Analysis of passive residual heat removal system in AP1000 nuclear power plant

J Sierchula

1 Poznan University of Technology, ul. Piotrowo 3a, 60-965 Poznań, Poland

E-mail: jakub.sierchula@put.poznan.pl

Abstract. The paper presents operating principles of passive safety systems used in modern nuclear power plants with AP1000 reactor. Paper describes in detail the passive residual heat removal system and the passive containment cooling system in above-mentioned power plant. Furthermore, the paper consists thermo-hydraulic analysis of a scenario, in which power plant loss off-site power, reactor is shut-down and the active elements (especially Diesel generators) failed. Considerations and calculations present the role of passive safety systems in nuclear power plant. In particular described phenomena concerns two above-mentioned systems, which are responsible for residual heat removal. Change of the few of the most important parameters, like reactor coolant temperature, medium flow or heat exchange in the refuelling water storage tank, were simulated, presented and described. Mathematical model also includes the role of passive systems and its impact on the main parameters in nuclear power plant with AP1000 reactor.

1. AP1000 reactor

AP1000 reactor is 3400 thermal MW pressurized water reactor design by American Westinghouse company. It is the most important element of nuclear power plant based on standard configuration, in which two separated cycles could be distinguished: primary and secondary.

The construction of the reactor and reactor vessel is very similar to the typical pressurised water reactors. The core consists 157 fuel assemblies with length of 426.7 centimetres and cross section of 17x17. The light water is both coolant, reflector and moderator. [1,2]

The thermal shield, located between the core and the sidewall of the vessel, stops γ radiation and protects the vessel against heat which is generated in the core. Reactor vessel is build of ferritic or alloy steel, inside part of the vessel is coated with stainless steel. By using the abovementioned materials, the AP1000 reactor vessel can easily withstand temperatures above 300°C and pressures up to about 16 MPa.

The core of the reactor consists three areas in which fuel is characterized by different degree of enrichment. Fuel enrichment varies from 2.35% to 4.80% 235U. The temperature coefficient of reactivity is strongly negative. Thanks to the large margins, provided for optimizing nuclear fuel management, the AP1000 reactor core has been designed to offer unique flexibility during the fuel cycle, which lasts for 18 months at a power factor of 93% and with fuel burnup rate of 60,000 MWd/t [1].

The length of the vessel is 12 m, inside diameter of the core is 4,039 m. The internal walls, which are in contact with the coolant during normal operation, are covered with a sheet made of stainless steel. The vessel itself was designed for a pressure of 17.1 MPa and a temperature of 343°C and expected
lifetime of facility of 60 years, which directly affects into the lifetime of the entire nuclear unit. Table 1 shows the main parameters of the AP1000 nuclear power plant.

| Table 1. Main parameters of nuclear power plant with AP1000 reactor [1]. |
|-------------------------------------------------|
| **Primary cycle**                               | **Secondary cycle**                      |
| Reactor coolant inlet temperature               | Feedwater temperature                    |
| 279.4°C                                         | 226.7°C                                  |
| Reactor coolant outlet temperature              | Steam temperature                        |
| 324.7°C                                         | 272.8°C                                  |
| Reactor coolant pressure                        | Steam pressure                           |
| 15.51 MPa                                       | 5.76 MPa                                 |
| Mass flow rate in primary cycle                 | Flow rate in normal conditions           |
| 14300 kg/s                                      | 1889 kg/s                                |

2. Passive Residual Heat Removal system

The main purpose of safety systems used in nuclear power plants is to prevent overheating of the reactor core. At present day, there are two types of nuclear power station's safety systems: active and passive. Active system is system in which main devices need to be powered by an external power source. Such devices include, for example, pumps or fans. The opposite of active systems are passive systems, which principle based on natural forces such as gravity, convection or pressure of compressed gases, their action are automatic and does not require external stimuli. One of the distinguishing features of the AP1000 nuclear power plant is the number of innovative passive safety systems, such as the passive core cooling system, the passive containment cooling system and the passive residual heat removal system, which is the subject of this paper.

