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NATURAL CIRCULATION COOLDOWN ANALYSIS FOR YONGGWANG 3&4 PER US NRC BTP RSB 5-1 REQUIREMENTS

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ABSTRACT

The Natural Circulation Cooldown (NCC) analysis from normal operations to shutdown cooling entry conditions for Yonggwang units 3&4 (YGN 3&4) was performed within the requirements of U.S. Nuclear Regulatory Commission (NRC) Branch Technical Position (BTP) RSB 5-1. The results showed that the YGN 3&4 can be cooled and depressurized to the shutdown entry conditions (350 °F, 410 psia) within 16 hours under natural circulation condition requiring only 78% of the minimum condensate water storage capacity in conformance with BTP RSB 5-1 requirements. The results also demonstrated that the safety grade Reactor Coolant Gas Vent System (RCGVS) has sufficient capacity for the RCS depressurization as well as for the steam void control in the reactor vessel upper head region.

1. INTRODUCTION

The U.S. NRC set forth requirements on the natural circulation cooldown operations in the Standard Review Plan under BTP RSB 5-1.[1] The BTP RSB 5-1 requires that the nuclear power plant demonstrate that it can be brought from normal operating conditions to cold shutdown under the natural circulation conditions using only safety-grade systems and functions and with only onsite or offsite (not both) power available and assuming a single failure. It also specifies the test requirements for boron mixing capability and natural circulation cooldown within the limits specified in the Emergency Operating Procedure.

In response to these requirements, the Combustion Engineering (CE) company performed a computer simulation for the System 80 plant using its LTC (Long Term Cooling) computer code.[2] Also, two tests for CE plants were conducted to demonstrate the conformance to the BTP RSB 5-1 requirements; San Onofre unit 2 for pre-System 80 plants[3] and Palo Verde unit 1 for System 80 plants.[4]

Although the analysis and test performed for the 3800 MWt System 80 CE plant have demonstrated its conformance to the U.S. NRC requirements, the Korea Institute of Nuclear Safety (KINS), a representative of Korean licensing authority, requested a demonstration of the natural circulation capability of YGN 3&4, a 2825 MWt System 80 design, within the BTP RSB 5-1 requirements. The YGN 3&4 auxiliary pressurizer spray system, which has been credited for RCS depressurization in the 3800 MWt System 80 natural circulation cooldown analysis,[2] is not accepted by KINS as a safety grade system to be used in the natural circulation cooldown analysis and testing. Therefore, the YGN 3&4 safety grade RCGVS, originally designed for the high-point venting, is used to depressurize the RCS.

Therefore, a natural circulation cooldown analysis for YGN 3&4 from normal operation to shutdown cooling entry conditions was performed within the requirements of BTP RSB 5-1, and the analysis results are presented in this paper. In this analysis, the LTC computer code[5] with a detailed node and flow-path approach is used to model the reactor coolant system with a rigorous modeling for the potential steam bubble formation in the Reactor Vessel Upper Head (RVUH).

2. ANALYSIS

2.1 Method

The computer simulation of the natural circulation cooldown analysis for YGN 3&4 utilized the LTC code which has previously been used by CE to perform 3800 MWt System 80 natural circulation cooldown analyses.[2] The LTC code employs a node and flow-path approach to model the RCS as shown in Figure 1. The LTC code model for the flow to the RVUH results in a mechanistic calculation of the normal flow into and out of the region under forced and natural circulation conditions. The flow into and out of the RVUH is very small during forced circulation conditions and even smaller when the reactor coolant pumps are not available. Following a loss of forced flow, the RVUH can remain relatively hot and thermally lag behind the remainder of the RCS during a cooldown. In addition, since the RVUH is at a higher elevation than the RCS, natural circulation induced flow into and out of the region is unlikely.

