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Analysis of Overpressure Protection at Low Temperature Condition in EU-APR

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1. Introduction

According to the U.S. NRC requirement [1], the application of pressure relieving systems that function during low-temperature operation ensures overpressure protection for the Reactor Coolant Pressure Boundary (RCPB) during low-temperature operation of the plant. Based on the U.S NRC requirement, two Low Temperature Overpressure Protection (LTOP) relief valves are installed in the downstream of the first isolation valves from each hot leg line of reactor coolant system (RCS) in APR1400.

Meanwhile, European countries also have the same requirement as U.S. NRC requirement with additional requirements such as diversity and staggered setpoints of the relief valves.

Therefore, the purpose of this paper is to modify the configuration of the related features of EU-APR in order to satisfy the European requirements and to demonstrate the performance of associated safety function.

2. Development of LTOP Features

2.1 Requirements

In the Finnish regulatory guideline, YVL B.5 [2], the following requirements are presented;

1) The diversity principle shall be applied in the design of the pressure control systems of the reactor cooling system to reduce the likelihood of common cause failures.

2) Systems related to pressure control shall be so designed as to ensure that it will not be necessary – during normal operation and anticipated operational occurrences – to remove primary coolant outside closed systems, with the exception of a potential brief discharge to manage an operational occurrence.

3) The primary circuit of a pressurized and boiling water reactor and the secondary circuit of a pressurized water reactor plant shall be provided with several redundant safety valves. Redundant safety valves protecting the same item shall be set to open in succession to ensure that no more valves than required are opened to relieve overpressure.

4) No shut-off valves may be placed in the discharge line of a safety valve, nor between the item being protected and a safety valve. Where possible, no shut-off valve should be installed in the control line required for opening a safety valve. If an exception is made to this rule to facilitate testing or maintenance or to prevent a safety valve from being stuck open, the inadvertent closing of the shut-off valve shall be reliably prevented.

2.2 Phenomenological Sequences and Selection of Limiting Events

During the low temperature condition, the RCS may be pressurized by the following aspect;

- Mass Addition to Reactor Coolant System (RCS)
- Energy Addition to RCS

In the low temperature overpressure protection analyses, the most limiting event for each event category (the DBC 2, the DBC 3, the DBC 4 and the DEC) is deduced from the pressure increasing events and the plant conditions in that category, respectively.

Table 1 Plant Conditions at Low Temperature

Description	Value or Status
Core Criticality, status	Sub-Criticality
LTOP In-service Temp.	177 ℃
Turbine-Generator	Stopped
Condenser	No Vacuum

2.2.1 Design Base Condition (DBC) 2

The following DBC 2 events are related to pressure increase during the plant condition in Table 1.

- Malfunction of chemical and volume control system (CVCS),
- A spurious start-up of safety injection system (SIS),
- An inadvertent start of a reactor coolant pump (RCP) when a positive steam generator secondary side water to reactor coolant ΔT exists.

Since the runout flowrate of SI Pump (259 m^3/h) is much higher than that of the charging pump (68 m^3/h). Therefore, the spurious start-up of SIS is selected as the most limiting event for DBC 2 as a mass addition.

An inadvertent start of a RCP when a positive steam generator secondary side water to reactor coolant ΔT exists is selected as the energy addition event since the phenomena of this event is different from the above mass addition event.

2.2.2 Design Base Condition (DBC) 3 and 4

There is no event related to pressure increase during low temperature operation in DBC 3 and 4 during the plant condition in Table 1.

2.2.3 Design Extension Condition (DEC)

The following DEC events are related to pressure increase during the plant condition in Table 1.

- Anticipated operational occurrence (AOO) causing primary circuit pressure increase with a common cause failure (CCF) of primary circuit safety valves of the same type

AOO causing primary circuit pressure increase with a CCF of primary circuit safety valves of the same type is the most limiting event as a low temperature overpressure protection event. However, the diversity of LTOP relief valves is applied. Therefore, the analysis of DEC can be covered within that of DBC 2 event.

2.3 Design Modification of the LTOP Features

Overpressure protection of the RCPB during low temperature condition is provided by the LTOP relief valves located in the shutdown cooling system (SCS) suction lines same as APR1400 Design.

Meanwhile, LTOP valves are located at the upstream of the first shutdown cooling isolation valves in each RCS hot leg line in EU-APR in Figure 1 and 2. Due to the change the location, the number of LTOP valves change from four into two. Furthermore, each of two LTOP valves are different types and has the different nominal setpoint so that the requirements of diversity and staggered opening are fulfilled as shown in Table 2.

