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HEAVY WATER CYCLE IN THE CANDU REACTOR

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ABSTRACT

Hydrogen atom has two isotopes: deuterium ${}_1H^2$ and tritium ${}_1H^3$. The deuterium oxide D_2O is called heavy water due to its density of 1105.2 Kg/m^3.

Another important physical property of the heavy water is the low neutron capture section, suitable to moderate the neutrons into natural uranium fission reactor as CANDU. Due to the fact that into this reactor the fuel is cooled into the pressure tubes surrounded by a moderator, the usage of D_2O as primary heat transport (PHT) agent is mandatory.

Therefore a large amount of heavy water (approx. 500 tons) is used in a CANDU reactor. Being a costly resource – it represents 20% of the initial plant capital cost, D_2O management is required to preserve it.

1 INTRODUCTION

The basic principle of the heavy water management is CONSERVATION. There are three important motivations to conserve the heavy water:

1) Personnel safety. Due to radiative neutron capture, deuterium turns into tritium as described in equation (1):

$${}_1H^2 + {}_1n^1 = {}_1H^3 + \gamma \qquad (1)$$

Tritium is a β radiation emissive isotope, therefore it represents a radiological hazard for station personnel.

2) Environment. For the same reason as above, the tritium releases to environment are minimised to maximum (the tritium half-life is 12.3 years);

3) Economics. Due to high price of heavy water (approx. 300$/Kg) the escapes from reactor systems are mostly recovered, minimising thereby the D_2O losses:

$$\text{Escapes} = \text{Losses} + \text{Recoveries} \qquad (2)$$

The D_2O recovery efficiency is calculated as:

D_2O recovery efficiency = 100*recovery/escapes [%]. (3)