During a cooldown, the fluid in the RVUH region must either be cooled by heat conduction (through the walls) or by a feed-and-bleed operation with the cooler reactor coolant fluid to equilibrate thermal conditions. The System 80 natural circulation cooldown analysis concluded that a normal RCS cooldown in conjunction with a conduction cooldown of the RVUH to shutdown cooling entry conditions required about 55 hours.[2] Although such a

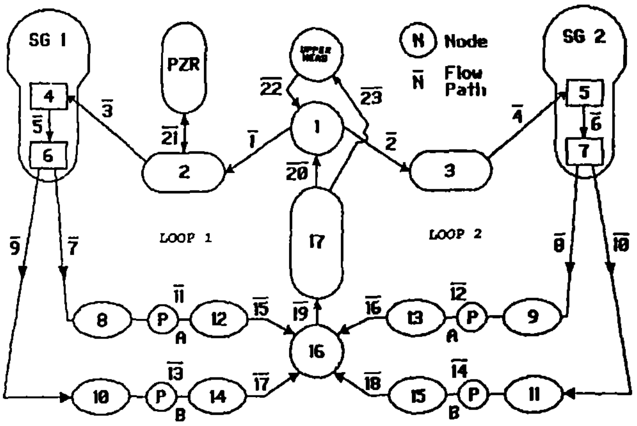

Figure 1. LTC Code RCS Nodes and Flow Paths

cooldown and subsequent depressurization would preclude steam bubble formation in the RVUH, this extended cooldown period would preclude entrance into shutdown cooling entry conditions within the capacity of the condensate storage tank. Therefore, a cooldown procedure allowing a RVUH steam bubble formation and utilizing a deliberate partial draining and refilling the upper head region was selected for the System 80 analysis and is also used for YGN 3&4.

The RVUH node consists of a two-region, non-equilibrium thermodynamic model. A momentum balance is used to calculate the coolant flow into and out of the RVUH. A mass and energy balance is also performed on the RVUH node. The state conditions that can exist for the two-region model are liquid in both regions (saturated or subcooled); steam (saturated or superheated) over liquid (subcooled, saturated, or two-phase); or steam in both regions (saturated or superheated).

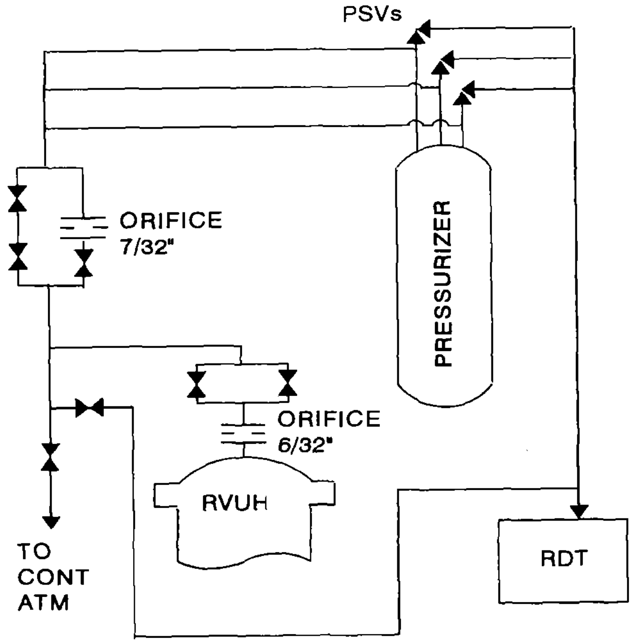

Figure 2. Schematics of RCGVS for YGN 3&4

The LTC pressurizer model consists of a two-region, nonequilibrium thermodynamic model (similar to RVUH model). The pressurizer model includes the surge line, heat transfer between pressurizer metal walls and fluid (including heat loss to the containment), main and auxiliary sprays, backup and proportional heaters, and pressurizer safety valves.

The RCGVS for YGN 3&4 has been modeled to accurately calculate the RCS depressurization and RVUH void collapsing. As shown in Figure 2, this system consists of a 3/4 inch vent lines connected to the top of pressurizer as well as to the top of RVUH. The RCGVS off the pressurizer has two flow paths; one has two solenoid valves and the other has a flow restricting orifice and a solenoid valve. The RCGVS off the RVUH has a common flow restricting orifice in the vessel head and two flow paths with one solenoid valve in each path. Both lines from the pressurizer and the RVUH are connected to the reactor drain tank via the pressurizer safety valve discharge line.

2.2 Acceptance Criteria

The acceptance criteria applied to this analysis are the requirements specified in the BTP RSB 5-1. However, some technical specification limits which yield the cooldown process in a conservative direction are also used. The major acceptance criteria are as follows :

A. The plant must be capable of completing a natural circulation cooldown by (1) assuming the loss of offsite power and a concurrent single failure, (2) maintaining the plant in hot standby condition for at least 4 hours following the loss of offsite power, and (3) using only safety grade equipment for the entire natural circulation cooldown process.

