Design Criteria of Primary Coolant Chemistry in SMART-P

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1. Introduction

SMART-P differs significantly from commercially designed PWRs. Materials inventories used in SMART-P differ from that at PWRs. All surfaces of the primary circuit with the primary coolant are either made from or plated with stainless steel. The material of steam generator (SG) is also different from that of the standard material of the commercially operating PWRs: titanium alloy for the steam generator tubes. Also, SMART-P primary coolant technology differs from that in PWRs: ammonia is used as a pH raising agent and hydrogen formed due to radiolytic processes is kept in specific range by ammonia dosing. Nevertheless, main objectives of the SMART-P primary coolant are the same as at PWRs: to assure primary system pressure boundary integrity, fuel cladding integrity and to minimize out-of-core radiation buildup. The objective of this work is to introduce the design criteria for the primary water chemistry for SMART-P from the viewpoint of the system characteristics and the chemical design concept.

2. SMART-P Primary Coolant Regime

The coolant chemistry in SMART-P differs from that in commercial PWRs in that ammonia is used instead of boric acid and lithium hydroxide. SMART-P has also different coolant chemistry with that of VVER Russian nuclear power plants because VVER reactors are characterized by the presence of boric acid. Boron concentration varies widely depending on reactor power and fuel burn-up. However, VVER reactors strong KOH alkali instead of LiOH is introduced to compensate for the acid properties of H_3BO_3. To suppress water radiolysis and oxygen formation, hydrogen excess is maintained by addition of ammonia and its radiochemical decay.[1] In SMART-P, the hydrogen concentration is maintained by ammonia dosing into the primary coolant where hydrogen and nitrogen is generated by its subsequent radiolytical and thermal decomposition. Water quality standard for the SMART-P primary coolant is specified in **Table 1**. During a normal operation, the concentration of dissolved hydrogen and dissolved nitrogen is in the range of 20-60 cm^3 H$_2$/kg and 1000-1500 cm^3 N$_2$/kg, respectively. Ammonia concentration varies typically between 10 to 100 ppm. Such a level of dissolved hydrogen guarantees the oxygen concentration in the PWR units below 5-10 ppb.[2]

Hydrogen gas in SMART-P is not added to the primary coolant, but is normally generated from the radiolysis of the ammonia as the coolant passes through the core. Ammonia is added once per shift because the SMART-P reactor has no letdown and charging system during power operation. Because of these competing processes, the concentrations of hydrogen, nitrogen and ammonia in the primary coolant are steady state concentrations, which depend on the decomposition /combination rate of ammonia. The given level of permissible oxygen concentration in the primary coolant is ensured by both a suppression of water radiolysis through maintaining a high enough hydrogen concentration in the primary coolant and by a restriction of the oxygen ingress into the primary coolant with the makeup water. Fortunately, there is no possibility to ingress the dissolved oxygen by a makeup operation during power operation because SMART is designed as a leak-tight reactor. Thus, this design feature prevents the corrosion of the structural materials contacting with the primary coolant during power operation.

One of major benefits of boron-free primary water chemistry is the avoidance of Axial Offset Anomaly (AOA). AOA is a flux depression caused by boron accumulation in fuel clad. The Axial Offset Anomaly (AOA) results from a flux depression in the top half of the core such that power is skewed to the bottom. The flux depression is caused by the concentration of

Table 1. Standard of Primary Coolant for SMART-P

Chemistry Parameters	Limits
pH(@ 25)	9.5 ~10.6
Ammonia, ppm	10 - 100
Dissolved Hydrogen, cm^3/kg H$_2$O	20~60
Dissolved Nitrogen, cm^3/kg H$_2$O	<2000
Dissolved Oxygen, ppm	<0.1
Chloride(Cl$^-$), ppm	<0.15
Fluoride(F$^-$), ppm	<0.15
Sulphate(SO$_4^{2-}$), ppm	<0.15

soluble boron in porous crud deposits as a result of subcooled boiling. It is believed that boron concentrates to the extent that a boron compound, most likely $LiBO_2$, precipitates within the crud deposit. It is the precipitates boron-rich solid that is responsible for the flux depression observed. There are three conditions that must be present for AOA to occur: soluble boron, a layer of porous crud sufficient thickness to serve as a medium for concentration of the soluble boron, and sufficient heat flux to cause subcooled boiling at the surface. In PWRs with high coolant temperature, these conditions exist for a large fraction of the feed fuel, and it is these high power fuel assemblies that drive AOA.[3]

