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STUDY OF SECONDARY COOLING SYSTEMS OF RESEARCH REACTORS

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ABSTRACT

The secondary cooling systems are often responsible for removing the heat generated in the facility in normal and shutdown condition. The heat is transferred to the atmosphere through the interface with other cooling systems. Normally, the only safety function of the system is to remove the decay heat in shutdown condition. The safety function of confinement for radioactive material, is not attributed to the secondary system due to the use of open circuit such as the ultimate heat sink in the research reactor. This paper presents a survey of various types of secondary cooling system and its ultimate heat sink for various Research Reactors around the world. Also this paper shows that in case of the utilization of tertiary cooling systems, the secondary system can be a additional function of barrier against leak of radiation to the atmosphere. The separation of the secondary cooling system according to the safety function of their equipment may be a good alternative to reduce the costs and optimizing the operation, providing a optimized operation too.

1. INTRODUCTION

Secondary cooling systems of Research Reactors (RR) perform important functions for the operation of the Facility and their operation is often vital to the availability of reactor operation. In addition, an important safety function of the reactor decay heat removal is also often attributed to the secondary system. In case of the utilization of tertiary cooling systems, the secondary system act as a further barrier against radioactive material release to the environment.

Within the design of a secondary system, issues such as safety functions, types of ultimate heat sink, availability of make-up water and its estimate consumption and prevention of problems of corrosion and deposits on heat exchangers should be discussed.

This paper proposes the realization of this study and its discussion.

2. SAFETY FUNCTION AND DIVISION IN CIRCUITS

According to the IAEA, “safety function is “a specific purpose that must be accomplished for safety”. The safety functions must be fulfilled by the design of a nuclear power plant in order to meet three general safety requirements:

(a) The capability to safely shut down the reactor and maintain it in a safe shutdown condition during and after appropriate operational states and accident conditions;
(b) The capability to remove residual heat from the reactor core after shutdown, and during and after appropriate operational states and accident conditions;
(c) The capability to reduce the potential for the release of radioactive material and to ensure that any releases are within prescribed limits during and after operational states and within acceptable limits during and after design basis accidents.
This guidance is commonly condensed into a succinct expression of three main safety functions for nuclear power plants:
(a) Control of reactivity;
(b) Cooling of radioactive material;
(c) Confinement of radioactive material."[1]

Normally, the safety function assigned to the secondary system is only the removal of the residual heat (item b).

Usually, the safety function of the confinement of radioactive material (item c) is not attributed to the secondary system due to massive use of open circuit cooling towers as ultimate heat sink for RR (see section 3). In case of the utilization of tertiary cooling systems (or yet closed circuit cooling towers), the secondary system starts to act as a further barrier against fission products release to the environment (section 3.2).

In this section it will be considered for the secondary system, only the safety function of decay heat removal.

Although it is vital to the operation of the installation, the removal of heat released by the reactor, when it is turned on in normal operation, it is not considered a safety function to the secondary system.

Most of the time the reactor pool is designed to ensure a passive safe cooling of the decay heat, by natural circulation, independently of others external sources. Based on the concept of defense in depth, applied to the safety of the reactor, the secondary system acts as an overlapping provision in failures occurrences, with redundancy, independence and diversity [2]. In this way, the secondary system plays a role of defense in depth in its security feature.

To ensure the fulfillment of this safety function, the system or equipments involved in this function should be classified as a seismic and safety class compatible with this function. Generally this classification is distinguished from systems or equipment without any safety function.

In just one second, the decay heat decreases to about 7% of the power reactor operation, and thereafter this value decreases exponentially (according to the history of reactor operation).

Therefore the classification as safety class for all the secondary system, designed to remove a power of 100% when its only need is to ensure the removal of powers lower than 7%, may involve unnecessary costs, as well as operations not optimized.

