ECONOMIC SIMPLIFIED BOILING WATER REACTOR (ESBWR) RESPONSE TO AN EXTENDED STATION BLACKOUT/LOSS OF ALL AC POWER

Antonio J. Barrett, Wayne Marquino

New Plants Engineering, GE Hitachi Nuclear Energy, 3901 Castle Hayne Road, M/C A75, Wilmington, North Carolina 28402, USA

email: antonio.barrett@ge.com, wayne.marquino@ge.com

ABSTRACT

U.S. Federal regulations require light water cooled nuclear power plants to cope with Station Blackouts for a predetermined amount of time based on design factors for the plant. U.S. regulations define Station Blackout (SBO) as a loss of the offsite electric power system concurrent with turbine trip and unavailability of the onsite emergency AC power system. According to U.S. regulations, typically the coping period for an SBO is 4 hours and can be as long as 16 hours for currently operating BWR plants. Being able to cope with an SBO and loss of all AC power is required by international regulators as well. The U.S. licensing basis for the ESBWR is a coping period of 72 hours for an SBO based on U.S. NRC requirements for passive safety plants. In the event of an extended SBO (viz., greater than 72 hours), the ESBWR response shows that the design is able to cope with the event for at least 7 days without AC electrical power or operator action. ESBWR is a Generation III+ reactor design with an array of passive safety systems. The ESBWR primary success path for mitigation of an SBO event is the Isolation Condenser System (ICS). The ICS is a passive, closed loop, safety system that initiates automatically on a loss of power. Upon Station Blackout or loss of all AC power, the ICS begins removing decay heat from the Reactor Pressure Vessel (RPV) by (i) condensing the steam into water in heat exchangers located in pools of water above the containment, and (ii) transferring the decay heat to the atmosphere. The condensed water is then returned by gravity to cool the reactor again. The ICS alone is capable of maintaining the ESBWR in a safe shutdown condition after an SBO for an extended period. The fuel remains covered throughout the SBO event. The ICS is able to remove decay heat from the RPV for at least 7 days and maintains the reactor in a safe shutdown condition. The water level in the RPV remains well above the top of active fuel for the duration of the SBO event. Beyond 7 days, only a few simple actions are needed to cope with the SBO for an indefinite amount of time. The operation of the ICS as the primary success path for mitigation of an SBO, allows for near immediate plant restart once power is restored.

ABSTRAK

Peraturan-peraturan Persekutuan A.S. memerlukan air sejuk menyejukkan loji kuasa nuklear untuk menangguhkan Station Blackouts untuk masa yang ditetapkan berdasarkan faktor reka bentuk untuk loji itu. Peraturan A.S. menentukan Stesen Blackout (SBO) sebagai kehilangan sistem kuasa elektrik di luar negara yang bersamaan dengan perjalanan turbin dan ketiadaan sistem kuasa AC kecemasan di tapak. Mengikut peraturan A.S., biasanya tempoh penangguhan untuk SBO adalah 4 jam dan boleh selama 16 jam untuk loji BWR yang sedang beroperasi. Mampu mengatasi SBO dan kehilangan semua kuasa AC diperlukan oleh pengawal selia antarabangsa juga. Dasar pelesenan A.S. untuk ESBWR adalah tempoh penangguhan 72 jam untuk SBO berdasarkan keperluan NRC A.S. untuk tumbuhan keselamatan pasif. Sekiranya SBO dilanjutkan (iaitu, lebih daripada 72 jam), tindak balas ESBWR menunjukkan bahawa rekabentuk mampu mengatasi kejadian ini selama sekurang-kurangnya 7 hari tanpa kuasa elektrik AC atau tindakan pengendali. ESBWR adalah reka bentuk reaktor Generasi III + dengan pelbagai sistem keselamatan pasif. Laluan kejayaan utama ESBWR untuk meringankan peristiwa SBO ialah Sistem

