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Passive Isolation Condenser Modeling With Apros Computer Code

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ABSTRACT

A fully passive system for decay heat removal, based on the concept of isolation condenser is the subject of project PIACE. The feasibility study of passive isolation condenser application to several types of nuclear power reactors, such as: pressurizer power reactor, boiling water reactor, CANDU, lead cooled fast reactor and accelerator driven system MYRRHA was performed. This paper focuses on application of isolation condenser to pressurized water reactor. The reference power plant was defined. The station black out accident was identified as accident where isolation condenser can be applied if other decay removal systems fails. Numerical simulations of the primary system and isolation condenser were performed with computer code APROS. The results show that such passive isolation condenser is capable of removing decay heat.

1 INTRODUCTION

The feasibility study of application of passive isolation condenser to Pressurized Water Reactor (PWR) was performed [1], [2]. The total power cycle of PWR is composed out of the three circuits: primary, secondary and tertiary. The primary circuit consists of the reactor vessel with a core, which heats the coolant that is pumped through it via the reactor coolant pump (RCP) and then flows into the steam generator (SG). U-type tubes inside SG transfer heat to the secondary circuit, where steam is generated and which flows toward the turbine through the steamlines. The turbine rotation is the motive power required for the generator that turns it into electric power and transfers it into the grid. The used steam from the turbine is cooled and condensed into water by the tertiary circuit that cools it, serving as the ultimate heat sink.

The considered plant has two loops, with thermal power of 2000 MWth. When operating at the steady state the average coolant temperature of primary circuit is 305°C, the flow rate through each of the two loops is 4500 kg/s and the reactor coolant system (RCS) pressure (measured in pressurizer (PRZ)) is 15.5 MPa. Steam pressure on the secondary side is approximately 6.3 MPa, the feedwater (FW) temperature flowing into the SG is 220°C and its flow rate is 540 kg/s in each loop. The steam at the secondary side is at the saturation pressure. The pathway through the main steamline (MS) can be interrupted with the closure of the main steam isolation valve (MSIV) when the steam flow or pressure deviation is to high, Consequently the turbine and the whole tertiary circuit is cut-off from the SG and the primary circuit. In those cases also the steam dump system (SD), which allows the 95% load rejection without reactor trip or at the occurrence of a reactor and turbine trip prevents the opening of the safety valves (SV), is cut-off. Alsogft the air operated SG power operated relief valves (SG PORV) are designed to pass 10% of steam flow in order to control the SG pressure.

Immediately after the plant shutdown the decay heat is estimated to be 6% of the full power (~120 MW) and then it decreases exponentially. The overall decreasing rate depends on the thermal power of the core, operation time and fuel type. Time dependent decay heat calculations for PWR reactor is considered. No neutronic feedback is considered in the calculations.

The safety systems are present to mitigate the consequences of an accident situation by providing additional coolant in the case of leaks and to provide decay heat removal after reactor trip. They have the capability to prevent the core uncovery and ensure its long-term cooling up to the large break loss of coolant accidents (LB LOCAs).

The components of the emergency core cooling system (ECCS) (high pressure (HPIS) and low pressure (LPIS) injections system and the accumulator (ACC)) provide the additional coolant inventory in the primary circuit in LOCA situations. Additional long-term cooling is established with recirculation and cooling via residual heat removal heat exchangers of the leaked coolant. Core overheating is also prevented by transferring the heat from primary circuit via steam generators into the secondary system where the auxiliary feedwater system (AFW), sometimes also called emergency feedwater (EFW), provides cold water that absorbs the heat by turning it into steam. The steam can also be released to environment via the SG PORVs. This occurs when the secondary pressure is above the pressure setpoint (7.8 MPa), depending on the PI controller that regulates the hysteresis around it. The safety valves (SV) are designed to maintain the secondary pressure below the 110% of the SG design pressure, opening when it rises above 8.2 MPa. As in the primary circuit the PRZ PORVs open, in order to prevent material overload at high internal pressure, when it is above 16 MPa.

