CONCEPTUAL DESIGN OF A LIGHT WATER COOLED PHWR

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ABSTRACT

A design concept of a new reactor core is proposed as a deuterium moderated pressure-tube type light-water cooled reactor (DeMoPTL). Based on the proven technology, reactor coolant system and control system would be the same as those of CANDU except for changes in fuel, coolant and calandria tubes. Slightly enriched UO_2 fuel poisoned with IFBA and light water coolant would give the benefits of reduced spent fuel production, lower tritium buildup and negative temperature feedback. Safety would be enhanced by installing an additional tube outside the calandria tube to add structural reinforcement. Heavy water inside these would work as moderator and an air annulus outside would provide a large channel for emergency shutdown and cooling. Fuel discharge burnup was shown to be doubled with 2.4 w/o enriched uranium fuel and all temperature coefficient were negative. Reactor module calculations done by HELIOS showed a feasibility in nuclear design.

INTRODUCTION

Innovations in advanced reactor development have focussed mainly on the addition of plant safety features such as passive decay heat removal and passive containment cooling. Many vendors have proposed evolutionary versions of PWR, BWR and CANDU, modified from commercial models on the basis of proven technology. Even though some revolutionary advanced reactors were proposed, they were restricted to small power rating. Recently, Todreas and Driscoll proposed a large-scale passive light water pressure tube reactor (PLPTR) without any design prototype. In this paper, a new large-size PWR design is proposed based on three design prototypes; CANDU, PWR and PLPTR.

Current PWR design has a few critical limitations upon performance improvement. First of all, the reactor core is confined in a large pressure vessel that is the major barrier against radiation and coolant release. Therefore, the vessel should be thick enough to maintain its integrity at high service pressures for more than 40 years. The reactor core also should be sealed tightly during an operational cycle. These features become drawbacks for large, low power density cores and when a longer cycle length strategy is used to enhance plant economics. The refueling outage sets an upper limit on the capacity factor of PWR. Secondly, a PWR core is smaller in size than the other reactors. While this is a favorable point for plant scale-up, there is not enough space in the core to accommodate additional control rods, burnable poisons, and nuclear instruments. Therefore it is not easy to achieve generic requirements for advanced reactors such as load-following operation, automatic control and on-power core monitoring.

On the other hand, CANDU has some favorable design features that avoid the above-mentioned problems. Separate pressure tubes that contain coolant and fuel bundles give large space between them for reactivity control and core monitoring devices. Because tubes are isolated, on-power fuel reloading can be done as well as on-line maintenance. However, natural uranium fuel loading produces larger amounts of spent fuel and requires a heavy duty cycle for the refuelling operation. Maintenance of heavy water inventories in a large calandria tank and steam generator also causes design limitations for the large-scale advanced reactors in some aspects – such as purity control, tritium generation and plant size.

A new reactor design - DeMoPTL (a deuterium moderated pressure-tube type light-water cooled reactor) adopts favorable design features from these two reactors - light water coolant, enriched uranium fuel and pressure tube type core in a calandria.

DESIGN GOALS AND FEATURES

The design goals of DeMoPTL are as follows:

1. A reactor should be based on proven technology. Geometrical design of the fuel bundles and pressure tubes are to be the same with those of CANDU. Therefore DeMoPTL could have the same NSSS and BOP as the CANDU plant. Use of light water instead of heavy water as coolant would not bring any impact on thermal-hydraulic safety limitations.
2. In order to compensate the reactivity loss, neutron moderation is enforced by the heavy water around the pressure tube similar to CANDU. Each pressure tube works as a module of the core where fuel (enriched uranium), coolant (light water), moderator (heavy water) and void calandria (air) are arranged in heterogeneous geometry. Different from CANDU, DeMoPTL has another pressure tube around the calandria tube that contains heavy water moderator and provides additional structural enforcement against tube sagging.
3. The use of light water for coolant requires enrichment of uranium fuel. However, the enrichment level should not be higher than that of PWR and should guarantee higher burnup than CANDU. Economic viability would not be strong without the possibility of on-power reloading. When the same size pressure tubes are used, a standard CANDU fuel reloading machine can be used. One of major weak points in CANDU design is positive coolant temperature coefficients under normal operational conditions. However, DeMoPTL could have negative coolant temperature coefficient as well as negative void coefficient.
4. Passive safety feature is not implemented in this reactor design. However, emergency cooling and long-term cooling can easily be achieved by passive flooding system. Emergency cooling water can be drained into a vacant calandria tank by gravity force by either active or passive valve opening. In the case of a pressure tube break, pressurization of the calandria tank can be avoided by pre-pressurization of moderator tubes around the coolant pressure tubes and passive flooding would provide a large amount of water as thermal sink.
5. One of major strong benefits of CANDU is the feasibility of automatic power control. Because enriched uranium fuels are loaded for longer cycle length, local pin peaking would be significantly increased without the use of burnable poisons. By utilization of proper burnable poisons, excess reactivity of fresh fuel can be controlled to be the same with CANDU fuel bundles. Therefore, CANDU control devices can be used without change.

