WATER COOLANT PERFORMANCE FOR FISSION AND FUSION REACTORS

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ABSTRACT

In this paper we review the technical challenges resulting from the choice of water coolant. Water is a common coolant used in existing fission reactor and more than 95% of the fission nuclear power (PWR, VVER, BWR, CANDU, etc..) in the world is derived from water cooled reactors.

Design and operation experience for many decades, but the Water has both advantages and disadvantages as a coolant in conceptual designs of future fusion power plants ITER, DEMO), Design choices involve complex relationships between materials and systems. It is very important to monitor and diagnose the concentrations of chemicals present in the water coolant periodically during (day-week-month) during normal operation and also during shutdown of the nuclear reactors.

Technical requirements and most important point's problems fission power plant:
- Corrosion in the primary coolant systems of water-cooled reactors (Clad- Zr, Pressure Vessel, U-tube Steam Generator...etc.).
- Chemistry of primary coolant in water cooled reactors (pH, Boron, Lithium, Zinc, Ammonia, Potassium. etc.)
- Radiolytically, neutron activation and gamma in water cooled reactors.

Technical requirements and most important points fusion power plant:
- High thermal conversion efficiency.
- Low activation materials.
- Passive safety, reliable containment.

1- INTRODUCTION

Water chemistry plays a major role in corrosion and in activity transport in NPP's. Although a full understanding of all mechanisms involved in corrosion does not exist, controlling of the water chemistry has achieved good results in recent years. Water chemistry impacts upon the operational safety of LWR's in two main ways: integrity of pressure boundary materials and, activity transport and out-of-core radiation fields [1].

The pressurized water reactor (PWR) falls, along with the boiling water reactor (BWR), in the class of light water nuclear power plants. In contrast to the (BWR), the (PWR) has a strict separation of the watersteam cycle from the primary water circuit Fig. 1. In total the (PWR) has three main water circuits: the primary water circuit, the water-steam cycle, and the cooling water system. The latter can be operated either by a cooling tower or by cooling water pass through. In a PWR only the primary water circuit contains radioactivity [2].
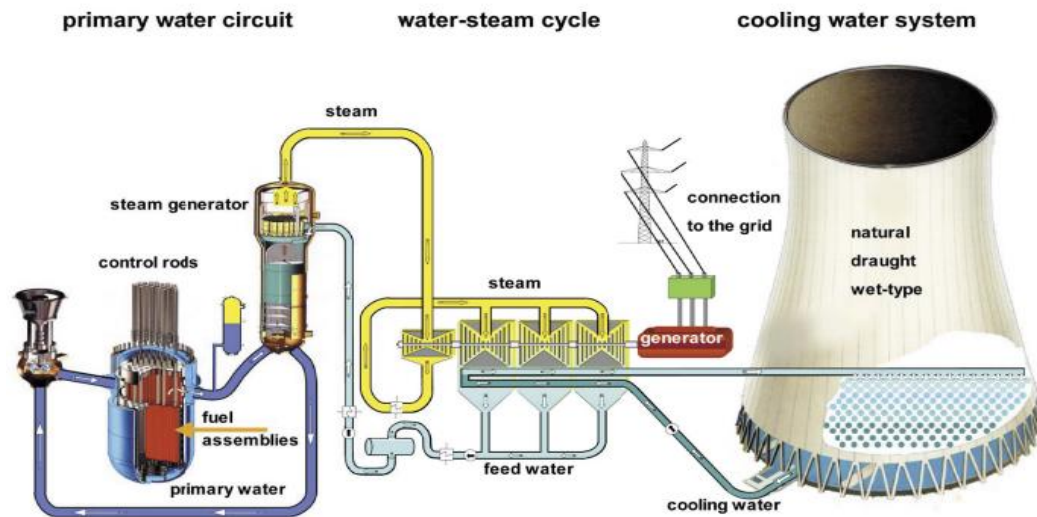

FIG.1. Basic Design of a PWR – Overview OF THE Three Main Circuits [2].

The IAEA coordinated research program entitled "Investigation on Water Chemistry Control and Coolant Interaction with Fuel and Primary Circuit Materials in Water

Cooled Power Reactors (WACOLIN)" was organized and carried out from 1987 to 1991. (IAEA Technical Reports Series No. 347 and IAEA-TECDOC-667) [3].