Pemisah Pemisah (ICS). ICS adalah pasif, gelung tertutup, sistem keselamatan yang memulakan secara automatik atas kehilangan kuasa. Selepas Stesen Blackout atau kehilangan semua kuasa AC, ICS mula mengeluarkan haba pelepasan dari Kapal Tekanan Reaktor (RPV) dengan (i) menghidupkan wap ke dalam air di penukar haba yang terletak di kolam air di atas pembendungan, dan (ii) memindahkan haba yang mereput ke atmosfera. Air pekat kemudian dikembalikan oleh graviti untuk menyejukkan reaktor lagi. ICS sahaja mampu mengekalkan ESBWR dalam keadaan penutupan selamat selepas SBO untuk tempoh yang panjang. Bahan bakar masih tertutup sepanjang acara SBO. ICS mampu mengeluarkan haba pereputan dari RPV selama sekurang-kurangnya 7 hari dan mengekalkan reaktor dalam keadaan penutupan selamat. Tahap air dalam RPV masih berada di atas bahan bakar aktif selama tempoh acara SBO. Lebih dari 7 hari, hanya beberapa tindakan mudah diperlukan untuk mengatasi SBO untuk jangka waktu yang tidak terbatas. Pengoperasian ICS sebagai jalan kejayaan utama untuk pengurangan SBO, membolehkan kilang segera mendekatkan segera setelah kuasa dipulihkan.

Keywords: ESBWR, Extended SBO, Advanced Reactor Safety Design

INTRODUCTION

The ESBWR is a 4,500 MWt (1,535 MWe) generation III+ natural circulation boiling water reactor with a robust array of passive safety features designed to mitigate transients and accidents. The ESBWR utilizes a taller vessel and shorter core to achieve fully natural circulation-driven flow through the core. This makes the design simpler because it does not require the use of pumps for core flow.

The ESBWR is an evolutionary design that builds on the ABWR and SBWR advanced technologies, development, and/or construction programs. The development of the ESBWR combines the lessons learned and benefits from the ABWR and SBWR programs with newly developed technologies and advanced passive safety features. The ESBWR utilizes these advanced passive safety features to mitigate accidents that would normally be more severe for other light water reactors.

A Station Blackout (SBO) is a challenge to cope with for BWR and PWR safety systems. U.S. regulations define an SBO as a loss of the offsite electric power system concurrent with turbine trip and unavailability of the onsite emergency AC power system. Additionally, these regulations require that light water cooled nuclear power plants cope with an SBO for up to 16 hours for existing BWR plants (the time may be shorter, depending on the plant specific parameters). The licensing basis coping period for the ESBWR is 72 hours. However, the passive safety features in its design allow for the ESBWR to cope with an SBO without AC electrical power or operator action for a period considerably longer than 72 hours.

In the event of an SBO, the ESBWR utilizes isolation condensers as a passive decay heat removal system to transfer reactor decay heat directly out of the Reactor Pressure Vessel (RPV) and to the atmosphere to mitigate the consequences of the event while maintaining the reactor in a stable condition for at least 72 hours without operator action. During an extended SBO (viz., an SBO which lasts beyond 72 hours), the Isolation Condenser System (ICS) remains the primary success path for the continued mitigation of the event and can safely cool the reactor for more than 7 days.

TRACG[1] is a GE Hitachi Nuclear Energy (GEH) proprietary version of the Transient Reactor Analysis Code (TRAC)[2,3]. TRACG has been extensively qualified against separate effects tests, component performance data, integral system effects tests and full-scale BWR plant data. The purpose of this qualification is to demonstrate the applicability of the basic models in TRACG and to quantify the model uncertainty. Several separate effects, component qualification, qualification against integral system effects tests, and actual plant data are reported in the TRACG qualification reports[4,5].

TRACG is used by GEH for licensing calculations of transients and accidents for the ESBWR. The ESBWR SBO licensing calculation was performed with TRACG and the results are presented in the ESBWR Design Control Document (DCD)[6]. The U.S. licensing basis SBO calculation for the ESBWR was performed with

TRACG for a coping period of 72 hours. In the event of an extended SBO, the ESBWR response shows that the design is able to cope with the event for a considerably longer period without AC electrical power or operator action. A TRACG calculation is used as the basis for the ESBWR response to an extended SBO presented in this paper.

ISOLATION CONDENSER SYSTEM DESCRIPTION[7]

The ESBWR is a passive plant relying almost exclusively on natural phenomena to drive plant functions. Following an SBO, when the normal heat removal system is unavailable, the ICS removes residual and core decay heat from the reactor in a passive way and with minimal loss of coolant inventory from the reactor.

The ICS is designed as a safety-related system to remove reactor decay heat following reactor shutdown and isolation and can be used to avoid unnecessary use of other engineered active safety features for residual heat removal. The isolation condenser heat exchangers are independent of plant AC power, and they automatically function whenever normal heat removal systems are unavailable to maintain reactor pressure below RPV design limits.

