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PCCS Model Development for SBWR Using the CONTAIN Code*

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Abstract

The General Electric Simplified Boiling Water Reactor (SBWR) employs a passive containment cooling system (PCCS) to maintain long-term containment gas pressure and temperature below design limits during accidents. This system consists of a steam supply line that connects the upper portion of the drywell with a vertical shell-and-tube single pass heat exchanger located in an open water pool outside of the containment safety envelope. The heat exchanger tube outlet is connected to a vent line that is submerged below the suppression pool surface but above the main suppression pool horizontal vents. Steam generated in the post-shutdown period flows into the heat exchanger tubes as the result of suction and/or a low pressure differential between the drywell and suppression chamber. Operation of the PCCS is complicated by the presence of noncondensables in the flow stream. Build-up of noncondensables in the exchanger and vent line for the periods when the vent is not cleared causes a reduction in the exchanger heat removal capacity. As flow to the exchanger is reduced due to the noncondensable gas build-up, the drywell pressure increases until the vent line is cleared and the noncondensables are purged into the suppression chamber, restoring the heat removal capability of the PCCS. This paper reports on progress made in modeling SBWR containment loads using the CONTAIN code. As a central part of this effort, a PCCS model development effort has recently been undertaken to implement an appropriate model in CONTAIN. The CONTAIN PCCS modeling approach is discussed and validated. A full SBWR containment input deck has also been developed for CONTAIN. The plant response to a postulated design basis accident (DBA) has been calculated with the CONTAIN PCCS model and plant deck, and the preliminary results are discussed.

1. Introduction

As part of the licensing certification process, General Electric (GE) is engaged in a program to demonstrate that the Simplified Boiling Water Reactor (SBWR) design can be safely shut down during a hypothetical accident without threatening containment integrity. In the case of

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a design basis accident (DBA), it must be shown that the containment pressure will not exceed the design pressure of the containment boundary during the accident. GE, in its effort to assure the safety of the design, has funded separate effects and integral tests and has performed plant analyses that are discussed in the GE Standard Safety Analysis Report (SSAR).[1] As part of the NRC review process, independent plant safety calculations are also being performed.

This paper reports on progress that has been made in using the CONTAIN code[‡,2,3] to predict SBWR containment loads during a DBA. CONTAIN is a containment analysis code developed at Sandia National Laboratories under NRC sponsorship. One SBWR application envisioned for CONTAIN is the calculation of the containment pressure response during the long-term heat-up phase of a DBA. This phase occurs after reactor coolant system (RCS) depressurization, when coolant in the RCS continues to boil off from core decay heat. In this phase the containment pressure is designed to be controlled by a passive containment cooling system (PCCS), described in Section 2 below. Since the proper modeling approach for the PCCS within the CONTAIN framework was not obvious, the development and validation of such an approach was undertaken as the first step in preparing CONTAIN for SBWR analysis.

In the following sections, the SBWR plant is first briefly described with respect to its containment safety features. The CONTAIN PCCS modeling approach is then discussed and its experimental validation presented. Next, a CONTAIN plant input deck is presented, and a preliminary long-term containment calculation of a postulated DBA is discussed. Conclusions are presented in the last section.

2. The SBWR Containment

General Description of Passive Features. The GE SBWR containment shown in Figure 1, like other BWR plant designs, is configured as two interconnected compartments: the compartment containing the reactor pressure vessel (RPV) is the drywell, and the compartment containing a large suppression pool is the wetwell. In the case of a coolant line break in the drywell, blowdown steam is vented to the wetwell through the main suppression vents to the suppression pool. The suppression pool is a short-term passive safety feature, useful in limiting the consequences of blowdowns. Over the short term, condensation of steam in the pool effectively suppresses the build-up of steam in the containment. To limit the containment pressure for long-term releases of steam generated from decay heat in the core, the SBWR plant has unique passive safety features including a passive emergency core cooling system (ECCS) and the passive containment cooling system (PCCS).