1.2 PRIMARY WATER CHEMISTRY

The challenges of NPP chemistry have changed a lot, although some aspects remain the same. In the past, avoiding the most typical cases of corrosion constituted the main objective. Then pH optimization of the primary water for dose rate limitation has evolved to a higher pH in the primary coolant; the addition of zinc in primary coolant is now seen as an additional way of decreasing occupational radiation exposure of plant staff. Mitigating crud-induced power shifts (also called axial offset anomaly) along the fuel elements is another challenge with high burn-up fuel and long cycles [4].

To describe the behavior of boric acid under primary water conditions, the common formulae is shown in Table 1. and overview of the boron chemistry under primary water conditions, is shown in Table 2. Dissociation of water and Temperature-dependent pH value of demineralized water is shown in Fig. 2.

TABLE1. OVERVIEW OF THE BORON CHEMISTRY UNDER PRIMARY WATER CONDITIONS [2]

$B(OH)_3 + OH^-$	$\leftrightarrows$	$B(OH)_4^-$	reaction {1}
$2\,B(OH)_3 + OH^-$	$\leftrightarrows$	$B_2(OH)_7^-$	reaction {2}
$3\,B(OH)_3 + OH^-$	$\leftrightarrows$	$B_3(OH)_{10}^-$	reaction {3}
$4\,B(OH)_3 + 2OH^-$	$\leftrightarrows$	$B_4(OH)_{14}^{2-}$	reaction {4}

$$K_{B1} = [B(OH)_4^-]/([OH^-]^*[B(OH)_3]) \qquad \text{Eqn. (1)}$$

$$K_{B2} = [B_2(OH)_7^-]/([OH^-]^*[B(OH)_3]^2) \qquad \text{Eqn. (2)}$$

$$K_{B3} = [B_3(OH)_{10}^-]/([OH^-]^*[B(OH)_3]^3) \qquad \text{Eqn. (3)}$$

$$K_{B4} = \gamma_{B4}^{2*}[B_4(OH)_{14}^{2-}]/([OH^-]^{2*}[B(OH)_3]^4) \qquad \text{Eqn. (4)}$$

γ: activity coefficient

$\log_{10}K_{B1} = 1573.21/T + 28.6059 + 0.012078^*T - 13.2258^*\log_{10}T$	Eqn. (5)	T[K]
$\log_{10}K_{B2} = 2756.1/T - 18.996 + 5.835^*\log_{10}T$	Eqn. (6)	T[K]
$\log_{10}K_{B3} = 3339.5/T - 8.084 + 1.497^*\log_{10}T$	Eqn. (7)	T[K]
$\log_{10}K_{B4} = 12820/T - 134.56 + 42.105^*\log_{10}T$	Eqn. (8)	T[K]

TABLE 2. DISSOCIATION OF WATER [2]

H_2O	$\leftrightarrows$	$H^+ + OH^-$	reaction {5}

$$K_W = \gamma_W^{2*}[H^+]^*[OH^-] \qquad \text{Eqn. (9)}$$

$$\log_{10}K_W = -14.938 + 0.042^*T - 2.103E\text{-}4^*T^2 + 6.220E\text{-}7^*T^3 - 8.738E\text{-}10^*T^4 \quad \text{Eqn. (10)} \quad T\,[°C]$$
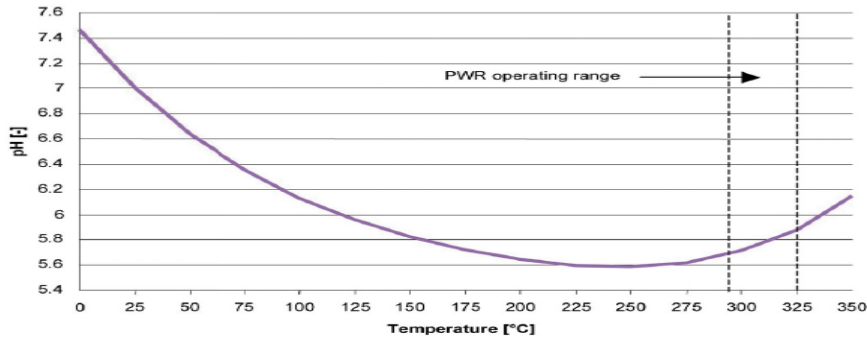
FIG. 2. Temperature-dependent pH value of demineralized water [2].