However, operator actions are needed to adjust set-point of pilot operated relief valve and to remove or to install the gagging provisions of spring loaded relief valve based on the RCS conditions so that the leakage through the LTOP relief valves is prevented during power operation and LTOP function is initiated

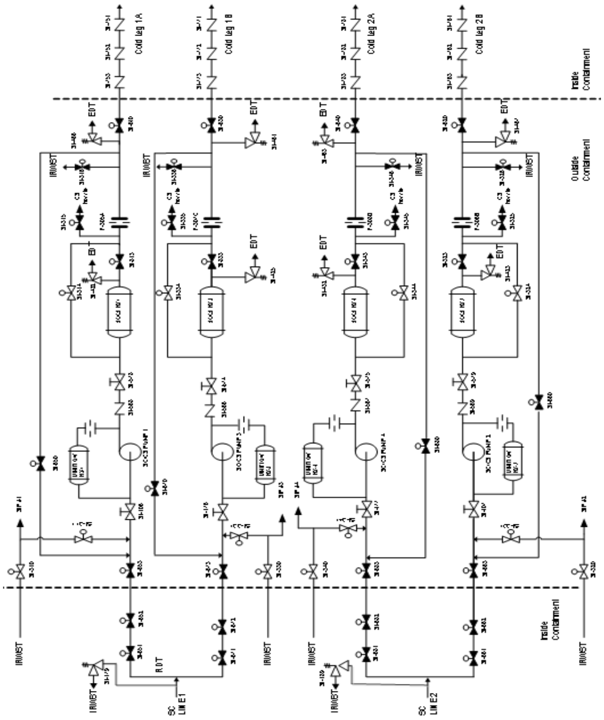

Figure 1 SCS Suction Line Schematic Drawing

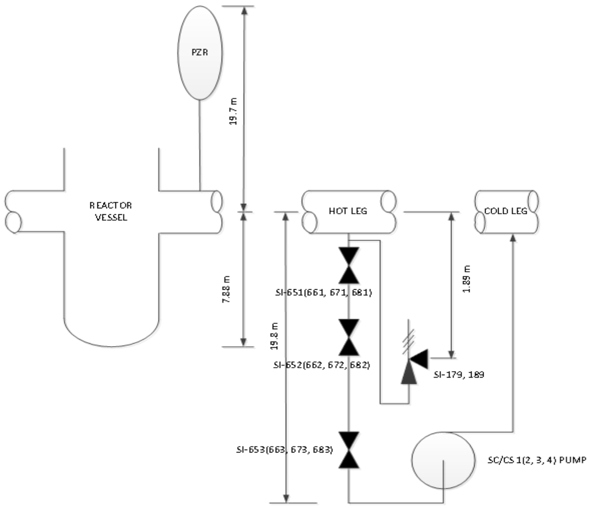

Figure 2 SCS Suction Line Vertical Schematic Drawing

Table 2 Parameters of LTOP Relief Valves

Parameter	Spring Loaded Relief Valve	Pilot Operated Relief Valve
Safety Class	1	
Nominal Set-point	3.75 MPa A	3.6 MPa A
Accumulation	10 %	
Blowdown	10 %	
Capacity	1760 , m^3/hr (@10% acc)	
Dead Tim	N/A	0.2 seconds
Stroke Time	N/A	0.2 seconds

3. Analysis and Results

3.1 Assumptions and Initial Conditions

3.1.1 Overpressure Transient due to Mass Addition

Four SI pumps (SIPs) deliver the In-containment Refueling Water Storage Tank (IRWST) water to the RCS if inadvertent Safety Injection Actuation Signal (SIAS) actuates when the RCS pressure is low enough. Also, only one centrifugal charging pump (CCP) is conservatively assumed to operate at runnout condition.

Normal heat inputs from pressurizer heaters, RCPs and decay heat during the transient are negligible because time interval during the transient is short. Therefore, the limiting mass input event consists of four SIPs and one CCP operation.

Since the lower fluid temperature results in the more pressurization in term of mass addition, the RCS water temperature and the fluid temperature from both of the SI pumps and charging pump are assumed to be 49 ℃ and 4.4 ℃, respectively. The RCS water temperature is assumed to be constant, because the mass addition transient occurs at a short period of time enough to assume isothermal condition in the RCS.

The temperature of the fluid at suction and discharge of the LTOP relief valve is assumed to be 177 ℃ instead of 49 ℃ to minimize the liquid mass flowrate through the LTOP relief valve.

