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Comparative Study between Cold-Leg and Hot-Leg Safety Injection during SBLOCA in a 4 Loop PWR NPP

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ABSTRACT
This article presents a comparison between two operation modes for the emergency core cooling system during a Small Break Loss of Coolant Accident (SBLOCA) in the cold leg of 4-loop PWR Westinghouse design nuclear power plant. In the first mode, the cold leg safety injection is used to mitigate the consequences of the accident and in the second mode the hot leg safety injection is used. The best estimate light water reactor transient analysis system code RELAP5 Mod3.3 was used in calculations. The plant nodalization consists of two loops; the first one represents the broken loop and the second one represents the other three intact loops. The results show that, in the cold leg safety injection the primary pressure decreases with time and remains higher than the secondary pressure for a period of time (~ 500 sec) during whichthe steam generators remains as a heat sink for the primary side, the accumulators start late and functioning on remaining transient time, and a repeatable loop seal clearing and refill occurs. During the hot leg safety injection the primary pressure decreases rapidly but remains higher than the secondary pressure for a longer period of time (~ 600 sec), the accumulators start early and functioning on a part of the transient time before they are totally discharged, and there is no repeatable loop seal clearing and refill. In the two modes the maximum clad surface temperature does not violate the safety limit.

Key word: *Pressurized water reactors, RELAP5 Mod3.3, Small break LOCA*

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I. INTRODUCTION

The safety of the nuclear power plants during postulated initiating events is one of the most important topics which must be demonstrated before the issuance of the operating license. One of the postulated initiating events is the Loss of Coolant Accidents (LOCA) due to a break in any component of the primary pressure boundaries. An essential Emergency Core Cooling System (ECCS) is installed to cope with those types of accidents and prevent its propagation to a Beyond Design Basis Accident (BDBA). In spite of the best estimate codes those are used today's in the safety assessment of NPP, the ECCS performance is still assessed against the same criteria, such as the peak clad temperature less than 2200 F, Maximum local clad oxidation less than 17% and core wide oxidation less than 1% [1].

Since TMI accident, the Small Break Loss of Coolant Accident (SBLOCA)takes more attention in the safety analysis of nuclear power plants [2-12].In general, the reactor system response to SBLOCA is slower compared to the large break LOCA which allows more time for the operator interventions. It is also noted that there are different paths for the consequences following a SBLOCA in PWRs. The scenarios may change drastically by many factors such as the reactor design, the break size, the core bypass flow, and the different operator interactions.

There are Different approaches for operating the ECCS; Safety injections on the cold leg, Safety injections on the hot leg, Direct Vessel Injections (DVI), or mixing between them. The widespread one is a cold leg injection during in the first stage of LOCA accident followed by a hot leg injection to provide a means for terminating boiling in the core, to maintain the core in a subcooled condition, and back-flush of boron which has plated out on the core structure [Westinghouse manual]. In Angra-2 four loops PWR 1350 MWe in Brazil, safety injection in the hot leg and/or cold leg is used during the LOCA accidents [2, 3, 4]. In new designs such as AP1000 DVI is used to control and overcome the LOCA accidents [1].

The aim of this work is the studying of reactor thermal hydraulic behavior during a postulated SBLOCA in the cold leg of the primary circuit. Two cases are considered; in the first case Cold Leg Safety Injection (CLSI) is used to mitigate and control the consequences of the accident, and in the second case the Hot Leg Safety Injection (HLSI) is used. In the two cases the auxiliary feed water system is functioning based on high/low signal of the void fraction in the upper part of steam generators. The charging system is permanently connected to the cold leg and functioning based on a high/low signal of pressurizer water level. The thermal hydraulic system code RELAP5 Mod3.3 is used in this simulation. Comparison between the reactor key parameters in the two cases is presented.