1.3 LITHIUM WATER CHEMISTRY

There are three main tools used to handle reactor coolant system chemistry: pH control, zinc injection and dissolved hydrogen. Boron-10 concentration is imposed by core characteristics and design and by the fuel burn up. It progressively decreases along the fuel cycle while the fuel burn-up increases. Consequently, the optimum high-temperature pH $300°C$ to be maintained requires a decreasing lithium concentration along the fuel cycle. In the past, a constant pH $300°C$ of 6.9 was recommended, because that was the point of minimum solubility of magnetite, thought to be the major component of crud. However, the primary constituent of crud turned out to be nickel ferrite, whose minimum solubility point is at a higher pH. However, extending the duration of a fuel cycle to 18 months or more meant that the boron concentration at the beginning of cycle had to be raised from 1200 to 1800 mg/kg (ppm). This requires a lithium concentration greater than 2.2 mg/kg to maintain optimum pH see Table 3 and Fig.3.

Table 3. Lithium chemistry, mass and charge balances under primary water conditions [2]

$LiOH \rightleftharpoons Li^+ + OH^-$	reaction {6}	
$K_{Li} = \gamma_{Li}^2 * [Li^+] * [OH^-] / [LiOH]$	Eqn. (11)	
$\log_{10} K_{Li} = -0.753 - 0.005 * T + 6.746E{-}6 * T^2$	Eqn. (12)	T [°C]
$[H^+] + [Li^+] = [B(OH)_4^-] + [B_2(OH)_7^-] + [B_3(OH)_{10}^-] + 2[B_4(OH)_{14}^{2-}] + [OH^-]$	balance /1/	
$[Li] = [Li^+] + [LiOH]$	balance /2/	
$[B] = [B(OH)_3] + [B(OH)_4^-] + 2[B_2(OH)_7^-] + 3[B_3(OH)_{10}^-] + 4[B_4(OH)_{14}^{2-}]$	balance /3/	
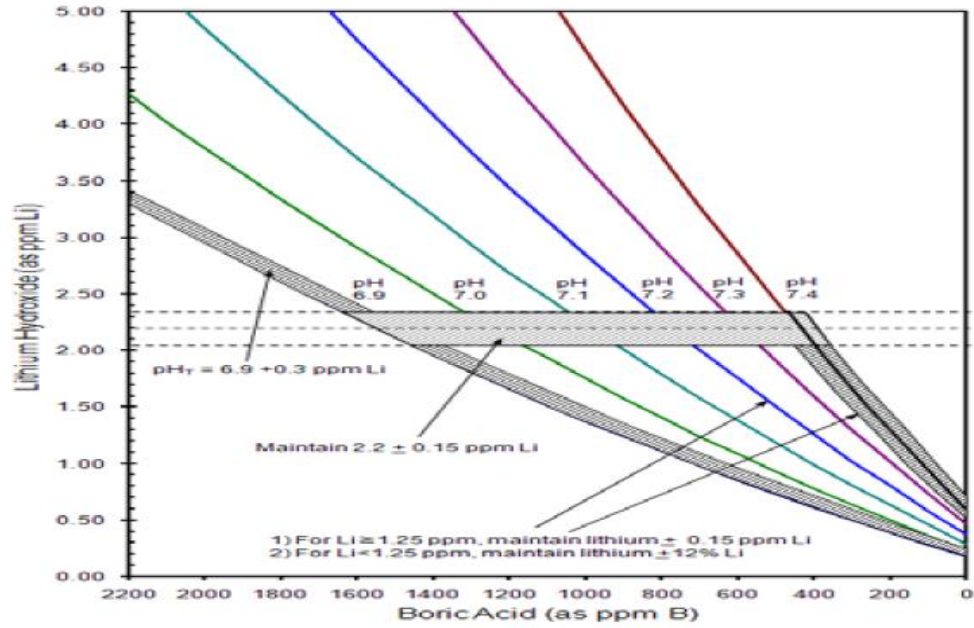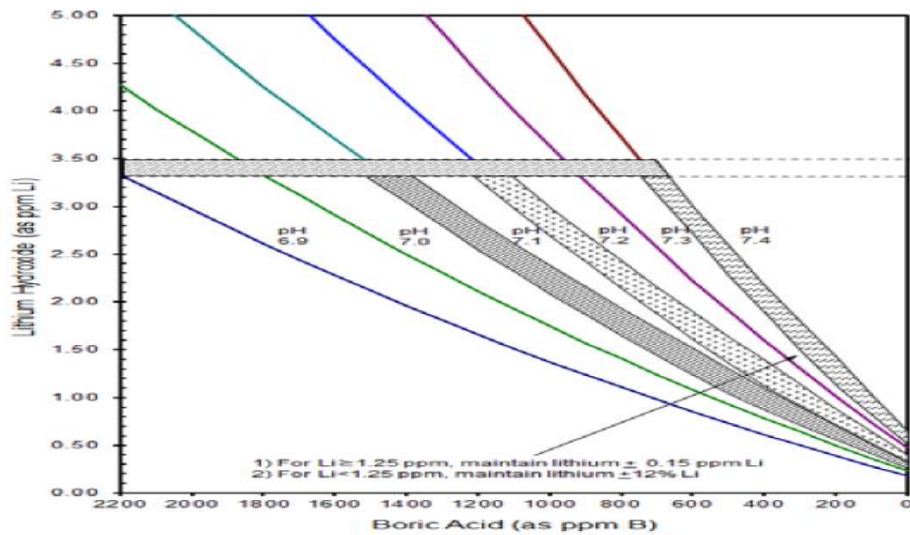
FIG. 4. pH control curves: (a) modified chemistry regime and (b) elevated pHT regime at 307 °C [5].