It is assumed that only one LTOP relief valve opens for this analysis to reduce the exit flow from the RCS. The letdown system is considered to be isolated and no flow exits from the RCS except the LTOP relief valve.

It is assumed that the pressurizer pressure provides the representative RCS pressure.

The LTOP relief valve set pressure in calculation is 3.80 MPa A with consideration of the uncertainty of instrument used in relief valve set pressure test, 1 % of 0-4.14 MPa A span, which is ±0.041 MPa as follow:

3.75 MPa A + 0.041 MPa = 3.80 MPa A

It is conservatively assumed that the LTOP relief valve starts to open at 3% tolerance above the set pressure to 30% of the full open position, then linearly opens, and finally opens to the full open position at 10% accumulation above the set pressure.

It is assumed that the pressure drop due to friction loss is proportional to the square of flowrate through the LTOP relief valve. The maximum friction loss between relief valve and the RCS is 3% of the relieving pressure in compliance with ASME Section III. Also, it is conservatively assumed that the relieving pressure does not exceed 110% of the set pressure. Therefore, the maximum allowable friction loss becomes:

0.03 x 1.1 x 3.80 MPa A = 0.125 MPa

Although the flowrate capacity of the LTOP relief valve is used as 1,760 m^3/hr, actual flowrate from LTOP relief valve is always less than 838 m^3/hr. Therefore, the maximum suction friction loss is always less than 3% of the relieving pressure. In this calculation, LTOP valve suction pipe friction loss of 0.125 MPa is used. In this calculation, LTOP valve discharge pipe friction loss is 0.062 MPa for the actual flowrate of 838 m^3/hr.

Table 3 Initial Conditions for Mass Addition Transient

Parameters	Values
Pressurizer Pressure	3.1 MPa A
RCS Temperature	49 ℃
Reactivity of Core	<0.99
RCP and Turbine	Stopped

3.1.2 Overpressure Transient due to Energy Addition

The following sources of energy are input to the RCS:

- Heat transfer from the secondary side of steam generators to the primary side due to the inadvertent operation of one RCP when the secondary temperature is higher than the primary temperature
- RCP heat
- Pressurizer heater
- Core decay heat

Initial secondary-to-primary temperature differential of 139℃ is assumed by the following: Shutdown cooling is initiated at 177 ℃. It is assumed that the secondary side of steam generators remains at 177 ℃, while the RCS is cooled to a refueling temperature of 49℃. The temperature difference is 139℃ with some margin for conservatism.

The analysis is performed with the steam generator secondary temperature of 177 ℃. For the purpose of this analysis, this temperature is assumed to be equal to the maximum temperature for SCS operation.

Based on the 139 ℃ temperature difference, the RCS water properties are obtained at 38℃. It is assumed that all the electrical power (BHP) of one RCP is transferred to the RCS based on calculation scheme for the conservatism. The RCS is assumed to be under water solid condition with no steam bubble in the pressurizer.

The assumptions related to LTOP relief valve used in this calculation is the same as the mass addition overpressure transient in section 3.1.1.

Table 4 Initial Conditions for Energy Addition Transient

Parameters	Values
Pressurizer Pressure	3.1 MPa A
RCS Temperature	49 ℃
Temperature Difference between RCS and SG	139 ℃
Reactivity of Core	<0.99
RCP and Turbine	Stopped

3.2 Methodology, Code and Nodalization

For the mass addition event, the RCS pressure transient is calculated based on a mass balance in the RCS through the delivery of various pumps such as SIP and CCP at very small time intervals. After each time increment, the RCS pressure is obtained by considering the variation of specific volume assuming a constant RCS volume and temperature. The specific volume of the RCS is changed due to the RCS mass change induced by actuation of pumps and LTOP relief valves.

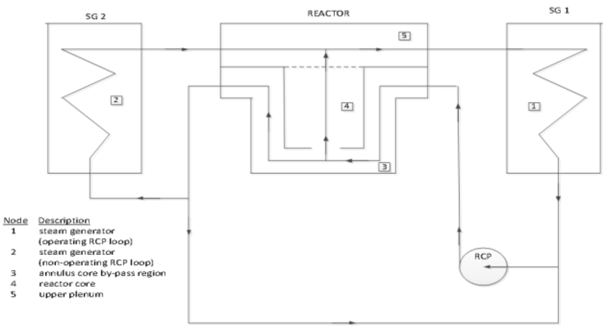

Figure 3 Model Nodes for RCP Start Transient

For the energy addition event, the computer code, POPLOVE is used to calculate the peak pressure and SCS suction line relief valve capacity as a result of the RCS pressure transient caused by a RCP start with the temperature differential between steam generator and reactor vessel (RV) under RCS water solid and low temperature conditions [3].