B. The formation of a steam void in the RVUH region is acceptable as long as it does not result in steam voiding in the reactor vessel outlet plenum and/or a loss of natural circulation flow through the reactor core.

C. The ability to control the RCS pressure and RVUH steam bubble, if it is formed, using the PZR gas vent system, RVUH gas vent system, and RCS makeup via throttled high-pressure safety injection (HPSI) flow must be demonstrated.

D. The degree of subcooling in the RCS hot legs must be maintained greater than 20 °F. Establishing 20 °F subcooling ensures the fluid surrounding the core is subcooled.

E. The cooldown from hot standby to shutdown cooling entry conditions shall be performed at, or below, the administratively controlled cooldown rate of 75 °F/hr.

F. The cooldown and depressurization to shutdown cooling entry conditions (350 °F and 410 psia) must be completed within the limitation of the available safety grade condensate storage capacity (minimum 300,000 gallons).

2.3 Assumptions

In order to conform the BTP RSB 5-1 requirements as well as to have conservative results, several assumptions are made. Also, the operator actions assumed in this analysis are taken from the ABB-CE Emergency Procedure Guidelines (EPGs)[6] and applied consistently throughout the whole cooldown/depressurization process. The assumed operational status of the key systems and components are listed in Table 1.

Table 1. Operational Status of Key Systems and Equipments

SYSTEM/COMPONENT	STATUS
Reactor coolant pumps	Unavailable
Pressurizer pressure CS	Unavailable
Pressurizer level CS	Unavailable
Letdown/Charging pumps	Unavailable
Pressurizer spray and heaters	Unavailable
Steam bypass control system	Unavailable
Main feedwater system	Unavailable
CEDM cooling fan	Unavailable
Reactor protection system	Available
Emergency diesel generators	One available
High pressure safety injection	One train available
Atmospheric dump valves	One available/SG
Auxiliary feedwater system	One train available
Seismic Category I condensate storage tanks, 300,000 gal.	Available
Refueling water tank	Available (4000 ppm)
RVUH gas vent system	Available
Pressurizer gas vent system	Available

Followings are the major assumptions and initial conditions along with their justifications :

A. Once the plant reaches shutdown cooling entry conditions, the plant will subsequently be cooled to cold shutdown using the shutdown cooling system.

B. The analysis is performed using the restrictions of BTP RSB 5-1, i.e., only safety grade equipment is used concurrent with a loss of offsite power and a single failure. The single failure assumed is one diesel generator failing to start, which disables one entire emergency power train and maximizes the time required to cooldown to the shutdown cooling entry conditions and, hence, maximizes the condensate water usage.

C. The RCS is initially at 100% steady-state conditions, 564.5 °F reactor inlet temperature, 2250 psia pressurizer pressure, and 1070 psia steam generator secondary pressure.

D. The initiating event is assumed to be a loss of offsite power at time zero resulting in an assumed loss of power to the reactor coolant pumps (RCPs) and thus nearly instantaneous reactor trip (i.e., CPC trip on low reactor coolant pump shaft speed).

E. Following the reactor trip, the operator manually controls the Atmospheric Dump Valves (ADVs) to restore and stabilize secondary pressure at normal no-load hot standby conditions (1170 psia secondary pressure).

F. The cooldown rate used is 50 °F/hr which is slower than the maximum administrative cooldown rate of 75 °F/hr and, hence, conservatively increases the condensate water usage.

G. The operator throttles the flow of one HPSI pump within its minimum delivery capacity during the cooldown as necessary to control pressurizer level and pressure. The pressurizer level is controlled between 20% and 70% to avoid a solid condition or a drained condition.

H. The operator manually controls the safety grade pressurizer gas vent system (using the line with the orifice) instead of the auxiliary pressurizer spray system to depressurize the RCS.

I. The operator manually controls the RVUH gas vent system and the HPSI flow to collapse a potential steam void in the RVUH. This analysis conservatively assumes that the size of the RVUH void is limited to one half the total RVUH volume or approximately 750 ft^3.

J. The heated junction thermocouple system, a part of the inadequate core cooling monitoring system (ICCMS), measures the collapsed liquid level in the RVUH. The operators are assumed to use the ICCMS as well as the pressurizer level increase to monitor the liquid level in the RVUH.