Another benefit of boron-free primary water chemistry is avoidance of boric acid induced corrosion of pressure vessels, bolting and other critical components as a result of primary system leaks.

The SG tube material of SMART-P is also different from the standard material of the commercially operating PWRs. In SMART-P, the titanium alloy is applied to the SG tube material which is known as a weight gain material while inconel-600 or inconel-690 used in commercial PWRs as weight loss materials. A significant improvement in corrosion resistance of the structural material was obtained by the adoption of the above material for SMART-P as shown in Figure 1. This result implies that a layer of protective titanium oxide formed on the surface of the sample during corrosion would increase to disturb the diffusion of the oxygen ion through the oxide layer, giving a decrease of corrosion rate as the corrosion reaction proceeded.[4,5] From this result, it is considered that the corrosion resistance of the titanium alloy (Ti-Al-Zr) is very higher than that of Inconel-600 in the ammonia solution. This result implies that a layer of protective titanium oxide formed on the surface of the sample during corrosion

would increase to disturb the diffusion of the oxygen ion through the oxide layer, giving a decrease of corrosion rate as the corrosion reaction proceeded. This is very helpful in reducing the coolant specific activity as well as in as low as reasonably achievable (ALARA).

3. Conclusion

The most essential differences in the water chemistry between the commercially operating PWRs and SMART-P are characterized by the presence of boron in water and the operating mode of the purification system. SMART-P is soluble boron free reactor, and the ammonia is used as a pH reagent. The titanium alloy for the steam generator tube material for SMART-P is high corrosion resistance. The batchwise purification of the primary coolant is determined by the selection of the materials with a high corrosion resistance under the chosen water chemistry conditions.

The ammonia water chemistry for the SMART-P is chosen for primary circuit of NSSS. This water chemistry ensures the reduction of the corrosion products with respect to the structural materials, offers simplification of plant operation and maintenance, also gives the reduction of the radioactive wastes volume to be processed. Corrosion damage of the fuel cladding can be avoided and coolant radiolysis suppressed. Design concept of the ammonia water chemistry does not allow for primary coolant purification during power operation because the primary circuit system is made of materials with a high corrosion resistance under the chosen water chemistry conditions.

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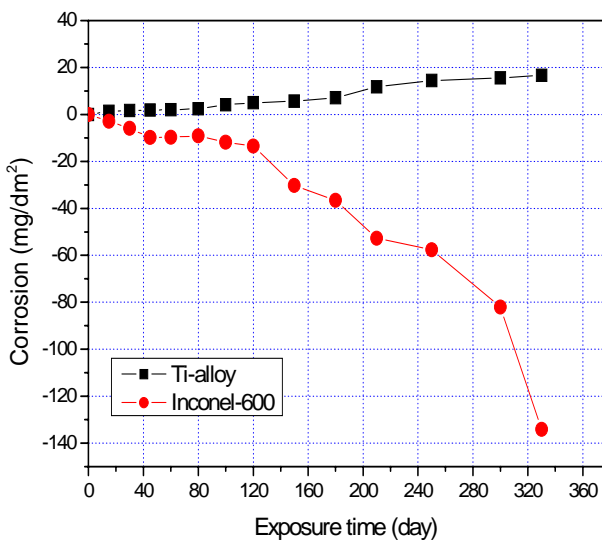
Figure 1. Corrosion behavior of steam generator tube materials at 360   in a pH-10 ammonia aqueous solution : Ti-alloy and Inconel-600.