1.1 Integration of the safety system for passive heat removal

The Passive Isolation Condenser (PIC) system is attached to the secondary system: on the AFW pipeline and the outlet of the steam header at each of the steam generators (Figure 1). Both PICs are immersed into the PIC water pool that acts as a heat sink. The PIC water pool should be of sufficient size to provide a heat sink to absorb all the decay heat transferred from the core in 7 days. The boiling is allowed, however the water level shall not be decreased lower than 6 m. This still allow margin of 1 m, in order to have fully immersed condenser to water. The initial depth of the PIC water pool is 10 m. The volume of PIC water tank is 3750 m3. There are isolation valves PIC AFW IV and PIC MS IV on connection pipes in order to prevent system activation during normal operating conditions. The elevation difference between SG and PIC is sufficient to achieve appropriate natural circulation.

Based on volume and elevation of the PIC water pool, its location can only be outside of the containment in PIC building. There is no need for new penetrations since it is connected to main steamline and auxiliary feed water pipe outside the containment. Building should be designed according to external events, such as: earthquake, flooding, tornado, plane crash. Long piping increases friction and reduces natural circulation flow; which is taken into account while designing the PIC system. The PIC water pool is open to environment, allowing the water to evaporate.

During normal operation the Isolation Condenser is in a stand-by state. During a transient when a given high pressure setpoint is reached, the two isolation valves should open, thus connecting the Isolation Condenser to the SG, from where the steam is cooled inside and condenses. The pressure setpoints opening the Isolation Condenser valves should be low enough to prevent the opening of the SG SVs.

The SBO refers to the complete loss of alternating current (AC) electric power from internal and external sources to the essential and nonessential switch gear buses in a nuclear power plant (NPP). Therefore, it involves the loss of offsite power concurrent with turbine trip, the failure of the onsite emergency AC power system and the failure of the emergency diesel generators operation. The only power available is from the buses powered via the inverters connected to the station batteries. Loss of the AC power causes unavailability of all normal equipment and most of the safety equipment. The unavailability of the key systems ensuring decay heat removal and containment heat removal can lead to severe damage. Unavailable SG PORVs are more demanding in terms of heat load for PIC.

Similar to SBO scenario are the loss of ultimate heat sink, which is usually considered for 30 days and longer, and the loss of the make-up water tank. The initiating events can be extreme external events like: beyond design earthquake, extreme flooding or man-made events like plane crash.

