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Adaptive Design and Criticality Analysis of the DARWIN Reactor Core Concept

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ABSTRACT

The DARWIN (Dispatchable Adaptive Reactor With Interchangeable compoNents) reactor core concept with a modular and adaptive design represents an option for flexible requirements. A comprehensive criticality analysis was performed using a simplified hexagonal 2D geometry in Serpent-2 code, investigating the effects of the fuel-to-moderator ratio by varying the pitch between the fuel pins at two temperatures. The results showed that optimal moderation is achieved at an approximate pin pitch $p_p = 1.6\,\mathrm{cm}$. At higher temperatures, the value of k_{eff} is lower, which represents a negative temperature feedback effect. For $p_p \approx 1.85\,\mathrm{cm}$ or more, the temperature feedback becomes positive. The feedback effect of the moderator temperature is negative for $p_p \leq 1.8\,\mathrm{cm}$ and that of the fuel temperature is negative for all p_p. Hot rod power peaking factor increases when the distance between the fuel rods is increased, unless the fuel rods are very close to each other ($p_p \leq 1.05\,\mathrm{cm}$ for $T = 300\,\mathrm{K}$ and $p_p \leq 1.2\,\mathrm{cm}$ for $T = 600\,\mathrm{K}$) and the fuel rod with the highest power density is not located in the central assembly. The peaking factor is generally lower at lower temperatures when the hottest rod is in the central assembly. For p_p between $1.2\,\mathrm{cm}$ and $1.6\,\mathrm{cm}$ the peaking factor is between 1.9 and 2.1 for $T = 300\,\mathrm{K}$ and 1.6 and 1.8 for $T = 600\,\mathrm{K}$.

1 INTRODUCTION

The concept of the Dispatchable Adaptive Reactor With Interchangeable compoNents (DARWIN) is addressing Charles Darwin's quote about the survival of the most adaptable species. It is a response to the flexible needs of the modern world.

For a successful and safe reactor core design, three things should be considered. The first is criticality, i.e. the design of a core in such a way that the chain reaction is maintained. The second is sufficient cooling to ensure that the temperature safety limits are not exceeded. Lastly, the containment of the radioactive materials.

The first section of this work presents an adaptive design of DARWIN. The second part deals with the criticality analysis and the power distribution of a simplified 2D model, which was created using the Serpent 2 Monte Carlo code [1].

In order to take account of the flexibility of DARWIN, a modular structure is assumed, as shown in Figure 1 as an example. The reactor consists of two modules: the primary module, which forms the core of the reactor, and various secondary modules designed for specific purposes. The main focus is on the development of the primary module with assemblies specially developed for the respective application and their arrangement in the reactor core.

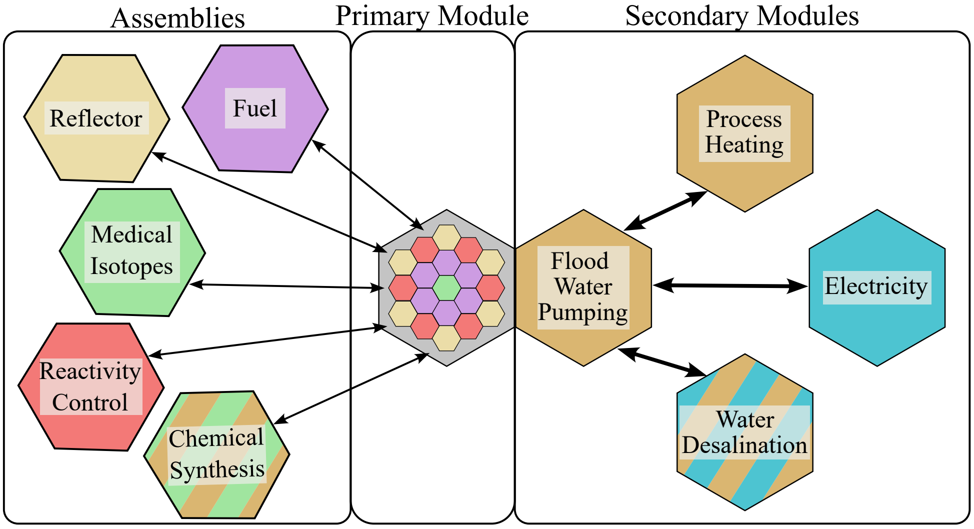

Figure 1: An example of the schematic structure of a DARWIN reactor. The core consists of various assemblies with different functions, which can be replaced by additional assemblies. A secondary module suitable for the selected task is coupled to the output side of the reactor.