The gravity-driven cooling system (GDCS), along with automatic depressurization valves

‡K. K. Murata et al., "CONTAIN 1.2 Code Manual, Draft for Review," Sandia National Laboratories, Albuquerque, NM, April 1993.

(ADS), makes up the SBWR ECCS. It is designed to passively maintain core coverage during a loss-of-coolant accident (LOCA). Steam generated and released from the RPV into the drywell is condensed in a large number of vertical condenser tubes that make up the PCCS. Figure 2 shows one of the three PCCS units, each consisting of two modules. Each module has 248 tubes. The condensate is returned to the GDCS pools, which in turn drain into the RPV to maintain core water inventory. Uncondensed steam and noncondensables are returned to the suppression pool via vent lines submerged below the pool surface. The heat of condensation from the steam that is condensed in the PCCS tubes is transferred through the tube walls to water pools outside the containment envelope. These pools, which are open to the environment, are designed to have a large portion of their inventory boiled off and released to the environment. Water coverage of the condenser tubes is designed to be maintained for 72 hours without adding water to the pools. The control of the containment pressure is to a large degree dependent on the condensing efficiency of the PCCS.

Operation of Passive Safety Features During a Drywell LOCA. A drywell LOCA event may be caused by a break in the main steam line or any other coolant service line located in the drywell and leading to the RPV. An accident may be characterized by three phases: (1) RPV blowdown and depressurization, (2) initial GDCS operation, and (3) long-term refluxing and decay heat removal with the PCCS. It should be noted that the operating atmosphere for the containment is nitrogen gas at an initial pressure of about one atmosphere.

The first phase typically lasts only a short time (~ 200 seconds) as blowdown steam is injected into the drywell and then vented into the suppression pool, through both the large suppression vents and the much smaller PCCS vent lines. Depressurization of the RPV is designed to be aided through the sequenced operation of the ADS safety relief and depressurization valves. Much of the drywell nitrogen is flushed into the wetwell during the blowdown.

After the RPV is depressurized, the second phase begins with the injection of cold gravity-fed GDCS water into the vessel from the three GDCS pools located above the core in the upper drywell. During this phase the reactor core cooling is enhanced, and there is a temporary reduction in the steam injected into the containment through the break and the ADS valves. The reduction in the steaming rate coupled with the relatively high rate of steam condensation in the drywell can cause the drywell pressure to decrease below the wetwell pressure. This pressure reduction can result in the opening of vacuum breakers between the wetwell and drywell, which allows a portion of the nitrogen purged from the drywell in the first phase to be reintroduced into the upper drywell region. This second phase of the accident can last for periods of up to several hours.

As the GDCS water in the vessel heats up, steaming will again occur and slowly pressurize the drywell during the third phase. This phase can last tens of hours to weeks. It may produce the maximum containment pressures and temperatures during the accident and therefore can be the period of the most concern with respect to containment integrity. To control the containment loads during this phase, steam is routed via supply lines in the upper drywell to the three PCCS condensers. The flow into the PCCS is driven in a passive manner by suction from the steam condensation and/or the pressure differential that exists between the drywell and wetwell. Condensate in the tubes returns by gravity to the GDCS pools and is available to drain back into the RPV. This refluxing is designed to keep the core covered.

Since long-term pressurization rates will depend on PCCS operation, it is important that the performance of this safety feature is modeled accurately in a containment code. One potential source of degradation could arise from the presence of noncondensable gases, such as nitrogen, in the feed to the PCCS. Recent releases of the CONTAIN code have both a mechanistic model for treating surface condensation in the presence of noncondensable gas and a recently added film tracking model for calculating dynamic liquid film thicknesses along a wall comprised of a number of contiguous heat structures. These two modeling capabilities are used to create a PCCS model that gives good agreement with experiment, without further modification to the CONTAIN code, as discussed in the next section.