The passive residual heat removal system (PHRS), shown in Figure 1, is intended to receive the heat generated in the core after it has been shut-down during the situations where it is impossible to transfer heat to the steam generators, due to a failure such as loss of coolant accident (LOCA) or loss of flow accident (LOFA). The first situation can occur, for example, in the case of a pipeline or vessel break, the second one concerns, for example, a pump failure or loss of external power, which of course, also leads to the shutdown of the cooling water pump.

The passive heat recovery system consists of the following components:

1. Passive Residual Heat Removal Heat Exchanger (PRHR HX) is a heat exchanger connected by a set of pipelines with a reactor vessel, consists of 689 C-shaped pipes and located in the In containment Refuelling Water Storage Tank (IRWST). During normal operation, the PRHR HX is separated from the cooling circuit by valves, which will open only if there is a failure due to lack of coolant circulation.

2. In containment Refuelling Water Storage Tank (IRWST) located above the reactor vessel, with capacity of 2100 m³. The IRWST tank is part of both the passive core cooling system and the passive residual heat removal system.
In the case of a failure, affecting the circulation of the coolant in the primary circuit, due to the large water density/temperature difference between the core and the in containment refuelling water storage tank, natural heat circulation occurs. Residual heat received in the IRWST tank heats up the water inside, which starts to boil after some time. The tank is an open structure, consequently steam is released inside the containment and deposited on its inner surface. The containment is made of steel, which from the outside is cooled by naturally circulating atmospheric air. The steam condenses on the steel surface of the containment (pressure is also reduced) and it is returned to the IRWST by channels/gutters, so amount of water in the tank can be assumed as constant.

As it can be seen, the passive residual heat removal system (PRHR) for properly work need to cooperate with passive containment cooling system (PCCS), which is shown in Figure 2. If the air flow is insufficient, the valves of PCCS water tanks, located above the steel containment, are opened. Water will fall naturally, under the force of gravity, and will sufficiently and reliably receive heat from the steel casing.
3. Simulations and results

The following section presents model of the passive residual heat removal system. The mathematical model was designed to verify the heat capacity and heat dissipation of the passive residual heat removal system in case of failure of both: external power supply and emergency diesel generators.

After the loss of external power at the nuclear power plant with the AP1000 reactor, the nuclear unit is shutdown. Safety rods made of highly neutron-absorbing materials are inserted into nuclear reactor core, so the fission reactions in fuel are practically stopped. Unfortunately, this does not mean that all nuclear transformations have been stopped. Radioactive fission products contained in the fuel continue to undergo radioactive decay, which generate so-called residual heat, which necessarily must be removed from the core. Diesel generators, which are responsible for supplying emergency power to the cooling pumps, which transfer residual heat, are not activated in the analysed scenario (for example by some malfunction/failure). According to the information provided by the Westinghouse, AP1000 reactor manufacturer, after a failure, the coolant circulation in the primary circuit is provided for approximately 120 seconds by specially designed flywheel in the coolant pump [1]. The heat received from the core is transferred to the water in the steam generator. After evaporating the water and reaching the minimum water limit value in the steam generator, the automatic safety system opens the valves of passive residual heat removal system. This system connects by pipelines the nuclear reactor with the incontainment refuelling water storage tank. Because of the large difference in density/temperature between the core and the passive heat exchanger (PRHR HX) submerged in the IRWST tank, there is a natural circulation of the coolant which, according to the manufacturer’s specifications, is approximately 65 kg/s in the first moments after start-up of abovementioned safety system [3].

Residual heat generated in nuclear reactors can be described by the following formula [4]:

\[ Q_{pow} = Q_0 \cdot 0.066 \cdot (t^{-0.2} - (t + t_s)^{-0.2}) \]  

where:

- \( Q_{pow} \) – residual decay heat \([W]\),
- \( Q_0 \) – reactor power before shut-down \([W]\),
- \( t \) – time since reactor shut-down \([s]\),
- \( t_s \) – time between start-up and shut-down \([s]\).