1.4 ZINC WATER CHEMISTRY

Another important aspect of water chemistry with growing interest is the addition of zinc. The beneficial influence of Zn has been discovered on shutdown dose rates in boiling water reactor (BWR) units with Cu/Zn alloy condensers [4]. Zinc is now added in the primary water of a growing number of PWR units at a concentration of about 5 µg/kg (ppb), which is sufficient to reduce the dose rates by 15% during the first fuel cycle and up to 30% to 40% after a few cycles with zinc injection. In some plants, Zn has been added to mitigate the initiation of primary water stress corrosion

cracking on Alloy 600 due to its incorporation in spinel oxide films, enhancing their stability. Corrosion rates of different alloys with and without zinc additions shown in Fig 5.
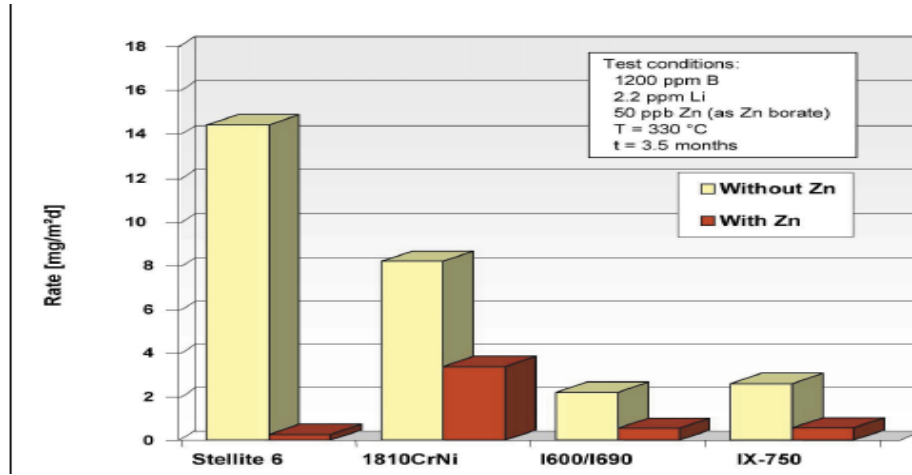

FIG. 5. Corrosion rates of different alloys with and without zinc addition [5].

The other controversial chemical parameter is hydrogen concentration, applied to mitigate water radiolysis. And Oxygen often plays a decisive role in corrosion processes. Radiolytical decomposition of water is shown in Fig. 6 [2].
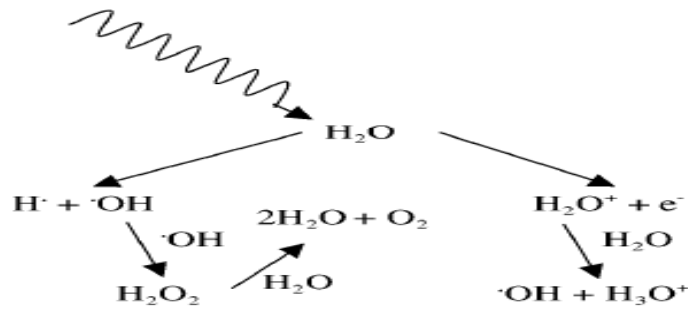

FIG. 6. Radiolytical decomposition of water [2,7].

Water chemistry control for nuclear power plants plays an important role in the degradation of materials, fuels integrity, and radiation control

The specifications of comparison of the primary coolant chemistries related to pH control are shown in Table 4. It has been reviewed to use ammonia and potassium, which are used in VVER [8] and SMART [9] for pH control for new soluble boron-free power plants.

