# AP1000 Core Design Development for Higher Burn-up and Long Operational Cycle Length

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**Abstract**. High fuel burn-up and long cycle length are the main objectives for economic and reliable operation of Advanced Nuclear Power Reactors. The selected cladding material to stand for high burn-up and long cycle length is HANA-4 alloy. AP1000 core was developed through increasing the fuel enrichment to higher values than the initial values and replacing the ZIRLO cladding by HANA-4 cladding to achieve higher burn-up and longer cycle length. The initial core and the developed core were simulated using Monte Carlo N-Particle Transport Code MCNPX. The criticality control parameter, core cycle length and spent fuel radionuclides inventory were calculated. The results showed that the developed reactor core can reach a cycle length up to 22 months at fuel discharge burn-up 75GWD/MTU safely using HANA-4 cladding compared to the initial design core which can reach to 18 months cycle length at fuel discharge burn-up of 60 GWD/MTU.

## 1. Introduction

Advanced Light Water Reactors has a gradual progression toward higher fuel discharge burn-ups and long operational cycle length. Based on that, the cost of the fuel cycle decreases, and the operational flexibility will increase by allowing the optimization of the fuel management scheme. Also, the volume of the fuel discharged will be reduced, which can eliminate the need for additional capacity for the spent fuel storage. Average discharge fuel burn-up are currently around of 50 GWD/MTU and for the high discharge burn-up are in the range of (60-100) GWD/MTU. For increasing burn-up beyond 60 GWD/MTU, there are technological limitations, operational limitation and safety optimization on the materials of the nuclear fuel and cladding. The Light Water Reactor (LWR) fuel vendors have developed advanced Zircaloy cladding materials (e.g. M5, E110, PCA-2b, ZIRLO and HANA) to withstand the creep, oxidation and corrosion to significantly higher local burn-up [1-3].

HANA (High performance Alloy for Nuclear Application) cladding material was developed by Korean Atomic Energy Research Institute (KAERI), in collaboration with Korean Nuclear Fuel Company (KNFC) to sustain high discharge burn-up to more than 70GWd/MTU. HANA developed six kinds of advanced Zr-alloy based, that were evaluated by the out-of-pile and in-pile properties to test the corrosion, creep, oxidation in Halden research reactor in Norway. HANA claddings showed better behavior for corrosion and oxidation than Zircaloy-4 as shown in Figure 1. Also, Thermal creep test was performed to evaluate the out-of-pile creep properties. The diametral creep strain of HANA claddings which were heat treated at 510°C and for 300 days showed a steady state secondary creep behavior after 75 days and a lower rate than Zr-4 as shown in Figure 2. The creep resistance of HANA-4 was improved by about 70% as compared to Zircaloy-4, as shown in Figure 3. According to a study by Kumar about creep locus of HANA-4 and ZIRLO; it was found that HANA-4 creep locus and Zircaloy-4 and ZIRLO in similar microstructural state revealed less anisotropy of creep deformation in HANA-4 alloy as shown in Figure 4. Therefore, HANA-4 cladding is regarded as a promising fuel cladding for high nuclear fuel performance [5-7].