The ICS consists of four independent trains. Each train contains an isolation condenser that condenses steam in the heat exchanger tubes thus transferring heat to the water in the ICS pools. These pools are vented to the atmosphere. A schematic of the ICS is shown in Figure 1.

The ICS pools are connected to various other pools above the containment during an extended SBO and are available for heat transfer from the ICS. The Isolation Condenser, connected by robust piping to the RPV, is placed at an elevation above the source of steam (vessel). When the steam is condensed, the condensate is returned to the RPV via a condensate return pipe. The steam side connection between the RPV and the isolation condenser is normally open and the condensate line is normally closed, which keeps the ICS in a standby “off” state. This allows the isolation condenser and drain piping to fill with condensate, which is maintained at a sub-cooled temperature by the pool water during normal reactor operation. The isolation condenser can be brought into operation by opening condensate return valves and draining the condensate to the reactor, thus causing steam from the reactor to fill the heat exchanger tubes which transfer heat to the cooler pool water.

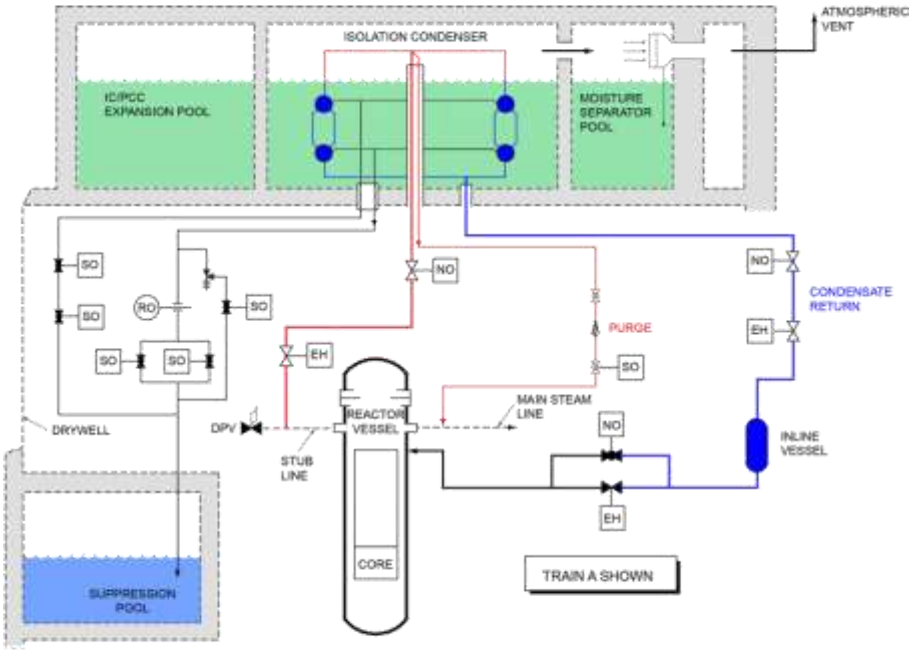

FIGURE 1. Isolation Condenser System Schematic.

The ICS valve that keeps the condensate return pipe closed is a fail-open valve designed to open without power and stay open in the unlikely event of a loss of DC power. This allows the ICS to be a fully passive cooling system for the ESBWR by requiring no DC or AC power to startup or operate.

The ESBWR ICS is most comparable to the BWR Reactor Core Isolation Cooling (RCIC) System. Unlike the RCIC system, which transfers RPV decay heat into the containment suppression pool, the ESBWR ICS removes decay heat out of the RPV and directly to the atmosphere. RCIC relies heavily on active systems to cool the reactor and requires additional actions and power to remove decay heat.

Isolation Condenser System Testing[8]

The ICS has undergone engineering development testing using a prototype to demonstrate the proper operability, reliability, and heat removal capability of the design over a range of pressures and temperatures

Full scale testing of the ICS was performed at a test facility which consists of an isolation condenser test section, a pool tank, a steam supply, a noncondensable gas supply system, a steam pressure vessel, drain and vent lines. Thermal hydraulic performance tests were conducted at the facility for both steady state and transient conditions. The tests demonstrate that the ICS meets its design performance requirements and provide a sufficient database for TRACG to predict its thermal hydraulic performance. Figure 2 shows one of the isolation condenser modules at the test facility.

