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Development of Advanced CANDU Fuel Bundles in Korea

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The current design of a standard CANDU fuel bundle is composed of 37 elements concentrically; 1 rod in a center ring, 6 rods in an inner ring, 12 rods in a middle ring, and 18 rods in an outer ring. These 37 elements are welded at both ends of each rod with the endplates to configure a circular type. A standard 37-element fuel bundle (37S fuel) has a parabolic power profile that makes the elements in the outer ring to have the highest Linear Element Rate (LER) or be the hottest. Hence, the safety margin for a fuel centerline temperature or fission gas release (FGR) can be determined based on the thermal characteristics of the outer elements (See Figures 1 and 2). On the contrary, the most probable initial CHF occurrences of a 37S fuel occur at the peripheral flow region of the center element under reactor operating conditions for even the crept pressure tubes due to aging. 37S fuel has bearing-pads located at three axial locations to avoid direct contact between the fuel bundles and a pressure tube, and a spacer plane at the axial center location of the fuel bundle to prevent direct contact among the adjacent elements. These appendages can play role in redirecting the flow of the coolant in the fuel channel, and can also affect the CHF as well as the pressure drop. During the 1980s, many studies have been performed to increase the CHF of a CANDU fuel bundle by introducing the additional bearing-pad planes, spacer planes, wire-wraps instead of the spacers, or turbulence promoters. The impacts of various types of CHF-enhancing bundle appendages on the dryout power and pressure drop in a 37S fuel were investigated experimentally, including the additional spacer and bearing-pad planes, short vortex generators or a square flow obstructing vanes in the larger square subchannels, grid spacers, and buttons of the type [1, 2, 3, 4]. All of the results showed that the CCP (Critical Channel Power), which can be determined by the CHF curve and hydraulic characteristics curve, could not be enhanced finally owing to the combining effects of the hydraulic and thermal characteristics, even if the CHF of the fuel bundle equipped with various CHF enhancing devices could be increased [5].

During the last few decades, advanced CANDU fuel bundles have been developed to enhance the operating performance and safety in Korea. One of the advanced CANDU fuels, a CANFLEX-NU fuel bundle, was developed to overcome the power de-rating in cooperation with KAERI (Korea Atomic Energy Research Institute)/AECL (Atomic Energy of Canada Limited) for over 10 years since 1991. A power de-rating of a

CANDU reactor was mainly caused by aging of the pressure tube or its diameter expansion due to the creep. When the diameter of the pressure tube is increasing, the coolant tends to flow into the low flow resistance region such as into a top section of the fuel bundle because the fuel bundles sit in the horizontal pressure tube. It should be noted that the CHF of a fuel bundle can deteriorate and finally worsen the thermal-hydraulic performance of a CANDU reactor. CANFLEX fuel is well designed to enhance the CHF of a fuel bundle as well as to minimize the worsening impact on the hydraulic characteristics of a fuel bundle [6]. Finally, it should increase the CCP of a CANDU reactor (See Figure 3).

Before developing the CANFLEX fuel, Korea localized the design and fabrication of a 37S fuel in the 1980's, and KAERI obtained a loading licensing approval for the design of the Korean 37S fuel from KINS (Korea Institute of Nuclear Safety) at 1987. After KAERI finished the localization of the Korean fabricated 37S fuel at 1987, 50 tons of fuel bundles, which were fabricated at the CANDU fuel fabrication plant at KAERI, were supplied to W-1 (Wolsong Unit #1) until the restructuring of the KAERI organization by the Ministry of Science and Technology (MOST) in Korea. In 1995, KAERI restructured and separated the business activities from the R&D group; the assignment of the NSSS design scopes of a nuclear power plant to the former KOPEC, of the fuel fabrication technology and plant to the former KNFC, and of an environment analysis group to the former NEWTEC.

