unreasonable for at least 24 hours in a severe accident. Thus, only the containment function to maintain a leak-tight barrier must be maintained, as in the Containment Isolation function.
Post-Accident Monitoring	Containment Isolation Valve Position Upper Drywell Temperature Lower Drywell Temperature Drywell Water Level Suppression Pool Level Drywell Pressure Wetwell Pressure Containment Area Radiation Combustible Gas Levels Associated Instrumentation	See discussion in 8D.4.6. In general, sensors are qualified, with design margin, to perform in a design basis LOCA. In addition, many functions have diverse and redundant systems as back up in the event of a primary system failure. As such, there is reasonable assurance that post-accident monitoring can be performed in a severe accident environment.

8D.6 SUMMARY

A systematic evaluation of ESBWR equipment capability in a severe accident environment has been conducted. The evaluation identified key functions needed to place plant in a controlled, stable state (i.e., accident progression terminated), which could be monitored. The equipment necessary to achieve these functions was identified. The severe accident environment was established considering credible severe accident scenarios as well as a non-mechanistic 100% fuel-clad metal water reaction.

The evaluation demonstrated that there is reasonable assurance that ESBWR equipment necessary to achieve a controlled, stable plant condition will function over the time span in which it is needed.

8D.7 REFERENCES

8D-1 SECY-93-016, "Evolutionary Light Water Reactor (LWR) Certification Issues and Their Relationship to Current Regulatory Requirements", January 12, 1990.

8D-2 SECY-93-087, "Policy, Technical and Licensing Issues Pertaining to Evolutionary and Advanced Light-Water Reactor (ALWR) Designs", April 2, 1993.

8D-3 10CFR50.34, "Contents of Application; technical information", Code of Federal Regulations.

8D-4 ABWR SSAR. Page AJ.1-21, "Methods and Assumptions". Reference AJ.9-32.