3. The PCCS Model

The CONTAIN PCCS model must deal with condensation heat transfer in the presence of noncondensable gas in an internal geometry. It is important to distinguish internal condensation processes, which are significantly affected by confinement within the heat transfer boundaries, from external condensation processes, which have access to the bulk medium. Unfortunately, the phenomenon of internal condensation in a vertical tube in the presence of noncondensables has not been studied as extensively as the process of external condensation. Reference 4 is one example of the numerous reports available on external condensation. Recently, in support of the SBWR program, GE has sponsored two single-tube experimental programs to investigate internal condensation processes with noncondensables. Tests have been conducted at the University of California at Berkeley (UCB)[5] and at the Massachusetts Institute of Technology (MIT).[6] These experiments are the basis for an empirical PCCS model used by GE in their analysis code TRACG.[1] Representative tests from these experimental programs were also used to validate the CONTAIN PCCS modeling approach, as discussed below.

PCCS Modeling. Figure 3 gives the geometry and some of the physical variables used in modeling the condensation process in the condenser tubes. A noncondensable gas film forms as the gas/vapor mixture drifts down the tube and accumulates at the liquid interface as the vapor condenses out. The resulting condensate is removed by liquid film flow down the wall. The condensation process is controlled by the thermal resistances of liquid and gas films and by the diffusion of vapor through the gas film, as described more completely in Reference 7. A temperature drop from bulk mixture to the interface develops as a result of the gas film thermal resistance which can be expressed as $1/h_{gas}$, where h_{gas} is the gas film heat transfer coefficient. In the case of the liquid film, the draining condensate thickness δ_L increases as a function of distance down the tube. For short tubes the liquid flow is laminar, in which case the heat transfer across the film is conduction-dominated and the thermal resistance of the film is δ_L/k_L, where k_L is the liquid thermal conductivity. It should be noted that the overall condensation heat transfer coefficient discussed below includes the effects of the latent heat of condensation and cannot be simply related to the respective film coefficients.

The Analytic Film Model. An analytic film model of the condensation process has been developed to evaluate the tube condensation coefficient along the tube. The results from this film model are then compared to experiment and to the corresponding results calculated by CONTAIN using a discrete nodalization. In the analytic film model, the gas film thermal resistance is characterized by a forced convective heat transfer correlation (the Dittus-Boelter equation). The vapor diffusion process is modeled using a heat and mass transfer analogy[7] that relates the Nusselt number determined by the forced convective heat transfer correlation to the Sherwood number for the equivalent mass transfer process. The flow equation for the liquid, which determines the liquid film thickness along the tube, includes the effects of gravity, gas mixture deceleration, and interfacial shear. The thermal resistance of the liquid film is calculated as described above.

The solution of the analytic film model is complicated by the fact that the gas mixture concentration and flow conditions are constantly changing along the tube length as a result of the condensation process. Integral methods were therefore used to determine the condensation rate along the tube. It should be noted that the analytic model includes phenomena that are not modeled in CONTAIN, such as gas mixture deceleration and interfacial shear effects. The importance of such phenomena is discussed below.

Figure 4 shows the comparison between the condensation heat transfer coefficients predicted by the analytic model and measurements for three condenser tube experiments. These experiments, with operating characteristics shown in Table 1, are representative of the SBWR condenser tube tests described in References 5 and 6. As indicated, the analytic model produces results that are in very good agreement with the data. This agreement verifies that the film modeling approach used here to describe condensation in vertical tubes is appropriate for the PCCS condensers.

Through the analytic model, various effects were studied to determine whether they should be included in the CONTAIN PCCS model. It has been determined, for example, that for the anticipated PCCS inlet flow conditions, effects such as gas mixture deceleration and interfacial shear are of secondary importance compared to factors determining the gas film resistance, which in most cases dominates the overall condensation process. Only in the case of nearly pure steam flows are effects such as deceleration and interfacial shear found important in the liquid film modeling and then only in the entrance region of the tube. After the steam quality has dropped to about 0.8 at some point down the tube, such effects no longer appear important. Even in the nearly pure steam cases, neglecting such effects may still be an acceptable approach since the omission should be conservative for determining containment loads.