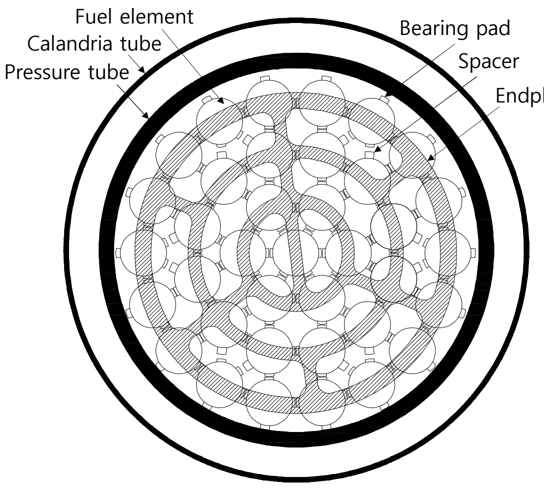


Figure 1. Configuration of 37S Fuel

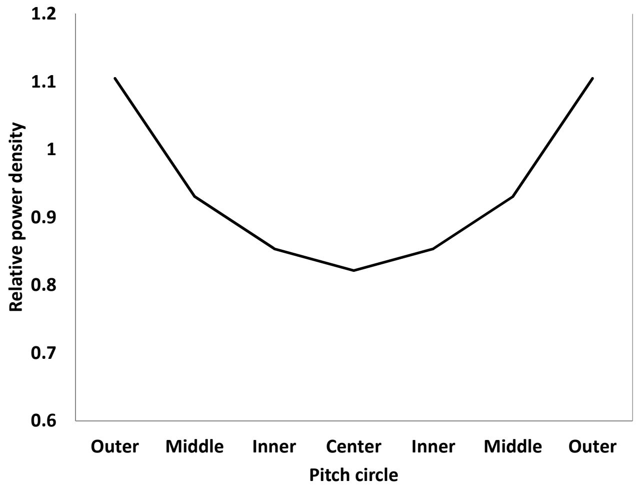


Figure 2. Ring Power Profile of 37S Fuel

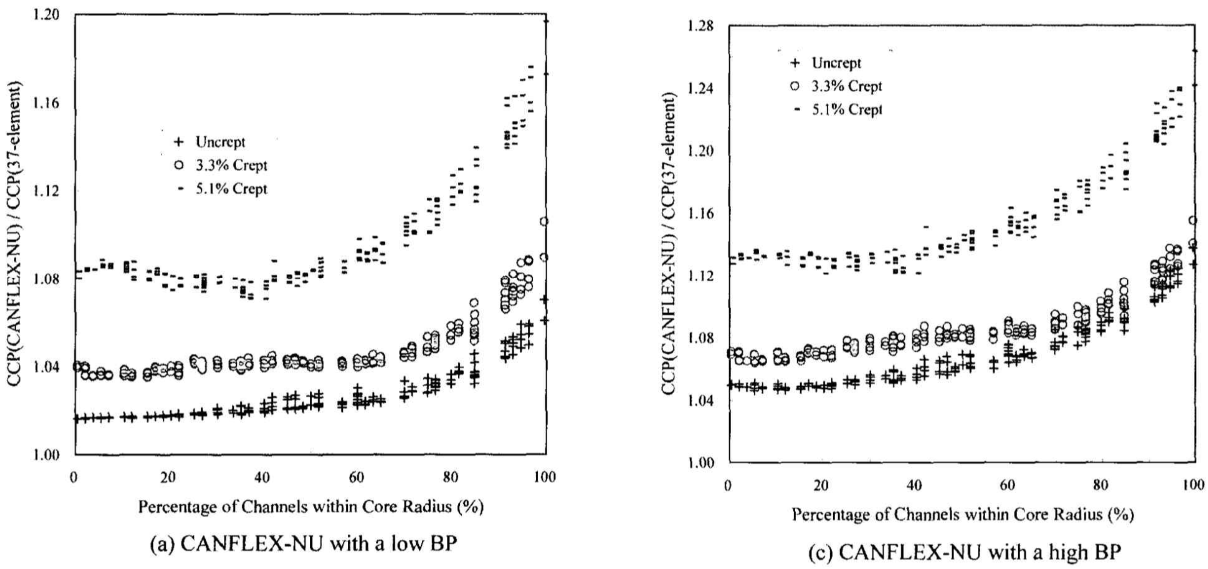


Figure 3 CCP Enhancement of CANFLEX-NU Fuel Bundle [6]