1.5 AMMONIA-BASED WATER CHEMISTRY

One strategy of the pH control for boron-free operation is to use the ammonia. Some of ammonia is decomposed to hydrogen and nitrogen by radiation in the reactor core.

The produced hydrogen gas is used for the removal of dissolved oxygen in the coolant. [10].

Fig. 7 shows the pH changes with ammonia concentration and temperature. This is useful as operating and design data for pH control by ammonia-based water chemistry. Also, this strategy is particularly useful in new power plants such as SMART-P to control the pressurizer with nitrogen. [6]
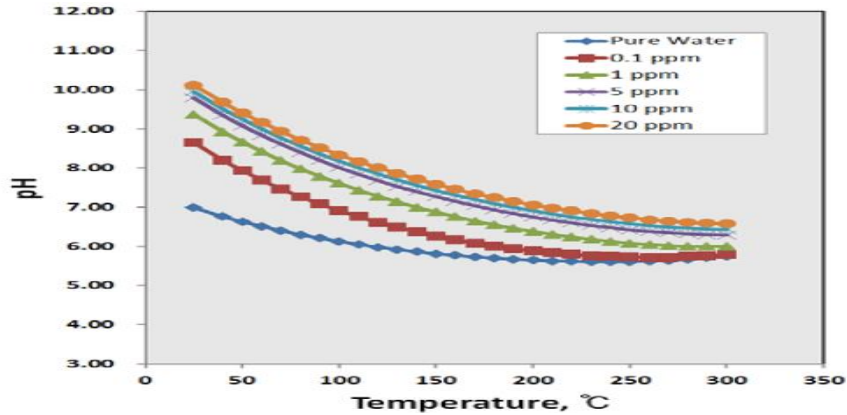

Fig. 7. pH changes with ammonia concentration and temperature.

However, ammonia-based water chemistry is not recommended for the following reasons;

- To avoid fluctuation of the pH value by ammonia radiolysis.

- To reduce C-14 production in reactor coolant from reaction with dissolved nitrogen.

1.6 POTASSIUM-BASED WATER CHEMISTRY

Another strategy of the primary water pH program for boron-free operation is to use the potassium which is different from existing commercial PWR using lithium.

Fig. 9 shows the calculated pH changes with potassium concentration and temperature. This is useful as an operating and design data for pH control by potassium-based water.
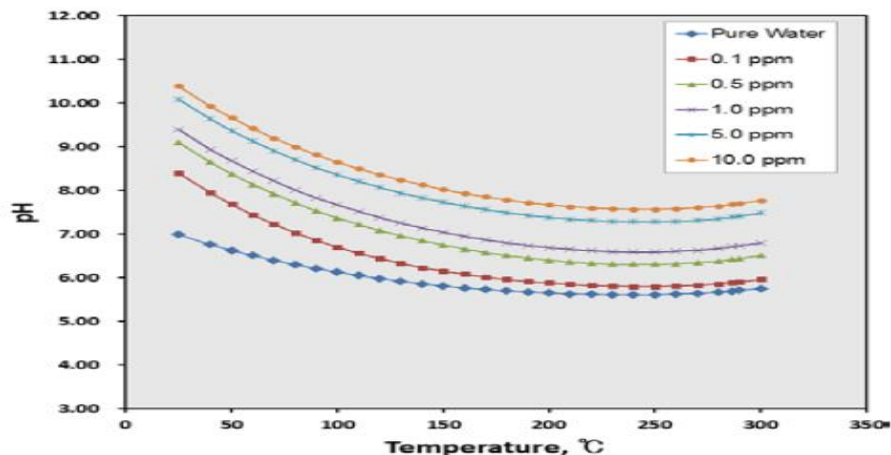
Fig. 9. Calculated pH changes with potassium concentration and temperature [5].

The ammonia and potassium-based water chemistry related to pH control PWR plant is recommended for boron-free operation as follows Table 4.

Table 4. pH control PWR plant is recommended for boron-free operation [8]

Chemistry parameter	Normal range
pH at 286.5 °C	6.9 - 7.4
pH at 25 °C	9.6 – 10.1
Potassium, ppm	1.7 – 5.0
Ammonia, ppm	≤2.0
Dissolved Hydrogen, cc/kg H2O	25 – 50
Dissolved Oxygen, ppm	≤0.005

2.1 NEUTRON ACTIVATION OF COOLANT WATER

Water is cooling fluid in many nuclear facilities, such as fission nuclear reactors and some fusion reactors. In fission reactors water is activated when passing through the reactor core, in fusion reactors however water is activated when cooling the blanket, or other components of the reactor such as diagnostic equipment. Activation of water consist of activation of oxygen and hydrogen as primary constituents of the H2O molecule, activation of dissolved gasses, corrosion products and additions to water and fission products in fission reactor. As all the latter are case specific, and decay of this activated isotopes, i.e., 16N, 17N and 19O. An analysis of activation of water in pressurized water reactors and in fusion reactors was performed.