2 HEAVY WATER CYCLE

The heavy water cycle is shown in **Figure 1.**

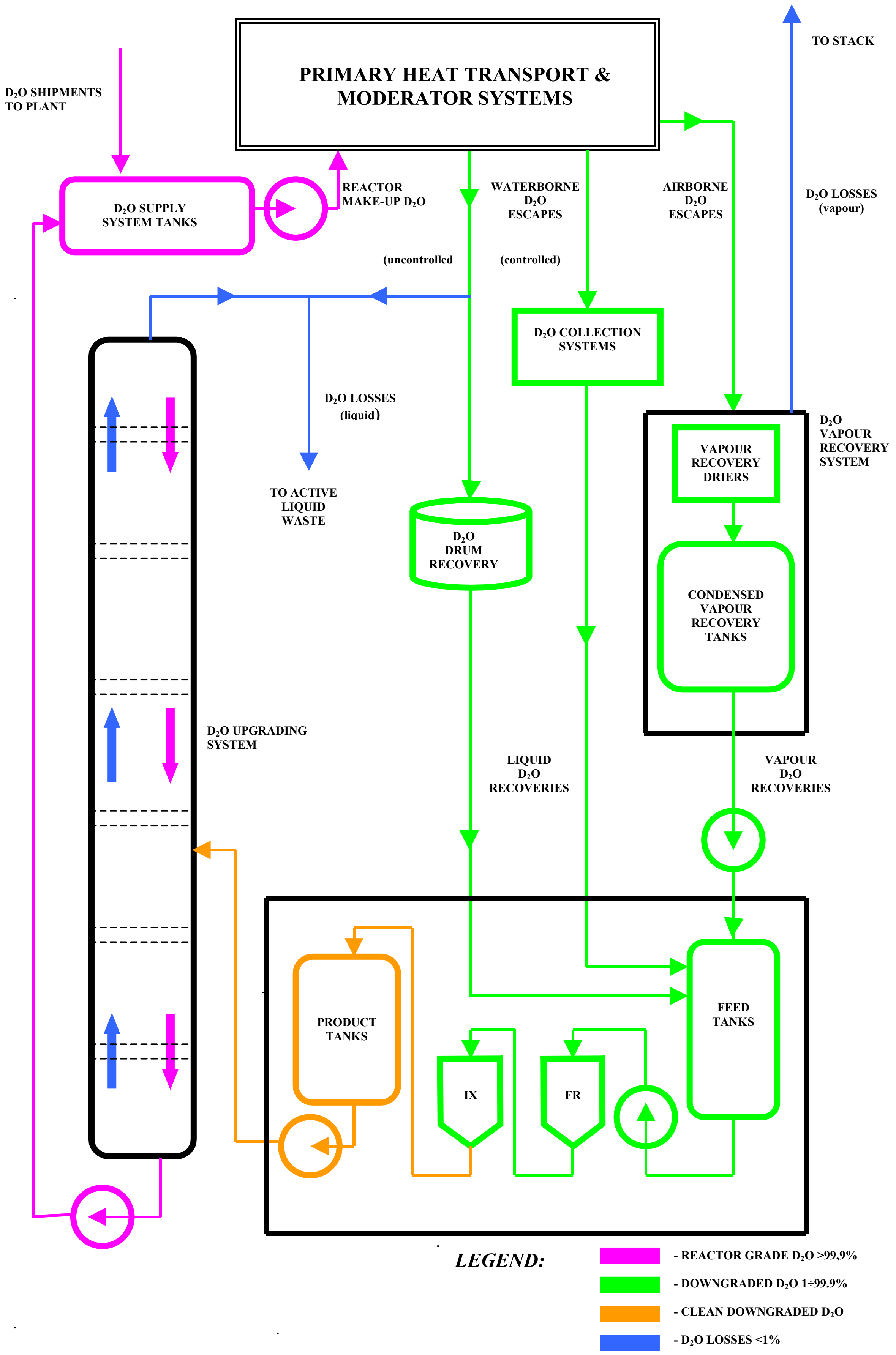

Figure 1. – Heavy water cycle in the CANDU reactor

Since there is no perfect sealed system, D_2O leaks occur from reactor systems. While the moderator system operating parameters are T = 70°C and p = 1.02 bar, the primary heat transport system is hot (T = 260°C) and pressurized (p = 99 bar), so the leaks appear mainly from PHT systems.

The D_2O escape points are: valve spindle seal packings, mechanical fittings (swagelocks), pumps packed glands, heat exchange tubes, end fitting closures, tubing erosion etc. Also, D_2O may escape due to operator's actions, such as deuteration and dedeuteration of ion exchange resins, heavy water sampling and equipment draining for maintenance work. All the leak points above, which are operating under high pressure and temperature conditions, are provided with collection lines part of the PHT and moderator collection systems. These systems are designed and operated to collect, store and transfer the most part of the liquid D_2O escapes, therefore the recovered escapes of D_2O are called controlled.

The liquid D_2O escapes from reactor circuits, which are not handled by the collection systems, are uncontrolled. This quantity of D_2O is collected in reactor building sumps then drummed.

2.1 D_2O vapour recovery system

The D_2O escapes from PHT and moderator systems also in a vapour form into the reactor containment rooms' atmosphere. To recover the D_2O vapours and to minimise the radiological hazard a special vapour recovery system is designed.

The vapour recovery system consist of 10 dryers, 3 tanks and appropriate transfer pumps. A typical dryer is shown in **Figure 2**.

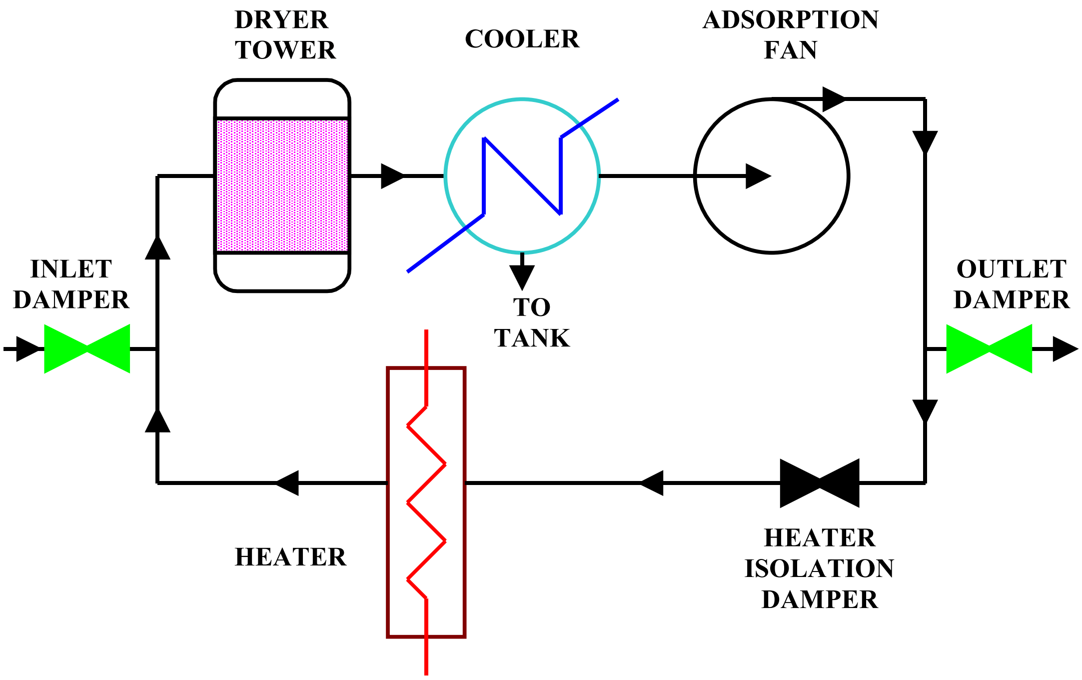

Figure 2. – Typical Dryer configuration

The dryer has two operating modes: adsorption and regeneration. The operating status of main system components is presented in **Table 1.**

	INLET DAMPER	OUTLET DAMPER	HEATER ISOLATION DAMPER	HEATER
ADSORPTION	OPEN	OPEN	CLOSED	OFF
REGENERATION	CLOSED	CLOSED	OPEN	ON

Table 1.

In the adsorption mode, the air from the dried room passes through the desiccant bed of the dryer tower (which is a molecular sieve) retaining the vapours. The flow of air is returned dried into the room by the fan.

