# The PAFS Design for Unlimited Operation

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## 1. Introduction

Safety is always main issue in NPP (Nuclear Power Plant). In history, safety systems were significantly improved at every big accident; Three Mile Island accident in USA, Chernobyl accident in Russia, and Fukushima accident in Japan. After Fukushima accident, passive safety systems receive increasing attention. The passive safety systems mean that the systems can operate without active component, and therefore uses natural force (gravity, density difference and etc.) as their driving force.

The PAFS (Passive Auxiliary Feedwater System) is one of the passive safety systems and is operated by natural circulation of density difference. The PAFS aims to remove decay heat by cooling down the secondary side of steam generator. There are two trains of PAFS in a NPP, because of single failure criteria. The PAFS consists of PCHX (Passive Condensation Heat Exchanger) and PCCT (Passive Condensate Cooling Tank). Operation time of the PAFS is limited by capacity of the PCCT, because the PCCT is final heat sink of PAFS. The current PCCT is designed for 8 hours operation after a PAFS actuation [1].

This paper designs the new PAFS which can operate infinitely and passively, and we call it the advanced PAFS in this paper for convenience. Dry cooling concept is considered for the advanced PAFS. The dry cooling uses the atmosphere as its heat sink which is the infinite heat sink. In addition, it can be operated by natural circulation. It means that the advanced PAFS can operate infinitely and passively. However, the air heat transfer coefficient is not compare with the water. Therefore design change of the PCHX is indispensable. This paper presents the conceptual design of the advanced PAFS and estimates its geometry and capacity.

## 2. Current Design of the PAFS

This part shows function, operating mechanism, composition and capability of the current PAFS.

### *2.1 The Function*

In some accidents which can't use secondary system; MSLB (Main Steam Line Break) accident and etc., the secondary system can't remove the decay heat. The PAFS is design to remove the decay heat in this situation.

### *2.2 The Operating Mechanism and Composition*

Because the PAFS is design to remove the decay heat without any active components, the PAFS uses natural circulation. From Fig. 1, the PAFS receives steam from the steam generator and the steam condenses into water by transferring its thermal energy to the PCCT water. Condensed water passively returns to the steam generator by the gravity. In this condensation, density difference between the steam to the condensed water makes driving force causing the natural circulation.

From Fig. 2, the PCHX is submerged in the PCCT. The PCHX comprises 4 bundles and each bundle has 60 tubes. The tubes are nearly-horizontal U-tubes shape. Diameter, thickness and length of the tubes are 50.8 mm, 3 mm and 8.4 m respectively. These values are design to fulfill heat removal requirement and prevent occurrence of a water hammer inside the PCHX [2].