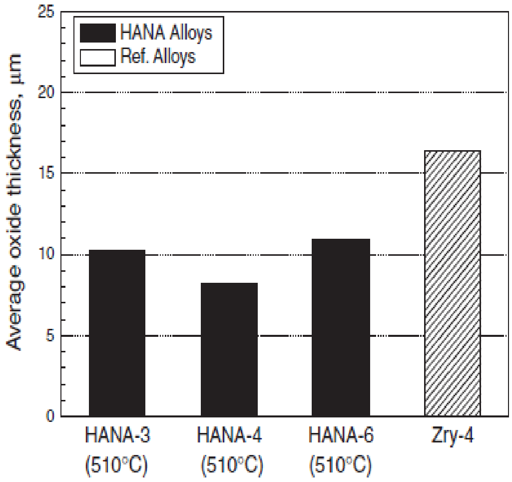


**Figure 1.** In-pile corrosion of HANA claddings [5]

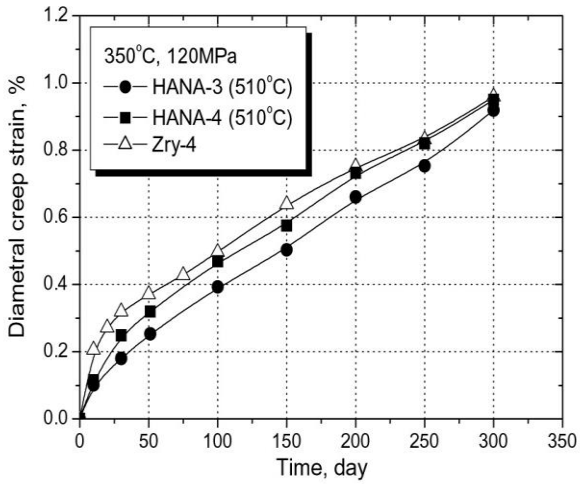


**Figure 2.** Thermal Creep of HANA Claddings [5]

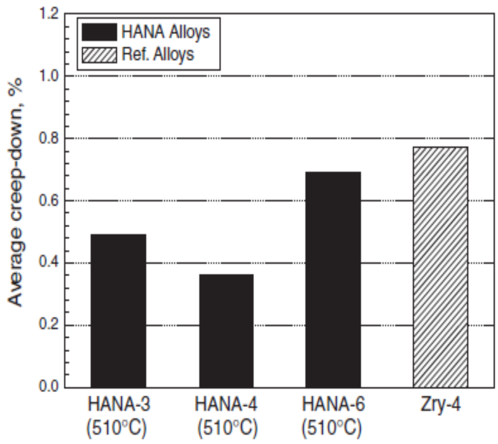


**Figure 3.** In-pile creep-down of HANA claddings [5]

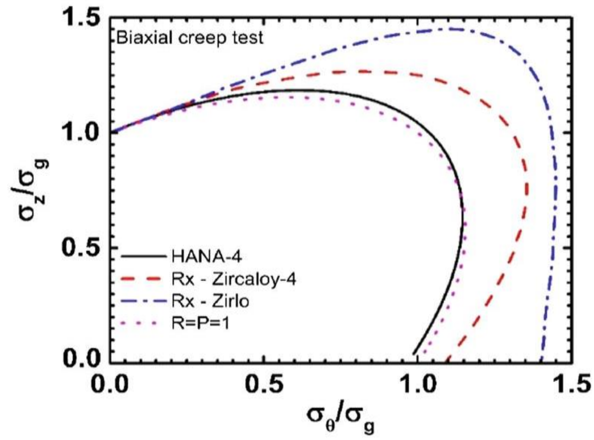


**Figure 4.** Creep loci of HANA-4 with recrystallized Zircaloy-4 and ZIRLO [7]

AP1000 is a Generation III+ Advanced Pressurized Water Reactor, with nominal thermal power of 3400 $MW_{th}$. Its core contains 157 fuel assembly, each one contains a matrix of 264 fuel rods, 24 guide tubes for control rod clusters, and one centrally located guide tube for in-core instrumentation, and all are arranged in a 17 x 17 square lattice array.

The reactor initial core has three different enrichment regions to tune the flux and the power profile over the radial core geometry. The beginning of initial cycle (BOC) consists of 2.35, 3.4 and 4.45% enrichments of Uranium dioxide ($UO_2$) fuel which are cylindrical pellets placed in ZIRLO™ cladding tubes.

To achieve higher burn-up value than the initial design value (60GWd/MTU) through longer length, the fuel enrichment was increased, and burnable absorbers (BAs) were used to decrease the initial excess reactivity and to flatten the radial power distribution at the beginning of cycle (BOC).