The load-following operation mode [2] will be necessary in the future due to the increasing share of intermittent renewable energy sources. Nuclear power can be used to compensate for the daily fluctuations in solar energy production [3].This mode of operation requires careful control of various parameters to ensure safe operation [4]. Different methods can be employed for control, such as the use of grey rods [5] or more advanced control drums, similar to those used in space reactors [6].

The production of medical isotopes requires a sufficiently high neutron flux with an appropriate neutron energy spectrum [7]. An accessible irradiation channel should be available so that the irradiated samples can be easily removed [8].

2 COMPUTATIONAL MODEL AND ANALYSIS

The hexagonal arrangement of the fuel pins and assemblies was selected for its efficient space utilization and uniform power distribution. An initial two-dimensional study was conducted with a single type of fuel pin, without simulating the pressure vessel components. Calculations were performed at room temperature ($300\,\mathrm{K}$) and approximatly operating temperature ($600\,\mathrm{K}$), along with a detailed study of temperature effects on both the fuel and moderator. The geometry is further detailed in the following subsection, using the ENDF/B-VII.0 nuclear data library [9] and Serpent-2 code version 2.2.0. A model was used for a generic search for the range of parameters for fuel assembly design.

By systematically changing the distance between the fuel pins and thus influencing the size of the core, a study was conducted to examine the effects on the multiplication factor and the hot rod power peaking factor. The aim of the study was to obtain a rough estimate of the behaviour of these two physical parameters as a function of the configuration of the core. The results are presented in the following subsections.

2.1 Geometry

The geometry used in this study was a simple hexagonal 2D arrangement, as shown in Figure 2. Each fuel pin consists of $3\,\%$ enriched UO_2 fuel, a helium-filled gap and a Zircaloy-4 cladding. Water is used as coolant and moderator. Each fuel assembly contains 127 fuel rods, and the core is composed of 37 fuel assemblies. The dimensions and properties of the fuel rods are shown in Table 1. Calculations were performed at two temperatures: 300 K and 600 K. All materials were assumed to be at the same temperature. With increasing temperature, only the densities of the helium gas in the gap of the fuel rod and the water decreased, all other thermal expansions were neglected.

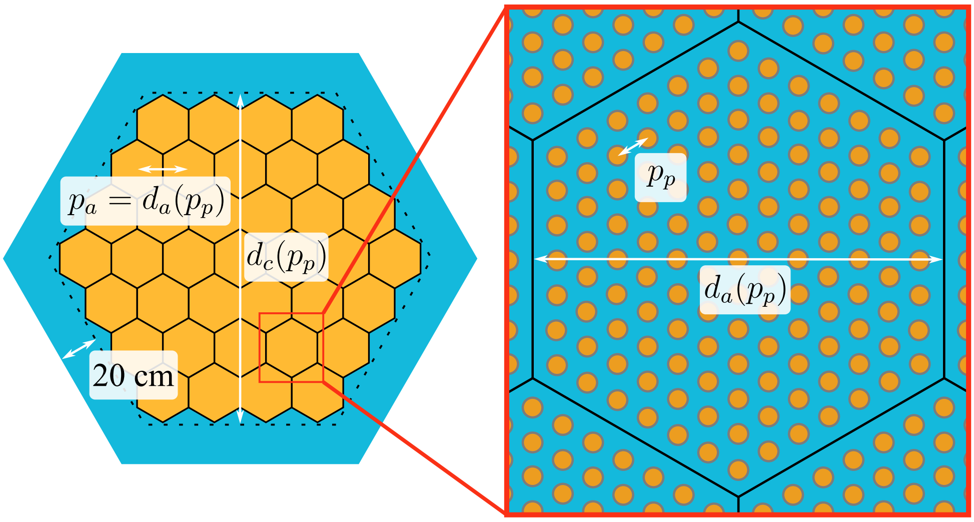

Figure 2: Geometry of a core used for a calculation. A core (right) with the dimension d_c consists of 37 fuel assemblies separated by a pitch p_a and is surrounded by a 20 cm band of water. Each fuel assembly (left) with a dimension d_a consists of 127 fuel rods separated by a pitch p_p. Assembly pitch p_a, dimensions d_a and d_c are calculated from a fuel pin pitch p_p. The size of the core d_a for $p_p = 1.00$ cm is 113 cm and for $p_p = 3.00$ cm is 260 cm.