Figures 1 to 3 present examples of three options of secondary systems, considering different approaches to the safety function. Equipments with safety function are highlighted in yellow. The heat exchangers of the primary cooling system will be always considered with safety function. A heat exchanger is considered a representative for all other systems that interfaces with the secondary system.

Fig. 1 shows a flow diagram of a hypothetical installation of a secondary cooling system (SCS) with two heat exchangers and the third as a redundant one for the primary system and two cooling towers and one redundant. The decay heat (safety function) is removed by the primary heat exchanger. The pumps, cooling towers and almost all the pipe of the secondary system have to be classified as a safety function and oversized for the decay heat removal.

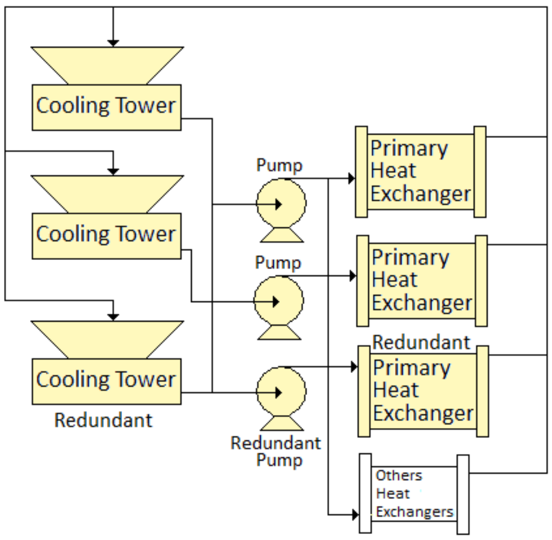

Figure 1. Flow diagram of SCS Option 1.

In Fig. 2 the secondary system removes heat decay from one heat exchanger (plus one reduntant) of the reactor pool. This configuration has two more heat exchangers and pumps than in option 1, all with safety function, but with smaller capacity and more closely to the needs of the decay heat removal, but the towers remain oversized for this heat removal.

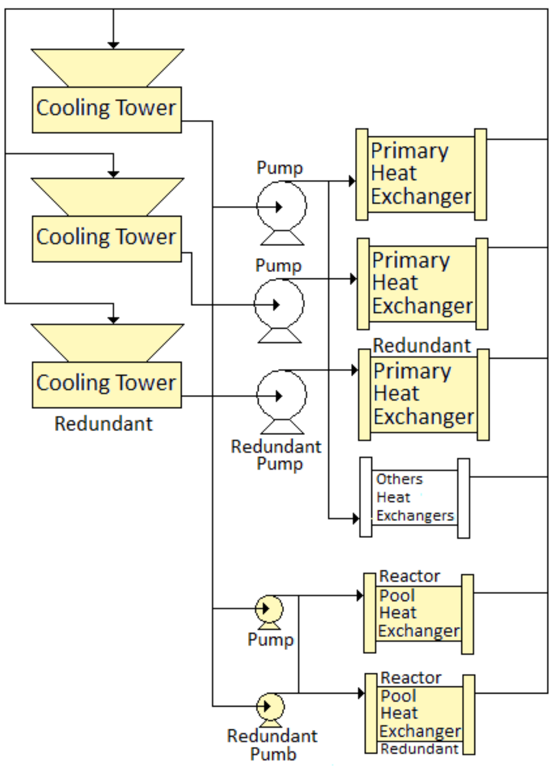

Figure 2. Flow diagram SRS Option 2.

Fig. 3 presents the option of dividing the secondary system into two independent circuits, according to its function, the circuit I without safety function and the circuit II with safety function. It has two more towers than option 2, but with equipment capabilities closer to the heat decay conditions.

