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Best Estimate Analysis for RHR Pump Failure in Two Loops PWR

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Abstract
This paper presents an examination of the consequences of a hypothetical failure of the Residual Heat Removal (RHR) system during the shutdown operating mode, in a two loops Pressurized Water Reactor (PWR). The purpose of the analyses presented in this paper is to determine: (i) the time window for the operator to put the standby train in operation (ii) the time for the pressurizer Power Operated Relief Valve (PORV) opening & (iii) the time window for the start of boiling of the core coolant. A best estimate analysis of this scenario has been performed using the system code RELAP5/mod3.4 for a two-loops PWR. The RHR train in operation is assumed failed at Reactor Coolant System (RCS) average temperature (~447.15K) and at pressure (~2.94MPa). The results of the analysis show that RCS becomes solid at 3490 seconds. After solidification the RCS pressure overshoots to pressurizer PORV setpoint. There is a time window of less than 1 h (3530 seconds) for the operator to put the standby RHR train in operation. The pressurizer pressure reaches in 3560 seconds to PORV opening set point (3.92 MPa) and boiling in RCS starts at 9195 seconds (~2.6 h). The pressure rise caused by the expansion of the RCS inventory is thus kept within acceptable limits for at least 2.6 h. After this time, the average primary circuit temperature reaches saturation and vapor production in the RCS increases, causing the PORV to remain permanently open.

Keywords
PWR shutdown; RHR isolation valve; RELAP5; accident analysis; deterministic safety analysis

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1.0 Introduction

In this paper we examine the consequences of the failure of Residual Heat Removal (RHR) system during the shutdown operating mode in a two loops PWR. If the RHR system decay heat removal capability cannot be replaced by any other system, then the energy released in the core will heat up the inventory in the RCS and will cause it to expand. If the thermal expansion is such that the entire RCS becomes "water-solid", that is, completely filled with water, then further expansion will result in a rapid increase of the RCS pressure. This situation could threaten the integrity of the RCS pressure boundary and lead to a dangerous break in the primary system or in the lines of the systems connected to it, e.g. RHR system. The pressure increase can be arrested by the opening of the pressurizer PORV at Low Temperature Over Pressure (LTOP) position or, in those PWRs in which the RHR system is not isolated after it fails, by the opening of the pressure relief valve in the RHR system line. In the plant under consideration, the RHR system is isolated as the pressure increases to 3.43MPa automatically. In such a situation, the RHR standby train will not be able to operate before reducing the RCS pressure to 2.94MPa. So the pressure will be arrested only by the pressurizer Power Operated Relief Valves (PORVs) at LTOP position.

The LTOP System controls RCS pressure at low temperatures so the integrity of the reactor coolant pressure boundary (RCPB) is not compromised by violating the pressure and temperature (P/T) limits of 10 CFR Part 50, Appendix G [1].

The purpose of the analyses presented in this paper is to determine the time window for RHR isolation, time for opening the pressurizer PORVs at LTOP position and to investigate the RCS boiling time. A best estimate analysis of this shutdown scenario has been performed with the system code RELAP5 (Mod3.4) and the results are presented below.

2.0 Description of the Model

Best estimate computer code RELAP5 (Mod3.4) is used for transient in plant shutdown operation mode with average temperature < 453.15k and pressure equal to 2.94MPa. The code is capable of modeling complex thermal-hydraulic systems and is primarily used for the prediction of nuclear power plant behavior in the case of transients/accidents. Inherent limits of the model are: one dimensional hydraulic volume, two phase separated nonequilibrium fluid flow (six constitutive equations), constitutive closure relations, empirical heat transfer correlations, one dimensional heat structure representation and point neutron kinetics. In order to be able to model thermal hydraulic systems, rather large amount of input data describing modeling object is needed [2-5].

The model has been established with the predefined fidelity of the plant physical parameters (geometry, thermal hydraulic parameters, control and protection system set points, etc.) and taking into account limits of the mathematical model and related assumptions with necessary simplifications. The model has been developed to a high level of detail and includes detailed discretization of all important components of the plant primary and secondary side (Reactor Pressure Vessel (RPV) and Steam Generators (SG)) and the models of the Emergency Core Cooling System - ECCS, Main Feedwater - SMF and Auxiliary Feedwater - SAF and simplified model of charging and letdown system. Protection and control system has been developed according to the plant available documentation. The model has been developed with necessary fidelity of geometrical and operating parameters.

