# Conceptual Design of the Two-row Hexagonal Fuel Assembly for SCWR

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## Abstract

A new hexagonal fuel assembly (FA) design which has two rows of fuel rods between the hexagonal moderator channels is proposed for the thermal supercritical water cooled reactor (SCWR). The new concept is first and foremost considered for the performance of uniform moderation and sufficient moderation, and with respect to structural size and thermal-hydraulic performance. The neutron physical performance of the two-row hexagonal FA with acceptable configuration is discussed. The results show clearly that a better balance between uniform moderation and sufficient moderation can be obtained in the two-row hexagonal fuel assembly.

## 1. Introduction

Supercritical water cooled reactor (SCWR) system is characterized as low flow rate, high enthalpy rise, and single-phase water-cooling, by which high thermal efficiency and simplified once through direct steam cycle system is achieved. The economics of the SCWR core is directly affected by the neutron economics and structure complexity of the fuel assembly (FA). Thus it is necessary to flatten the power distribution inside the fuel assembly to obtain a higher coolant exit temperature and a consequently elevated system thermal efficiency. A large number of SCWR fuel assembly designs have been proposed for the sake of effectively decreasing the local power peaking factor (PPF). However, there is still biggish challenge to obtain a PPF less than 1.10 under the condition of acceptable assembly configurations and simplified fuel rods.

A new hexagonal fuel assembly design which has two rows of fuel rods between the hexagonal moderator channels is proposed in this paper. The two-row hexagonal fuel assembly concept is first and foremost considered for the performance of both uniform moderation and sufficient moderation, and with respect to structural, as well as thermal-hydraulic performance. Same fuel rod dimensions and components are adopted in the assembly which makes the most simplification of fuel rod types.

The local power peaking factor and infinite multiplication factor of the two-row hexagonal fuel assembly are analysed considering the coupled neutron-physics and thermal-hydraulics characteristics in the present study. Physical performance of the new proposal is then estimated under the consideration of the locating stuff and the control rod guide tubes with acceptable assembly configurations and dimensions.

## 2. Methodology

The calculations for the physical performance analysis in this study are performed with the MCNP [1] code. The local PPF ($F_L$) is defined as Eq. (1).

$$F_{\mathrm{L}} = P_{\mathrm{rod}}^{\max} / P_{\mathrm{rod}}^{\mathrm{ave}} \qquad (1)$$

Where $P_{\text{rod}}^{\max}$ and $P_{\text{rod}}^{\text{ave}}$ are the maximum and the average rod relative power density in the assembly, respectively.

An active height of 4.2 m and the inactive part of 30 cm of the fuel assembly is modelled. The coolant and moderator densities varying along the axial direction of the active region are divided into 21 segments with respect to the SCWR typical water density distribution which is obtained by coupling calculation [2]. The inactive parts below and above the active part are considered as two moderator volume cells according to reference [3]. Full reflective boundary condition is adopted in the radial direction while vacuum boundary condition in the axial direction.

## 3. Contrastive analysis for assembly performance

### 3.1 Conventional hexagonal fuel assembly

The hexagonal fuel assembly arrangement is a choice concept of SCWR FA. A hexagonal arrangement which has first been proposed by Dobashi [4] is shown in Figure 1. Another hexagonal arrangement shown in Figure 2 has been proposed by Bittermann [5].