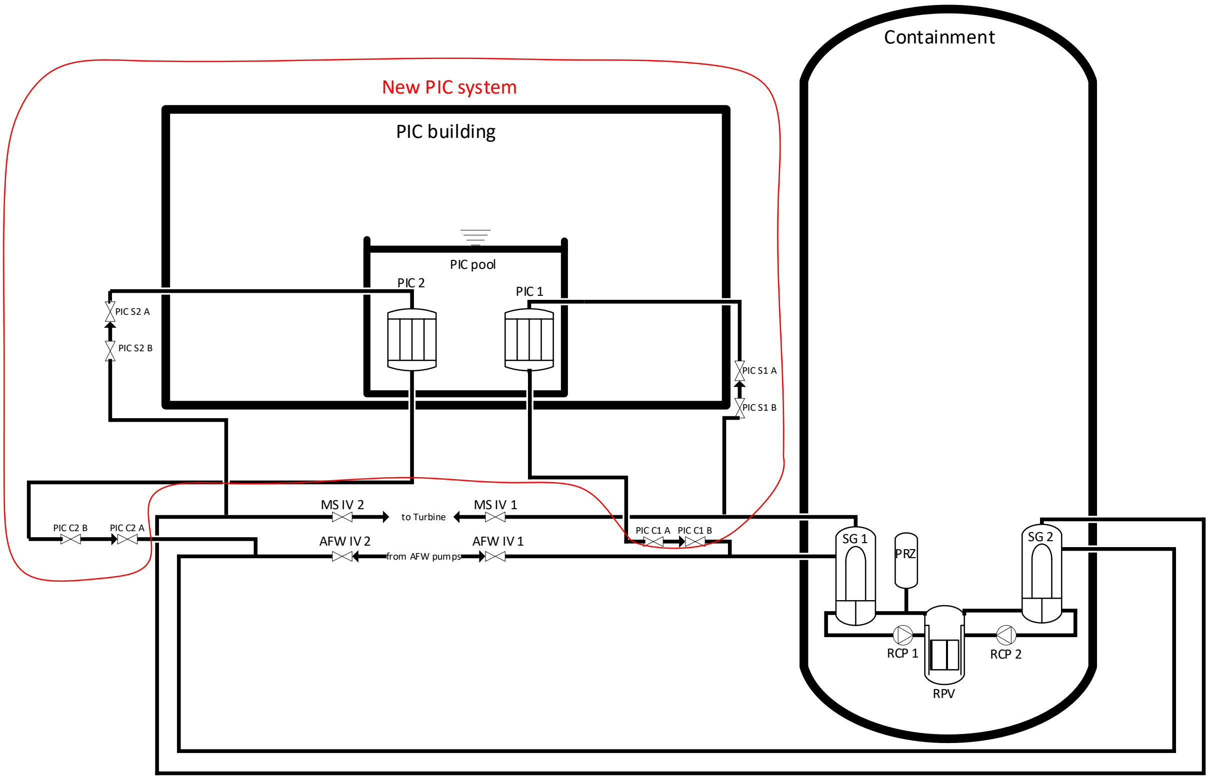

Figure 1: Basic integration scheme of the Passive Isolation Condenser attached to the SG

The introduction of the PIC aims to ensure a passive heat removal tool and thus avoid core and vessel damage.

The main assumptions for the SBO scenario are:

- reactor trip from 100 % power,
- RCPs trip,
- turbine trip,
- FW isolation, trip of main FW (MFW) pumps and motor-driven auxiliary feedwater (MD AFW) pumps,

- main steamline isolation (MSIV closure),
- SD unavailable,
- RCS charging and letdown flow unavailable,
- HPIS and LPIS unavailable,
- PRZ heaters unavailable,
- SG and PRZ safety valves (spring type) available,
- TD AFW pump unavailable,
- SG PORV can either be available or not,
- containment spray unavailable,
- containment fan coolers unavailable,
- passive components (accumulators) and piping available,
- no operator actions.

2 MODEL IN APROS

2.1 Model

The model was build in thermal-hydraulic code Apros 6 [3]. The model consists of primary system [4] and passive isolation condenser system, developed in project PIACE. The model consist of more than 1000 thermal-hydraulic volumes, and more than 1600 other modules.

2.2 Initial conditions

The PIC system that is initially filled with liquid at temperature of 20°C and 1 bar. The initial temperature of PIC water pool is 20°C. The decay heat is taken conservatively for reactor at full power, at end of the cycle.

3 RESULTS

The pressure in pressurizer is plotted on Figure 2. The SG PORV and safety valves do not open. The accumulator activation can be observed at 4.5 h. The initial heat flow in each PIC condenser is about 18 MW (total 36 MW). The temperature in PIC water pool is increasing (Figure 3). The boiling temperature of PIC pool water is reached after 29 h. The natural circulation is developed in this time and cold water from PIC system is transferred to SG. The limit, defined by technical specifications is 55.6 °C/h, defined as hourly measurement. During the operation of PIC, the maximum cooldown rate is 18 °C/h. The average cooldown rate is about 13.5 °C/h (Figure 4). There is no need for nitrogen injection, since the RCS cooldown rate limit is not exceeded. The decay heat is removed during whole SBO sequence, except for the first 400 s (Figure 5).