FIGURE 2. Isolation Condenser Test Module.

ESBWR EXTENDED SBO RESPONSE

At the onset of an extended SBO (SBO longer than 72 hours), the ESBWR is assumed to lose all offsite AC power and is also assumed to lose onsite emergency AC power (standby diesel generators). The loss of all AC power causes the reactor to trip, resulting in both a loss of power supply to the feed-water pumps, and an initiation of a load rejection which trips the turbine. Safety-related DC batteries are available to power safety systems for 72 hours.

The ESBWR copes with an extended SBO by maintaining the reactor in a stable condition: maintaining the reactor water level above the top of active fuel and maintaining the containment temperatures and pressures below their design limits. The ICS is used as the primary success path to cope with an extended SBO by providing vessel inventory and pressure control. The rest of the safety systems don't actuate and are not credited in the mitigation of an extended SBO in the scenario described herein. The containment temperature and pressure limits are maintained because the only release to the wet-well is small amounts of non-condensable gases and steam from venting of the ICS to ensure that buildup of non-condensable gases does not occur. Leakage from the RPV is minimal because there are no recirculation pumps, the RPV is isolated early, and the ICS reduces the RPV pressure significantly.

After the loss of all AC power, the ICS is automatically initiated by the opening of the condensate return valve. The ICS fails in-service if DC power is lost. The liquid inventory contained in the ICS and the isolation condenser drain tanks during normal operation drains into the RPV to provide initial coolant inventory makeup to the RPV.

Once the ICS is initiated, the system begins to remove residual and core decay heat by condensing steam from the RPV in the isolation condenser heat exchanger tubes and transfers the heat to the ICS pools located above the containment. The steam rises from the reactor to the heat exchangers in the pool, condenses, then gravity pulls the cool water down into the reactor. Figure 3 depicts the ICS steam and condensate return loop.

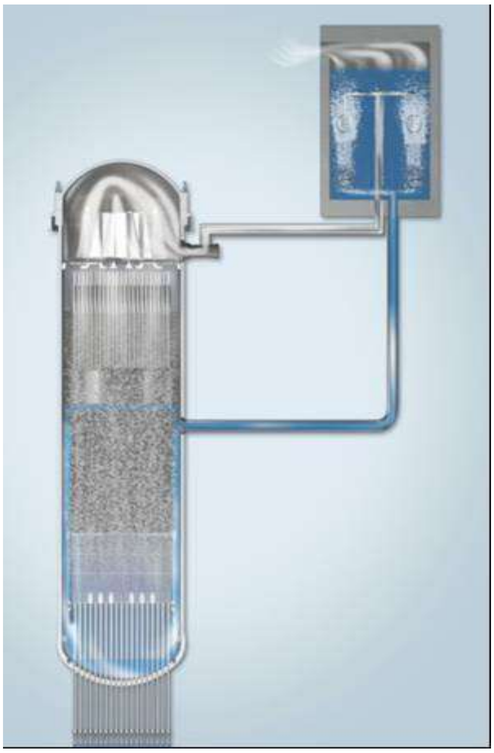

FIGURE 3. ICS Steam and Condensate Return Loop Depiction.

As the ICS pools are boiled off, the steam is passively and directly vented to the atmosphere. The ICS pools are made of dense concrete and the vent to the atmosphere contains a moisture separator. In the scenario described herein, credit is not taken for steam produced in the ICS pool compartment being condensed on the concrete or water inventory retained by the moisture separator, which would allow that water inventory to remain in the pool. The steam that is created is assumed to go directly to the atmosphere. The cross connect valves that connect the ICS pools to the other pools located above the containment open when the water level reaches ¾ of the Isolation Condenser tube height. This provides additional water inventory for heat removal. The cross connect valves are opened using the safety related DC power supply.

As the ICS continues to remove decay heat, the vessel depressurizes. During operation of the ICS, noncondensables gases begin to build in the IC tubes and can degrade the heat transfer capability. Fail-open vent valves open to allow constant but extremely minimal venting of these noncondensable gases to the suppression pool. The vent valves are opened using the safety related DC power supply.

The water level in the RPV remains well above the top of active fuel for at least 7 days after onset of the SBO. The vessel is depressurized and the system inventory remains relatively constant as shown in Figure 4. The measured level has some changes due to liquid density changes as the reactor pressure and liquid temperature changes. The RPV dome pressure is shown in Figure 5. The containment has insignificant heat up and pressurization over the period of interest. The timing for the sequence of events described above is located in Table 1.