For the purpose of shutdown analysis, the RHR system has been included in the model in the following stages:
(1) Gathering and organizing required data of RHR system for complete loop
(2) Defining and nodalizing the problem
(3) Definition of the model initial and boundary conditions
(4) Running and analyzing the problem.
The schematic can be viewed in Fig. 1.

3.0 Transient Description

To achieve initial conditions for this analysis the RCS is cooldown from 553.15 k to less than 453.15 k through Steam Generators PORVs and auxiliary feed water system after reactor trip. The RHR train in loop-a is taken in operation (at about 8.3 hours after reactor trip) when RCS temperature becomes less than 453.15 k, RCS pressure 2.9 MPa and pressurizer level about 8.0m (according to plant procedure). The set point of pressurizer PORVs is set at LTOP value (3.92MPa).

If the RHR system decay heat removal capability cannot be replaced by any other system, then the energy released in the core will heat up the inventory in the Reactor Coolant System

(RCS) and will cause it to expand. If the expansion is such that the entire RCS becomes "water-solid", that is, completely filled with liquid water, then further expansion could threaten the integrity of the RCS pressure boundary and lead to a dangerous break in the primary system or in the lines of the systems connected to it, e.g. RHR system. The pressure increase can be arrested by the opening of the pressurizer relief valves (PORV) or, in those PWRs in which the RHR system is not isolated after it fails, by the opening of the pressure relief valves in the RHR system line.

4.0 Initial and Boundary Conditions

The initial conditions are summarized in Table 1.

Table 1 - Initial Conditions

Parameters	**Unit**	**Initial Conditions**
Decay Power	MW	RELAP5 Curve
RCS average Temperature	K	447.15
Pressurizer pressure	MPa	2.9
Pressurizer level	m	8.0
Isolation valves setpoint	MPa	3.43
Pressurizer PORV set point	MPa	3.92

The boundary conditions for this analysis are the following:

- Pressurizer heaters are closed at the time of events
- Pressurizer PORVs are at LTOP position (set point 3.92MPa)
- The Reactor Coolant Pumps are running
- Letdown and charging are in operation
- Main Steam Isolation Valves are closed
- Safety Injection signal is blocked and Accumulators are unavailable

5.0 Results

The transient is initiated at zero second by tripping the RHR pump. The results of the analysis are represented from Fig. 1 to Fig. 6 and time sequence of main events is given in Table-2.

Table-2 Time sequence of main events

Event	**Value**	**Unit**
Transient starts (500 seconds)	0	seconds
RCS becomes solid	3490	seconds
RHR isolation valves setpoint	3530	seconds
Pressurizer PORV setpoint	3560	seconds
Boiling starts	9195	seconds

On failure of RHR pump at zero second, the temperature of the RCS starts to increase due to addition of decay heat energy, as shown in Fig. 1.

The increase in temperature causes expansion of RCS inventory (Fig. 2). As RCS becomes water-solid i.e. completely filled with liquid water, further increase in temperature results in a rapid increase of the RCS pressure (Fig. 4). In 3530 seconds the RCS pressure increases to RHR isolation valves set point and in 3560 seconds to PORV set point (3.92MPa) and it starts open/close in cyclic mode.