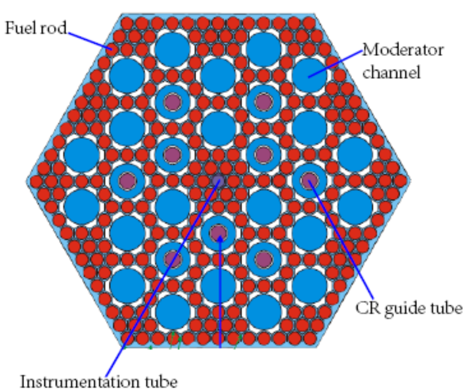


Figure 1 Fuel assembly concept by Dobashi

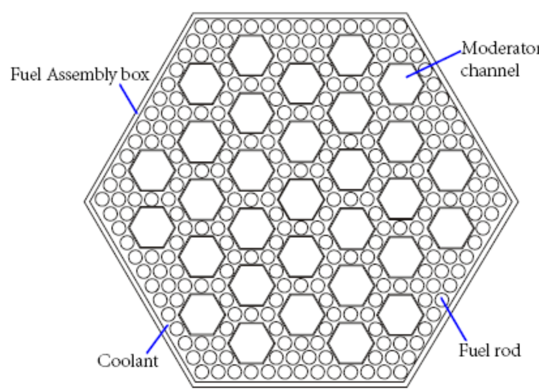


Figure 2 Fuel assembly concept by Bittermann

There are more fuel rods in the centre and the corner than those in the middle of the assembly in Dobashi FA concept. Therefore the moderations for the dense distributing fuel rods are weaker than those sparse distributing fuel rods. Thus it causes a strong non-uniform distribution of the radial power density. Therefore different enriched fuel rods in a fuel assembly are needed and then the complexity of the FA and core design is enlarged. The same problem also occurs in Bittermann FA concept. The local PPF is still much higher than 1.10 with the same enrichend fuel rods, even if the corner fuel rods are replaced by dummy rods which have the same geometric configuration but not heated.

Some other SCWR FA concepts incline to square arrangement because of the more uniform energy distribution and enthalpy rise. At the same time, recent studies [5] show that the local heat transfer in square lattice is much non-uniform than in hexagonal lattice, and the ununiformity of the enthalpy rise in hexagonal FA could be availably improved by increasing p/d ratio. Here p indicates the pitch of the fuel rod while d indicates its diameter.

## 3.2 Comparison with square assembly

An optimized disposal for one-row foursquare fuel assembly which has two kinds of fuel rods with different enrichment is shown in Figure 3. Figure 4 and Figure 5 show schematically the geometric arrangement of the two-row foursquare fuel assembly and the two-row hexagonal fuel assembly (D6-1 type) respectively, in both of which there is only one kind of fuel rods. All the fuel rods in these three assembly types have the same dimensions for convenient comparison. The fuel rod diameter is 10.2 mm. Inconel718 is adopted as the material for the assembly box and the moderator channel box. The performance comparison of these assembly types are summarized in Table 1.

Table 1 Performance Comparison between the Foursquare Fuel Assembly and the Two-row Hexagonal Fuel Assembly

| Parameter | Assembly type | | |
|---|---|---|---|
| | One-row foursquare FA | Two-row foursquare FA | Two-row hexagonal FA |
| Fuel rods number | 300 | 180 | 186 |
| Fuel enrichment (%) | 5.5/6.6 | 6.0 | 6.0 |
| Average moderation area ($cm^2$/rod) | 1.307 | 0.995 | 0.838 |
| Pitch-to-diameter ratio (-) | 1.1 | 1.1 | 1.3 |
| Wall thickness of moderator box (mm) | 0.2 | 0.1 | 0.1 |
| Wall thickness of assembly box (mm) | 3 | 1 | 1 |
| Thickness of outer water gap (mm) | 6 | 0 | 0 |
| Infinite multiplication factor, $k_\infty$ | 1.245 | 1.276 | 1.281 |
| Local power peaking factor, $F_L$ | 1.112 | 1.141 | 1.062 |