On the other hand, several types of CANDU fuel bundles, such as 39 elements, 43 elements, 51 elements and 61 elements, were studied to increase the fuel burnup as well as the fuel safety after finishing the localization of a 37 element fuel design and fabrication. To consider a higher burnup and higher safety of a fuel bundle than previous versions, it was believed that the power density of a fuel element should be lowered. In 1990, KAERI's senior vice-president, Mr. C. S. Rhim visited AECL, and recognized that AECL had also considered an advanced fuel bundle, a 43-element dual sized fuel bundle. This was the best opportunity for the two different organizations to cooperate internationally and develop together the advanced CANDU fuel bundle. On February 21 1991, KAERI/AECL finally signed an agreement to develop the CANFLEX fuel bundle together under a program called the JCDP (Joint Development of CANFLEX Program) for international cooperation between KAERI/AECL. The actual program of the JCDP was proceeded under cooperation in all areas that should be considered to develop an advanced fuel bundle. At that time, for instance, KAERI had kept a Hot Test Loop in which the hydraulic endurance test could be performed under the same conditions as the CANDU-6 operating temperatures and pressures. KAERI has performed hydraulic tests such as pressure drop and endurance tests needed for designing CANFLEX fuel, while AECL has performed CHF tests such as a 3-rod test to optimize the size and shape of an additional appendage, which is called a button, to enhance the CHF and a full bundle CHF test in the MR3a Freon loop. At the beginning stage of the

CANFLEX fuel development, utilizing a slightly enriched uranium fuel for a higher burnup as well as CHF enhancement was initially pursued. In the early 1990s, PLGS (Point Lepreau Generating Station) was anxious about the power de-rating owing to the pressure tube creep. Thus, the main purpose of the CANFLEX program was altered to develop the CANFLEX-NU fuel to overcome the power de-rating of the old CANDU plants. The CANFLEX-NU fuel development program was continued until late 1990s. The development program of the CANFLEX fuel was finished in 2002 after ending the DI (Demonstration Irradiation) of the CANFLEX fuel in W-1 in Korea, and its DI previously in PLGS in 1998. Even though CANFLEX-NU fuel was attempted to be commercialized power reactors at several times, such as PLGS, W-1, or G-2 (Gentillty-2), such attempts have failed owing to the economics and other factors.

At the same time as the CANFLEX fuel development period, a DUPIC (Direct Use of Spent PWR Fuel in CANDU) program was launched under an international cooperation program among KAERI/AECL/LANL with participation of the IAEA. In order to develop a fuel cycle technology that can utilize the spent fuels in an economic way with enhanced proliferation resistance, the concept of the DUPIC fuel cycle has been proposed to reuse the spent PWR (pressurized water reactor) fuels as new fuels for CANDU reactors without the reprocessing operations typical of recycling fuel cycles (See Figure 4). Since 1991, KAERI, AECL and the United States (Department of State and Los Alamos National Laboratory), with the participation of the IAEA, have been engaged in a practical exercise to develop a spent fuel recycle process to extend resources and reduce waste, while enhancing the proliferation resistance over typical recycle options. The residual content of fissile materials in spent PWR fuel is about 1.5wt% of U-235 and Pu-239 combined, for a discharge burnup of 35,000MWd/MTU [7]. Since the CANDU reactor was designed to use natural uranium oxide fuel with 0.7% U-235, it has an excellent neutron economy that allows it to use spent PWR fuel directly without a reprocessing stage, even though it contains fission products and transuranic elements. DUPIC fuel burnup was expected to be about 15,000MWd/MTHE, which was about twice that of natural uranium fuel at 7,000MWd/MTU. The main characteristics of the DUPIC fuel cycle technology are the enhancement of the proliferation resistance for the reuse of spent nuclear fuel without removing all of the fission products, the simplicity of the fuel treatment process, and a great reduction of the radioactive process waste owing to inherent features of the direct dry process. The implementation of the DUPIC fuel cycle will provide multiple benefits, such as (i) eliminating accumulated PWR spent fuels by burning them in CANDU reactors, (ii) reducing CANDU spent fuel arising from the higher burnup of the DUPIC fuel, and (iii) saving natural uranium resources required to produce a CANDU fuel. However, this program was finished in 2011 before developing a remote fabrication technology to assemble the elements for a bundle. Since then, most technologies of remote controls for a DUPIC program were transferred to the Pyro-processing for SFR fuel fabrication.