K. It is conservatively assumed that no heat transfer occurs from the RVUH to the containment atmosphere via the control element drive mechanism (CEDM), although heat loss from the RVUH to the containment via the CEDM will exist even with the CEDM cooling fans unavailable.

L. This analysis conservatively assumes no heat transfer from the fluid in the RVUH to the fluid in the outlet plenum via the upper guide structure.

M. Decay heat values used in this analysis are the 1971-ANS Decay Heat Model.[7]

N. To prevent pressurized thermal shock during the cooldown process, the maximum subcooling margin allowed is set to be 150 °F, which is taken from the ABB-CE EPGs[6] with some additional margin.

O. The steam generator water level is controlled at the normal operating water level of 79% (wide range). This will maximize the auxiliary feedwater usage since it accounts for the steam generator level shrink after a reactor trip.

P. The pressurizer heat loss to the containment is conservatively assumed to be less than the minimulm insulation design requirement value for YGN 3&4.

Q. The most negative moderator temperature and Doppler reactivity feedback coefficients, a minimum shutdown rod worth, and a zero initial RCS boron concentration with a maximum inverse boron worth are used to conservatively evaluate the shutdown margin availability.

3. RESULTS AND DISCUSSIONS

Immediately following the loss of offsite power (and the assumed loss of power to the RCPs), flow through the core decreases as the RCPs coast down. This results in a CPC reactor trip on low reactor coolant pump shaft speed. Full natural circulation flow is then established in the RCS in less than 10 minutes. Shortly after the reactor trip, the operator utilizes the ADVs to stabilize the NSSS at hot standby conditions. Also, the auxiliary feedwater flow to the steam generators is manually controlled to slowly refill the steam generators without overcooling the RCS.

The plant is maintained at hot standby for 4 hours consistent with the BTP RSB 5-1 requirements. The operator controls ADVs to maintain the steam generator pressure (Figure 3) at 1170 psia and thus the RCS cold leg temperature (Figure 4) at 564.5°F. During this hot standby period, the pressurizer pressure decreases slowly and reaches 2075 psia at the end of 4-hour hot standby (Figure 5). Due to a constant RCS temperature, the pressurizer level remains constant at approximately 40% after an initial decrease following the reactor trip (Figure 6). The RVUH temperature decrease (Figure 7) is small as a result of the small amount of flow between RVUH and RCS.

At 4.0 hours, the operator opens the pressurizer gas vent valve to depressurize the RCS to the point where the RCS subcooling margin decreases to 25°F (Figure 8). This is done in order to ensure an early HPSI flow initiation for RCS inventory makeup as RCS cooldown commences.