The CONTAIN PCCS Model. The CONTAIN model for the PCCS condenser uses the same heat and mass transfer analogy and forced convection heat transfer correlation as the analytic model above. In the CONTAIN film tracking model, liquid film flow is assumed to depend only on gravitational forces. The results from the analytic model discussed above indicate that the neglect of gas mixture deceleration and the interfacial shear acting on the film are minor and in the conservative direction.

To model a condenser tube using CONTAIN, the condenser tube is nodalized into a number of vertically stacked cells as shown in Figure 5. The cells are required to track changing gas/vapor flow conditions, liquid film thickness, and wall temperatures along the tube axis. Figures 6 and 7 show the results of a CONTAIN calculation for UCB condenser test #26. For the calculations, the tube is nodalized into six cells as shown in Figure 5. The differences between results and data mainly reflect errors that arise when applying a discrete nodalization to the continuously varying condensation process along the tube. In general, increasing the number of cells improves the results, as shown in Figure 8 for a twelve cell representation of the tube. However, the added computational costs associated with reduced time steps to maintain solution stability for small cells effectively limits the discrete model to the more practical six cell scheme. It should be noted that the six cell nodalization will predict condenser efficiencies that are slightly less than measured; therefore, the model is expected to be a conservative model with respect to containment loads in the long-term heat-up phase.

In the PCCS representation that is used in the plant calculations below, a six cell nodalization of the condenser is used to represent the *average* condenser tube for all three PCCS units. The model includes an additional cell to describe the PCCS outlet plenum. Adopting the approach followed by GE in the SSAR, the pool surrounding the condenser tubes is not modeled explicitly; rather, the outer tube thermal boundary condition is approximated with a wall-to-pool heat transfer coefficient of 4500 W/m^2-K, which is typical of a nucleate boiling heat transfer coefficient, and the pool temperature is set at the saturation temperature corresponding to the hydrostatic pressure at the tube depth.

4. CONTAIN SBWR Plant Deck

Nodalization. A layout of the CONTAIN SBWR plant input deck is shown in Figure 9. Five cells are used to model the drywell compartment; the regions modeled are the drywell head, upper drywell, central annulus, annulus, and lower drywell regions. Cell number 7 in Figure 9 represents the RPV volume and is simply used as a repository node for GDCS pool water. The suppression chamber above the suppression pool is modeled as one cell. As noted above, the PCCS is nodalized with seven cells. Six cells are used to model the condenser tubes, and one cell is used to model the PCCS outlet plenum, including piping. In Figure 9, the condenser tubes are denoted by cells 8 through 13.

Heat Sinks and Fluid Flow Paths. The concrete containment envelope is modeled using one-dimensional heat conducting slabs. Heat conduction between compartments separated by a common structure is modeled using the connected structure option, which allows heat to be conducted between two heat sinks in different cells through a common interface. Vacuum breakers and the main suppression vents that connect the drywell and wetwell are also modeled. The PCCS vent line, which is submerged in the suppression pool, is modeled. However, due to a current limitation in CONTAIN, only one submerged vent path can be operative in the code at one time. To accommodate this limitation, the main suppression vents are activated during the first two phases of the accident. Then, during the long-term heat-up phase when the main vents are normally closed, the vent path is changed on a problem restart to model the PCCS vent line. The amount of steam condensed in a pool during submerged venting is calculated by assuming thermal equilibrium between the pool and an essentially saturated gas/vapor bubble. Saturated vapor and gas essentially at the pool temperature are released to the suppression chamber above the pool.

Water distribution within the plant is also modeled. PCCS condensate is drained from the PCCS lower plenum (Cell 13) into the GDCS pool located in the upper drywell. The GDCS pool water is drained into the RPV cell.