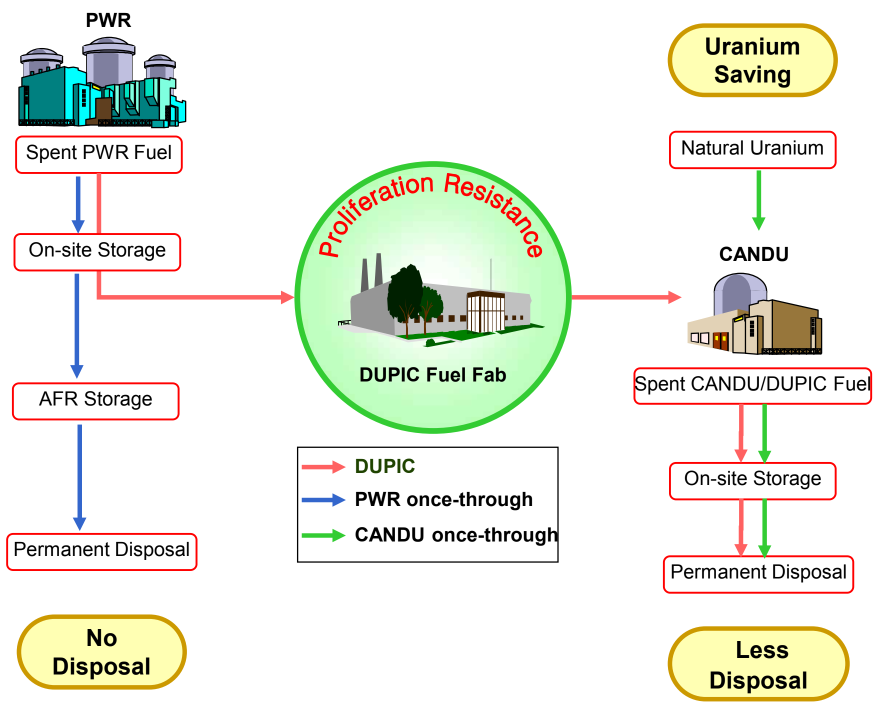


Figure 4. Concept of DUPIC Fuel Cycle

After the CANFLEX-NU was developed and finished the DI in W-1 in 2002, no more programs of the advanced CANDU fuel except for the DUPIC program existed in Korea before the refurbishing of W-1 began. Meanwhile, in Canada, after finishing the CANFLEX-NU program, AECL developed and performed a DI of the CANFLEX-LVRF, which was characterized as dysprosium mixing in a central element among 37 elements with 1.0% enriched uranium to enhance the safety margin of the Bruce reactors. However, it was not commercialized in the Bruce reactors, but alternatively, an enhancement of the safety system was applied to the Bruce reactors.