Table 1: Fuel pin dimensions and some properties at two different temperatures.

	outer radius [cm]	material	T=300 K	T=600 K
fuel pellet	0.4096	UO_2	3 % enriched [10]	
gap	0.4178	He	$0.001591\ g/cm^3$	$0.00079\ g/cm^3$
cladding	0.4750	zircaloy-4	predefined in Serpent-2 [1]	
coolant	/	H_2O	$1.0034\ g/cm^3$	$0.66114\ g/cm^3$

The dimensions of the fuel assembly and the entire core are determined by the distance between the fuel rods, known as the pin pitch (p_p). All dimensions are shown in Figure 2. The size of the fuel assembly d_a is calculated based on the pin pitch (p_p) using the following formula:

$$d_a = p_p(N_p - 0.5 + 1/6)\sqrt{3}, \tag{1}$$

where N_p is the number of fuel rods along one side of the hexagon, which in this case is 7. The size of the assembly d_a corresponds to the distance between the assemblies (assembly pitch) p_a. Similarly, the size of the reactor core (d_c) is calculated using:

$$d_c = p_a(N_a - 0.5 + 1/6)\sqrt{3}, \tag{2}$$

where N_a is the number of assemblies along one side of the hexagon, which in this case is 4. In the simulation, a surrounding band of 20 cm of water was added.. The size of the core d_a for $p_p = 1.00$ cm is 113 cm and for $p_p = 3.00$ cm is 260 cm.

Varying the distance between the fuel pins (pitch) p_p changes the overall dimensions of the core, and since the dimensions of the fuel pin remain the same, the amount of water also changes. The amount of water present in the reactor core influences the moderation and thus the physical properties of the core. The change in temperature reflects the temperature feedback effect. In the following subsections, the results of these variations on the integral parameter k_{eff} and the power distribution, described by the hot rod power peaking factor, are presented.

2.2 Criticality analysis

The fuel pin pitch p_p defines the ratio between the amount of moderator and fuel. As p_p increases, the amount of water, which acts as a moderator, also increases. The amount of moderator has a considerable influence on the criticality and also on the stability of the system. Figure 3 shows the effective multiplication factor (k_{eff}) for this simplified 2D geometry at two temperatures, with the pitch adjusted in increments of $2\,\mathrm{mm}$ and $1\,\mathrm{mm}$. In this case, this optimal point is at a pitch of about $1.6\,\mathrm{cm}$, which corresponds to the optimum amount of moderator in the water.

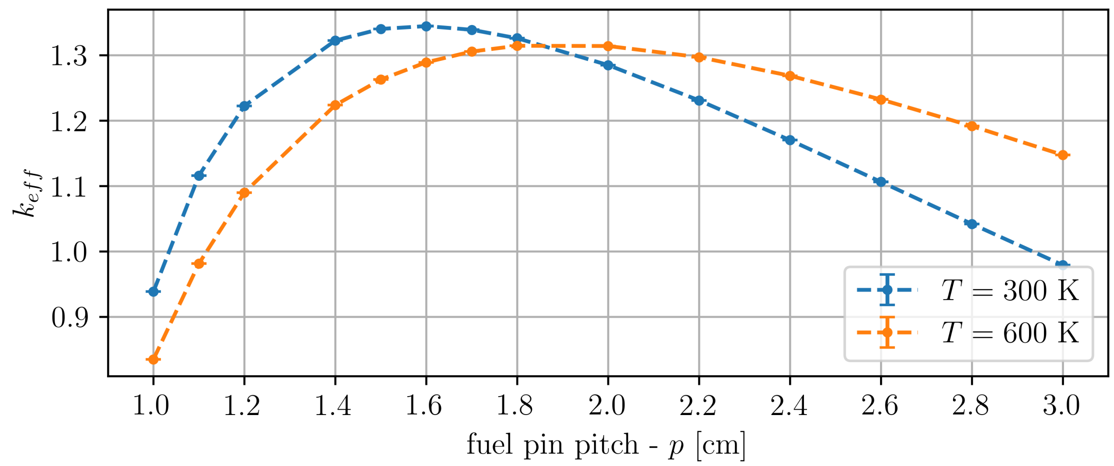

Figure 3: Dependance of of the effective multiplication factor k_{eff} on the fuel pin pitch, which defines the amount of moderator present in the core. Left of the point is under-moderated region and right is over-moderated region. The maximum statistical uncertainty of k_{eff} is $8.5\,\mathrm{pcm}$.