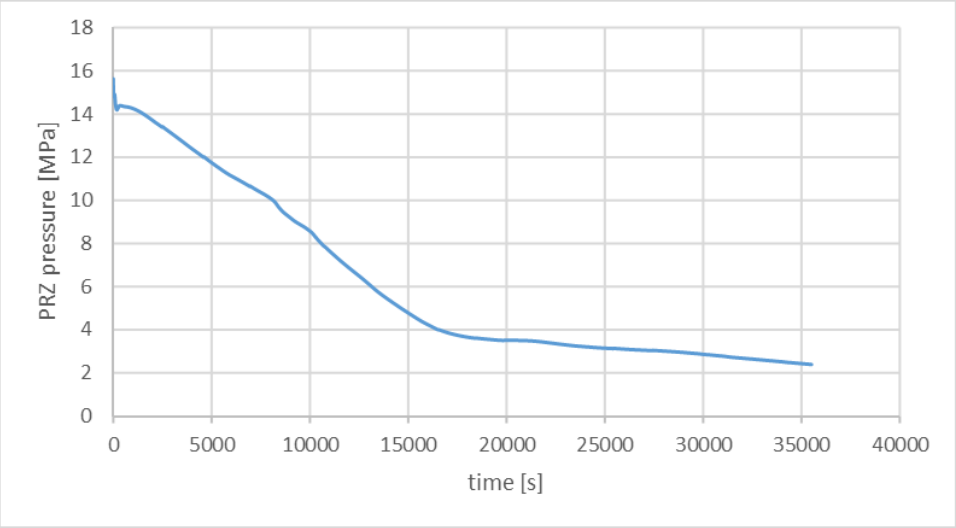

Figure 2: PRZ pressure.

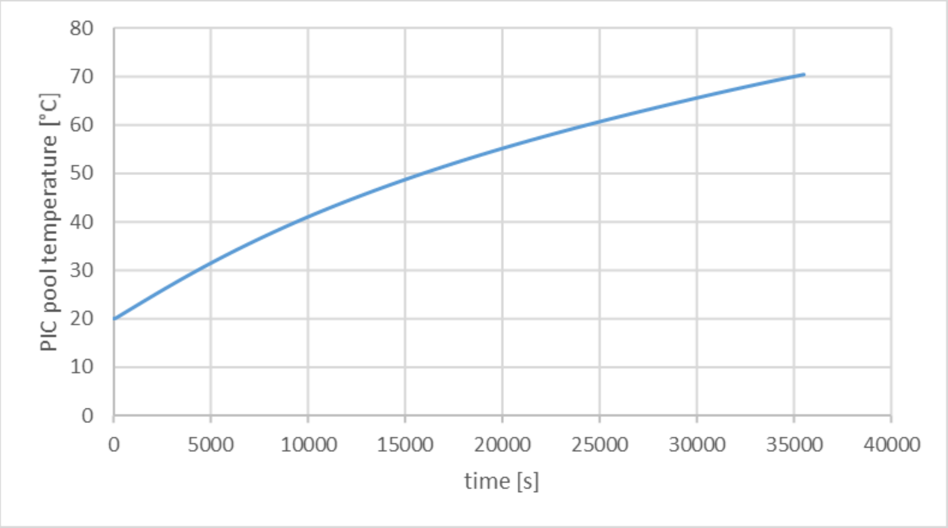

Figure 3: PIC pool temperature.

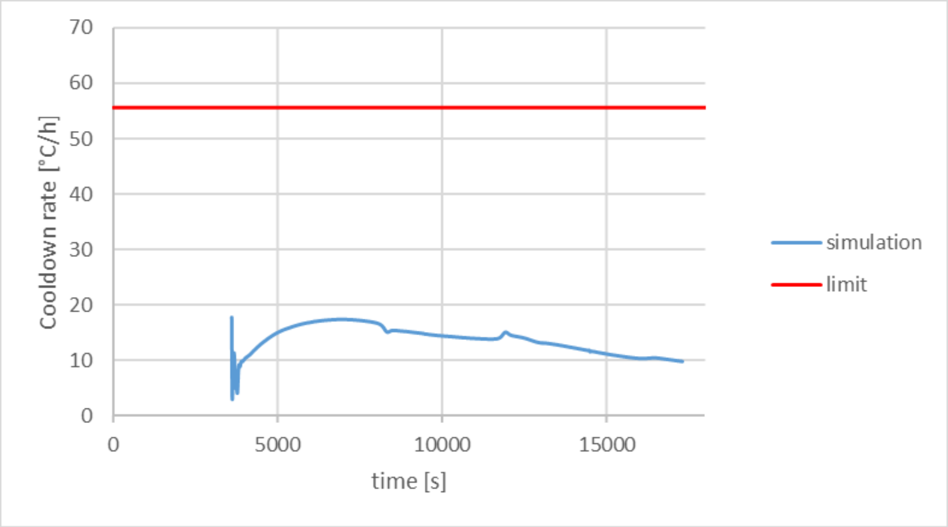

Figure 4: Cooldown rate.

