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A Scoping Analysis of Venting Capability During Loss of RHRS Events

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Abstract

Venting capability to prevent excess pressurization caused by loss of Residual Heat Removal System (RHRS) during mid-loop operation has been evaluated analytically and the peak Reactor Coolant System (RCS) pressure was compared with the results of the MIDLOOP computer code. Even though analytical method is relatively simple, the results are in a good agreement with those of the computer code. For both methods, the peak pressures have not exceeded the nozzle dam design pressure, if the vent paths such as pressurizer safety valves or a pressurizer manway are available in a closed RCS configuration with the nozzle dam installed.

1. Introduction

Loss of RHRS during non-power operation and the consequences of such a event have been of increasing concern for years. The report of Diablo Canyon [1], stated that operating a plant with a reduced RCS inventory was a particularly sensitive condition and identified many generic weaknesses in RHRS. After the loss of vital alternating current power and RHRS during shutdown at Vogtle Unit 1 on March 20, 1990 [2], attention has been increased on the need to evaluate system performance following such an event in Pressurized Water Reactors (PWRs). When the loss of RHRS occurs during shutdown, with the reduced inventory, other available capabilities to remove decay heat should be implemented. There are several processes which can be utilized as a cooling methods such as gravity drain, core boil-off, and reflux condensation at steam generator U-tubes. Among these, the core boil-off process is discussed in this study to evaluate the venting capability of the UCN 3&4. This process can be used during shutdown in situations where 1) feed to the reactor coolant system is not available or has been lost, 2) steam generators are not available for reflux condensation. The initial RCS water is assumed to be subcooled. In a configuration of nozzle dams installed, steam pressurizes the RCS and escapes through any openings after the initiation of the core boil-off process. A steady state pressure is reached when the steam production rate due to decay heat is equal to the steam flow through the vent. The smaller the vent area is, the higher the resulting pressure is. If the steam is unvented, the pressure will continue to rise. As the core water boil-off progresses, the mixture level will drop in the core if the replacement of liquid is not established. A simplified approach is adapted to assess the venting capability of various available venting paths of the UCN 3&4 such as pressurizer safety valves, a pressurizer manways and safety depressurization system pipings. The analytical results are compared with those of 1-D thermo-hydraulic MIDLOOP code developed independently.

2. Analysis Methodology

Analytical evaluations were performed to determine vent sizes that are adequate to accomodate core boiloff without significant RCS pressurization in similar way presented in NUREG-5855 [3]. Possible vent paths were identified as pressurizer safety valves and a pressurizer manway. Vent area and flow resistance factor for each vent path are presented in Table 1. Major assumptions are as follows : 1) Prior to reaching steady state boil-off conditions, any noncondensables gases initially in the primary system have been completely vented. 2) the RCS is initially at mid-loop configuration, with the upper head in place and the core liquid in a state of saturated boiling. 3) There is a continuous replacement of boiled off liquid. 4) The containment pressure is maintained at atmospheric conditions. 5) Heat removal through the steam generators or condensation on internal surfaces is not considered.

In this analysis, steam flow rate out of vent is calculated using a modified Darcy formula for compressible flow [4] checking the critical conditions at vent paths.

$$\dot{W}_{vent} = Y \cdot A_{vent} \cdot \sqrt{\frac{2g_c \cdot 144 \cdot \Delta P \cdot \rho}{K_{vent}}} \tag{1}$$

The steam production rate due to decay heat can be simply and conservatively calculated as follows;

$$\dot{W}_{evap} = \frac{Q_{decay}}{h_{fg}} \tag{2}$$

The steady state pressure is achieved when the steam production rate due to the decay heat and the steam flow rate out of vent path are balanced. An iterative calculation continues adjusting the RCS pressure until the difference between the steam production rate and the vent rate reduces below an appropriate tolerance. Schematic iterative calculation procedure is presented in Figure 2.

The MIDLOOP code was developed for the evaluation of the RCS pressurization transients initiated from a loss of RHRS event during mid-loop operation and provides a capability for studying parametrically the response of important plant parameters such as pressure, temperature, and water level to various plant conditions of the primary side venting, makeup, and leakage procedures and the steam generator conditions. The primary and secondary sides of the MIDLOOP code consist of the hot and cold sides as shown in Figure 1. Since the flow area of the alignment key path for the UCN 3&4 is large enough to allow a large amount of hot steam of the RCS hot side to migrate to the RCS cold side through this path, the RCS cold side is assumed to have the same pressure as RCS hot side. The primary and secondary sides were represented by four nodes as shown in Figure 1. The fluid property and mass for each node are determined by solving the conservation equations of mass and energy in conjunction with the equation of state and the volume constraints. For the RCS vent cases without active steam generator (wet layup condition) and makeup/leakage, the basic differential equations governing mass conservation for the RCS node were derived by considering manometric flow between the hot and cold sides of the RCS, steam bubble rise in the hot sides of the RCS, and steam vent out of RCS. The time derivatives of enthalpy for the hot and cold sides of the RCS were determined by considering the core heat generation and heat transfer to the metal, and heat loss through the vent path. The RCS pressure was determined using volume constraints. Homogeneous Equilibrium Model (HEM) critical flow equation or orifice equation is used to calculate the vent flow rate. After all the air occupied in the vent path between the core and venting location (upper part of the pressurizer) is completely vented, the steam generated by core boiling is assumed to be vented. Therefore, all the air in the RCS cold side and hot leg in the loop without pressurizer remains there during the transient. The ordinary differential equations derived were solved by using a sixth order Runge-Kutta method. The global error in numerical computations was 1.0×10^{-4}. Code compiling, debugging, and running are performed on a IBM™ PC using Lahey FORTRAN™ software package.