II. REFERENCE PLANT

The plant considered is a Westinghouse 4-loop PWR Nuclear Power Plant with thermal power 3411 MW_{th}. The reactor core consists of 193 fuel assemblies. Each fuel assembly is arranged in a 17x17 arrays and includes 264 fuel rods. Each loop consists of a hot leg, U-tube steam generator, intermediate leg, reactor cooling pump, and cold leg. A pressurizer connected to one of the hot legs. An emergency core cooling system consisting of four accumulators, two very high head safety injection pumps (charging pumps), two high head safety injection pumps, two low head safety injection (Residual heat removal pumps)**.**

III. ESTABLISHING NODALIZATION

Figure (1) shows the coolant loop nodalization adopted for the 4-loop reactor considered in the present investigation. The nodalization consists of two loops; broken loop and intact loop. The intact loop simulates the three loops other than the broken one. The nodalization simulates all the main components of the reactor, such as the reactor vessel internals, main coolant pumps, steam generators, pressurizer, feed water systems…etc. Also, the ECCS is simulated, including the charging system, the high safety injection system, and accumulators. The low pressure safety injection is not considered in the present simulation. Table(1) gives the main components and their equivalent code number in the nodalization.

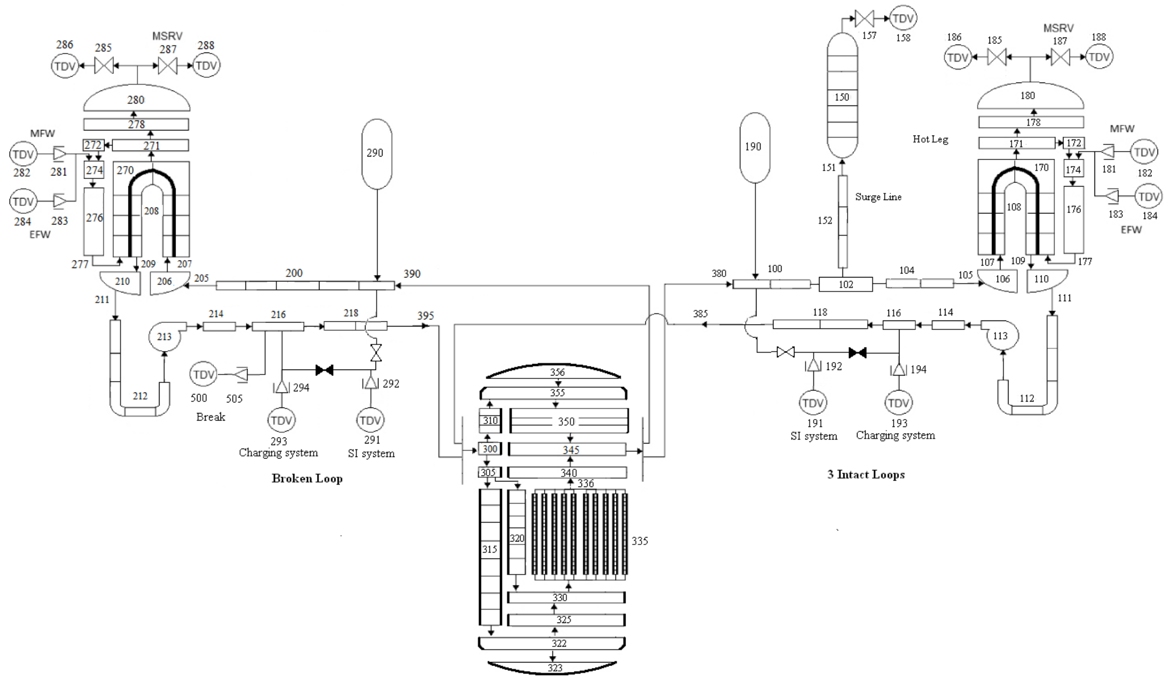

Figure (1): NPP Nodalization

Table (1): Main Components of the Nodalization

Component	Equivalent Code
Hot Leg	100, 200
Cold Leg	116,118, 216, 218
Steam Generator Primary Side	108, 208
Steam Generator Secondary Side	170-180, 270-280
Reactor Primary Pumps	113, 213
Pressurizer	150
Main Feed Water System	182, 282
Auxiliary Feed Water System	184, 284
Accumulators	190, 290
High Safety Injection System	191-192, 291-292
Charging or very high safety injection System	193-194, 293-294
Reactor Core coolant channel (one channel)	335
Fuel Heat Structures	336
Break Valve	505

IV. STEADY STATE NODALIZATION QUALIFICATION

For the reliability of code transient simulation, a nodalization qualification step is performed. After asteady state run extended for 300 sec, the calculated values of the main parameters are compared with the corresponding nominal values of the reference plant. The comparison is outlined in Table 2 and the difference as a percentage of the reference value is presented in the last column.