3.3 Acceptance Criteria

According to ASME Section III, Appendix G-2222(c), it is recommended that when the flange and adjacent shell region are stressed by the full intended bolt preload and by pressure not extending 20% of the preoperational system hydrostatic test pressure, minimum metal temperature in the stressed region should be at least the initial RT_{NDT} temperature for the material in the stressed regions plus any effects of irradiation at the stressed regions [4].

Based on the preoperational system hydrostatic test pressure of 21.6 MPa A for the APR1400, the acceptance criterion is defined as the system pressure shall not exceed 4.31 MPa A during a low temperature overpressure event to prevent brittle fracture considering neutron irradiation.

Table 5 Acceptance Criteria for LTOP

Description	Value
RCS Hydrostatic Test Pressure	21.6 MPa A
RCS Maximum Pressure at the Bottom of Reactor Vessel	4.31 MPa A
Min. RCS Temperature enabled for LTOP during cool-down	105 ℃
Min. RCS Temperature disenabled for LTOP during heat-up	149 ℃

3.4 Result

3.4.1 Overpressure Transient due to Mass Addition

The peak pressures for the limiting energy addition event are calculated to be 4.06 MPa A at the LTOP relief valve inlet and 3.85 MPa A at the top of the pressurizer, respectively as summarized in Table 6.

The pressure difference due to elevation difference between the LTOP relief valve inlet and the RV bottom is 0.059 MPa in Figure 2. So the maximum pressure at the RV bottom which is below the limits in Table 5;

$$4.06 + 0.059 = 4.12 \text{ MPa A}$$

Table 6 Sequences of Mass Addition Event

Time (sec)	Events	Value or set-point
0.00	Four SIPs start by an inadvertent SIAS while one charging pump is operating.	3.1 MPa A (PZR P)
0.40	One spring loaded or pilot operated relief valve opens.	3.54 MPa A (PZR P)
2.20	Pressurizer pressure stabilizes at 3.85 MPa A.	3.85 MPa A (PZR P)

3.4.2 Overpressure Transient due to Energy Addition

The peak pressures for the limiting energy addition event are calculated to be 3.96 MPa A at the LTOP relief valve inlet and 3.75 MPa A at the top of the pressurizer, respectively as summarized in Table 7.

The maximum pressure at the RV bottom considering the elevation difference is 4.02 MPa A, which is below the limits in Table 5.

Table 7 Sequences of Energy Addition Event

Time (sec)	Events	Value or set-point
0.00	One RCP starts inadvertently by operator.	3.1 MPa A (PZR P)
1.70	One spring loaded or pilot operated relief valve opens.	3.54 MPa A (PZR P)
9 .00	Pressurizer pressure stabilizes at 3.75 MPa A.	3.75 MPa A (PZR P)

4. Conclusion

We have modified the arrangement of LTOP features to meet the European requirements and demonstrated the performance of it features to meet the maximum allowable pressure limit.

The application of different types and opening setpoins of LTOP relief valves implemented in accordance with the requirements for diversity, redundancy, and staggered setpoints as shown in Table 2.

Arrangement of LTOP relief valves at the SCS suction line in Figure 1 and 2 meet criterion for no shut-off valves between RCS and relief valves.

The maximum pressures of the bottom of the reactor vessel, which are 4.06 MPa A for mass addition event and 4.02 MPa A for energy addition event, are within the maximum allowable pressure in Table 5.

Table 8 Summary of Compliance with Requirements

Requirements	EU-APR
Diversity and Redundancy	Satisfied
Staggered setpoint	Satisfied
No shut-off valve between the safety valve and the protected item	Satisfied
Maximum Allowable Pressure	Satisfied

REFERENCES

[1] "U.S. NRC, Standard Review Plan," Section 5.2.2: Overpressure Protection, Rev. 3, NUREG-0800, March 2007

[2] Finnish Regulatory Guideline on Nuclear Safety (YVL) B.5: Reactor Coolant Circuit of a nuclear power plant, November 2013

[3] Software Verification and Validation Report for POPLOVE, 00000-FS-VV-003, Rev. 00, June 30, 2010

[4] ASME Section III, Appendix G-2222.