For the safe operation of a nuclear reactor, the core should be under-moderated (to the left of the optimum point). Under-moderation leads to a negative feedback loop when the amount of moderator present changes (the presence of voids or thermal expansion decreases k_{eff}).

The increase in temperature has a considerable influence on the criticality of the core. In the under-moderated region, the increase in temperature causes the value of k_{eff} to decrease, which represents a negative feedback loop that ensures safe operation. In the over-moderated region, for the pin pitch of more than $p_p \approx 1.85\,\mathrm{cm}$, the effect of the temperature change is opposite, k_{eff} is increased when the temperature increases. This effect can be expected in the over-moderated region even from the curve at room temperature ($300\,\mathrm{K}$) if you consider the fuel-to-moderator ratio as an independent variable and not the pin pitch, which increases when p_p is reduced. As temperature rises, the moderator volume decreases due to the thermal expansion of water, thereby increasing the fuel-to-moderator ratio. This shift causes the k_{eff} curve to move leftward, resulting in a higher k_{eff} value.

For a more detailed study of the temperature effect, the temperature changes for fuel and moderator were analysed separately. The effect of temperature on reactivity is described by temperature feedback coefficients, which are defined as follows

$$\alpha_j = \frac{\partial \rho}{\partial T_j}, \tag{3}$$

where the index j stands for a material (fuel or moderator), $\partial \rho$ represents change in reactivity and ∂T_j represents a change in temperature of material j. Coefficient α_j is in the unit pcm/K, where $1\,\mathrm{pcm} = 10^{-5}$. The fuel temperature was changed from $560\,\mathrm{K}$ to $1080\,\mathrm{K}$ in steps of approximately $100\,\mathrm{K}$, while the moderator temperature was kept constant. When changing the fuel temperature, only the effect of the change in nuclear data due to the Doppler effect was taken into account. The moderator temperature was changed from $560\,\mathrm{K}$ to $600\,\mathrm{K}$ in steps of $10\,\mathrm{K}$ while the fuel temperature was kept constant. The change in moderator temperature was considered as a change in the nuclear data, moderator density and hydrogen thermal scattering data. Both cases were performed for different values of p_p. The value of α for moderator and fuel was determined by fitting a line to the effective reactivity of the core at different temperatures. The results are summarised in Table 2. The moderator temperature feedback coefficient is negative up to $p_p \leq 1.8\,\mathrm{cm}$, after which it becomes positive. The fuel coefficient is always negative, but its magnitude is smaller than the moderator coefficient. The relatively high value (in absolute terms) of the moderator coefficient is due to the absence of boron in the moderator, which reduces the value.

Table 2: Temperature feedback coefficients.

pitch [cm]	moderator [pcm/K]	fuel [pcm/K]
1.0	-92.40 ± 0.05	-4.453 ± 0.002
1.4	-48.13 ± 0.04	-1.550 ± 0.002
1.6	-28.23 ± 0.04	-1.181 ± 0.002
1.8	-12.56 ± 0.03	-0.996 ± 0.002
2.0	3.45 ± 0.03	-0.901 ± 0.002
2.4	32.73 ± 0.03	-0.882 ± 0.001
3.0	78.94 ± 0.02	-1.0703 ± 0.0003

The distance between the pins is $1.26\,\mathrm{cm}$ for the PWR AP1000 from Westinghouse [11] and $1.23\,\mathrm{cm}$ for the PWR VVER 440 from Rosatom [12]. The VVER 440 uses hexagonal fuel assemblies with almost the same number of fuel rods, but with a guide tube in the centre and different arrangements of differently enriched fuel and fuel elements in the core.

2.3 Hot rod power peaking factor analysis

The amount of moderator also affects the power density distribution within the reactor core. One of the parameters that can describe this is the hot rod power peaking factor f_{hr} [13], which is defined as:

$$f_{hr} = \frac{(P_{rod})_{max}}{(P_{rod})_{av}}, \tag{4}$$

where $(P_{rod})_{max}$ is the maximum power released by a single fuel rod and $(P_{rod})_{av}$ is the average power of a rod, calculated as:

$$(P_{rod})_{av} = \frac{P}{N}, \tag{5}$$

where P is the total power of the reactor and N is the total number of fuel rods. In this study, P is normalised to 1 and N is the product of the number of fuel assemblies and the number of fuel rods per fuel assembly. In the geometry used N is $37 \times 127 = 4699$.