Table (2): Steady state qualification

Parameter	Reference value [1]	Calculated value	Difference (%)
Reactor parameters			
Total power MWth	3,411	3,361	-1.466
Core inlet temperature (K)	565	566.8	0.318
Core outlet temperature (K)	599	599.8	-0.133
Primary pressure (bar)	155	153.56	-0.929
Total coolant flow rates (Kg/s)	17438	17574.24	-0.781
Steam Generator parameters			
Steam flow/SG (Kg/s)	480	469.8	-2.12
Steam pressure (bar)	69	62.7	-9.13

As shown in Table (2), good agreements are found between the steady state results and thecorresponding nominal values of the reference plant.

V. ACCIDENT DESCRIPTION AND ASSUMPTIONS

The transient analyzed is a Small Break Loss of Coolant Accident (SBLOCA) in the cold leg of one of the loops other than that contains the pressurizer. The break size is a 4-inch in diameter. The transient initial conditions are as follows: the reactor operates at 100% of nominal power; the offsite power is not available; the emergency diesel generators of the four loops are available; and all the ECCS trains are available. The simulation of accident was performed by incorporating the operational logic of the reactor protection system. The imposed events involved in this transient with their set points are outlined in table (3). Due to a lack of data, the set point for stop/start of the charging system is assumed at ± 10 % of the pressurizer level. In the transient simulation, the high safety injection system and the accumulators are connected to the cold leg or the hot leg based on the case under simulation; CLSI or HLSI. The connection of the charging or very high safety injection is permanently connected to the cold leg.

Table (3): Imposed Sequence of Events

Imposed Event	Time/Set point
Steady -state normal operation	0 – 100 s
Break initiation	at 100 s
Reactor tripsignal	Pressurizer pressure 1860 psi (12.82 MPa)
Reactor coolant pump stop/Main feed water stop	Reactor trip signal
Main steam valve closure	Reactor trip signal
Auxiliary feed water system in the intact or broken loops (start/stop)	14 sec. delay after reactor trip + high/low setting of void fraction at SGs volume 172 and 272 (0.39578/0.30838)
Charging system (very high safety injection) start/stop	Reactor trip time + low/high setting of Pressurizer water level (27.816/ 34.771 ft)
High Safety injection (HPSI) start	Pressurizer pressure 1500 psi (10.34 MPa)
Accumulator injection start	Pressurizer pressure 600 psi (4.14 MPa)
End of transient	2000 sec

VI. RESULT ANALYSIS AND DISCUSSION

The SBLOCA transient is initiated after 100 s of steady state operation through the opening of break valve, valve 505 in figure (1).In the following paragraphs, comparative results ofreactor thermal hydraulic parameters during cold leg and hot leg safety injection are analyzed.

The primary and secondary pressure in the two cases is shown in Figures 2 &3. As general remarks; the pressure behaves in a similar way and can be divided into four stages. In the first stage, extended for few seconds, the primary pressure decreases sharply due to single phase sub-cooled liquid discharged from the break.