As shown in Table 1, on the one hand, all these three assembly types can be provided with sufficient moderation. The infinite multiplication factor of the one-row foursquare FA in which more structural material is adopted is a little lower than those of the two-row. On the other hand, $F_L$ of the two-row hexagonal FA (1.062) is much lower than that of the two-row foursquare FA (1.141), and is also better than that of the optimized one-row foursquare FA (1.112) which adopts two enrichment-level fuel rods. It can be concluded that the uniform moderating capability of the two-row hexagonal FA is better than the foursquare ones mainly due to the arrangement of the fuel rods. The moderating effects in the peripheral directions of the square water channel differ a lot, which makes the moderating effects to the fuel rods located on different positions around the water channel much non-uniform. Although the weaker moderation to the fuel rods near the assembly wall can be conquered in the two-row foursquare FA compared to the one-row FA, the moderation to the fuel rods near the corner of the square water channel is still much feebler, and subsequently a strong non-uniform distribution of the radial power density will occur. Being much closer to a circle than square one, Hexagonal channel has a better peripheral uniformity and can make a better balance between uniform moderation and sufficient moderation. Therefore, the two-row hexagonal FA with hexagonal moderator channels is recommended under the permission of the assembly configuration.

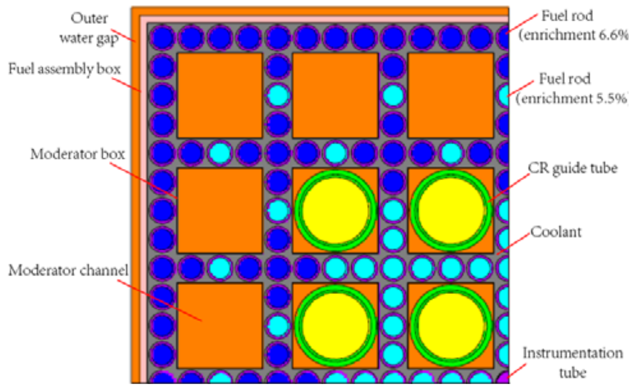


Figure 3 Optimized One-row Foursquare Fuel Assembly (1/4FA)

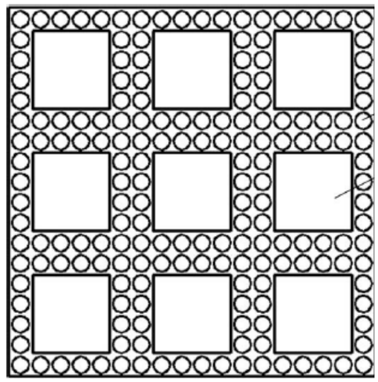

Figure 4 Two-row Foursquare Fuel Assembly

## 4. Performance analysis on the two-row FA concept

It is impossible to entirely arrange integrated hexagonal lattice in a two-row hexagonal FA. There will be trapeziform lattice or trigonal lattice on the inner side of the assembly box. Thus redundant abnormal lattices should be avoided for the convenience of implementing the assembly configuration in the FA concept design. In addition, more elements such like assembly side, uranium content and structural material should be taken into account in the engineering FA design.

For the D6-1 type FA concept shown in Figure 5, the opposite side distance of the FA is only 185 mm with the fuel rod diameter of 8.0 mm and the pitch-to diameter ratio of 1.3 (current values in the hexagonal FA studies), and this dimension makes against to the disposal of the control rod drive mechanism (CRDM). At the same time, more than 300 fuel assemblies are needed for the core loading because of the small quantity of $UO_2$ in one FA (only about 283 kg), which makes against to the core disposal. Therefore, D6-2 type FA concept with thin rods (see Figure 6) and D6-1 type FA concept with thick rods (see Figure 5) are proposed in this study taking account of the practicality in the engineering application.