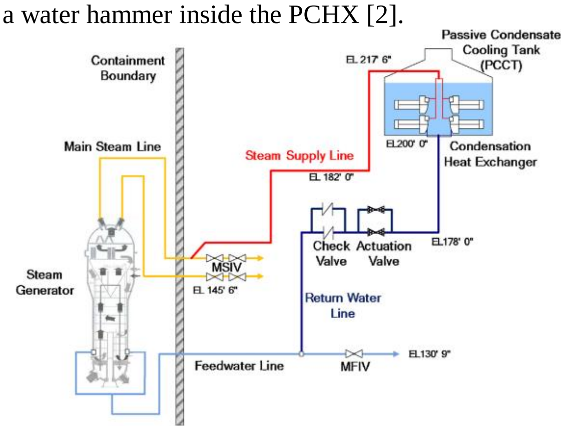


**Fig. 1.** A schematic diagram of the PAFS [3]

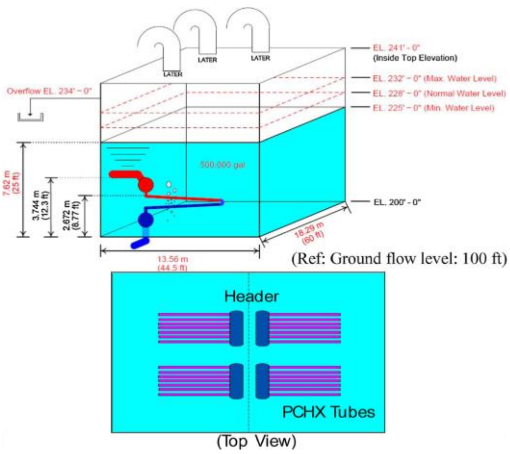


**Fig. 2.** A schematic diagram of the PCCT and PCHX [3]

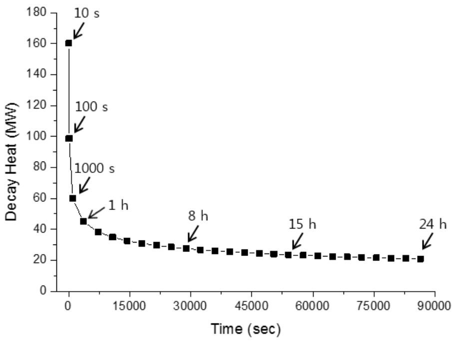


**Fig. 3.** The decay heat curve

*2.3 Capability*

The PAFS operation time is limited for 8 hours after reactor shutdown, because of the PCCT water capacity. Fig. 3 show the decay heat curve of the reactor which has 4000 $MW_{th}$ of normal operation. The decay heat is about 160 MW at 10 seconds, but it decreases exponentially with time. The PCCT water can be able to fulfill the high decay heat during first period after the reactor shutdown. At 8 hours, the decay heat (27 MW) is just 0.68 % of the normal operation, but is still high enough to destroy the reactor. Therefore, the decay heat must be removed continuingly after 8 hours.

## 3. Concept of Advanced PAFS

The advanced PAFS overcomes time limit (8 hours) of the current PAFS. The advanced PAFS uses both the water and atmosphere as its heat sink. The advanced PAFS removes the decay heat by using the water of PCCT for first period after shutdown. As water level decreases by evaporation, the advanced PAFS remove the decay heat by using the atmosphere. The main advantages achievable are:

- The water remove the high decay heat during first period after the reactor shutdown,
- The air remove the decay heat infinitely, and shift from the water heat sink to the air heat sink is automatic.

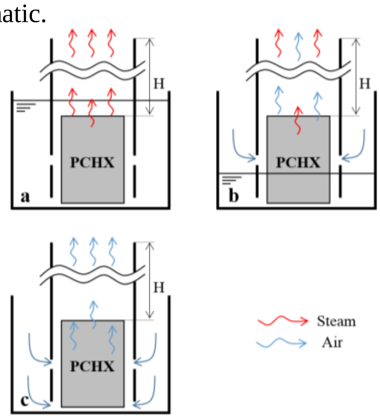


**Fig. 4.** Scheme of the advanced PAFS: (a) initial condition and boiling water condition, (b) mixed heat sink condition with the water and air, (c) dry cooling condition

Fig. 4 shows scheme of the advanced PAFS. The PCCT is divided by wall, but the water and air can go into the PCHX through holes of the wall. The decay heat is removed by the water, and the water level decreases with time (Fig. 4-a). By decreasing of water lever, the air can go into the PCHX through the hole which is on the middle of the wall, and the decay heat is removed by both the water and the air (Fig. 4-b). When all water is evaporated, the decay heat is removed by the air (Fig. 4-c). The natural air circulation is generated by density difference between cold inlet air and hot outlet air of the PCHX. In addition, there is a H meters height chimney and it helps the natural air circulation.

The air heat transfer coefficient is smaller than the water. Therefore, design change of the PCHX is indispensable. The current PCHX has 240 nearly-horizontal U-tubes. However another shapes of PCHX are considered for the advanced PAFS. Dimension and total number of tube are also reconsidered to fulfill the thermal requirement. In addition, the height of chimney is determined to minimize the total length of tubes

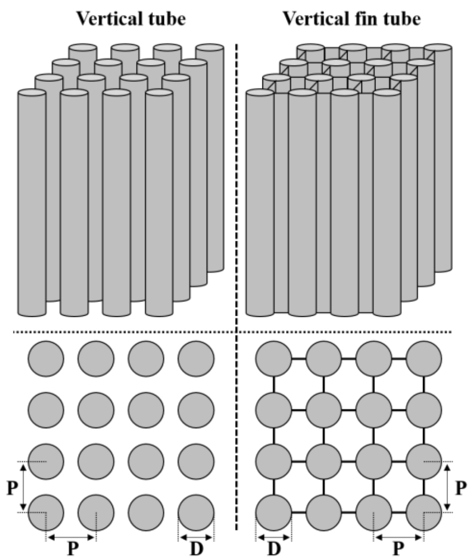


**Fig. 5.** Schematic diagram of two type of PCHX

In this paper, two types of PCHX are considered: vertical tube type and vertical pin tube type. Fig. 5 shows schematic diagram of two types of PCHX. Pitch (P) and diameter (D) are fixed as 0.1 m and 0.05 m respectively. Calculate amount of heat removal per one tube by changing length of tube and height of chimney. In addition, the number of tube to eliminate decay heat (27 MW), total length of tubes and air velocity are also calculated. Energy balance equation and momentum balance equation are used for those calculation. Table 1 and Table 2 show result of vertical tube type and vertical fin tube type respectively. In Table1 and 2, H, $L_1$, V, T, Q, N and $L_2$ are chimney height, tube length, average air velocity, outlet air temperature, amount of heat removal per one tube, tube number to eliminate 27 MW and total tube length respectively.