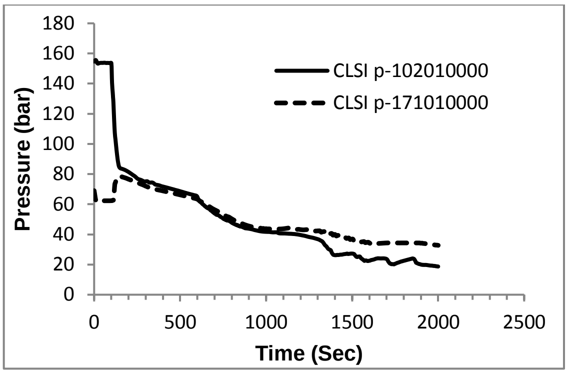

Figure 2, Primary and secondary pressure during the cold leg safety injection

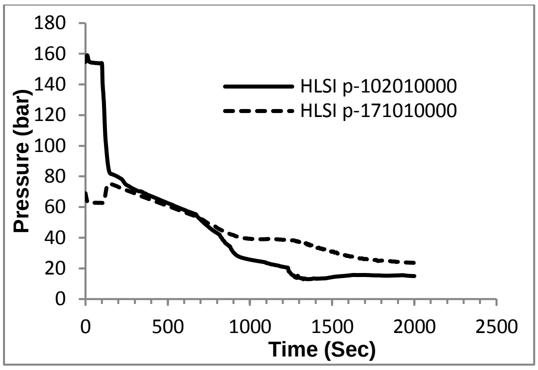

Figure 3, Primary and secondary pressure during the hot leg safety injection

The second stage extended for several hundreds of seconds, the primary pressure is slightly higher than the secondary pressure and the Steam Generators (SGs) still works as a heat sink for the primary side. In the third stage, the primary pressure is slightly lower than the secondary pressure and the primary cooling system loss the SGs as a heat sink. In the fourth stage, the primary and secondary pressure decreases with a higher rate and the difference between them increases. During CLSI this stage is characterized by repeated loop seal clearing and refill and the break's mass flow fluctuated due to fluctuations in the break's flow void fraction.
The primary pressure signal is one of the most important signals for control of operating components and safety systems. Therefore, during the first stage different events occur including; reactor trips, the primary pumps stop, the main feed water pumps stop, and the main steam valve closed. Also, the very high safety injection and high safety injection start. These remarks are common in the HLSI or CLSI.
Specific different remarks between the HLSI and CLSI are present in the following. First one is the shortness of stage three and the rapid decrease of primary pressure during the HLSI. This returns to the steam condensation which occurs due to the ECC injection of sub-cooled water in the hot leg.
Second one is the repeatable loop seal clearing and refill. The loop seal clearing is usually associated with a sharp decrease in the break's discharged flow due to an increase in its void fraction. On contrary to the CLSI in which a repeatable loop seal clearing occurs, loop seal clearing occurs only two times during the HLSI. The first one occurs at 666.7 sec, 72 sec later than that in the CLSI which occurs at 594.7sec. The second one occurs near the end of transient as shown in Figures 4 and 5.

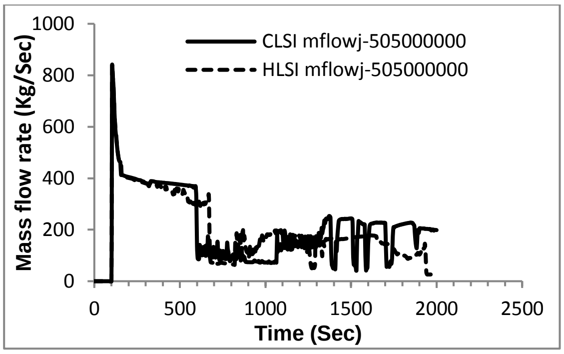

Figure 4, the break's mass flow rate

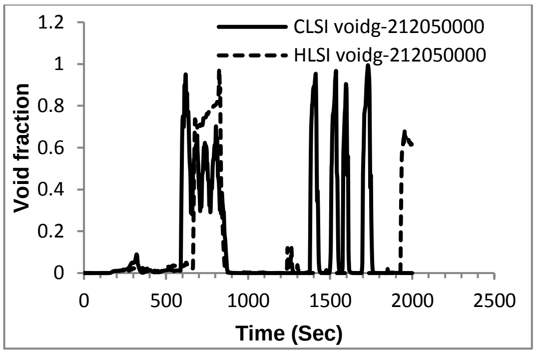

Figure 5, the void fraction in the up flow part of the loop seals

Third one is the behavior of safety injection system. The charging and high safety injection systems are start injection during the first stage. As discussed before, the HLSI primary pressure decreases faster than the CLSI. Therefore, the accumulators start earlier during the HLSI than CLSI. The accumulators usually inject a huge amount of coolant in a short time compared with the charging or high pressure safety injection as shown in Figures 6 and 7. Therefore, the HLSI causes rapid condensation for vapor, more decreasing in primary pressure, more accumulator discharged flow, and finally early empting of accumulators as shown in Figure 8. With empting of accumulators, its non-condensable gas (N2) is discharged in the primary loops as shown in Figure 9.