The types of the BAs used are the Discrete Burnable Absorber Rods (PYREX) and the Integral Fuel Burnable Absorber rods (IFBA) [8].

## 2. Mathematical Modelling for AP1000 Core Development

AP1000 core was modeled and simulated using Monte Carlo Code (MCNPX) to validate the initial core design with the aim of applying core development to increase the discharge fuel burn-up with extending the cycle length by using new fuel enrichment patterns and new cladding “HANA-4” to endure the long irradiation exposure of fuel [9-10]. In the core modeling of AP 1000, we assumed a clean core, which means that all the control rods are completely withdrawn.

### *2.1. Core Development for Higher Burn-up*

The main purpose of core development of AP1000 reactor is to increase the fuel burn-up with extending the cycle length to higher values than the initial reference design values. The fuel integrity should be maintained without exceeding the operational limits and safety conditions by using HANA-4 as a cladding material. The developed core configuration contains $UO_2$ fuel with higher enrichment with three different batches (3.5, 4.5 and 4.95) %. HANA-4 cladding was used for the fuel rods to withstand the radiation doses and protect the fuel from any metallurgical damage resulting from the higher burn-up values.

Also, the developed core contains of 1558 PYREX rods and 8832 IFBA rods which serve as BAs. These burnable absorbers are necessary for reactivity balance through reducing the value of the effective multiplication factor at the BOC then its effect decreases at the EOC to reach the reactor operation up to 21 months.

## 3. Results and Analysis

The results showed that, for the developed $UO_2$ core using HANA-4 cladding, the effective multiplication factor $K_{eff}$ was reached to a value of about 1.27 at BOC and then reduced to a value of about 1.094 using BAs with burn-up value of 25.3GWD/MTU for 641 Effective Full Power Days (EFPD), as shown in Figures [5-6]. So, at the time of fuel discharge from the reactor core, i.e. (after 3cycles), the burn-up can reach to a value of 76 GWd/MTU safely which is higher burn-up compared to the burn-up value of 60 GWD/MTU for the initial core design of AP1000.

This increase in the fuel burn-up and the extension of operational time cannot be achieved safely without the use of HANA-4 instead of ZIRLO, because the mechanical properties for HANA-4 are better than ZIRLO at high burn-up and long irradiation time based on the experimental performance tests. So, AP1000 developed core achieved the purpose of extending the cycle length, higher burn-up, the economic consideration of assembly discharge and non- proliferation strategy.

The inventories of the major actinides in the burned fuel were calculated. We can notice that the consumed fuel radionuclides, U-235 and U-238 were reduced by increasing the burn-up and the buildup of Pu-239, Pu-240 and Np-237, as shown in Figure 7. The knoweldge of the amount of radionuclides in the inventory is an essential requirement for nuclear fuel safeguard, long term spent fuel storage, fuel handeling and reporcessing, and for manufacture of MOX fuel by mixing the remaining U-235 with the produced amount of Pu-239.