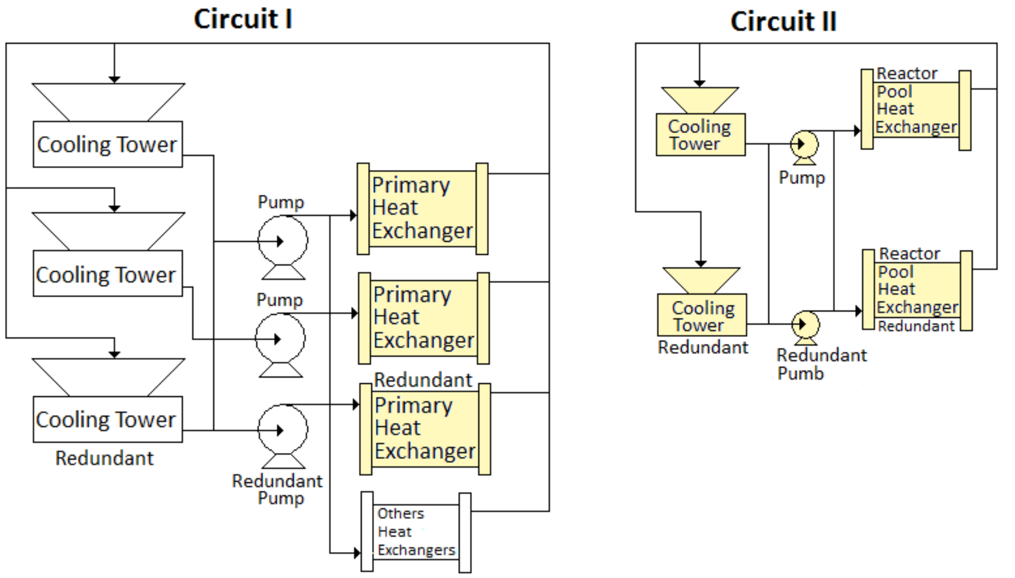

Figure 3. Flow diagram SRS Option 3.

We also emphasize the importance of conducting an analysis of system reliability with a Probabilistic Safety Analysis (PSA) to define the best system configuration.

3. TYPES OF SECONDARY COOLING SYSTEMS AND ULTIMATE HEAT SINK

Generally secondary cooling systems are often responsible for the removal and transference of practically all the heat generated in the Facility to the atmosphere, through the interface with other cooling systems.
Most of RR has secondary systems with semi-open circuit with recirculating water. These reactors use conventional or open-circuit cooling towers as ultimate heat sink.
Table 1 presents a selection of 20 RR from various countries around the world, with their ultimate heat sink.
We can see that some modern reactors as the 100 MW Russian PIK reactor and the 20 MW German FRM-II reactor, have beyond the secondary (or intermediate) system, a tertiary system (or cooling tower system) with conventional cooling towers.
The French (European) 100 MW Jules Horowitz reactor also has secondary and tertiary systems. The tertiary system is an open system with cold water supplied by the "Canal de Provence".
The HFH reactor in the Netherlands has a hybrid once-through secondary system that takes sweet water from the Noord-Hollands Kanaal and seawater from the North Sea.

Table 1. Ultimate Heat Sink of Research Reactors [3]

Country	Reator	Construction (Reform)	Power (MW)	Secondary Cooling Tower	Secondary Once-Through	Tertiary Cooling Tower	Tertiary Once-Through
Argentine [4]	RA3	1963	10	Yes			
Australia [5]	Opal	2002	20	Yes			
Brazil [6]	IEA-R1	1956	5	Yes			
Brazil [7]	RMB	planned	30	Yes			
Brazil [8]	TRIGA IPR-R1	1958 (under licensing)	0,1 (0,25)	Yes			
China [9]	CARR	2002	60	Yes			
Egipt [10]	ETRR-2	1992	22	Yes			
France [11]	Jules Horowitz	under construction	100				Yes
France [12]	Osiris	1964	70	Yes			
Germany [13]	FRM-II	1996	20			Yes	
Japan [14]	JRR-3M	1962 (1985)	10 (20)	Yes			
Netherlands [15]	HFR	1961	45		Yes		
Russian Federation [16]	PIK	under construction	100			Yes	
South Corea [17]	Hanaro	1995	30	Yes			
USA [18]	ATR	1961	250	Yes			
USA [19]	HFIR	1961(2007)	85	Yes			
USA [20]	MITR-II	1956(2011)	6	Yes			
USA [21]	MURR	1963	10	Yes			
USA [22]	NBSR (heavy water)	1963(1985) (2011/12)	20	Yes			
USA [23]	RINSC	1962 (planned)	2(5)	Yes			