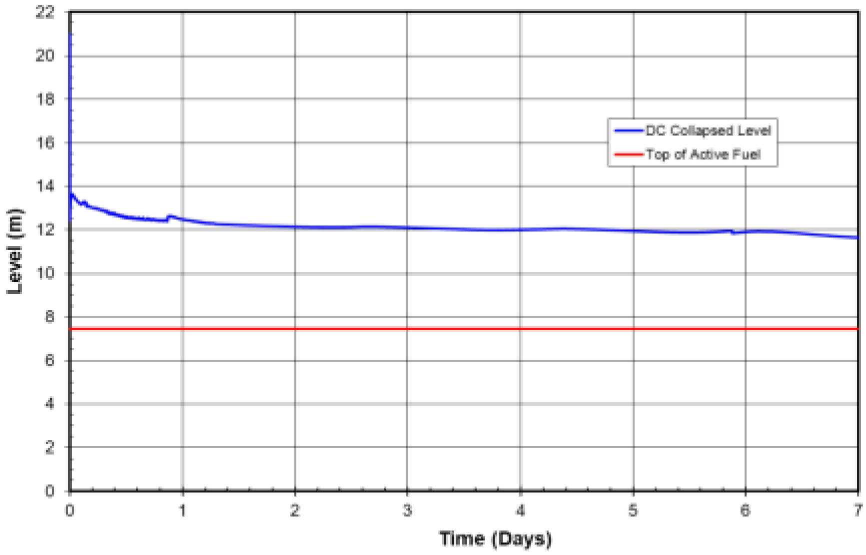

FIGURE 4. RPV Downcomer Collapsed Water Level.

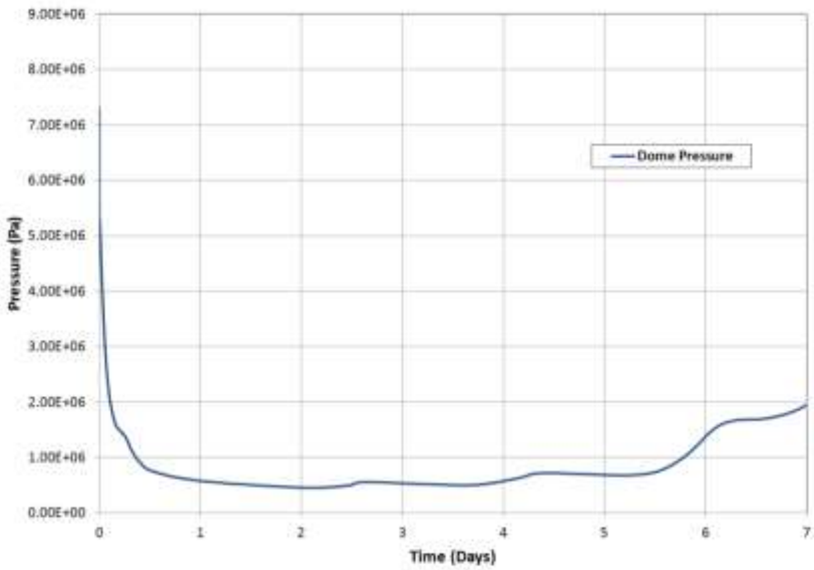

FIGURE 5. RPV Dome Pressure.

TABLE 1. Sequence of Key Events.

Event	Event Time, s (Days)
Start of Station Blackout/loss of power	0 (0)
Feedwater and condenser pumps are tripped due to loss of power.	0 (0)
Loss of power is detected and initiates a reactor scram.	2 (0)
Activation of Isolation Condensers.	3 (0)
Feedwater flow stops.	5 (0)
Vessel water level reaches Level 2, initiates containment isolation.	11 (0)
MSIV closure on low steamline pressure setpoint reached.	12 (0)
MSIV begins to close.	13 (0)
MSIV is totally closed.	16 (0)
Isolation Condenser begins to drop cold water inside the vessel.	18 (0)
Isolation Condenser drain valve is fully open.	33 (0)
Isolation Condenser lower header vent valves open.	21600 (0.25)
Isolation Condenser pool level has reached 3/4 IC tube height. Expansion pool cross connect valves open.	216324 (2.50)
RPV pressure below 2 MPa and the water level is above the top of active fuel.	604800 (7.00)