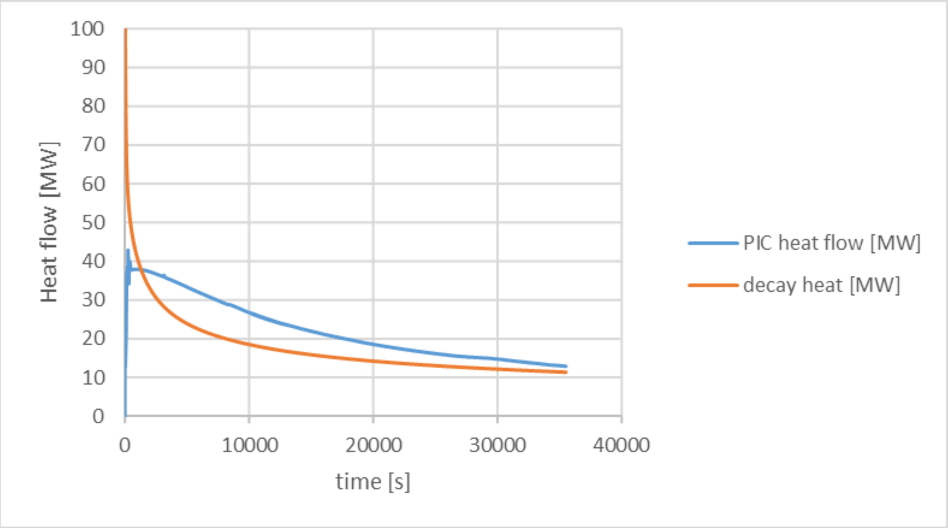

Figure 5: Decay heat and total PIC power.

3.1 Different nominal heat power

The number of control volumes inside the pipes and pipe heat structure walls, does not have major effect on the results.

The number of pipes in PIC was varied in order to get different nominal heat power. The sensitivity study was performed for nominal power (9 MW, 18 MW, 32 MW and 64 MW). As seen from Figure 6 the decay heat removal is adequate and there is no significant increase in RCS temperature, however the cooldown rate reaches the limit (Table 1).

We answered several questions during sensitivity analyses**:**

- What is the minimum design PIC heat power to remove decay heat?

  Minimum 2 PIC of nominal power of 9 MW, or one at 18 MW
- What is the maximum PIC heat power not to reach limit of cooldown?

  Maximum 2 PIC of nominal power of about 30 MW
- Can decay heat be removed with one PIC in case of STGR?

  Yes, if the nominal power of one PIC is higher than 18 MW.

Table 1: Sensitivity analyses of nominal heat power (per PIC)

Nominal heat power [MW]	**Number of pipes**	**Maximum cooldown rate [°C/h] Limit=55.6**
9	75	5.0
18	150	17.7
32	300	50.8
64	600	73.2

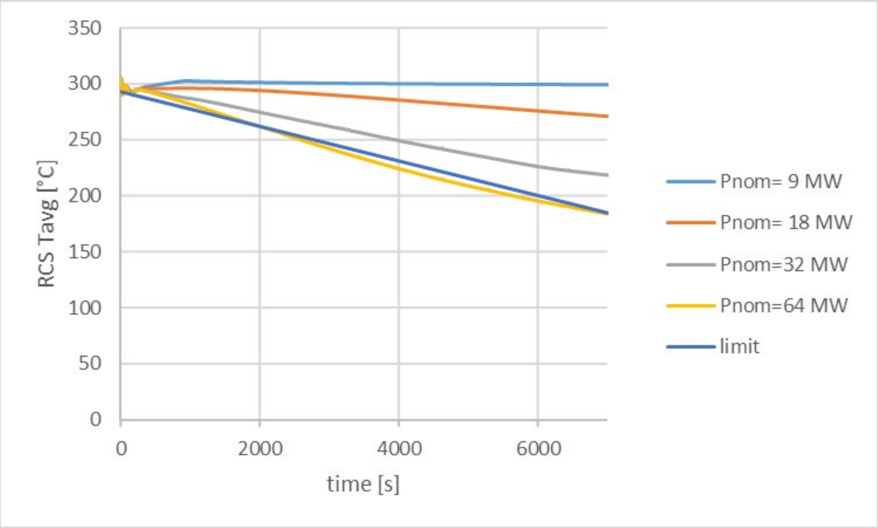

Figure 6: RCS Tavg for different Pnominal.