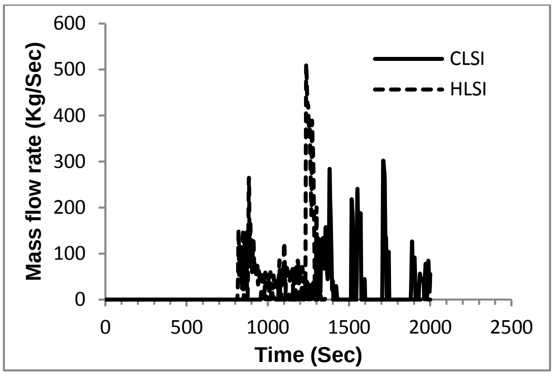

Figure 6, Accumulators safety injection flow rate

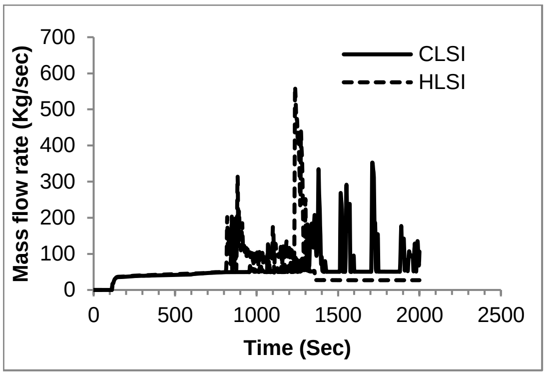

Figure 7, Total safety injection flow rate

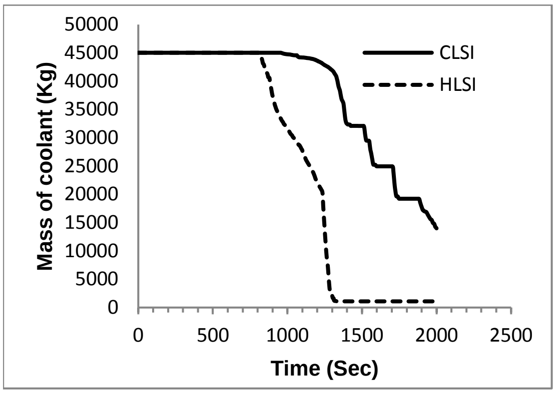

Figure 8, Variation of accumulator's mass of coolant during HLSI and CLSI

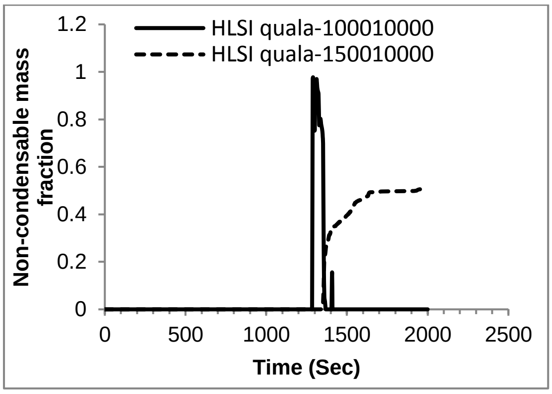

Figure 9, Non-condensable mass fraction in the primary loop during the HLSI

Fourth one is the pressurizer behavior. The pressurizer starts out-surge on time with the beginning of transient at 100sec. The pressure and coolant level in the pressurizer are shown in Figures 10-12. As the primary pressure shown on Figures 2 & 3, the pressurizer pressure during the HLSI decreases more rapidly than that in the CLSI. While the pressurizer pressure generally equals the primary, its value becomes lower on a narrow period of transient, 1333-1360 sec, during the HLSI as shown in Figure 11. During this narrow period and due to a steam condensation in the hot leg a huge amount of coolant discharged from the accumulators surged into the pressurizer as shown in Figure 12.With increasing the pressurizer water level, the charging pumps stop due to issuance of a high level signal as shown in Figure 13.