2.2 NEUTRON ACTIVATION OF WATER

Activated cooling water in nuclear facilities can present a significant radiation source around primary cooling system causing radiation damage to electrical components, increasing doses to personnel and in the case of fusion facilities additional heating to superconducting coils. Activation of oxygen isotopes in water and decay of this activated isotopes, i.e., 16N, 17N and 19O [9].

Table 5. Summarized data of activated isotopes of cooling water obtained from ENDF/B-VII.1 data library (Chadwick et al., 2011). The marked energies present the dominant energies of decay products [9].

Isotope	Natural Abundance [%]	Reaction	Activation product	$t_{1/2}$ [s]	Decay products

^{16}O	99.76	(n, p)	^{16}N	7.13	2.742 MeV gamma (1%)
					6.129 MeV gamma (67%)
					7.115 MeV gamma (5%)
					0.383 MeV neutron (35%)
^{17}O	0.04	(n, p)	^{17}N	4.14	0.884 MeV neutron (1%)
					1.171 MeV neutron (53%)
					1.700MevV neutron (7%)
					0.110 MeV neutron (3%)
					0.197 MeV gamma (63%)
		(n, γ)			1.357 MeV gamma (33%)
^{18}O	0.04		^{19}O	26.9	1.444 MeV gamma (3%)

2.3 ACTIVATION OF COOLING WATER IN PWR

The reaction rates were calculated by the Monte Carlo particle transport using the MCNP code. A geometrical model of a typical 2 GW two loop PWR reactor vessel and steam generator were constructed in MCNP. The model is presented in Fig. 10 and Fig. 11 [9].
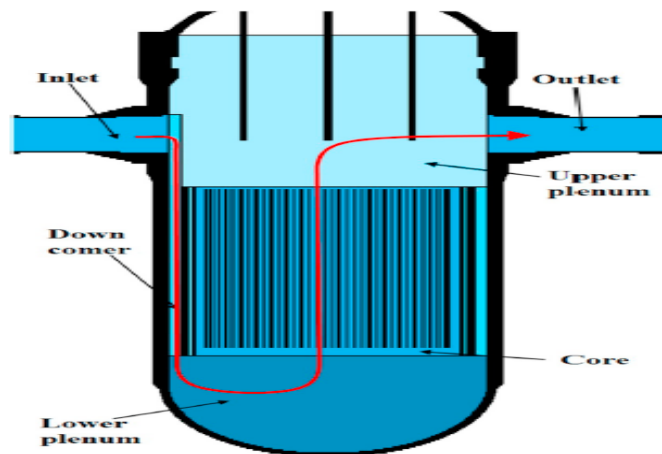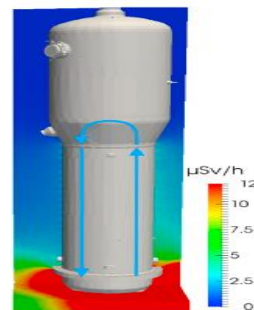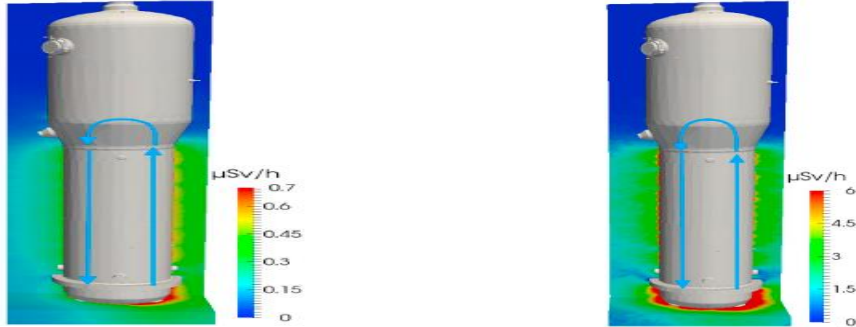

FIG. 10. MCNP model of reactor vessel in a typical PWR with marked regions for reaction rates calculation and marked direction of water flow in reactor vessel [9].