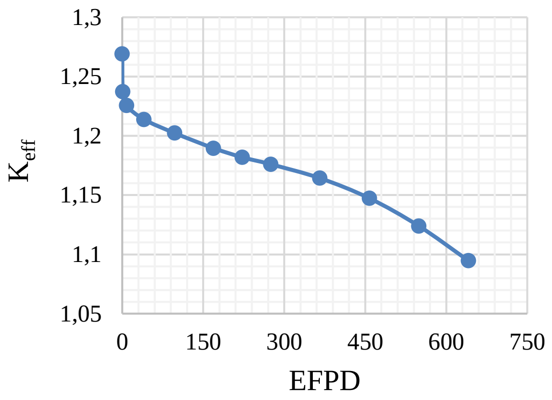


**Figure 5.** $K_{eff}$ vs Effective Full Power Days (EFPD) for the developed core

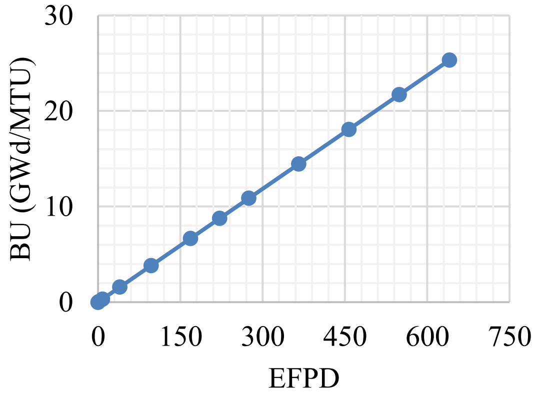


**Figure 6.** BU vs Effective Full Power Days (EFPD) for the developed core

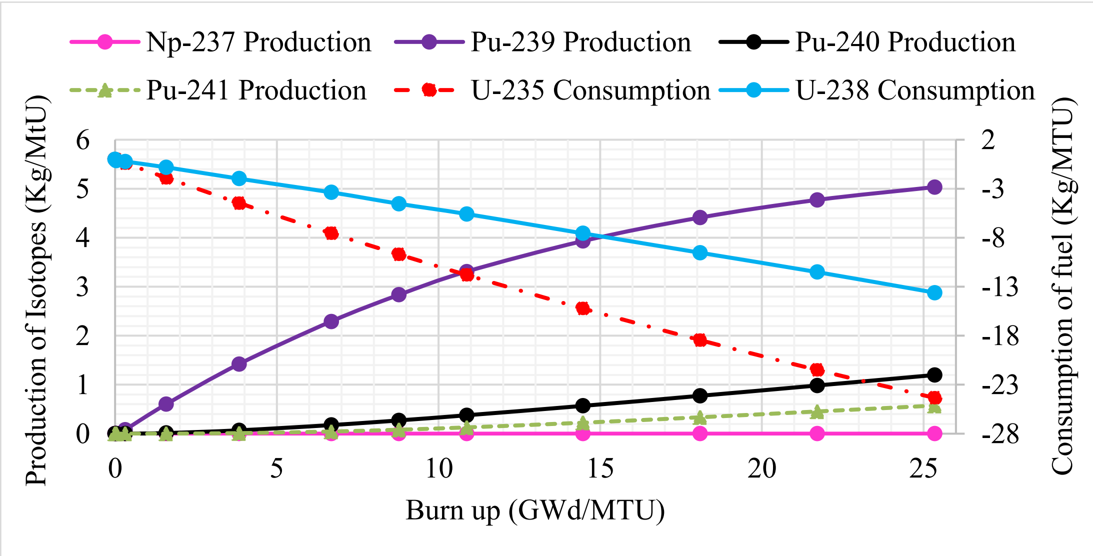


**Figure 7.** Inventory of major actinides for $UO_2$ for the developed core (One Cycle)

## 4. Conclusions

AP1000 core was developed through the replacement of the initial fuel enrichment to higher values and replacing ZIRLO cladding by HANA-4 cladding, with the purpose of achieving higher burn-up and longer cycle length. The effective multiplication factor for the developed core, $K_{eff}$ was about 1.27 at BOC, then reduced to 1.094 at EOC using burnable absorbers. The burn-up reached to 25.3GWd/MTU for 641 EFPD and the discharge burn-up can reach to 76GWd/MTU safely using HANA-4 cladding which is higher burn-up compared to the initial burn-up value of 60GWD/MTU at cycle length of 18 months for the initial core of AP1000. The inventory of fuel consumption and the major actinides build up were calculated, for its importance as a requirement for long term spent fuel storage, reprocessing and waste management. The increase of Pu-239 production with the increased burn-up can be mixed with the remaining U-235 to manufacture the mixed oxide fuel MOX.

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