During the last W-1 refurbishment, a generic safety feature of a CANDU reactor was issued, i.e., a positive power coefficient reactivity (PCR) of a CANDU reactor. The PCR of a CANDU reactor was found to have a positive value, which came from a positive fuel temperature coefficient reactivity (FTCR) after the physics code system for a CANDU reactor was updated with the WIMS-IST code system instead of the PPV code system. It was debated for quite a long time until the license for the continuing operation of W-1 was approved whether a W-1 is generically safe even under severe accident conditions. In parallel with preparing the position report for the argument of concern regarding a positive PCR, an advanced CANDU fuel that can keep a negative FTCR was studied and proposed to make a negative FTCR or PCR. The excellent concept to make a negative FTCR of a CANDU fuel was proposed for utilization of a small amount of Erbium mixed with enriched uranium of the fuel elements of the CANFLEX geometry (See Figures 5 and 6). The results show that the PCR of a high safety fuel bundle can be certainly negative with a small burnup loss owing to a poison material of less than 20%. The results can be found in reference [8]

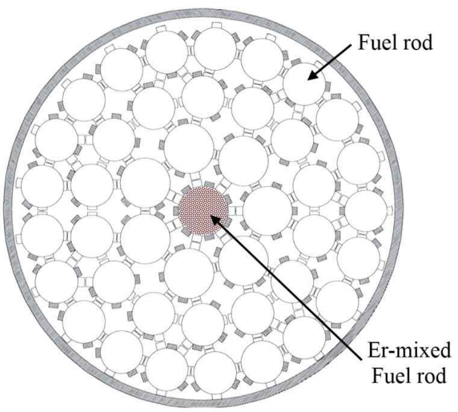


Figure 5. CANFLEX fuel with Erbium [8]

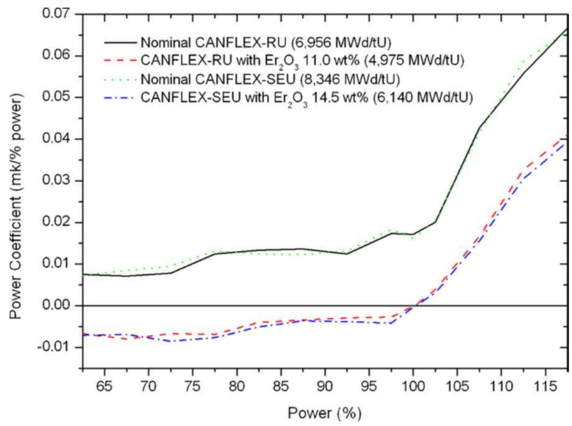


Figure 6. Comparison of Power Coefficients at the Mid-burnup for the CANFLEX Fuels [8]

Recently, KHNP (Korea Hydro and Nuclear Power) joined the 37M fuel development program under COG JP (CANDU Owner's Group Joint Project), which OPG (Ontario Power Generation) has led for the fuel development during the last decade in Canada [9]. Since 2015, KHNP has irradiated the 37M fuels into W-2 and submitted its results to the KINS to obtain licensing approval for its commercialization in order to overcome the power de-rating of Wolsong CANDU reactors owing to the pressure tube aging. It is being processed now.

While the 37M fuel has been proposed in Canada, a different modification of the 37S fuel has been studied at KAERI. The main idea here is an increase in the inner ring radius of 37S fuel instead of using a smaller center element to enlarge the center subchannel flow area (See Figures 7 and 8). This has been studied at KAERI to enhance the CHF [10]. From previous studies, the CHF can be enhanced by adjusting the fuel bundle geometry configuration such as a modification of the ring radius or bearing pad height [11]. Not only an inner ring radius modification but also the middle and outer ring radii modifications were studied for further improving the CHF characteristics of a 37S fuel. From such configuration changes of the cross section of a 37S fuel, quite remarkable results for CHF enhancement were recently obtained without any impacts on the fuel fabrication cost or safety (See Figure 9).