Assuming that prior to the emergency the reactor had been operated without major interruptions, it may be assumed that time \( t_s \to \infty \), therefore above formula can be simplified to the following form:

\[ Q_{pow}(t) = Q_0 \cdot 0.066 \cdot (t^{-0.2}) \]  

In practice, it can be assumed that the above formula concerns at least one year of operation of the reactor. Using this dependence and taking into account that the passive residual heat removal system started 120 seconds after the loss of external power supply and emergency diesel generators, Figure 3 shows the change in decay heat generation over time.

![Figure 3. Decay heat generation as a function of time.](image_url)
The model presented in this paper is an extension of the concept presented in [5]. Similarly to that article, there are also several assumptions and specified geometrical dimensions of the system.

1. Amount of heat transferred through each channel of the passive heat exchanger (PRHR HX) is identical.

2. Length of the single channel is $l = 5.5\, \text{m}$, inner radius $r_1 = 0.017\, \text{m}$, outer radius of the channel $r_2 = 0.019\, \text{m}$, number of channels $n = 689\, [3]$.

3. Thermal conductivity for the material (690Alloy) from which the passive heat exchanger is made is $\lambda = 13.5\, \text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}\, [3]$.

4. Initial temperature in incontainment refuelling water storage tank (IRWST) is $T_{wb} = 20\, ^\circ\text{C}$, water volume in tank $V = 2100\, \text{m}^3\, [3]$.

5. Working medium temperature at the passive heat exchanger (PRHR HX) inlet at the moment of passive residual heat removal system activation is $T_1 = 297\, ^\circ\text{C}$, primary circuit pressure $p = 15.5\, \text{MPa}\, [3]$.

6. Coolant mass flow in the primary circuit $\dot{m} = 65\, \text{kg/s}\, [3]$.

The main task of described safety system is to receive residual heat. It means, that all the heat generated in the core must be equal to heat received in exchanger. In order to determine the value of the heat received in passive heat exchanger three different stages should be taken into account. First stage is heat transfer from medium (water in the channels) to exchanger wall. Then conduction of heat through the exchanger wall and at the end heat transfer from the wall to the heated medium, which in this case is water in incontainment refuelling water storage tank (IRWST). Therefore, the total heat flux transferred in the PRHR HX exchanger may be determined as follows:

Heat transfer from medium to the inner wall of exchanger:

$$Q_1 = \alpha_1 \cdot 2\pi \cdot r_1 \cdot l \cdot (T_1 - T_{s1}) \quad (3)$$

Heat penetration through a single-layer cylindrical wall:

$$Q_2 = 2 \cdot \lambda \cdot \pi \cdot l \cdot \frac{T_{s1} - T_{s2}}{\ln \frac{r_1}{r_2}} \quad (4)$$

Heat transfer from the outer wall of heat exchanger to medium:

$$Q_3 = \alpha_2 \cdot 2\pi \cdot r_2 \cdot l \cdot (T_{s2} - T_{zh}) \quad (5)$$

The heat transfer is steady, therefore $Q_1 = Q_2 = Q_3$. After adding the above-listed formulas the following relation describing the heat flux transferred from $n$ tubular elements within the exchanger could be determined:

$$Q = \left( \frac{1}{\alpha_1 \cdot 2 \cdot r_1} + \frac{1}{2\lambda} \ln \frac{r_1}{r_2} + \frac{1}{\alpha_2 \cdot 2 \cdot r_2} \right)^{-1} \cdot \pi \cdot l \cdot (T_1 - T_{zh}) \cdot n \quad (6)$$

where:

- $l$ – PRHR HX exchanger length [m].
- $T_1$ – water inlet temperature to the exchanger [°C].
- $T_{zh}$ – water temperature in the IRWST tank [°C].
- $r_1$ – internal wall radius [m].
- $r_2$ – external wall radius [m].
- $\lambda$ – thermal conductivity for the wall [W\cdot\text{m}^{-1}\cdot\text{K}^{-1}].
- $\alpha_1$ – heat transfer coefficient for the inner wall surface [W\cdot\text{m}^{-2}\cdot\text{K}^{-1}].
- $\alpha_2$ – heat transfer coefficient for the outer wall surface [W\cdot\text{m}^{-2}\cdot\text{K}^{-1}].