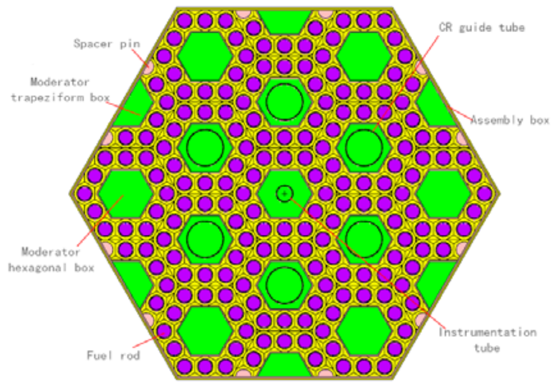


Figure 5 Two-row Hexagonal Fuel Assembly (D6-1)

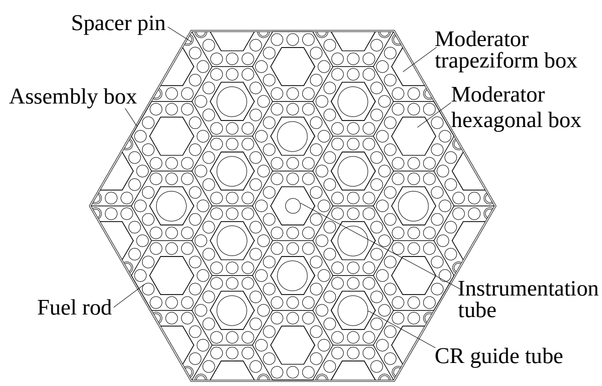


Figure 6 Two-row Hexagonal Fuel Assembly (D6-2)

## 4.1 D6-2 type FA with thin rods

The fuel rods of 8.0 mm diameter are adopted in D6-2 type FA concept, the pitch-to-diameter ratio (p/d) is 1.3, and the opposite side distance of the FA is 236 mm. There are 288 fuel rods in one assembly and the $UO_2$ content is 464 kg. Compared to the D6-1 type FA with thin rods, the opposite side distance of the D6-2 type FA is larger, which is appropriate to the disposal of the CRDM and the reactor core. Furthermore, compared to other conceivable two-row FA concept, D6-2 type FA which has less abnormal lattices is convenient for the assembly configuration actualizing.

Physical performance of the D6-2 type FA is estimated under the consideration of the locating stuff, control rod guide tubes and instrumentation tube with acceptable wall thickness of assembly box and moderator box. Then the improvement for the design aim that $F_L$ less than 1.10 is suggested. The wall thickness of the hexagonal moderator box and the assembly box are respectively selected as 0.8 mm and 1.0 mm with respect to structural performance and thermal-hydraulic performance. Inconel718 is selected as the material for structure stuff, guide tube, cladding and box wall. The $^{235}U$ enrichment in the fuel is 7.5%. The physical performance results under different guide tubes and spacer pins are given in Table 2. For the D6-2 type FA without spacer pin or guide tube, there are two neighboring water voids in the six corners of the assembly. The much more coolant water here gives a stronger moderation to the fuel rods nearby and a higher power density in the corner, and subsequently a larger $F_L$ (1.117). More uniform moderation over the fuel rods on the other positions in the FA could be achieved as a $F_L$ of less than 1.05.

Spacer pins located in assembly corners are considered to reduce the power density of the corner fuel rods and flatten the power distribution in the FA. Decreasing the enrichment of the corner rods is another effective measure without the localization of single fuel enrichment. This measure is not adopted because the advantage of simplified fuel rods for two-row hexagonal FA will not be represented. The $F_L$ of the FA without control rod guide tubes could be decreased to 1.061 by adopting spacer pins in corners while the $F_L$ of the FA with control rod guide tubes could be depressed to 1.105. At the same time, considerable reactivity will be lost by the introduction of spacer pins and guide tubes. As shown in Table 2, the FA with solid spacer pins and guide tubes will lose about 2% reactivity compared to the “clean FA” without spacer pins and guide tubes.