5. Containment Response to a Postulated DBA

Using the CONTAIN PCCS modeling approach and plant deck discussed above, a DBA calculation has been carried out, and the preliminary results are presented here. The DBA analyzed is a main steam line break (MSLB) that occurs in the annular region of the drywell located above the main suppression vent inlet and between the reactor shield wall and RPV vessel. In the calculation, blowdown steam injection is specified through input, using an external source table. Late-time steam injection from steaming in the RPV is also handled through an external source table. In the case of the blowdown source, mass rate and specific enthalpy tables were obtained from RELAP5[8] calculations of an SBWR MSLB LOCA, performed at the Idaho National Engineering Laboratory (INEL). The late-time injection rates are separately determined from estimates of the core decay heating rate, with the assumption that all of the decay heat is used to generate steam.

The timing of the various phases of the accident are noted in Table 2. Containment pressure histories for the drywell and wetwell are shown in Figure 10. The late-time pressure difference is equal to the hydrostatic head corresponding to submergence of the PCCS vent line in the suppression pool. The constant pressure difference for the long-term heat-up phase indicates that the PCCS vent line is being continuously vented into the suppression pool. The long-term pressure continues to increase slightly during the calculational period. This means that the PCCS energy transfer rate to the environment does not exceed the core decay heating rate (the only source of heating) in this calculation. Although the PCCS system is rated at a seemingly ample 30 MW[1], this rating is based on a pure steam feed at 308 kPa. In the present calculation, the pressure is lower (~ 220 kPa) and the feed is not pure steam. The PCCS heat removal rate under these conditions should be considerably less than the rating. The calculation shows a pressure ramp that the PCCS system is unable to reverse the during the first ten hours of the accident. The question of whether the PCCS efficiency might be higher than calculated depends not only on the degree of conservatism built into the CONTAIN PCCS modeling, but on the possibly more important extent to which nitrogen gas is present in the late-time feed to the PCCS.

Of the nitrogen inventory in the containment, 60 % of the inventory is contained in the drywell region (CONTAIN Cells 1-4 and 6 in Figure 9) at shutdown. Later, at the start of the long-term heat-up phase, about 30 % of the total nitrogen inventory remains in the drywell. Time-dependent nitrogen inventories for the drywell regions are shown in Figure 11. During the blowdown phase the annulus and upper drywell regions are rapidly purged of nitrogen, but the drywell head, central annulus, and lower drywell regions retain a significant nitrogen inventory. In fact, the nitrogen mass increases in the lower drywell as some nitrogen from the upper drywell and annulus regions are forced into the lower region by the blowdown steam.

During the initial GDCS draining period, the steam injection to the containment is significantly reduced and containment pressure decreases as steam condenses on structures. Since a large portion of the drywell is nearly pure steam as compared to the suppression chamber, condensation is faster in the drywell than in the suppression chamber; therefore, the drywell pressure decreases faster. The high condensation rate that occurs in the upper drywell region causes an inflow of nitrogen from the drywell regions that retained large nitrogen inventories such as the upper and lower drywell regions. Also, for a very short time, the vacuum breakers between the suppression chamber and upper drywell open, allowing approximately 200 kg of nitrogen to flow into the upper drywell, as indicated by the suppression chamber nitrogen inventory plot shown in Figure 12.

The amount and distribution of nitrogen in the drywell at the start of the RPV steaming phase is important to the long-term operation of the PCCS. Initially, most of the nitrogen in the upper drywell will be purged through the PCCS units as a result of the steam injection from the RPV. However, even a small amount of nitrogen in the PCCS feed can significantly reduce the heat removal capacity of the system. For example, in standalone calculations involving the CONTAIN PCCS nodalization, the PCCS operating efficiency at 250 kPa was found to be reduced by 17% compared to the pure steam case, when the inlet flow has a nitrogen mole fraction of only 0.003. In the case of the plant calculation, the degradation of the condenser efficiency is further enhanced by gas buildup in the condensers. This effect is clearly shown in plots of energy flux along the tube in Figure 13. The maxima in the energy fluxes, especially evident for the cells in the bottom of the tube, is an indication that the nitrogen is accumulating in the lower tube regions.