As can be seen from the above relationship, it is necessary to calculate the heat transfer coefficients $\alpha_1$ and $\alpha_2$ to determine the heat received by the PRHR HX exchanger. These coefficients can be calculated from formula (7) [6], provided that the Reynolds number (Re) is between 10,000 and 120,000 and Prandt number (Pr) is between 0.7 and 120 [7].
\begin{equation}
\alpha_1 = 0,023 \cdot \frac{\lambda_{\text{wody}}}{2r_1} \cdot Re^{0,8} \cdot Pr^{0,33}
\end{equation}

Reynolds number and Prandtl number are defined as:
\begin{align}
Re &= \frac{\rho \cdot u \cdot l}{\mu} \\
Pr &= \frac{C_p \cdot \mu}{\lambda}
\end{align}

where:
- \(\rho\) – density of the fluid [\text{m}^3/\text{kg}].
- \(u\) – velocity of the fluid with respect to the object [\text{m/s}].
- \(l\) – characteristic linear dimension [\text{m}].
- \(C_p\) – specific heat [\text{J/kg} \cdot \text{K}].
- \(\lambda\) – thermal conductivity [\text{W/m} \cdot \text{K}].
- \(\mu\) – dynamic viscosity of the fluid [\text{Pa} \cdot \text{s}].

The model prepared for this paper takes into account changes in the above parameters over time due to the change of the working medium temperature during the circulation. The following is an example of calculating Reynolds and Prandtl numbers for a single channel in the initial state (\(T = 297 \, ^\circ\text{C}, p = 15.5\) MPa):
\begin{align*}
Re &= \frac{\rho \cdot u \cdot l}{\mu} = \frac{732,61 \cdot 0,141 \cdot 0,017}{9,24 \cdot 10^{-5}} = 19\,083 \\
Pr &= \frac{C_p \cdot \mu}{\lambda} = \frac{5388 \cdot 9,24 \cdot 10^{-5}}{0,58} = 0,86
\end{align*}

As can be seen from the above calculations both the Reynolds number and the Prandtl number are within the given limits, so that the heat transfer coefficients \(\alpha_1\) and \(\alpha_2\) can be determined. \(\alpha_1\) is approximately 993 W/m\(^2\)K\(^{-1}\) and \(\alpha_2\) is approximately to 888 W/m\(^2\)K\(^{-1}\) for initial state.

Knowing the thermal power transferred to water in the IRWST tank, it is possible to calculate the outlet temperature of the water in PHRH HX exchanger by following formula :
\begin{equation}
Q = \dot{m} \cdot c_p \cdot (T_1 - T_2)
\end{equation}

then:
\begin{equation}
T_2 = T_1 - \frac{Q}{\dot{m} \cdot c_p}
\end{equation}

Results, obtained from the calculations based on heat transfer model, which was described in detail above, are presented in the following graphs.
Table 2 presents the relationship between initial water temperature in the incontainment refuelling water storage tank, maximum temperature in the passive residual heat removal circuit and time after which IRWST water boiling occurs.

| Water temperature in IRWST tank [°C] | Maximum temperature in cooling cycle [°C] | Time after which water boiling occurs [h] |
|-------------------------------------|------------------------------------------|------------------------------------------|
| 20                                  | 413.57                                   | 5.01                                     |
| 25                                  | 418.69                                   | 4.61                                     |
| 30                                  | 423.87                                   | 4.25                                     |
| 35                                  | 429.00                                   | 3.89                                     |
| 40                                  | 434.10                                   | 3.52                                     |

As shown in Figure 4, the heat curves of heat generated from the fission products contained in the fuel as well as the curves of heat received in the passive heat exchanger, overlap almost completely. The average difference between residual and received heat during the entire simulation is only about 0.0019%. However, it should be noticed, that errors in the first and second iteration are quite significant (respectively 30.18% and 11.46%), but in further iteration errors are less than 1%. At this point, it is also worth to add, that the heat transfer at the initial stage is greatly influenced by the size of the channels in the passive heat exchanger. Some additional calculations for 7 m long channel were made and the results are presented in Table 3.