Table 1. Result of vertical tube

| H(m) | | 50 | | | |
|---|---|---|---|---|---|
| $L_1$(m) | V(m/s) | T(°C) | Q(W) | N | $L_2$(km) |
| 3 | 5.09 | 56 | 1,720 | 15,697 | 47 |
| 5 | 5.59 | 76 | 2,834 | 9,527 | 48 |
| 7 | 5.76 | 93 | 3,741 | 7,217 | 51 |
| 9 | 5.78 | 109 | 4,453 | 6,063 | 55 |
| 11 | 5.72 | 122 | 4,996 | 5,404 | 59 |
| 13 | 5.61 | 134 | 5,399 | 5,001 | 65 |
| 15 | 5.49 | 144 | 5,687 | 4,748 | 71 |
| H(m) | | 100 | | | |
| $L_1$(m) | V(m/s) | T(°C) | Q(W) | N | $L_2$(km) |
| 3 | 7.06 | 54 | 2,240 | 12,053 | 36 |
| 5 | 7.85 | 72 | 3,744 | 7,212 | 36 |
| 7 | 8.14 | 89 | 4,996 | 5,404 | 38 |
| 9 | 8.21 | 104 | 6,007 | 4,495 | 40 |
| 11 | 8.17 | 117 | 6,803 | 3,969 | 44 |
| 13 | 8.06 | 128 | 7,415 | 3,641 | 47 |
| 15 | 7.91 | 139 | 7,874 | 3,429 | 51 |

Table 2. Result of fin vertical tube

| H(m) | | 50 | | | |
|---|---|---|---|---|---|
| $L_1$(m) | V(m/s) | T(°C) | Q(W) | N | $L_2$(km) |
| 3 | 6.34 | 65 | 2639 | 10,231 | 30 |
| 5 | 7.04 | 86 | 4,144 | 6,515 | 33 |
| 7 | 7.31 | 102 | 5,227 | 5,165 | 36 |
| 9 | 7.35 | 114 | 5,954 | 4,535 | 41 |
| 11 | 7.28 | 123 | 6,410 | 4,212 | 46 |
| 13 | 7.15 | 130 | 6,666 | 4,050 | 53 |
| 15 | 6.98 | 135 | 6,780 | 3,982 | 60 |
| H(m) | | 100 | | | |
| $L_1$(m) | V(m/s) | T(°C) | Q(W) | N | $L_2$(km) |
| 3 | 8.74 | 63 | 3,439 | 7,851 | 23 |
| 5 | 9.78 | 82 | 5,480 | 4,927 | 25 |
| 7 | 10.22 | 98 | 7,005 | 3,854 | 27 |
| 9 | 10.35 | 110 | 8,080 | 3,342 | 30 |
| 11 | 10.30 | 120 | 8,795 | 3,070 | 34 |
| 13 | 10.16 | 127 | 9,238 | 2,923 | 38 |
| 15 | 9.97 | 133 | 9,479 | 2,848 | 43 |

## 4. Conclusions

This paper studies concept of the advanced PAFS to overcome the current PAFS operation time limit. The dry cooling is considered for the advance PAFS. During first period of the reactor shutdown, the water removes the high decay heat. After all water is evaporated, the air removes the decay heat. The shift from the water heat sink and the air heat sink is automatic.

The air heat transfer coefficient is smaller than the water heat transfer coefficient. Therefore, the PCHX design change is indispensable. The tube geometry and total number are changed to fulfill the thermal requirement. The advanced PAFS has the chimney to make proper natural air circulation. This study not only presents the concept design of the advanced PAFS, but also estimates its geometry and capacity. The amount of heat removal increases with chimney height and tube length. However, Total tube length also increases. Large chimney height and small tube length make minimum total tube length. However, too small tube length is not suitable for this system, because minimum submerged region of PCHX is needed to remove the decay heat during the condition change from the boiling condition to dry condition. Therefore, tube length and chimney height should be determined with consideration of heat removal and condition change.

## REFERENCES

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