3.2 SGTR case

In case of SGTR only one PIC with power 18 MW is available. This is still enough to remove the decay heat after 150 min Figure 7. There is no significant temperature rise in RCS during first two hours and afterwards the temperature is decreasing at appropriate pace. The heat removal by faulted SG was neglected.

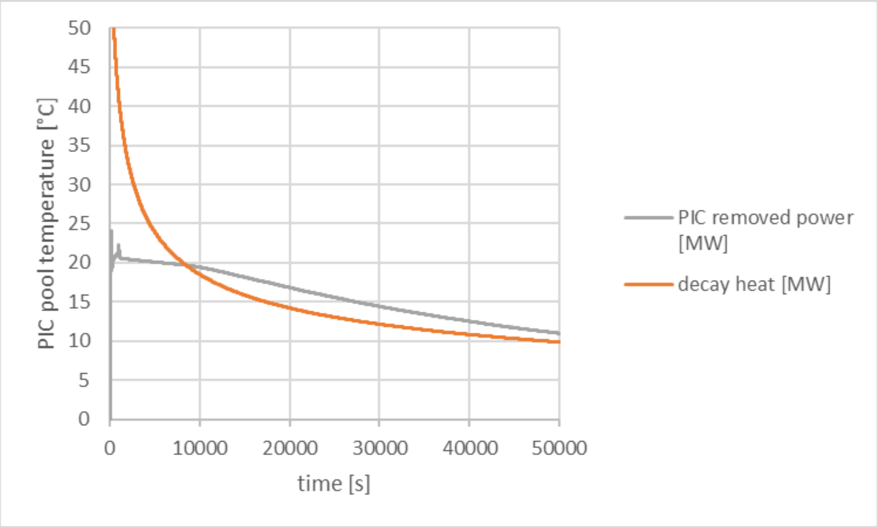

Figure 7: Decay heat and total PIC power, SGTR.

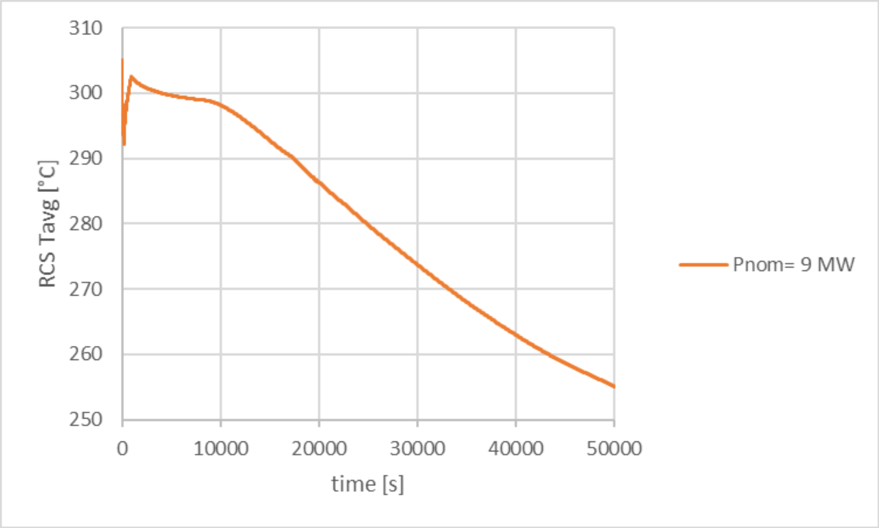

Figure 8: RCS Tavg, SGTR.

4 CONCLUSION

The feasibility study of passive isolation condenser application to PWR was performed. The size of passive isolation condenser (PIC) and PIC pool was calculated. The PIC system was conceptually designed. The safety function of the PIC system is to remove decay heat from reactor core to alternative ultimate heat sink with no power supply. The thermal-hydraulic analyses of SBO or loss of UHS was performed. The PIC system successfully removes decay heat with only minor RCS temperature excursion. The cool down is not larger than limitation. The designed PIC system is also capable to remove heat during SGTR. The PIC can be installed to new NPPs and existing NPPs.

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