The conditions up to and including 7 days are evaluated to determine whether the ESBWR can cope with an SBO for a 7 day period. The response of the design shows that the ICS alone is capable of maintaining the ESBWR in a safe shutdown condition after an SBO for an extended period. Throughout the SBO event the fuel remains covered. At 7 days, the ICS pool level is low, the ICS heat removal capacity is degraded, and some pressurization of the RPV takes place and will continue as the pool level continues to decrease. At some time after 7 days the water inventory in the ICS pools will boil off to the lowest heat transfer surface. At this point there is still significant water inventory inside of the RPV but the ICS is no longer able to maintain the RPV dome pressure below the SRV set-point. When the SRVs have reached their set-point they will begin to actuate. When the SRVs begin to actuate, the remaining water inventory in the RPV will begin to boil off and exit the RPV via the SRVs. This allows additional time to refill the pools before the fuel is uncovered.

If a few simple actions are taken by the operator anytime in the first 7 days of the event to replenish the pool inventory, the ESBWR ICS cooling can continue indefinitely with renewed heat removal capacity keeping the fuel cool and the RPV pressure within acceptable levels. These simple actions include using any available pump and available water supply (almost any water supply is deemed suitable) to refill the ICS pools. Either the permanently installed diesel-driven pump drawing from the on-site water storage tanks, a fire truck, or a small gas or diesel engine driven water pump (similar to the one shown in Figure 6) connected to robust pipe connections outside the reactor building could refill the water inventory in the ICS pools.

FIGURE 6. Small Engine Driven Water Pump.

CONCLUSIONS

During an extended SBO, with the ICS as the primary success path and no operator action, the ESBWR design maintains the RPV water level well above the top of active fuel for at least 7 days and maintains the reactor in a safe shutdown condition (the reactor is subcritical and decay heat is being removed at a controlled rate). Beyond 7 days, only simple actions are needed to cope with the SBO for an indefinite amount of time. The operation of the ICS as the primary success path allows for near-immediate plant restart once power is restored.

NOMENCLATURE

ABWR	Advanced Boiling Water Reactor
AC	Alternating Current
BWR	Boiling Water Reactor
DC	Direct Current
DC	Downcomer (Figure 5)
DCD	Design Control Document
GEH	GE Hitachi Nuclear Energy
IC	Isolation Condenser
ICS	Isolation Condenser System
NRC	Nuclear Regulatory Commission
PWR	Pressurized Water Reactor
RCIC	Reactor Core Isolation Cooling
RPV	Reactor Pressure Vessel
SBO	Station Blackout
SBWR	Simplified Boiling Water Reactor
SRV	Safety Relief Valve
TRAC	Transient Reactor Analysis Code

ACKNOWLEDGMENTS

Significant technical contributions to the formulation of this paper were provided by Dr. MD Alamgir and William F. Berg. The expert reviews by Brian Hunt and Richard Williams are greatly appreciated. The hard work and dedication of many individuals who have worked on the ESBWR project, whom are too numerous to name individually, have contributed to make this paper possible, and their influences are greatly appreciated.

REFERENCES

1. GE Hitachi Nuclear Energy, "TRACG Model Description," NEDO-32176, Class I (Non-proprietary), Revision 4, January 2008.
2. J. A. Borkowski, et al., TRAC-BF1/MOD1: An Advanced Best-Estimate Program for BWR Accident Analysis, NUREG/CR-4356, Idaho National Engineering Laboratory, August 1992
3. TRAC-PF1/MOD2, NUREG/CR-5673, Los Alamos National Laboratory.

GE Nuclear Energy, "TRACG Qualification," NEDO-32177, Class I (Non-proprietary), Revision 3, August 2007.

5. GE Nuclear Energy, "TRACG Qualification for SBWR," NEDO-32725, Class I (Non-proprietary), Revision 1, 2002.
6. GE Hitachi Nuclear Energy, ESBWR Design Control Document Tier 2, Chapter 15, 26A6642BP, Revision 9 December 2010.
7. GE Hitachi Nuclear Energy, ESBWR Design Control Document Tier 2, Chapter 5, 26A6642AR, Revision 9 December 2010.
8. GE Nuclear Energy, "SBWR Testing Summary Report," NEDO-32606P, Class I, August 2002.