The main advantages of using secondary systems with conventional cooling towers as ultimate heat sink are:

- ✓ simplicity;
- ✓ versatility;
- ✓ good range of manufacturers
- ✓ low-cost; and
- ✓ great experience of usage in RR.

The main disadvantages are:

- problems of corrosion and deposits formation in heat exchangers;
- the need for heavy chemical treatments in the secondary system water;
- high make-up water consumption in the towers;
- Not too high reliability, especially the fans;
- In case of leakage in heat exchangers there is a possibility of radiation release to the atmosphere through the towers (for projects where the primary system pressure is higher than the secondary system pressure) or contamination of the primary system and the reactor pool (for projects where the primary system pressure is lower than the secondary system pressure).

As a sequence of this work we discuss the following aspects:

- high consumption of make-up water lost in cooling towers;
- the use of tertiary systems or closed circuit cooling towers to: a) protection of the heat exchangers against the corrosion and deposits problems; b) prevent the release of radioactive material into the atmosphere or contamination of the reactor pool.

3.1. High Consumption of Make-up Water in the Cooling Towers

The abundance and low price of water is already a past reality in many countries. Today we live in a world with increased restrictions on water use, parallel with a dwindling availability.
The reliable supply of make-up water for the losses in the cooling towers is vital to ensure the availability of the RR operation.
The towers lose a lot of water to the atmosphere due to evaporation, drift and blown-down [24], [25], [26].
Evaporation (Ev) is the main cause of water loss in the towers. It is linked to the process of heat removing, basically evaporative, and depend of the heat load, the flow of recirculating water, the temperature range in the towers, the relative humidity and the approach to wet bulb temperature (output and the wet bulb temperatures difference). Ev (%) can be calculated by:

$$Ev = (0{,}185) \times \Delta T \quad . \tag{1}$$

were ΔT is the temperature range in the cooling tower in ^{o}C.
Drift loss (Dr) occurs as air flows through the cooling tower and carries water droplets out of the tower. It is directly related to the geometry of the tower. Drift eliminators are installed in the discharge stream to remove water droplets from the air. In a properly maintained system, efficient eliminators will reduce drift loss to a negligible percentage of the designed flow rate. Dr varies from 0% to 0,3%.
Blow-down (Bd) is caused in order to remove suspended and dissolved solids in the circulation water. With the continuous evaporation of a small portion of the recirculating spray water, the impurities originally present remain in this water. Thus the concentration of the dissolved solids increases over time and can reach unacceptable levels. The airborne impurities can also be introduced into the recirculating water. These impurities and contaminants should be effectively controlled to avoid scaling, corrosion, and sludge accumulations that reduce heat transfer efficiency and increase system-operating costs, potentially shortening the lifetime of the equipment. Bd (%) can be calculated by:

$$Bd = \left(Ev \div (C-1) - Dr\right) \quad . \tag{2}$$

were C is the number of cycles of concentration, and:

$$Cv = CR \div CM \qquad . \qquad (3)$$

were CR is the concentration in recirculating water in ppm and CM is the concentration in make-up water in ppm.
Bd can varies from 0,06% to 0,63%
The Make-up (Mk) (%) is given by:

$$Mk = Ev + Dr + Bd \qquad . \qquad (4)$$

And the Make-up Flow (Q_{Mk}) in m^3/h is given by:

$$Q_{Mk} = Mk \times Q_{RW} \div 100 \qquad . \qquad (5)$$

were Q_{RW} is the recirculating water flow, or the cooling tower flow (m^3/h).
Each MW dissipated in the cooling towers has an estimated flow of make-up water from 1,7 to 2,5 m^3/h, which corresponds to an approximated consumption of 40 to 60 m^3 per day.
Failure to provide the make-up water causes the shutdown of the reactor. This water flow should be provided to allow programming and operation needs of the Facility.
For a good and reliable availability of the installation operation, it must have a water supply of the same type.
Depending on the size of installation and availability of water supply on site, tanks, reservoirs and / or lakes should be planned and provided, to assure this supply.
Tanks and reservoirs with safety function should also be provided to the reactor decay heat removal.