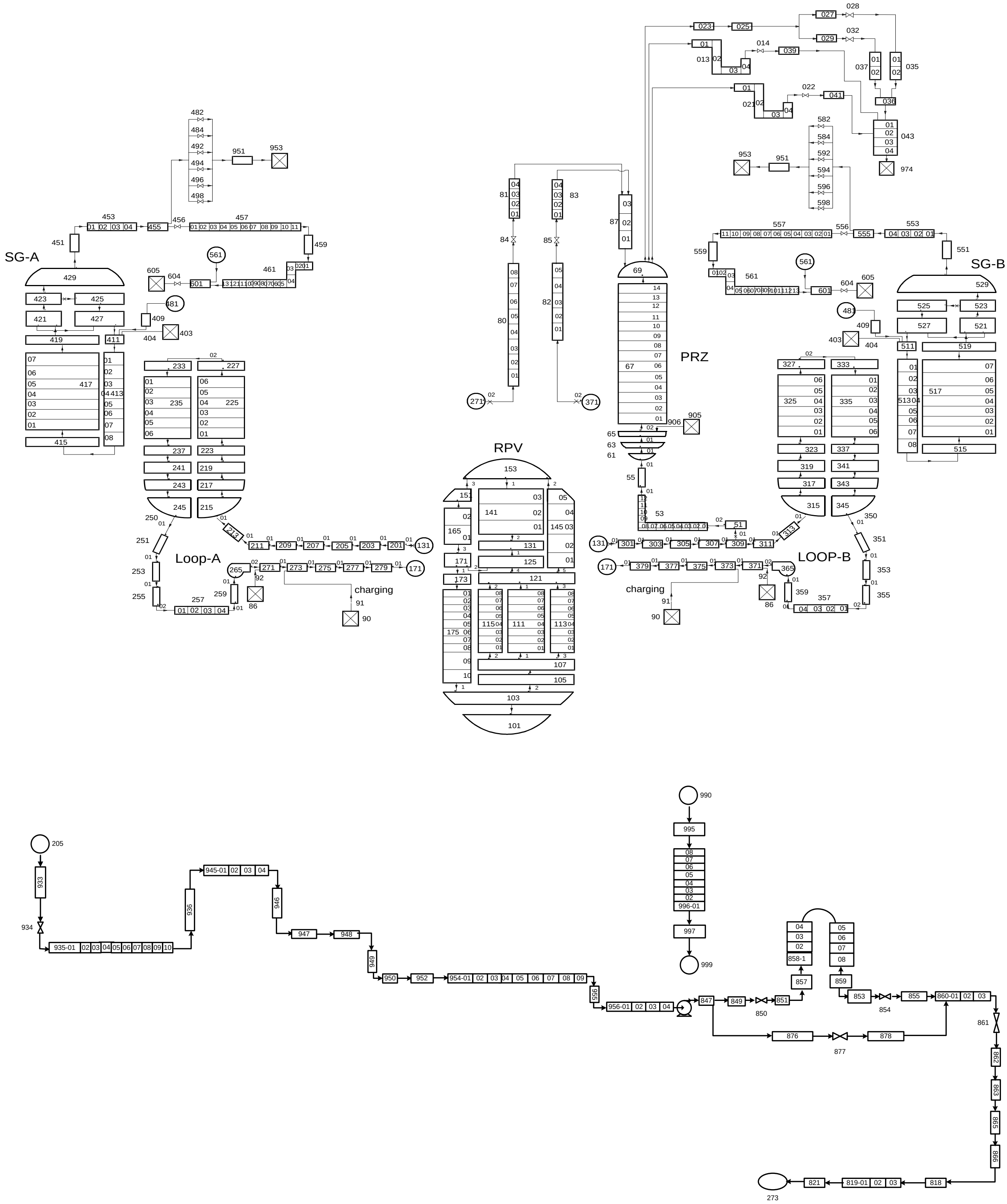

Fig. 1 RELAP5 Nodalization for shutdown analysis

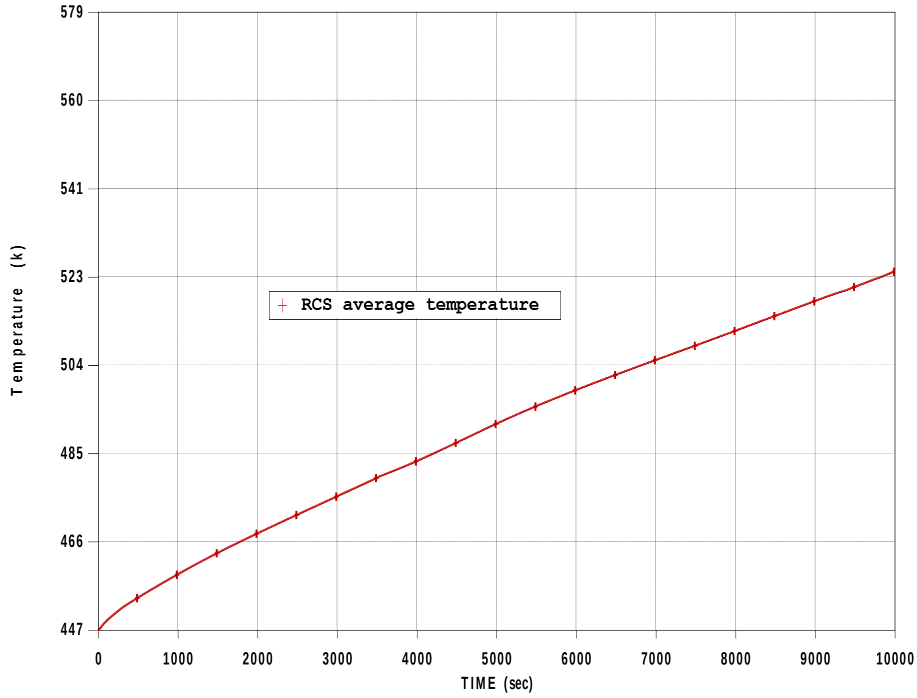

Fig. 2 RCS average temperature

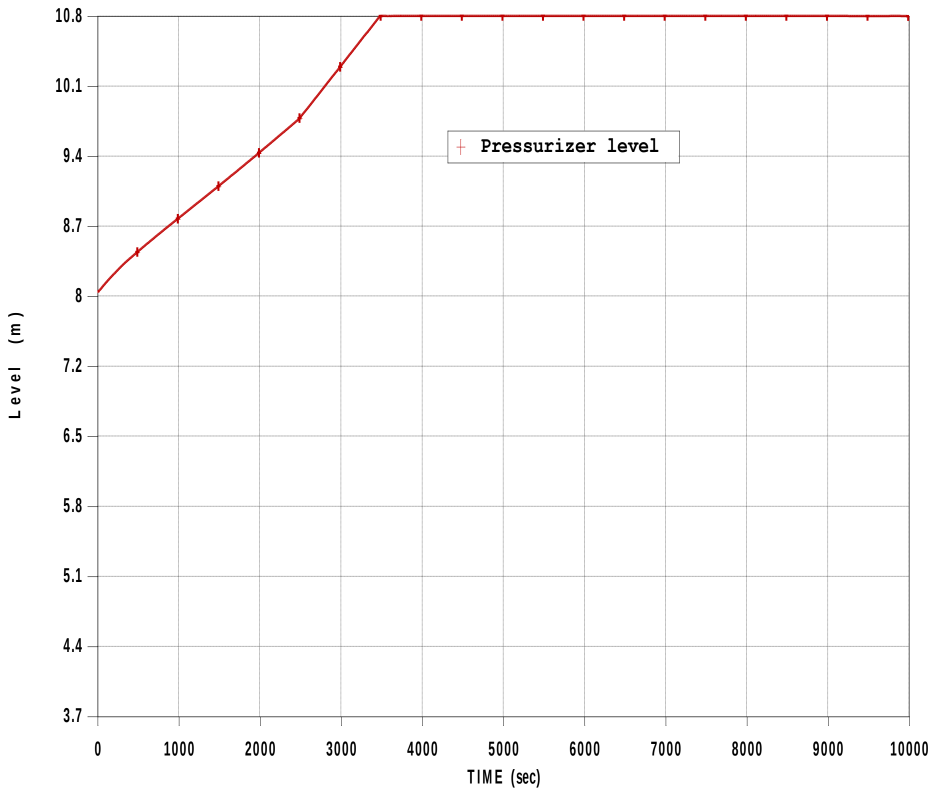

Fig. 3 Pressurizer Level

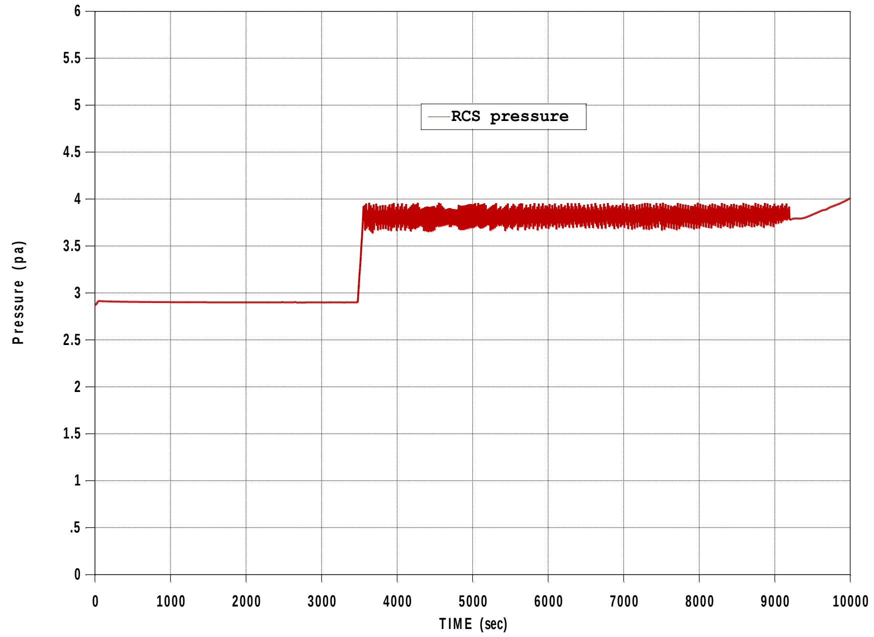

Fig. 4 RCS Pressure

In 9195 seconds pressure overshoots beyond the PORV setpoint & PORV will remain open (Fig. 5). At this time boiling starts in most of the RCS and temperature at core exit reaches to its saturated temperature (Fig. 6).