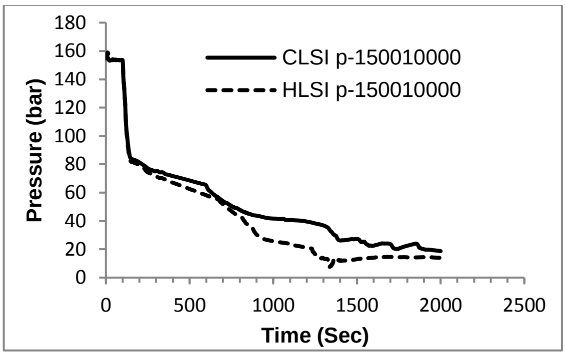

Figure 10, Pressurizer Pressure during the HLSI and CLSI

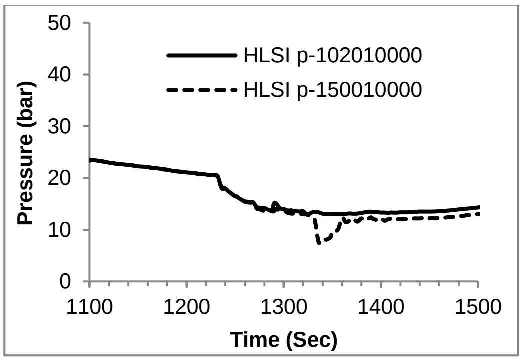

Figure 11, Hot leg and pressurizer pressure on time span 1100-1500 during the HLSI

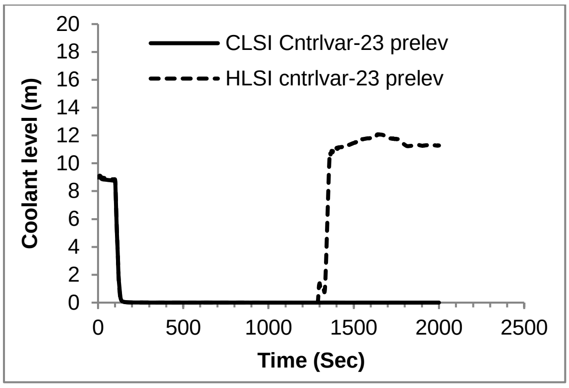

Figure 12, Pressurizer water level during CLSI and HLSI

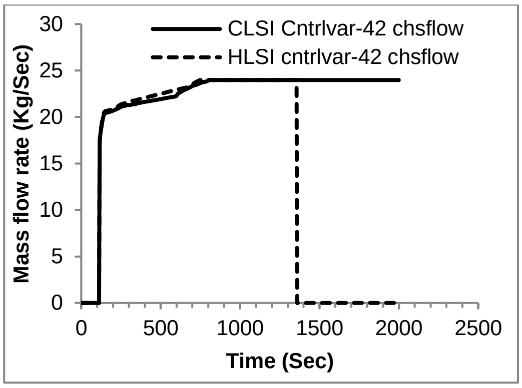

Figure 13, Mass flow rate of charging system during CLSI and HLSI

Fifth one is the core void fraction. Figures 14 and 15 illustrate the core void fraction during the HLSI and the CLSI. In the two cases the core boil but doesn't uncover. Due to the lower primary pressure during the HLSI and except for a small period in which the core void fraction becomes zero, the average void fraction during the HLSI is higher than that in the CLSI.

Sixth one is the fuel clad surface temperatures shown on Figures 16 and 17 demonstrate that the ECCS performance satisfy its internationally acceptance criteria which mention that the peak cladding temperature must be less than 1204.4 °C(2200 °F). Also, the fuel cooling rate during CLSI is better than the cooling rate during the HLSI. In Addition, the clad surface temperature during the CLSI, Figure 16, continuously decreases along the transient time and there is a positive effect for the repeatable loop seal clearing and refill at the later transient time.