3.2. Tertiary Cooling System and Closed Circuit Cooling Towers

As it was told in section 3, one of de big problems connected to SRSs operation is the corrosion and development of deposits in the heat exchangers that have interface with it, during the use of the conventional cooling towers of open circuit.
In order to fight this problem, a rigid chemical treatment of SRSs is, most of the time, demanded to assure the integrity of the exchangers and minimize their maintenance problems.
Besides, when occur leaks in the heat exchangers of the primary system, there can be, or the release of radioactive material to the atmosphere through the cooling towers when there is a project where the pressure of the primary system is greater than the pressure of secondary system, or the contamination of the primary system and the pool of the reactor, when there are projects where the pressure of the primary system is smaller than the pressure of the secondary system.
In this section two alternative options are evaluated for the protection of the heat exchangers, of the pool of the reactor and of the primary system, as well as the atmosphere, the use of tertiary cooling systems and of closed circuit cooling towers.

3.2.1. Tertiary cooling system

As it was mentioned in section 3, few RR use tertiary cooling sistems.
Fig. 4 presents a schematic fluxogram of the three cooling sistems of Germany Reator FRM-II of 20 MW. FRM II's fuel element is cooled by the primary cooling system circuit. The waste heat is transferred to the tertiary circuit passing the secondary circuit. Finally the waste heat is passed to the surrounding by means of the air cooler of the tertiary cooling circuit.

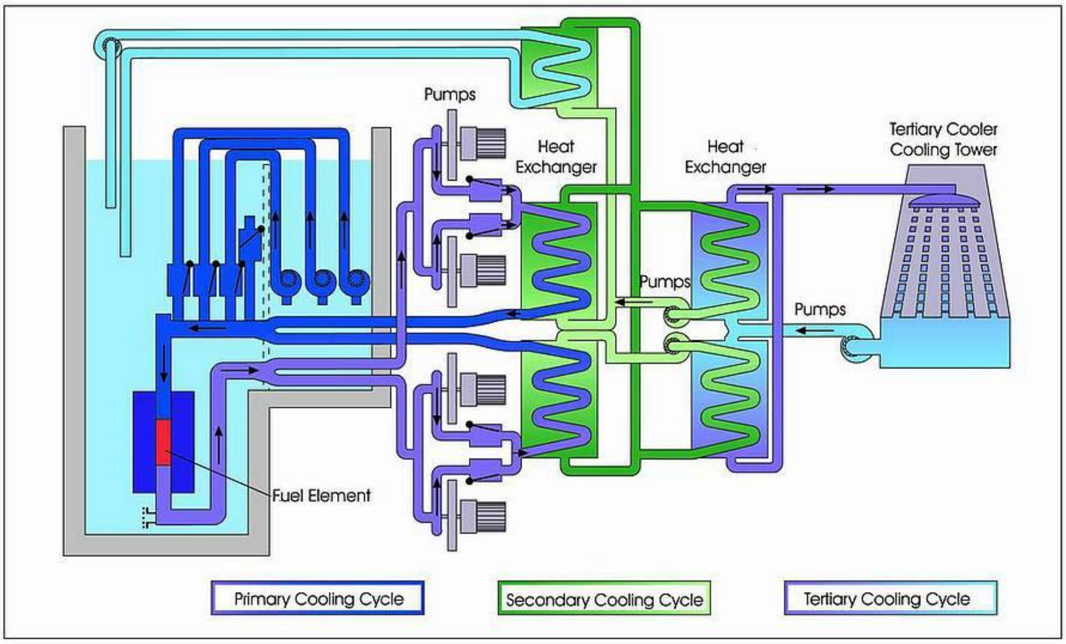

Figure 4 The Three Cooling Systems of the FRM-II Reactor [27]