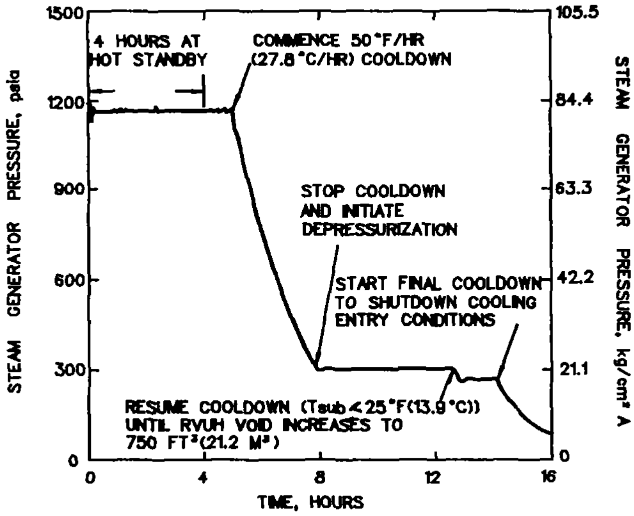

Figure 3. Steam Generator Pressure

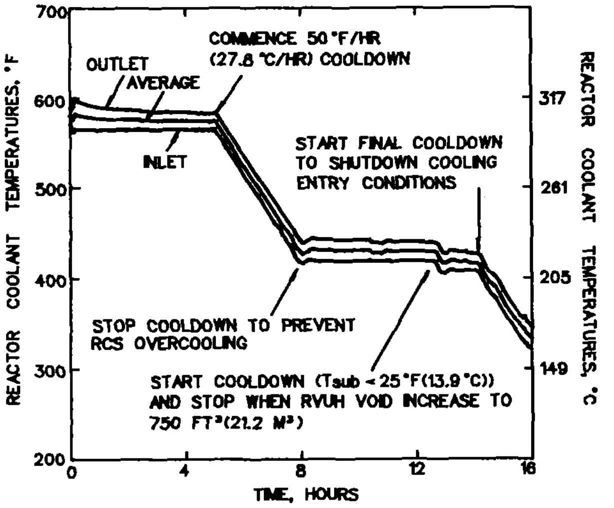

Figure 4. Reactor Coolant Temperatures

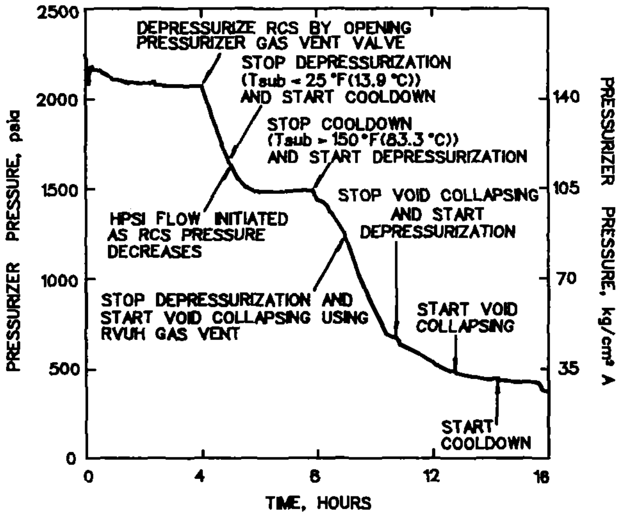

Figure 5. Pressurizer Pressure

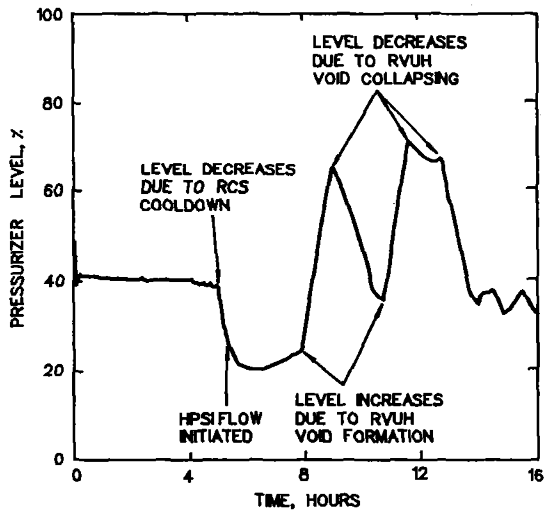

Figure 6. Pressurizer Level

After the pressure reaches 1572 psia, which corresponds to the RCS subcooling margin of 25 °F, a 50 °F/hr cooldown is initiated by increasing steam flow through ADVs. This increased steam flow causes a decrease in the steam generator pressure and RCS temperatures (closely follow the saturation curve). As the RCS starts to cooldown, the pressurizer level and pressure begin to decrease, and the operator controls HPSI flow as necessary to maintain pressurizer level. As the HPSI starts, the pressurizer level stops decreasing and slowly begins to increase. The pressurizer pressure then remains relatively constant due to the compensating effects of the pressure increase effect due to HPSI flow injection and the pressure decrease effect due to the RCS cooldown. The RVUH temperature thermally lags far behind the loop temperature during the first two hours of the cooldown, dropping by only 5°F (see Figure 7).

At 7.8 hours, the RCS subcooling margin reaches 150 °F (Figure 8), at which the operator stops cooldown to prevent RCS overcooling and initiate RCS depressurization by opening the pressurizer gas vent valve. As the RCS pressure decreases, the coolant in the RVUH reaches saturation condition and a steam void forms (Figure 9). This steam void formation in the RVUH reduces the RCS depressurization rate because of the increase in RCS water volume which is eventually seen in the pressurizer.

The steam void in the RVUH continues to increase in size as long as the pressurizer gas vent valve remains open because the RVUH fluid temperature exceeds the saturation temperature and the fluid will vaporize. When the steam void in RVUH increases to 750 ft^3, about one-half of the total RVUH volume, the operator closes the pressurizer gas vent valve and, then, opens the RVUH gas vent valve to collapse the steam void. As the RVUH void decreases, the RVUH temperature decreases *dramatically due to* the cold coolant insurge (Figure 7).