The benefits of DeMoPTL – while not yet well verified – are expected because it may overcome drawbacks of PWR and CANDU. First of all, enriched uranium fuel bundles can be loaded in continuous mode, which will bring economic benefits. Secondly, many control devices and core monitoring devices can be arranged within the reactor, leading eventually to on-line monitoring, on-line maintenance and reactor automation. Measuring devices, therefore, can be calibrated at any time if proper redundancy is installed. Thirdly, certain drawbacks of the CANDU design can be overcome: the D_2O-H_2O interface across S/G tubes is changed into a water-water interface, leading to much lower tritium buildup and the amount of spent fuel generated and requirements for heavy water maintenance are reduced by a large ratio.

NUCLEAR FEASIBILITY TEST

Figure 1 showed a unit cell of CANDU fuel channels where natural uranium fuel bundles are cooled by pressurized heavy water in the pressure tube, and the space outside of calandria tube is filled with heavy water moderator. The annular space between these two tubes is filled with CO_2 gas as a thermal insulator. In a DeMoPTL design, four reactor module design concepts were proposed and tested. Figure 2 shows these four candidates that were design modifications of CANDU modules. In this paper, nuclear calculations were done only for the repeated reactor modules as shown in Figure 2. Fuel depletion calculation for these heterogeneous module with reflective boundary conditions was done by the code 'HELIOS'.

As the minimal change from CANDU module, design #1, heavy water coolant was replaced with light water coolant. As shown in Figure 3, reactivity of the module was much larger than CANDU if 2.4 w/o enriched uranium fuels were used instead of natural uranium fuels. This design gave the highest excess reactivity resulting in the lowest enrichment requirement or the highest discharge burnup, as well as the lowest production of spent fuels. Because this concept results from a single design change of the coolant, this design looks like a light water cooled CANDU.

Design #2 was modification of design #1. The whole space between the calandria tubes do not need to be filled with heavy water. Reduction of the heavy water moderator region around the fuel channel gives space for emergency water flooding for reactor shutdown and post-accident cooling. This void calandria tank doesn't have a large moderator reservoir, leading to benefits of plant scale-up. With a thickness of 1.6 cm in a moderator layer, excess reactivity was reduced compared to design #1, but discharge burnup was still much longer than CANDU. This design needs another tube outside the calandria tube which would add parasitic neutron absorbtion. However, this would provide structural reinforcement against tube sagging.

The third design module was a light water version of design #2. The use of light water moderator is more compatible than heavy water moderator in a light water cooled reactor. Because of higher neutron absorption in light water, excess reactivity of the module became the lowest among four candidates.

Design #4 was another modification of design #2. In this design, fuel rods in the inner region were designed to be thicker than the rods in outer region in order to reduce the pin peaking in the fuel bundle. As shown in Figures 3 and 4, this fuel bundle gave the best nuclear design performance. However, the design adds complexity to the fuel bundle.

Among the four candidates, design #2 was chosen as the reference design of DeMoPTL. In Figure 5, the possibility of reactor shutdown was checked in the case of water flooding to the void calandria tank. The negative reactivity insertion due to light water injection was more than 50% throughout the cycle. Figures 6 and 7 showed calculated CTC (coolant temperature coefficient) due to temperature change in pressurized coolant and MTC (moderator temperature coefficient) due to temperature change in heavy water moderator outside pressure tubes. Contrary to those of CANDU, CTC and MTC were shown to be negative through out the fuel burnup cycle.

The excess reactivity of module in design #2 was much higher than that of CANDU as shown in Figure 3. It means that a new reactivity control system is required once this module is adopted. In order to use the identical reactivity control system of CANDU, the excess reactivity should be dropped to the level of that of CANDU module. By utilization of IFBA burnable poison rods for the central six fuel pins, excess reactivity could be controlled as shown in Figure 8.