Figure 14 shows the nitrogen mole fraction in the drywell during the accident. During the GDCS draining period the upper drywell nitrogen mole fraction increases and then, when the RPV steaming begins, the nitrogen concentration drops. The drop in concentration does not continue but stabilizes at a mole fraction of about 0.004 to 0.003. A continuous supply of nitrogen is apparently flowing into the upper drywell from the drywell head and lower drywell regions. The removal of nitrogen from these regions is shown clearly in Figure 11.

It is not clear whether the calculated flow of nitrogen from these regions during the steaming period is physically reasonable, or whether it is simply a numerical artifact. When the default CONTAIN flow solver error tolerance of 1 Pa is used, as in the present calculation, it may be difficult for the flow solver to properly resolve flows from these regions under the nearly steady-state conditions of the steaming phase, since the pressure ramp is only about 1 Pa per second. The reasons for the mixing of nitrogen into the upper drywell are currently being studied.

Another issue is the rate of buildup of noncondensables in the lower condenser regions, as shown in Figure 15. As the gas mixture is purged through the bottom of the tubes and lower plenum, slight errors in the nitrogen flow rates through the calculational cells can result in substantial inaccuracies in the extent of buildup of nitrogen in the condenser, even during continuous venting to the suppression pool. Analyses of the GE separate effects experimental programs are currently being pursued, in part to gain insight into the factors influencing the buildup.

6. Summary

An integral part of the modeling of the SBWR containment is the modeling of the PCCS. Both an analytic film model and a CONTAIN PCCS model have been formulated to study vertical tube condensation in the presence of noncondensable gas. Results from the analytic model, together with comparisons to the CONTAIN model and experimental measurements have verified the CONTAIN PCCS modeling approach and have shown that it is slightly conservative.

A CONTAIN plant input deck for the entire SBWR containment has also been developed and has been exercised for a postulated DBA that is initiated with a main steam line break. In the application of this deck to a long-term plant calculation of this DBA, preliminary results indicate that the containment pressure is kept below the containment design pressure for the 10-hour duration of the calculation. However, the pressure is observed to be increasing slightly throughout this period. This pressure ramp is partially the result of a gradual degradation of the PCCS from noncondensable gas buildup. Extremely small amounts of nitrogen are present in the PCCS feed for long periods because of mixing from regions in the drywell that were not purged of nitrogen during the blowdown phase of the accident. The small amount of nitrogen in the condenser flow plus the observed accumulation of nitrogen in the bottom of the condenser tubes prevents the PCCS from operating at a higher efficiency that could reverse the observed pressure ramp. Additional studies of drywell mixing and the buildup effect are currently underway. Studies of the latter effect will include analysis of the GE separate effects experiments. These studies should provide additional insight into the modeling requirements for the physical processes affecting PCCS efficiency, in the manner observed in the present CONTAIN SBWR plant calculation.

7. References

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Table 1. Inlet Conditions for Representative Condenser Tube Experiments from References 5 and 6

Experiment	Gas Mixture Flux (kg/s-m^2)	$Re_{mixture}$	Air Molar Fraction	Inlet Pressure (MPa)
UCB #26	12	19000	0.08	0.37
MIT #B24	3.8	12900	0.11	0.21
MIT #B52	8	23000	0.35	0.48

(UCB: 22.7mm i.d. copper tube, natural circulation)
(MIT: 46mm i.d. stainless steel tube, forced flow)

Table 2. Event Timing for the CONTAIN SBWR DBA Calculation

Accident Period	Time Range (seconds)
Blowdown	0 - 200
GDCS Drain Down	200 - 1200
RPV Steaming	1200 - 2.59×10^5