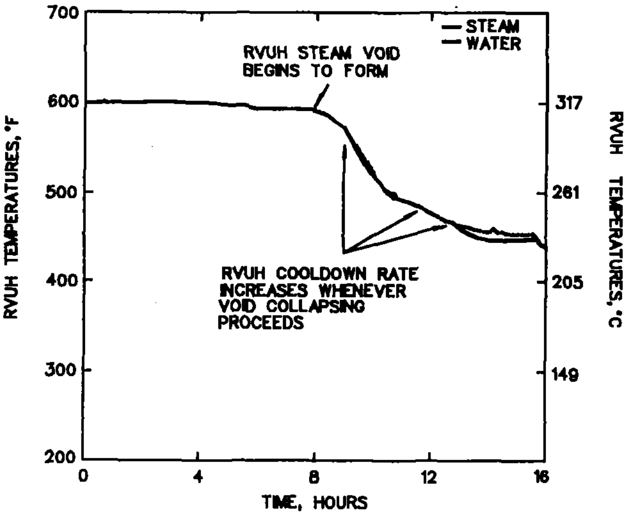

Figure 7. RVUH Temperatures

By 10.7 hours, the steam void in the RVUH is reduced and the operator closes the RVUH gas vent valve and, then, resumes depressurization by opening the pressurizer gas vent valve. During this depressurization period, the RVUH void increases again to 750 ft^3 where the operator closes the pressurizer gas vent valve and reopens the RVUH gas vent valve in order to collapse the void. Since the depressurization and the void collapsing by opening the gas vent valves also reduce the RCS pressure, the RCS subcooling margin decreases to 25 °F before the completion of void collapsing (Figure 8). At this time, the operator resumes RCS cooldown with a cooldown rate of 50 °F/hr.

At 12.8 hours, the RVUH void increases to 750 ft^3 and the operator stops the cooldown and starts RVUH void collapsing. After the RVUH void has decreased, the operator resumes the RCS cooldown all the way down to the shutdown cooling entry conditions. At 15.8 hours, the RCS pressure and temperature reach the shutdown cooling entry conditions of 410 psia and 350°F, respectively.

By 16.0 hours, the RVUH steam void has collapsed and the RVUH water temperature has been lowered to 440 °F even though no heat transfer is assumed from the RVUH to the containment atmosphere. The forced cooling by forming and collapsing steam void in the RVUH region provides a fast cooldown of the RVUH region.

The minimum RCS subcooling and the water level in the RVUH are maintained during the entire transient demonstrating that a single-phase subcooled natural circulation flow can be maintained with appropriate operator actions. The RCS boron concentration, which is conservatively assumed to be zero initially, increases due to the HPSI flow, which has a 4000 ppm boron concentration. This boron concentration increase provides additional negative reactivity into the core and provides additional shutdown margin. The positive reactivity insertion due to the RCS cooldown is compensated by the boron concentratilon increase, resulting in a sufficient shutdown margin throughout the transient.