CONCLUSIONS

A DeMoPTL core module was designed for the nuclear design feasibility test. The key design parameters are as follows: 2.4 w/o fuel enrichment , CANDU fuel bundle geometry, light water in pressure tubes, a 1.6 cm layer of heavy water moderator around the calandria tube, and large vacant air space, approximately 13 cm between tubes, for emergency water flooding. Expected fuel discharge burnups would be about double those of CANDU. All temperature feedback coefficients would be negative. The nuclear characteristics of this reactor module design are concluded to be feasible and there would be no major impact on thermal-hydraulic design and MMIS design. More parametric studies for design optimization will be included in future work.

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KEY WORDS

Advanced reactor, reactor design, CANDU, PWR, pressure tube, nuclear design, feasibility

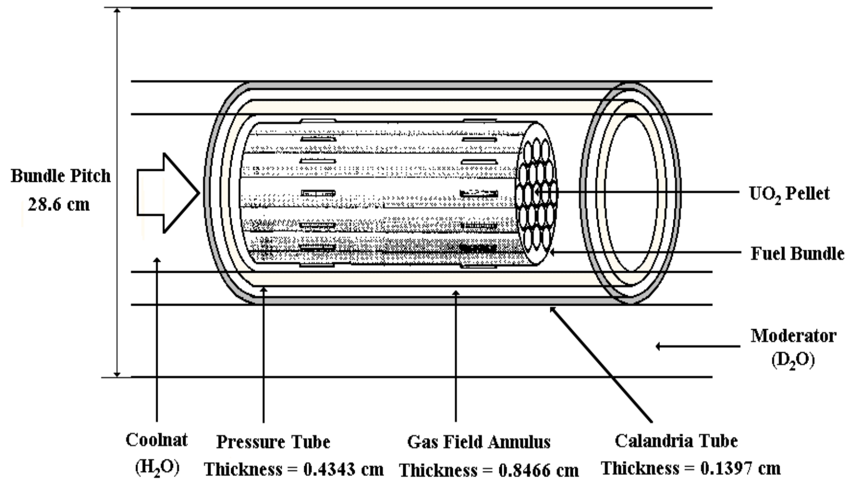

Figure 1. Unit Module of CANDU reactor channels

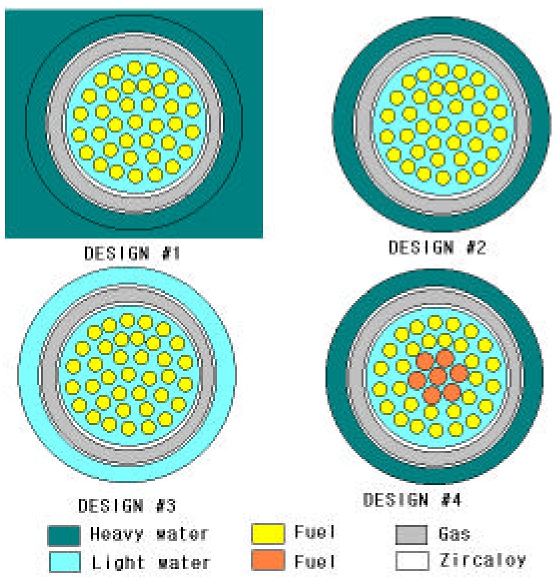

Figure 2. Reactor Modules of Fuel, Coolant, and Moderator

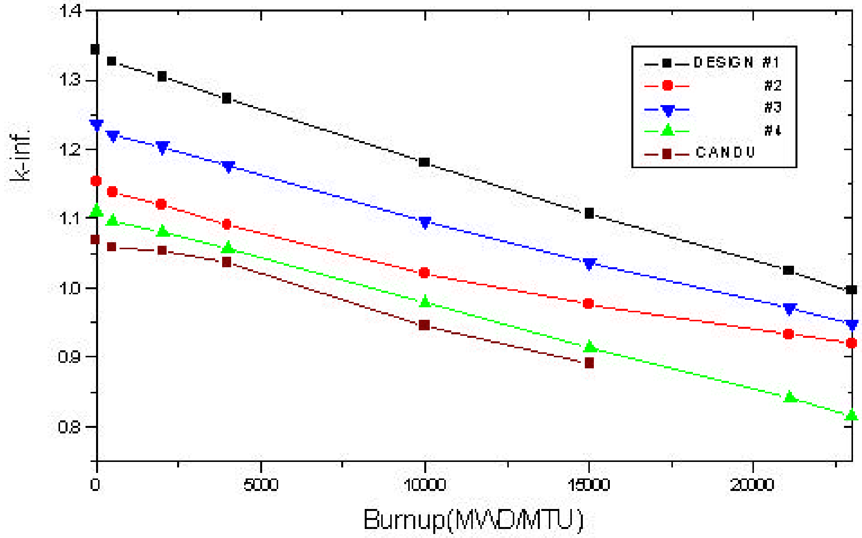