In the regeneration mode the fan recirculates the air through the heater which is in service. The hot flow of air passing through the molecular sieve extracts the humidity from it, then is directed into the cooler. The mixture of D_2O and H_2O vapours is condensed, then gravitationally drained into a tank. When the molecular sieve is dried, the dryer switches in adsorption mode.

Due to its hygroscopic property, D_2O is mixing with H_2O, so the isotopic ratio of water collected by dryers varies between 1 to 25% depending of the system leak rate, atmospheric humidity and R/B area. The system tanks collect a mixture of D_2O and H_2O which is pumped out to D_2O Cleanup system.

Excepting the D_2O recovery, this system has also three important functions:

1. Zoning of the reactor building (R/B). The system acts like a ventilation facility for the inaccessible rooms of R/B, while a separate ventilation system is provided for accessible areas. The flow of air is always directed from the accessible areas with low radiation probability towards the rooms with high radiation probability to minimise the radiological hazard.
2. Tritium segregation. The vapour recovery system has two separate circuits for rooms containing moderator D_2O systems (high tritium content) and for rooms containing PHT D_2O systems (low tritium content), providing a tritium based segregation of the recovered D_2O.
3. D_2O tanks vents. All systems tanks containing D_2O are vented to vapour recovery system inlet ducts preventing D_2O evaporation and tritium releases into atmosphere.

2.2 D_2O cleanup system

All D_2O recoveries are transferred from D_2O collection systems, D_2O vapour recovery system and drums to D_2O cleanup system. Its purpose is to collect, store and process downgraded D_2O chemically impure to obtain pure downgraded D_2O suitable for upgrading system feeding.

The impure D_2O collected into feed tanks is processed through an active charcoal filter (FR in **Figure 1.**) to remove oil, suspended solids and organics from the water, then through a mixed bed of anionite and cationite resins of the ion exchange column (IX in **Figure 1.**)

The removal of the ionic impurities is described in the equations (4) and (5) below:

$$X^+ - OH^- + R^- - H^+ \Rightarrow X^+ - R^- + H_2O \quad (4)$$

or $$X^+ - OD^- + R^- - D^+ \Rightarrow X^+ - R^- + D_2O$$

and $$Y^- - H^+ + R^+ - OH^- \Rightarrow Y^- - R^+ + H_2O \quad (5)$$

or $$Y^- - D^+ + R^+ - OD^- \Rightarrow Y^- - R^+ + D_2O$$

where:

X^+, Y^- - cationic and anionic impurities;
R^+, R^- - anionite and cationite resin radicals;
OH^- - hydroxide radical; H^+ - hydrogen
OD^- - deuterium monoxide; D^+ - deuterium

As described above, the impurities are retained by the resin bed while the product remains clean. This mixture of D_2O and H_2O is stored in the product tanks then pumped-out to feed D_2O upgrading system.

The system has two separate circuits for high and low tritium D_2O to ensure the tritium content separation.

2.3 D_2O upgrading system

The purpose of D_2O upgrading system is to separate the heavy and the light water from the mixture delivered by the D_2O cleanup system. The separation of D_2O and H_2O is based on different boiling points at the same pressure and temperature, being accomplished by a fractionated distillation process.

In the system distillation columns there is a continuous flow of vapour and liquid mixture of D_2O and H_2O going in opposite directions: while the bottom product is reboiled raising to the top, the head product is condensed flowing to the bottom. By this way, the liquid and vapour phases are permanently in contact, the interface providing the isotopic separation.

At the top of the column the water is extracted at an isotopic ratio of $<0.2\%$ and then transferred to radioactive liquid waste circuit.

At the bottom of the column the water is extracted at an isotopic ratio of $>99.9\%$, representing reactor grade D_2O. From the upgrading system the heavy water is transferred to D_2O supply system.

2.4 D_2O supply system

The main purpose of the D_2O supply system is to ensure the:

1. D_2O make-up for moderator and PHT systems to compensate the escapes.
2. Minimum operating reserve which will allow the operator enough time to shutdown the plant in a safe manner in case of an accident. The plant reactor grade D_2O reserve is maintained with D_2O from the upgrading system and virgin D_2O shipped to the station to replace the heavy water loss.

By compensating the D_2O escapes from the reactor circuits, this system closes the heavy water cycle in the CANDU reactor.

3 CONCLUSIONS

The application of the D_2O CONSERVATION principle into the plant is made by the heavy water cycle.

The efficiency of this cycle in the station is accomplished through three means:

1. maintaining the D_2O recovery efficiency at 90 ÷ 95%;
2. improving the operating practices in D_2O handling and D_2O systems;
3. maintaining the D_2O systems at high operating parameters.

Due to a high cost and radiological hazard of D_2O, a special program of D_2O management is implemented to reduce the loss of heavy water and consequently the production costs. For this purpose, any D_2O movement between plant systems is recorded and a quarterly D_2O physical inventory is performed. This allows to station management to identify leak source and loss path in order to take appropriate actions to minimise them.

4 REFERENCES

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