(a)The gamma dose field distribution 16N

(b)The neutron dose field distribution, 17N

(c)The prompt gamma field distribution, 17N   *(d)The gamma dose field distribution 19O.*

FIG. 11. Results of prompt gamma and neutron due to decay of isotope 16N, 17N and gamma dose field due to decay of isotope 19O [9].

Activated cooling water in nuclear facilities can present important source of radiation next to the radiation source in the nuclear facility itself thus causing radiation damage to electrical components and increasing doses to personnel working near primary cooling system. Heat exchangers are one of the bigger components in a cooling loop and the cooling water is majority of circulation time in them. As they are normally shielded form radiation of the source, decay of activated cooling water can present the main source of radiation. In the case of steam generator in a 2 GW thermal power PWR, the decay of activated cooling water causes biological dose rates in order of several mSv/h in the air surrounding the steam generator while in a 2 GW thermal power fusion power plant the biological dose rates can be on the order of 100 Sv/h due to five orders of magnitude higher activity of activated water isotopes, especially higher activity of isotope 16N, indicating that using water as coolant in fusion reactors might not be the best choice from radiation point of view.

3. COOLING WATER SYSTEM DESIGN FOR FUSION TOKAMAK REACTOR

3.1 INTRODUCTION

Considering the water-cooling system in fusion reactors, there are several fusion-specific challenges in designs of in-vessel components and their cooling water systems (CWS). In this research, solutions of the challenges have been discussed and indicate the CWS concept of Japan's DEMO [10]. On the other hand, water cooling systems have the efficient heat removal capability and this means that fast coolant speed is not necessary, and pressure loss and required pump power are much less than that of helium cooling systems. Additionally, water cooling systems have been used widely for a long time in fission reactors such as pressurized water reactors (PWR) [11,12].

In spite of the proven technology of the fission reactors, handling water in a fusion plant is still premature and there are several fusion-specific challenges. Water cooled in-vessel components should be designed to satisfy the fusion specific required functions such as tritium breeding in addition to heat removal performances. In such components, pipe arrangement will be complex, and the pressure loss in the

components will be high. Thus, allowable pressure loss of pipes from the in-vessel components to pumps are decreased than that of existing fission reactors, and this makes the design of cooling water systems more challengeable. Additionally, the fusion output fluctuation should be considered. The fusion output is sensitive to temporal changes in the plasma parameters such as density or temperature and it is more difficult than existing fission reactors to keep the thermal output from the core constant. Thus, the effect to a turbine system should be evaluated. the main components of Japan's DEMO for the Water cooled in-vessel components, Breeding blanket, Divertor, Back plate and vacuum vessel as shown in Fig. 12 and Table 6 [10].
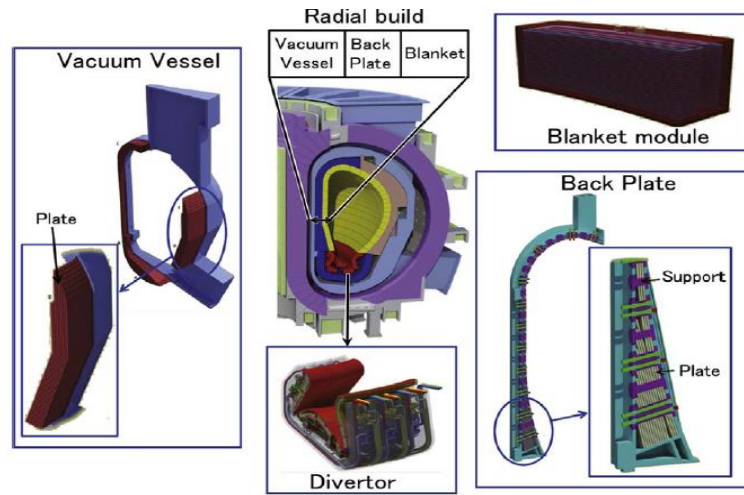

FIG. 12. In-vessel components image of Japan's DEMO [10].