The two main advantages of the use of tertiary circuits are:

- ✓ the protection of the heat exchangers of the primary (and other) systems, of the problems connected to corrosion and development of deposits in them; and
- ✓ the secondary system becomes an aditional barrier to the release of radiation to the environment. In case of failures or leaks in the primary heat exchangers, the water of the primary system remains confined in the secondary system.

As disadvantages, we have:

- a higher cost of installation;
- the transfer of the same problems of corrosion and deposits, in the heat exchangers of the several systems served by the secondary system to the heat exchangers of the secondary system. Even being a disadvantage it is important to know that the concentration of problems in heat exchangers of several systems for just the secondary system is clearly an advantage. The placement of the secondary heat exchangers making easier its cleaning and maintenance is an advantage too; and
- the need of water treatments common to the conventional secondary systems (without tertiary ones).

3.2.2. **Closed circuit cooling tower**

Closed circuit cooling tower are operation equipments very similar to the conventional open cooling towers, they use the same principle of evaporative heat transfer. The main difference is that the water to be cooled (secondary system) passes through a closed coil, without any contact to the environment. The closed circuit cooling tower counts on a cooling system composed by a pump and pipes, totally independent of the system to be cooled (secondary system).
Fig 5 presents a schematic diagram of a closed wet cooling tower.

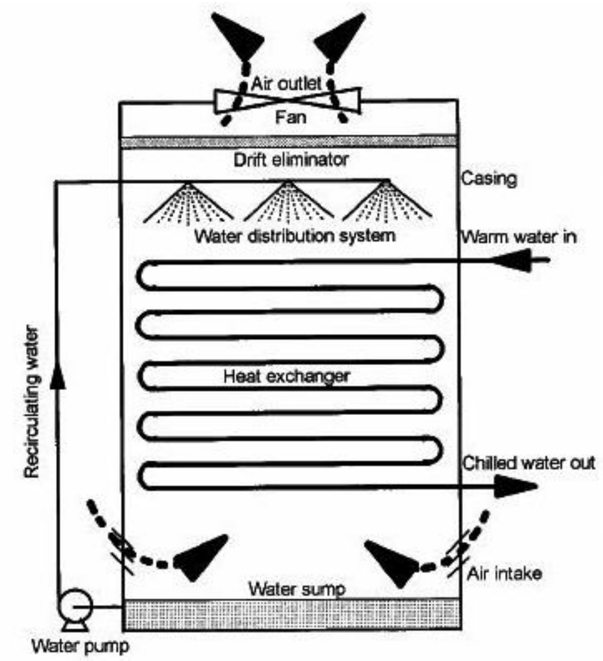

Figure 5 Schematic Diagram of a Closed Wet Cooling Tower [28]

Fig. 6 presents a closed circuit cooling tower model VF of BAC (Baltimore Aircoil Company).
Depending of the operating and climate conditions of the installation, we can also opt for a hybrid system that use water and/or air cooling, as shown in Figure 7. This equipment can reach economies of make-up water of about 70% [30].
Advantages of closed circuit cooling tower:

- ✓ further barrier to the release of radioactive material into the atmosphere;
- ✓ protects the heat exchangers that have interfaces with the secondary system, against the corrosion and deposits problems.

Disadvantages of closed circuit cooling tower:

- have higher costs than conventional open-circuit cooling towers,
- few manufacturers; and
- it seems they have never been used in RR.