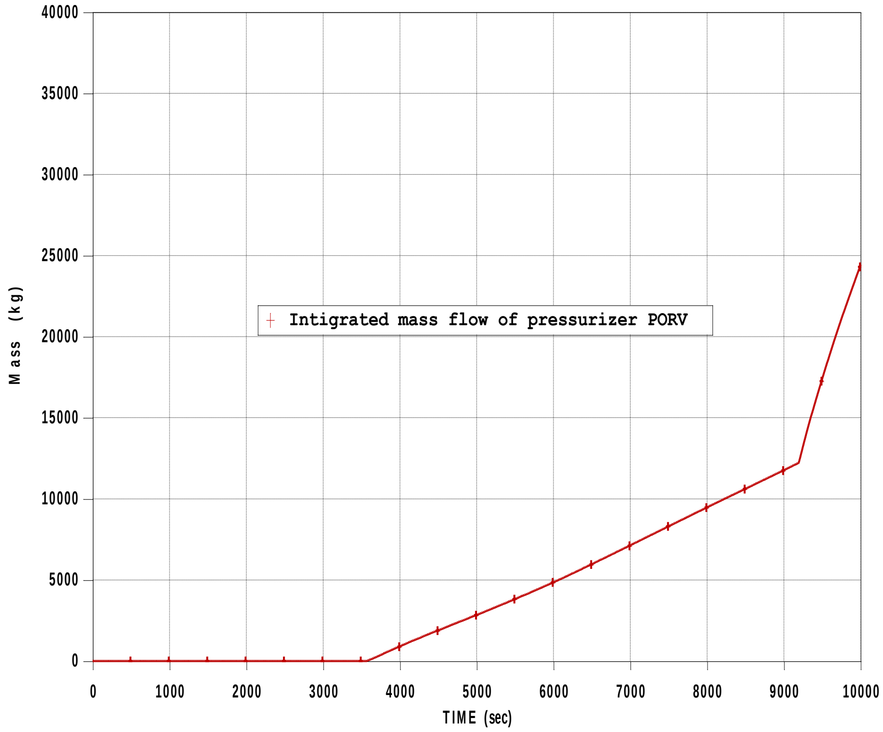

Fig. 5 PORV mass flow

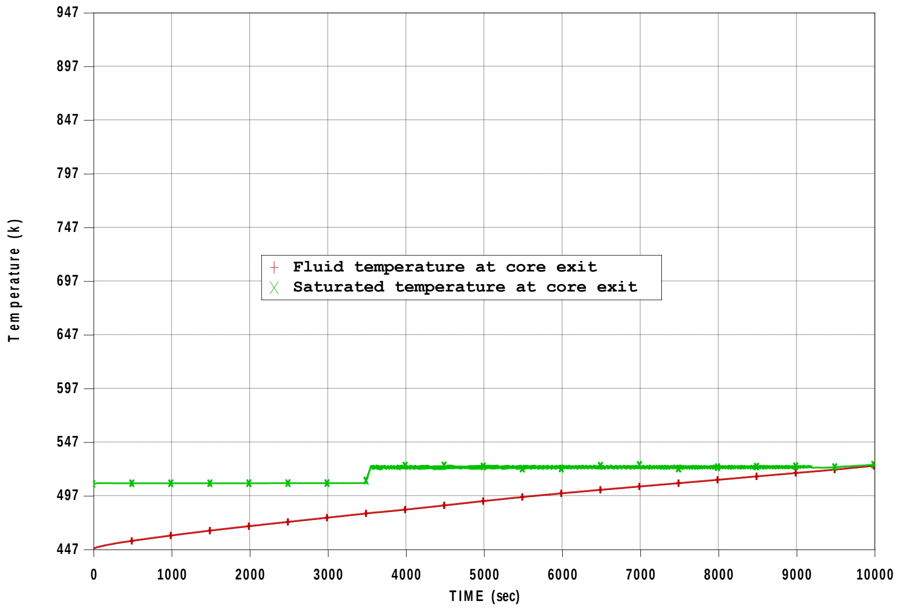

Fig. 6 Core exit temperature

6.0 Conclusions

The best estimate computer code RELAP5/Mod3.4 was used for the analysis of RHR system failure. The initial conditions for the transient are given in Table-1. For decay heat the built in curve in RELAP5 is used, which decreases with the passage of time (Fig. 7).

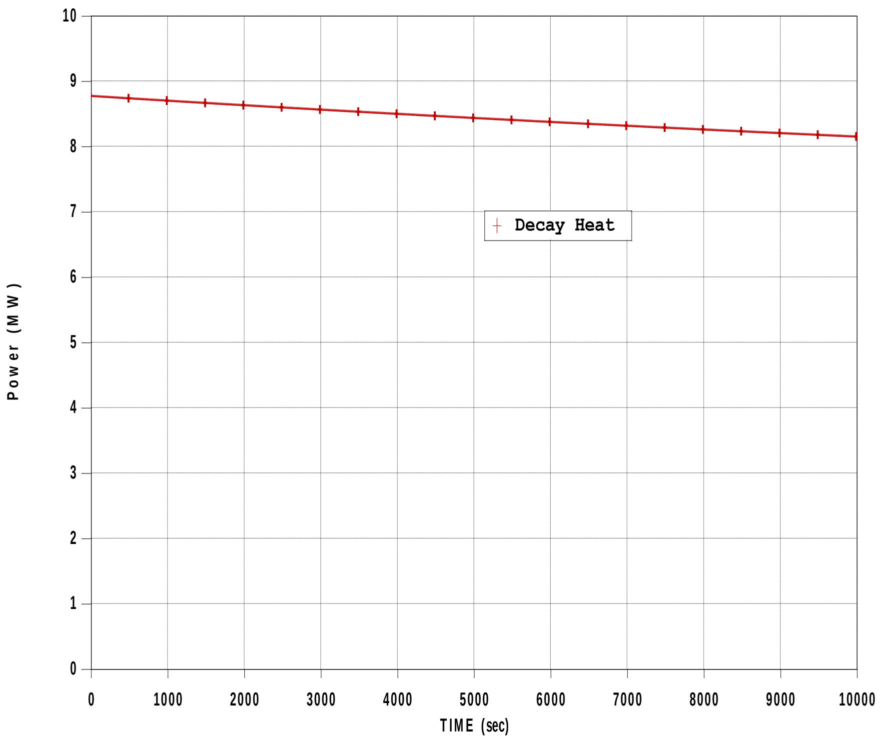

Fig. 7 Decay heat

The purpose of this analysis is to calculate the time window for the operator to put the standby train in operation, time for pressurizer PORV opening and the time window for boiling in the core after failure of RHR system.

The RHR isolation setpoint (3.43MPa) is reached in 3530 seconds (~1hr). The RCS pressure reaches in 3560 seconds to pressurizer PORV opening set point (3.92 MPa) and boiling in RCS starts at 9195 seconds (~2.6hrs).

Operator Action: The Operator will have to take standby train of RHR in loop-b into operation within 3530 seconds.

7.0 References

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