3. Results and Discussions

The peak RCS pressures as a function of time after shutdown are shown in Figure 3 for various vent paths available for the UCN 3&4. The time after shutdown employed in both methods are 3, 5, 10, and 20 days. The peak pressures are presented in percentage of the UCN 3&4 nozzle dam design pressure, which is 20 psig. As shown in Figure 3, the peak pressure decreases as the time after shutdown gets longer for all the cases due to the decrease in decay heat. Differences in the peak pressures between analytical evaluations and calculational results of MIDLOOP code becomes small as the primary vent area increases. The results show that a fairly good agreement exists between two results. The most important thing is that if the vent paths such as pressurizer safety valves or a pressurizer manway are available in the closed RCS configuration with the nozzle dam installed, the peak pressures have not exceeded the design pressure of the nozzle dam. The steam vent flow rates at the peak RCS pressure are presented in Figure 4 as a function of time after shutdown. As expected, the vent flow rate decreases as the time after shutdown gets longer for all the cases. The results show that the vent flow rates obtained analytically are slightly greater than those of MIDLOOP code for all the vent paths, since the extremely conservative model adapted for steam production rate as shown in Equation (2) in the analytical method, while the steam bubble rise model was employed in MIDLOOP code. Therefore, the analytical steam vent flow rate can be conservatively used in estimating the core uncovery time. The analytical results are also useful for the calculation of gravity drain capability of Refueling Water Tank (RWT) because the RCS pressure acts as a back pressure during the gravity drain process.

4. Conclusions

In the present study the venting capability of various available vent paths for the UCN 3&4 has been evaluated by a analytical method and a simple 1-D computer code. The results for both approaches are in a good agreement each other and analytical method has been found to be very effective way of predicting venting capability during the loss of RHRS events. The venting capability of the UCN 3&4 such as pressurizer safety valves and a pressurizer manway has been verified to be enough to prevent the peak RCS pressure from exceeding the design pressure of the nozzle dam.

References

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2. A. Chaffee, "Loss of Vital AC Power and the Residual Heat Removal System During Mid-loop Operations at Vogtle Unit 1 on March 20, 1990," NUREG-1410, U.S. Nuclear Regulatory Commission, June 1990.

3. S.A. Naff, G.W.Johnson, D.E. Palmrose, E.D.Hughes, C.M.Kullberg, and W.C.Arcieri, "Thermal-Hydraulic Processes During Reduced Inventory Operation with Loss of Residual Heat removal," NUREG/CR-5855, April 1992.

4. CRANE Technical paper 410, "Flow of Fluid through Valves, Fittings, and Pipe," Crane Co., 1985.

Nomenclature

$\dot{W}_{vent}$: Flow rate out of vent path, lbm/sec

Y : Net expansion factor

A_{vent} : Flow area with the greatest velocity in vent flow path, ft^2

g_c : Gravitational constant, 32.2 lbm-ft/lbf-sec^2

ΔP : Pressure difference between RCS and containment, psi

ρ : Upstream density of vent flow, lbm/ft^3

K_{vent} : Effective flow resistance factor based on the greatest velocity in vent flow path

$\dot{W}_{evap}$: Steam production rate, lbm/sec

Q_{decay} : Decay heat rate, Btu/sec

h_{fg} : Latent heat of vaporization, Btu/lbm

Table 1. Vent areas and flow resistance for each vent path

Vent size	2 PSV Pipings	3 PSV Pipings	PZR manway
A_{vent} (ft^2)	0.29348	0.44023	0.55947
K_{vent}	4.027	5.91	6.6