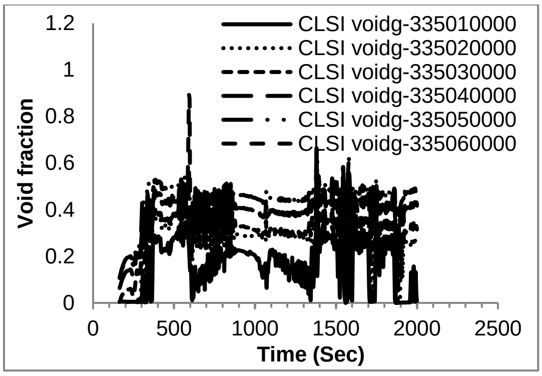

Figure 14, Core void fraction during CLSI

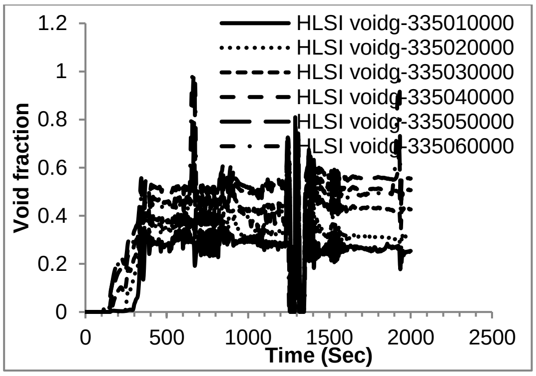

Figure 15, Core void fraction during HLSI

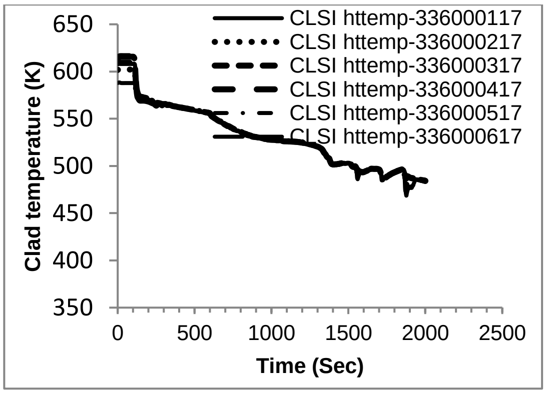

Figure 16, fuel clad surface temperature during the CLSI

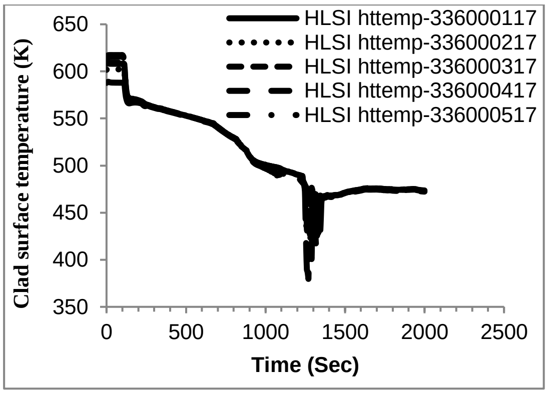

Figure 17, Fuel clad surface temperature during the HLSI

This paper presents a comparison between two operation modes for the emergency core cooling system during a Small Break Loss of Coolant Accident (SBLOCA) in the cold leg of 4-loop PWR nuclear power plant. In the first mode, the cold leg safety injection is used to mitigate the consequences of the accident and in the second mode the hot leg safety injection is used. The best estimate light water reactor transient analysis system code RELAP5 Mod3.3 was used in calculations. The results show that, in the cold leg safety injection the primary pressure decreases with time and remains higher than the secondary pressure for a period of time (~ 500 sec) during which the steam generators remains as a heat sink for the primary side, the accumulators start late and functioning on remaining transient time, and a repeatable loop seal clearing and refill occurs. During the hot leg safety injection the primary pressure decreases rapidly but remains higher than the secondary pressure for a longer period of time (~ 600 sec), the accumulators start early and functioning on a part of the transient time before they are totally discharged, the pressurizer is refilling, and there is no repeatable loop seal clearing and refill. In the two modes the maximum clad surface temperature does not violate the corresponding internationally accepted safety limit.

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