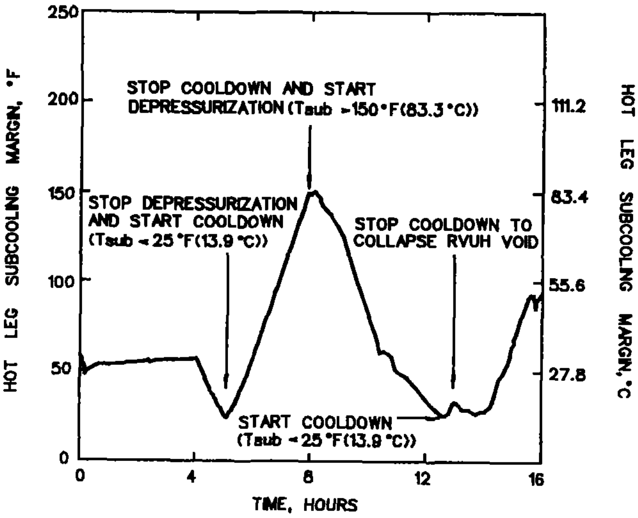

Figure 8. Hot Leg Subcooling Margin

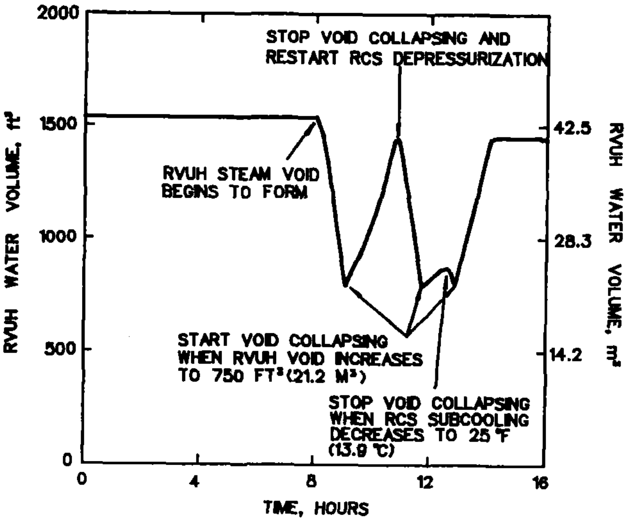

Figure 9. RVUH Water Volume

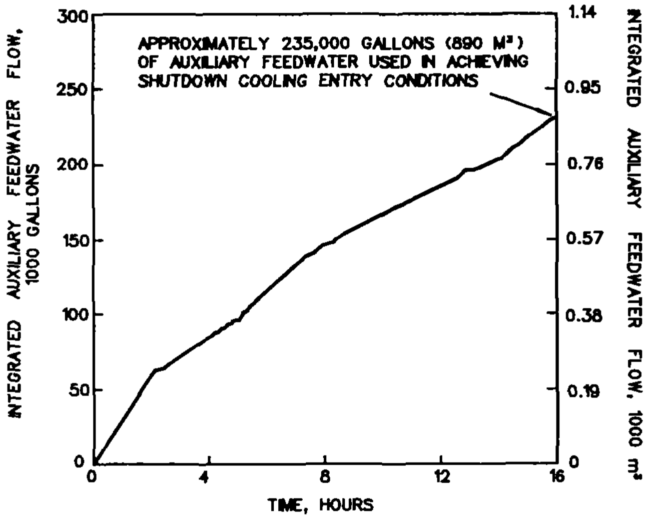

Figure 10. Integrated Auxiliary Feedwater Usage

The amount of safety grade auxiliary feedwater (Figure 10) used is 235,000 gallons. This demonstrates that the natural circulation cooldown to shutdown cooling entry conditions, per BTP RSB 5-1 requirements, can be performed well within the limit of condensate storage tank capacity (i.e., minimum capacity of 300,000 gallons). The total amount of condensate water used is broken down into the amount used in removing decay heat, removing sensible heat, and restoring the steam generator water level as shown in Table 2.

Table 2. Auxiliary Feedwater Usage for YGN 3&4 NCC

Auxiliary Feedwater Usage	gallons
Decay Heat Removal	188,000
Sensible Heat Removal	24,000
SG Inventory Recovery	23,000
Total	235,000

4. CONCLUSIONS

The YGN 3&4 natural circulation cooldown analysis results demonstrate that a cooldown and depressurization to the shutdown cooling entry conditions is achievable within the BTP RSB 5-1 requirements. These requirements include the use of only safety grade equipment, the loss of offsite power, a concurrent single failure, and condensate usage within the minimum capacity available.

If a steam void is formed in the RVUH, the void can be easily controlled and/or collapsed using the RVUH gas vent system. The collapsing of a RVUH steam void results in a rapid cooldown of the RVUH region as RCS loop water is drawn from the outlet plenum into the RVUH. This technique of forced cooling in the RVUH permits the completion of the cooldown/depressurization/void collapse process within 16 hours requiring only about 235,000 gallons of auxiliary feedwater.

The assumed single failure of one emergency diesel generator failing to start does not impose any limitations or restrictions on the natural circulation cooldown process. The capacities of one HPSI pump, one auxiliary feedwater pump, one ADV (per steam generator), the RVUH vent system, and the pressurizer vent system are sufficient to accomplish the natural circulation cooldown. Therefore, it is concluded that the YGN 3&4 NSSS can be cooled down and depressurized to the shutdown cooling entry conditions in conformance with the BTP RSB 5-1 requirements.

5. REFERENCES

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