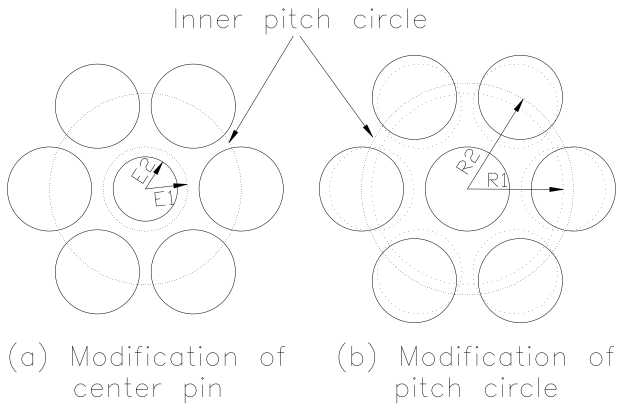


Figure 7. Schematic Views of Increasing the Flow Area of the Center Subchannels [11]

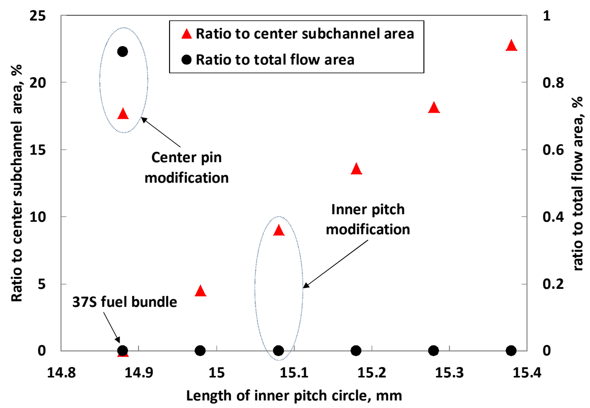


Figure 8. Variation of the Inner Subchannel Area According to Increasing Inner Pitch Circles [11]

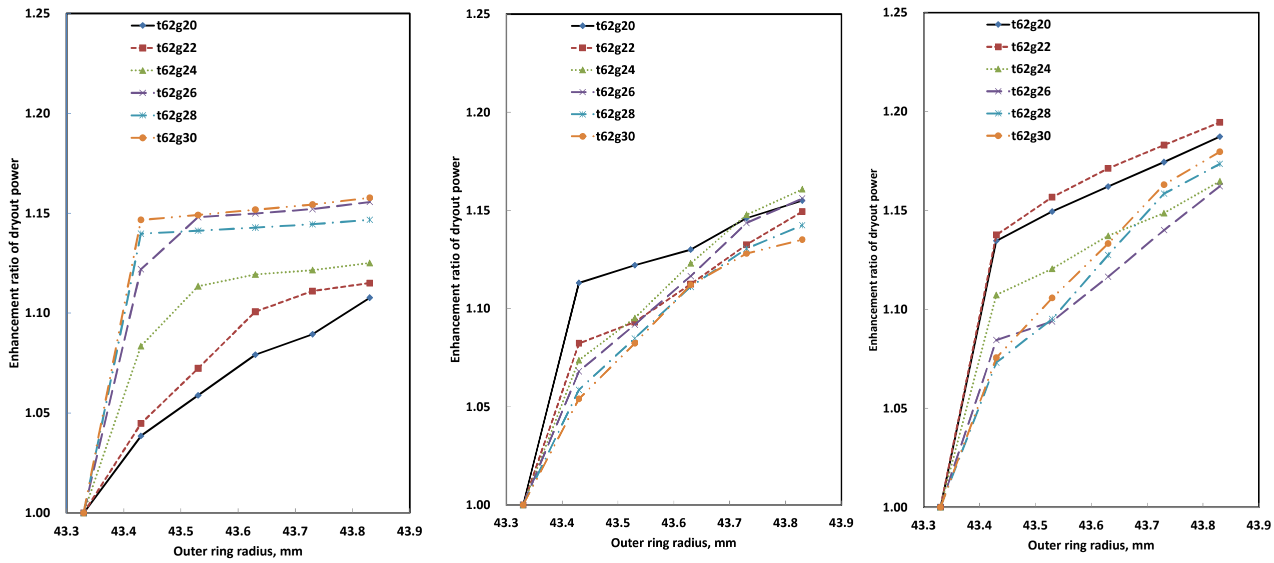
From these reviews of the advanced CANDU fuel developments and the current circumstances in Korea nuclear power plants, we should consider three aspects for the present and future demands in the Wolsong Units for a future advanced CANDU fuel development in Korea.