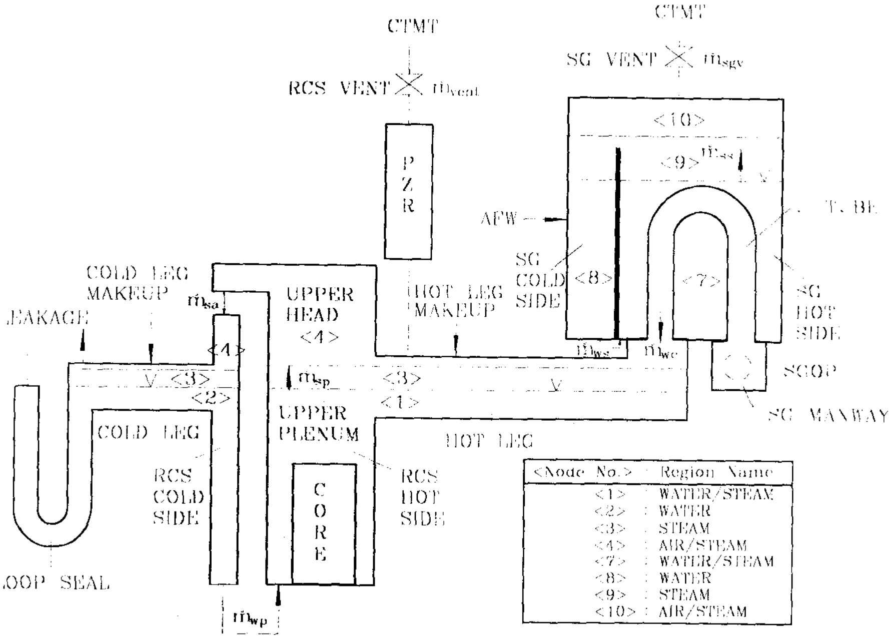


Figure 1. MIDLOOP Code Nodalization

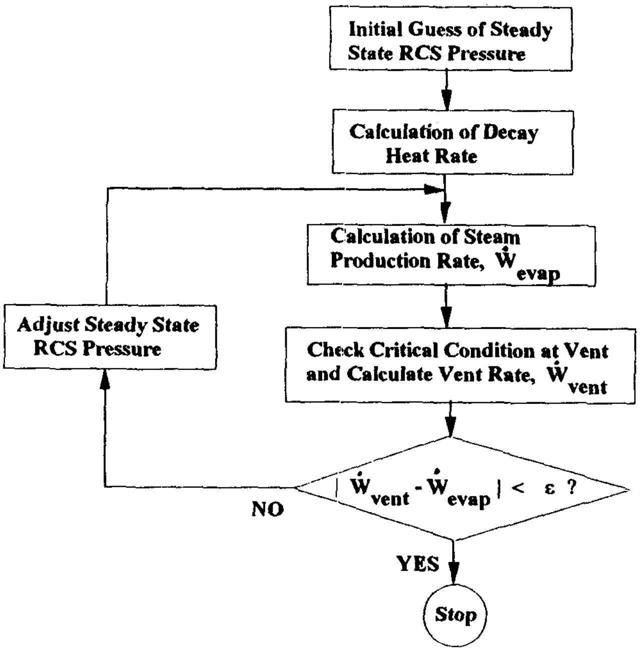
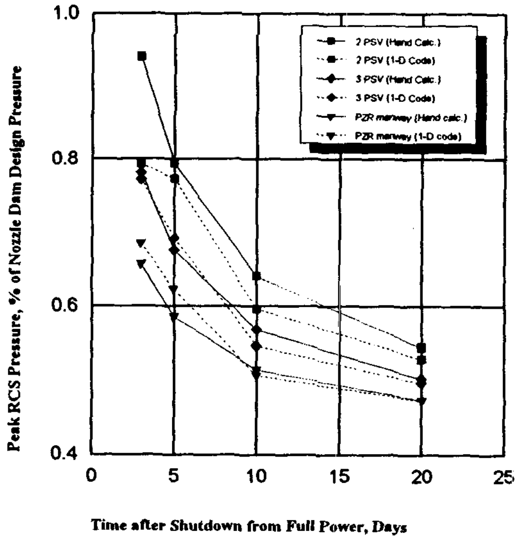


Figure 2. Schematic Diagram of Iterative Calculation Procedure



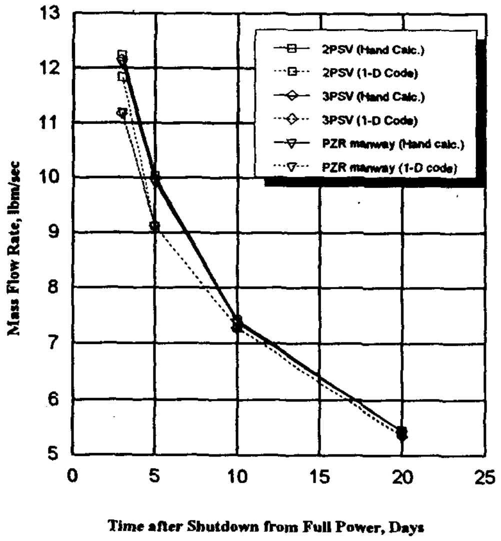


Figure 3. Peak RCS Steam Pressure vs. Time after Shutdown

Figure 4. Steam Vent Flow Rate vs. Time after Shutdown