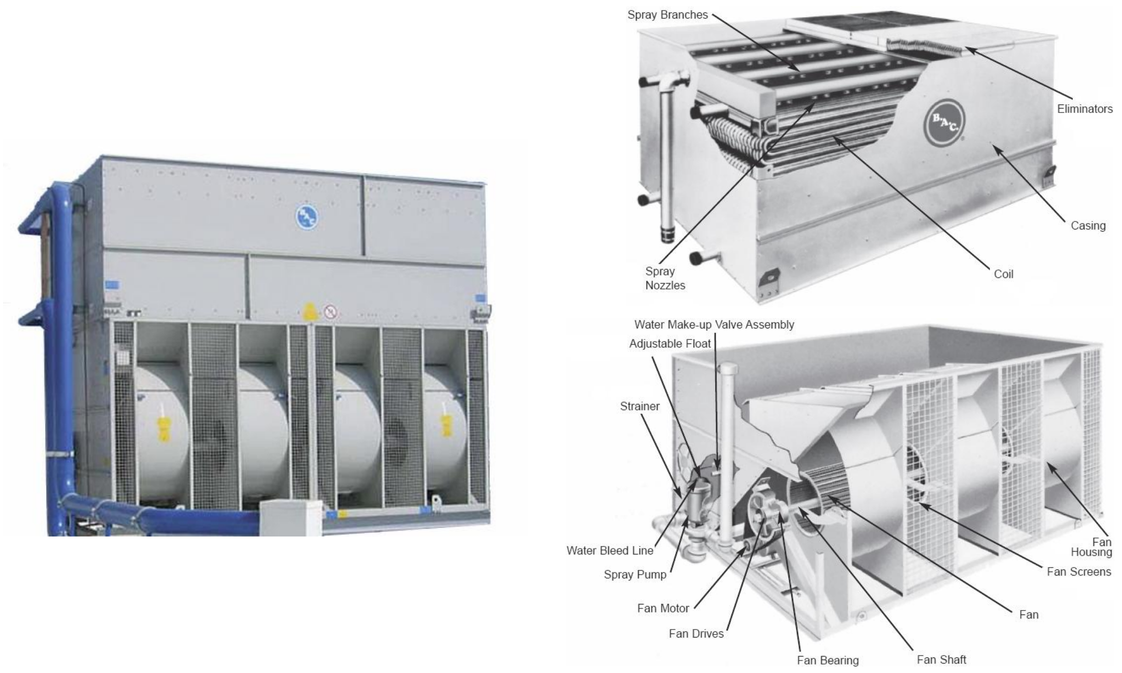

Figure 6 Closed Circuit Cooling Tower Model VF of BAC [29]