Table 3. Differences between residual heat and heat received in the IRWST tank.

| Time since PRHS start-up [s] | Residual decay heat [MW] | Heat transferred to IRWST tank [MW] for 5.5 m long channel | Heat transferred to IRWST tank [MW] for 7.0 m long channel |
|-----------------------------|--------------------------|----------------------------------------------------------|----------------------------------------------------------|
| 1                           | 85.9935                  | 60.0373                                                 | 76.4111                                                 |
| 3                           | 85.7120                  | 81.4004                                                 | 85.0897                                                 |
| 5                           | 85.2999                  | 85.2934                                                 | 85.3411                                                 |
| 10                          | 84.6386                  | 84.6618                                                 | 84.7067                                                 |
| 100                         | 76.2332                  | 76.2804                                                 | 76.2491                                                 |
| 10000                       | 35.4795                  | 35.4786                                                 | 35.4784                                                 |
Model of passive residual heat removal system has been used to illustrate changes of water temperature in the IRWST tank and at the reactor inlet/outlet. Based on the results presented in Figure 5, it can be seen that the temperature at the core outlet grows for the first few seconds, after which it reaches a maximum point of about 414°C, and then begins to drop sharply. It is worth remembering that the system is at this time in a transitional state in which a cooling system based on pump operation and heat dissipation for steam generators is turned off and a passive residual heat removal system starts. Furthermore, it is important to note that in the first moments of the simulation, the values of the residual decay heat are highest, and then drop as rapidly as the water temperature at the outlet of the core. Water temperature at the inlet to the core (at the outlet of the passive heat exchanger) is behaving in an analogous way. In the initial stage it rises and then decreases as a result of the decrease of the residual decay heat. After some time, a slight increase in both inlet and outlet temperatures is observed, due to the decreasing difference between the lower and the upper temperature sources. It is obvious that the heat received by the passive heat exchanger causes an increase of water temperature in the IRWST tank. As it can be seen in Figure 5, the temperature rises gently and after about 5 hours the temperature stabilizes at a constant level. After this period of time, boiling process occurs in tank (water reached 100°C) and the heat received by the passive heat exchanger is used only for evaporation. About 36 hours after the failure, reactor obtains safe shut-down conditions without the need for any human intervention. After that time, the heat generated in the reactor does not exceed 0.6% of the nominal power.

4. Conclusions

Model described above, which develop conception presented in [5], was designed to confirm the possibility of receiving residual decay heat from the passive residual heat removal system and to illustrate changes of water parameters in cooling circuit and in IRWST tank. Obtained results, especially in terms of residual heat transfer, are very satisfying.

As already mentioned, this paper develops the model presented in [5]. Figure 6 and figure 7 show the main differences between present and old results. As it can be seen, changes implemented in current version improves capabilities in terms of receiving heat in the PRHR HX exchanger, which this time is almost the same as residual decay heat generated in the core. Moreover, increase of water temperature in the cooling circuit and at the reactor inlet (at the outlet of the passive heat exchanger) can be observed. Furthermore, it is also noticeable that time after which boiling in IRWST tank occurs is slightly prolong. The modifications implemented in the model include for example changes in water viscosity or changes in materials’ thermal conductivity including. Obtained results are very satisfying, the results almost completely matched the predictions.

![Figure 6. Residual heat comparison.](image-url)
Figure 7. Temperature differences comparison.

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