*Table 6. Cooling water conditions and thermal energy of each in-vessel component [10]*

Component	Temperature	Pressure	Thermal energy
Blanket	290–325 °C	15.5 MPa	1574 MW
Divertor (RAFM)	290–325 °C	15.5 MPa	291 MW
Divertor (Cu-alloy)	200–230 °C	5 MPa	172 MW
Back plate	200–210 °C	3 MPa	16 MW
Vacuum vessel	100–105 °C	1.1 MPa	0.043 MW

4. WATER RADIOLYSIS IN FUSION NEUTRON ENVIRONMENTS FOR ITER

Activated cooling water in nuclear facilities can represent a significant radiation source

around primary cooling systems causing radiation damage to electrical components, increasing doses to personnel and, in the case of fusion facilities an additional heating to superconducting coils [13].
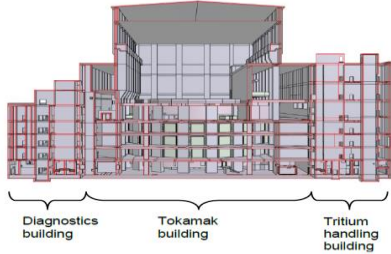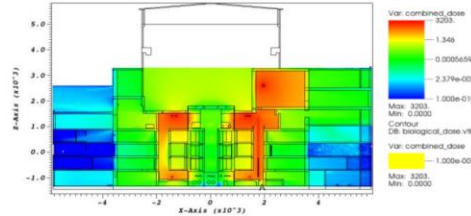
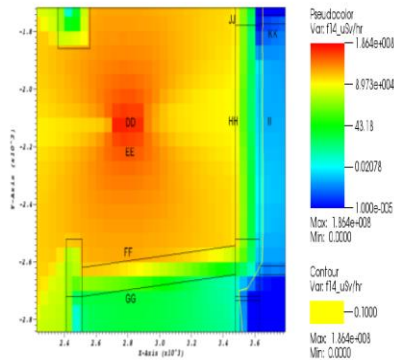(a)Illustration of the three buildings constituting the ITER complex.
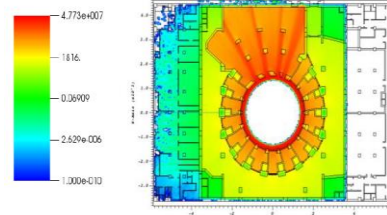
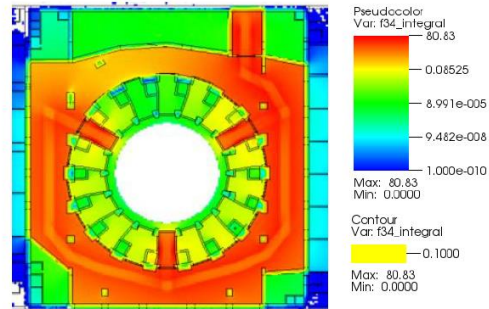(b)Biological dose rate μSv/hr, neutrons during plasma operation – example results, level L2.
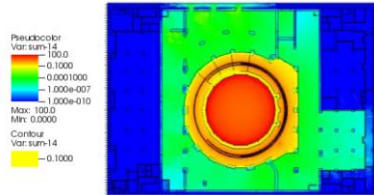
(c)Biological dose rate Activated pipe chases and cryostat μSv/hr, at 106s after shutdown – example results.

(d)Total photon dose rate (Sv/h), during plasma operation.

(e)Total photon dose rate (μSv/h).

(f)Integral dose to silicon from 54 cask transfers (from three port cell locations), in units of Gy.

FIG. 18. MCNP Calculation results for detailed radiation maps of the ITER complex have been produced during plasma operation and after shutdown to the required dose rate cut-off criteria [13].

On-load dose rates from neutrons were shown to be below 1 Sv/h inside the port cells, whilst on load photon dose rates near the upper cooling pipes reached 3.2 kSv/h. Off-load photon dose rates from activated pipe chases, 106 s after shutdown, were of the order of a few Sv/h near the cooling pipes.

CONCLUSIONS

Optimization of Water Coolant Chemistry to Ensure Reliable Water Reactor Fuel Performance at High Burnup and in Ageing Plant, it was necessary to control the

chemical water by added suitable chemical elements, to avoid corrosion problems and also to properly adjust the normal operation and shutdown the nuclear power plant, and this has already been implemented for decades and it is a proven technology (PWR، VVER, BWR, CANDU, etc.), But in the case of fusion reactors, Still under research ، for example Japan's DEMO, it is clear in this research that Japan's DEMO   use of water as a coolant is used in the same range of temperatures and pressures used In (PWR).

There is another problem, radiolytically decomposition of water, that arises when using water as a coolant in nuclear reactors fission and fusion reviewed these studies in PWR and ITER by using MCNP code, Neutron Activation of Coolant Water, this problem can be solved by protecting against radiation (neutron. Gamma) by surround the pipes and various components of the nuclear plant with appropriate shielding materials [14,15,16].

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