Initially, a CHF enhanced fuel bundle should be developed in terms of increasing economics, while the prime unit cost to generate electric power from the Wolsong CANDU units was definitely reversed after the refurbishment of W-1 against the PWR case.

Second, a safety enhanced CANDU fuel should be considered in order to make a PCR or FTCR be definitely negative for promoting the public acceptance of CANDU safety in Korea.

Third, Korea is suffering from the management of accumulated spent fuels, especially the amount of the CANDU spent fuels due to the site limitation of the dry storage facility at backyard of the Wolsong Units. High burnup CANDU fuel should be developed to achieve the life time extensions of the Wolsong Units, whose design life will end from 2026.

In conclusion, we believe that Korea should develop in the near future an advanced CANDU fuel that has a higher burnup, higher safety, and higher operating performance.



(a) 0% Crept PT (b) 3.3% Crept PT © 5.1% Crept PT

Figure 9. Dryout Power Enhancement for Ring Radius Modifications of a 37S Fuel

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References

1. McDonald, A.G. and Sutradhar, S.C., 1988. CANFLEX Bundle Thermalhydraulic Experiments: Part 4, Freon CHF Tests on the 37E-Hybrid Bundle, Equipped with Two Space Planes and Four Bearing pad Planes. HPBP-32/ARD-TD-124.
2. Sutradhar, S.C., and Groeneveld, D.C., 1989. CANFLEX Bundle Thermalhydraulic Experiments: Part 5, Overview of the effect of spacer and bearing-pad location on CHF in 37-eleements bundle. ARD-TD-189 (1989).
3. Groeneveld, D.C., Yousef, W.W., 1980. Spacing devices for nuclear fuel bundles: a survey of their effect on CHF, post-CHF heat transfer and pressure drop. In: Proceedings of the NURETH-1, NUREG/CP-0014, vol. 2, Saratoga Springs, NY, 5–8 October, pp. 1111–1130.
4. Leung, L.K.H., Salcudean, M.E., Snoek, C.W., Groeneveld, D.C., 1984. Effect of Stream-lining on Bundle Pressure Drop, Multi-phase Flow and Heat Transfer. III. Part A: Fundamentals, pp. 405–420.
5. D.C. Groeneveld, L.K.H. Leung and J.H. Park, 2015. Overview of methods to increase dryout power in CANDU fuel bundles. Nuclear Engineering and Design, 287, 131-138.
6. J.S. Jun, 2005. Thermalhydraulic Evaluations for a CANFLEX Bundle with Natural or Recycled Uranium Fuel in the Uncrept and Crept Channels of a CANDU-6 Reactor. Nuclear Engineering and Technology, Vol. 37, No. 35, 479-490.
7. H. Choi, B.W. Rhee and H. Park, 1997. Physics Study on Direct Use of Spent Pressurized Water Reactor Fuel in CANDU (DUPIC). Nucl. Sci. Eng., Vol. 126.
8. G. H. Rho, Y. H. Kim and N. Z. Cho, 2011. Improvement of Power Coefficient by Using Burnable Poison in the CANDU Reactor. Nuclear Engineering and Design, Vol. 2041, 1565-1578.
9. A. Tahir, Y. Parlatan, M. Kwee, W. Liauw, G. Hadaller, and R. Fortman, 2011. Modified 37-element bundle dryout, NURETH-14, Hilton Toronto Hotel, Toronto, Ontario, Canada.
10. J.H. Park and Y.M. Song, 2014. The effect of inner ring modification of standard 37-element fuel on CHF enhancement. Annals of Nuclear Energy 70, 135-140.
11. J.H. Park, J.Y. Jung and E.H. Ryu, 2015. CHF Enhancement of Advanced 37-element Fuel bundles. Science and Technology of Nuclear Installations, Vol. 2015, Article ID 243867.
12. Jun, J.S., Leung, L.K.H., 2005. Comparison of dryout power data between CANFLEX Mk-V and CANFLEX MK-IV bundle strings in uncrept and crept channels. Nucl. Eng. Technol. 37, 565–574.