Figure 3. K-infinite Change of Reactor Modules vs. Fuel Burnup

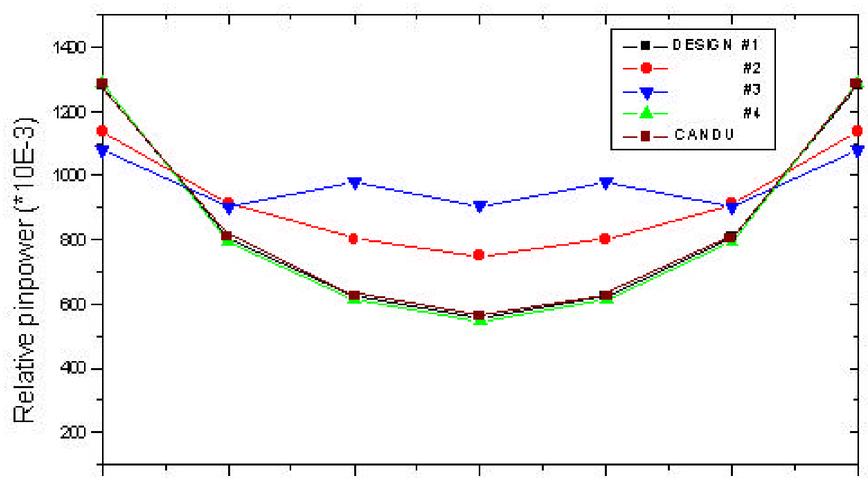

Figure 4. Relative Pin Power Distribution in Fuel Bundles

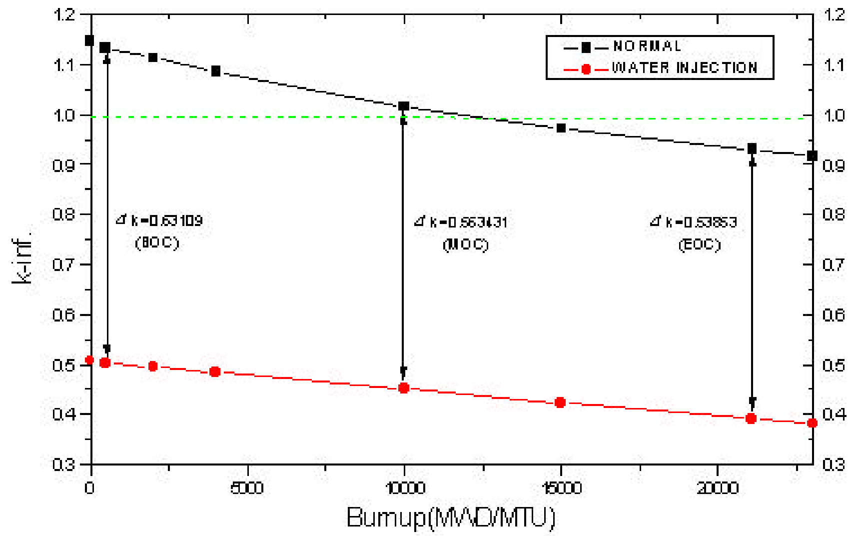

Figure 5. Reactivity Change of Reactor Module for the Emergency Water Injection

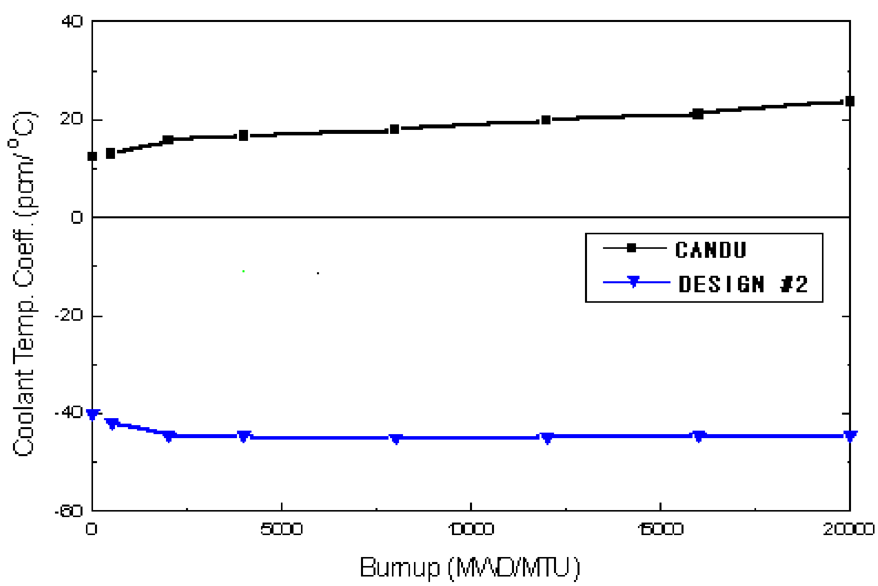

Figure 6. CTC of Reactor Module Design #2

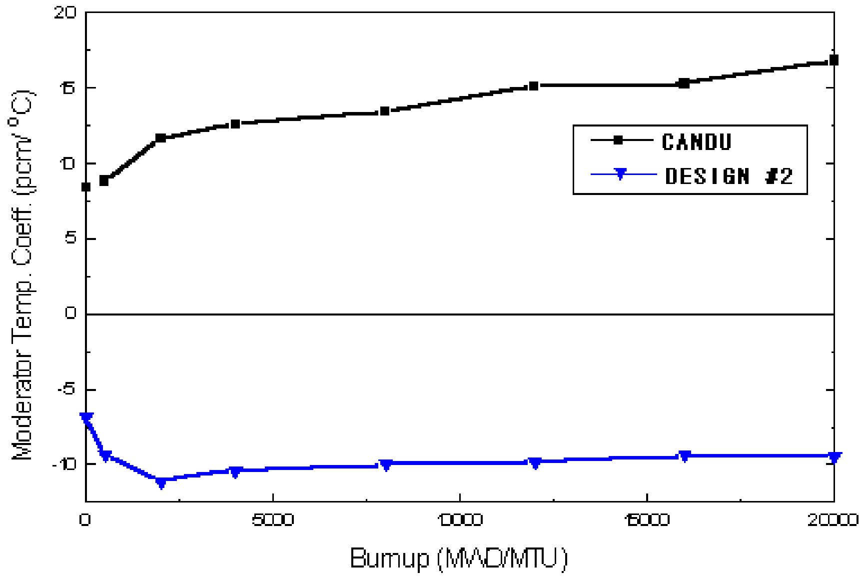

Figure 7. MTC of Reactor Module Design #2

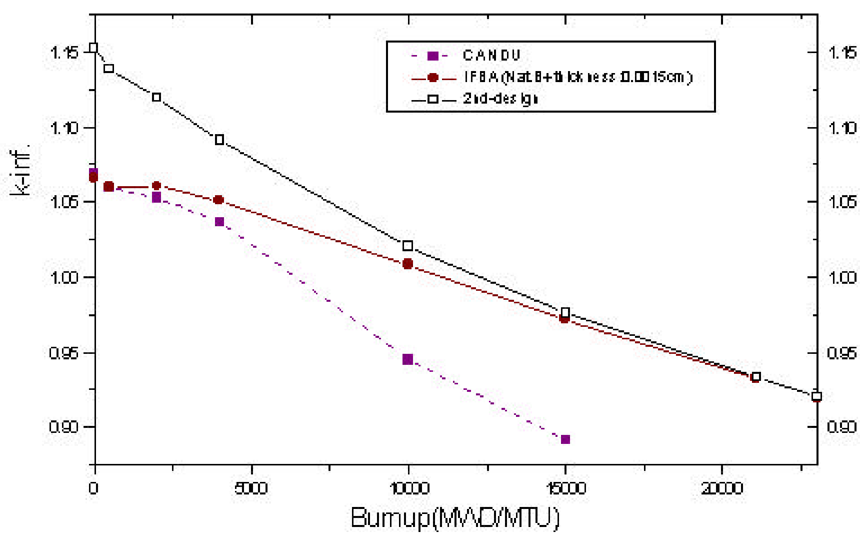

Figure 8. Excess Reactivity Change with IFBA in Design #2