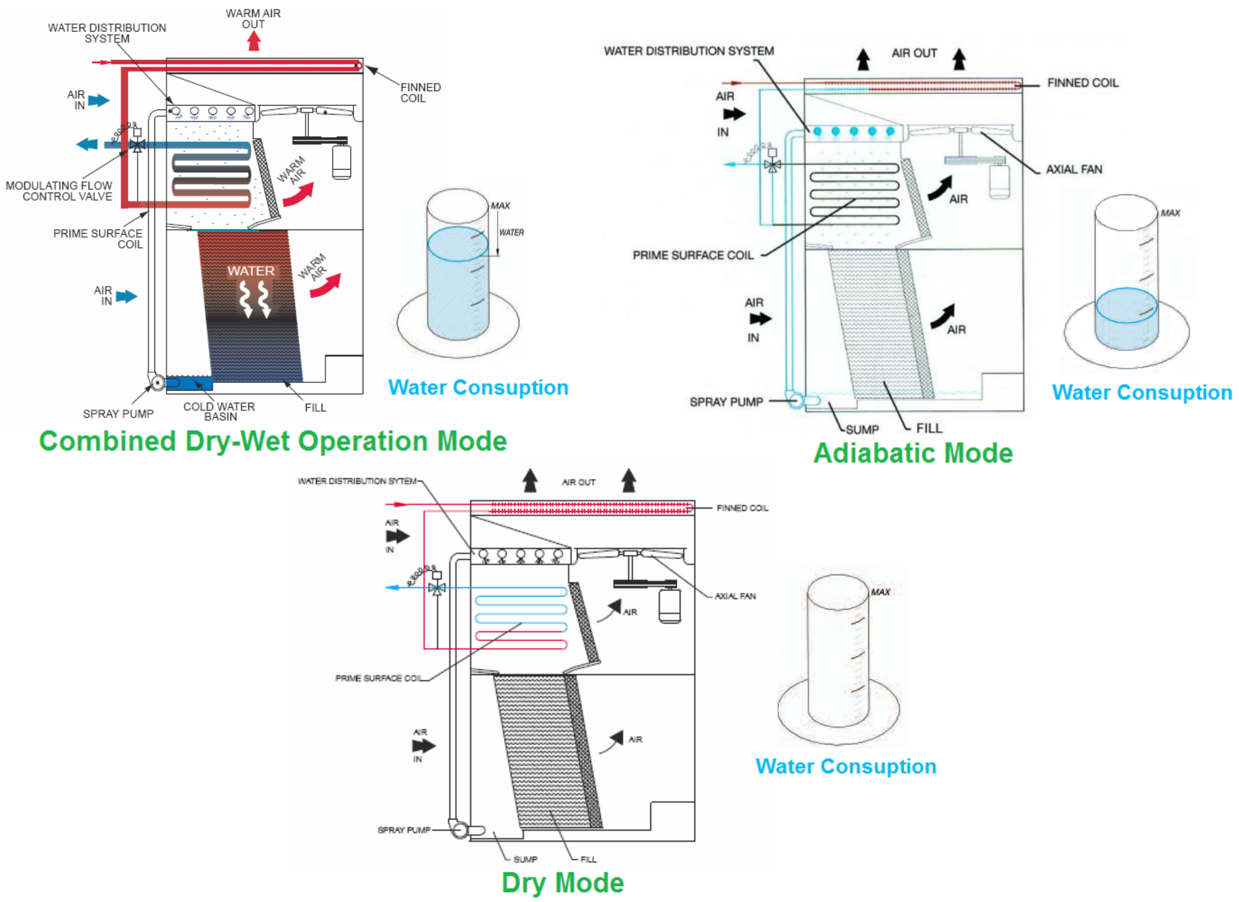

Figure 7 Hybrid Closed Circuit Cooling Tower Model HXV of BAC

Advantages of closed circuit cooling tower:

- ✓ further barrier to the release of radioactive material into the atmosphere;
- ✓ protects the heat exchangers that have interfaces with the secondary system, against the corrosion and deposits problems.

Disadvantages of closed circuit cooling tower:

- have higher costs than conventional open-circuit cooling towers,
- few manufacturers; and
- it seems they have never been used in RR.

4. CONCLUSIONS

As mentioned in the Introduction, this paper proposes to discuss some important topics related to the design of secondary cooling systems of RR, so we can highlight that:

- ✓ a better separation of the secondary cooling system according to the safety function of their equipments may be a good alternative to reduce the costs and optimizing the operation, providing a optimized operation too;
- ✓ most of RRs have secondary systems with conventional or open-circuit cooling towers as ultimate heat sink. A small number of modern reactors have tertiary cooling systems;
- ✓ the use of tertiary systems or closed circuit cooling towers: a) protects the heat exchangers that have interfaces with the secondary system, against the corrosion and deposits problems; b) serves as a further barrier to the release of radioactive material into the atmosphere; and c) prevents the contamination of the reactor pool and the primary system;
- ✓ the disadvantages of tertiary systems are higher costs and the transfer of the problems to the secondary system heat exchangers;
- ✓ closed circuit cooling towers have higher costs than conventional open-circuit cooling towers, few manufacturers and it seems they have never been used in RR;
- ✓ must be provided a reliable water make-up with the planning and provision of tanks, reservoirs or lakes to assure their supply and the availability of the Facility.

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