Table 2 Physical Performance of the Two-row Hexagonal FA

| Assembly parameter | | | Performance value | |
|---|---|---|---|---|
| Type | Guide tube | Spacer pin | $F_L$ | $k_\infty$ |
| D6-2 d=8.0mm | without | without | 1.171 | 1.257 |
| | with | with | 1.105 | 1.218 |
| | without | with | 1.061 | 1.237 |
| D6-1 d=10.2mm | without | without | 1.098 | 1.276 |
| | without | with | 1.048 | 1.261 |
| | with | with | 1.049 | 1.248 |

## 4.2 D6-1 type FA with thick rods

Larger water voids in the corners of the D6-2 type FA make against to uniform moderation. However the moderations in D6-1 type FA are more uniform. As a result of that the lesser fuel content and geometry dimension of D6-1 type FA with thin rods make against to the disposal of the CRDM and the reactor core, the concept of D6-1 type FA with thick rods is proposed. The fuel rods of 10.2 mm diameter are adopted in D6-1 type FA concept, the p/d is 1.3, and the opposite side distance of the FA is 241 mm. There are 186 fuel rods in one assembly and the $UO_2$ content is 486 kg. The wall thickness of the hexagonal moderator box and the assembly box are respectively selected as 0.8 mm and 1.0 mm. Inconel718 is selected as the material for structure stuff, guide tube, cladding and box wall. The $^{235}U$ enrichment in the fuel is 7.5%.

The physical performance results for D6-1 type FA with thick rods are shown in Table 2. The $F_L$ of the D6-1 type FA without spacer pin or guide tube is 1.098 which is profited from the uniform moderation. The $F_L$ of the FA with and without guide tubes under the adoption of spacer pins are 1.049 and 1.048 respectively, both of which are less than the design aim 1.10. In addition, from the results in Table 2 we can find that lower $F_L$ and higher $k_\infty$ could be more easily obtained in D6-1 type FA with thick rods compared to the D6-2 type FA with thin rods because of its more uniform moderation and less configuration material.

## 5. Conclusions

A new concept of thermal SCWR fuel assemblies which has two rows of fuel rods between the hexagonal moderator channels is proposed in this paper. The new concept can easily resolve the contradiction between the uniform moderation and sufficient moderation. Larger infinite multiplication factor and smaller local power peaking factor could be obtained in this proposal. The design objective of the local power peaking factor less than 1.10 can be achieved under the condition of using the same enrichment fuel and containing no burnable poison.

Taking account of the practicality in the engineering application, two kinds of two-row hexagonal FA concepts, i.e. one with thin fuel rods (d=8.0 mm) and the other with thick fuel rods (d=10.2 mm), are proposed under the consideration of the locating stuff and the control rod guide tubes with acceptable assembly configurations and dimensions. The results achieved so far can be summarized as follows:

(1) The design objective of the local power peaking factor less than 1.10 can be achieved in both thin rods and thick rods two-row hexagonal FA concepts.
(2) Compared to the D6-2 type FA concept, lower $F_L$ and larger $k_\infty$ could be more easily obtained in D6-1 type FA which also has a simpler configuration.

Further study will be carried out for the coupled neutron-physics and thermal-hydraulics analysis and the optimization analysis on the two-row hexagonal fuel assembly concept.

## 6. References

[1] Briesmeister Judith F, MCNP-A General Monte Carlo N-Particle Transport Code [R].LA-12625-M, 1997

[2] J.Hofmeister, C.Waata, J.Starflinger, T.Schulenberg, E.Laurien, Fuel assembly design study for a reactor with supercritical water [J]. Nuclear Engineering and Design Vol.237 (2007) P1513-1521

[3] C.L.Waata, Coupled Neutronics/Thermal-hydraulics Analysis of a High-Performance Light-Water Reactor Fuel Assembly [D]. Deutschland: Institut für Kern-und Energietechnik Programm Nukleare Sicherheitsforschung, 2006

[4] K.Dobashi，Y.Oka，S.Koshizuka, Core and plant design of the power reactor cooled and moderated by supercritical light water with single tube water rods [J]. Ann Nucl Energy，1997，24 (16): 1281~1300

[5] X.Cheng, T.Schulenberg, D.Bittermann, P.Rau, Design analysis of core assemblies for supercritical pressure conditions [J]. Nuclear Engineering and Design, 2003, 223: 279~29