The results for two different temperatures are shown in Figure 4. For each temperature, two cases are considered. The first case refers to the search for the fuel pin with the highest power $(P_{rod})_{max}$ across the entire core, and the second focuses on finding this maximum within the central assembly, where power density peaks are expected.

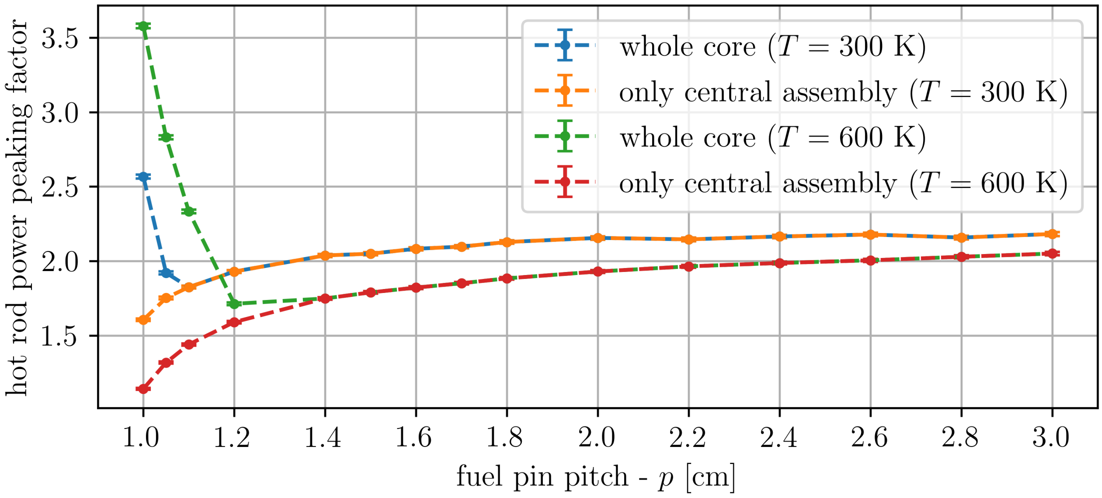

Figure 4: Values of the hot rod power peaking factor for different distances between the fuel pins at two different temperatures. For each temperature, there is the case where the search for the pin with the highest power density was performed in the entire core and only in the central assembly. The maximum statistical uncertainty is 0.015.

It was initially assumed that these two cases would yield the same results, meaning the hottest rod would always be in the central assembly. However, for very compact fuel pin arrangements (for $p_p \leq 1.05\,\mathrm{cm}$ at $T = 300\,\mathrm{K}$ and $p_p \leq 1.2\,\mathrm{cm}$ for $T = 600\,\mathrm{K}$), the peak power density does not occur in the central fuel assembly. Furthermore, even at larger pitches, the pin with the highest power density is not the central pin in the central fuel assembly. Although it is located in the central fuel assembly, it is at the edge of the fuel assembly, i.e. furthest from the centre. The first case where the highest power density is indeed in the central pin occurs at $p_p = 3.00\,\mathrm{cm}$. A position of the fuel pin with the highest power density for $p_p = 1.00\,\mathrm{cm}$ is shown in Figure 5 is shown. As expected, the power density distribution at the fuel assembly scale is highest in the central assembly and decreases toward the periphery. Assemblies with lower power density in some radial directions than expected are due to varying distances from the centre and the positions of neighbouring assemblies near the periphery (corner or edge). The pin with the highest power density is located on the outside of one of the fuel assemblies at the periphery of the core. The distribution of power density in the central fuel assembly is the reverse of what would be expected – the highest power densities are at the periphery and the lowest in the centre. This could result in higher activation and damage to the surrounding structures. The reason for the unusual results could also be a calculation of steady-state transport that is only valid for k_{eff} close to 1 for a strongly supercritical core, which is the case for the model used here without reactivity control. This calculation can lead to a distortion of the flux distribution.

The observed power density distribution is primarily influenced by the distribution of the moderator. Power output is higher when more moderator surrounds a fuel pin. The distance between the fuel pins at the edge of one fuel assembly and the pins at the edge of the other fuel assembly is greater than the value of the pitch. For the smallest value of p_p, this distance is greater than the pitch, but still significant enough to cause the highest power density to occur

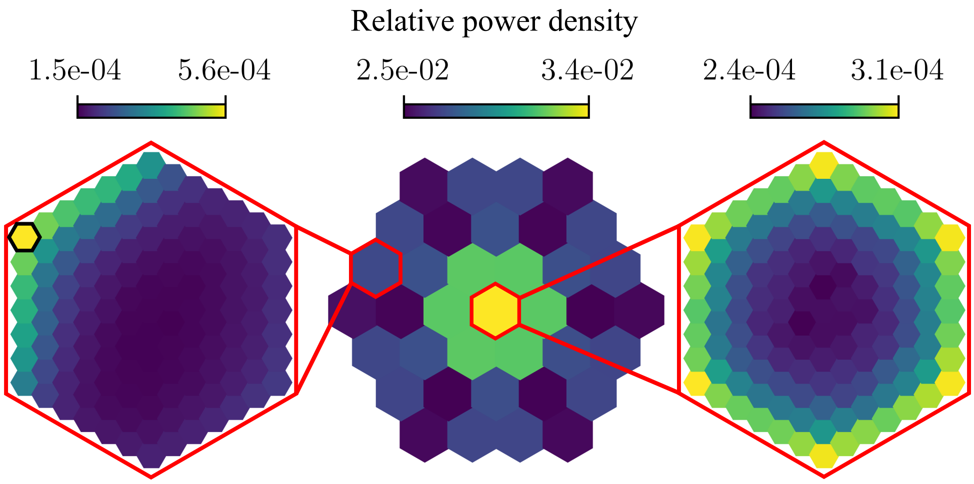

Figure 5: Pin-wise power distribution in the assembly with the pin with the highest power density (left) and in the central assembly (right) and assembly-wise power distribution of the entire core (centre) for a case with $p_p = 1.00\,\mathrm{cm}$ at $T = 300\,\mathrm{K}$. The pin with the highest power density is marked with the black hexagon.

at the edge of the core. For $p_p = 3.00\,\mathrm{cm}$, the size of the gap between the fuel assemblies approaches the value of the pin pitch and the distribution is more in line with the expectations for a homogeneous reactor. The correctness of this larger gap confirms the pin and fuel assembly spacing values of VVER 440, and the arrangement of differently enriched fuel pins in the VVER 440 fuel assembly (less enriched at the edge and more in the centre) is indicative of the power density distribution observed in this study [12]. In the future, the effects of fuel assembly spacing should be investigated more thoroughly.

The reason why the hottest fuel rod is not located in the central assembly at higher temperature, even at slightly larger pitches (up to $1.2\,\mathrm{cm}$ instead of $1.05\,\mathrm{cm}$), is due to the lower density of the moderator, which acts like a smaller distance between the fuel rods. The effects of temperature to power distribution need to be studied in more detail in the future by analysing the effects of the moderator and the Doppler effect in the fuel separately.

3 CONCLUSIONS

The DARWIN concept has a modular structure and consists of a primary module and secondary modules. The primary module serves as the reactor core, which consists of various assemblies adapted for different purposes, e.g. for load-following mode of operation or the production of medical radioisotopes. This study has identified a preliminary design space for the future development of the reactor core.

The Serpent-2 code was used to create a simplified 2D model of fuel pins in hexagonal assemblies. A criticality study was conducted by varying the distance between fuel rods, thereby adjusting the fuel-to-moderator ratio at two different temperatures. Optimal moderation was achieved at a pin pitch of $1.6\,\mathrm{cm}$, compared to $1.23\,\mathrm{cm}$ in the VVER 440 assembly, indicating operation within the under-moderation region, which supports safe operation. The temperature feedback on k_{eff} was negative for pin pitches of $1.85\,\mathrm{cm}$ or less. The feedback coefficient of moderator temperature was negative for $p_p \leq 1.8\,\mathrm{cm}$, while the fuel temperature feedback was negative for all p_p. Although the effect of boron on moderator temperature feedback was not analysed, it should be considered in future studies, which should also include burnup and the effects of reactor cycle length.

A similar study examined the effects of pin pitch on the pin power peaking factor, which generally increases with larger spacing between fuel rods. However, when rods are very close together ($1.05\,\mathrm{cm}$ or less at $300\,\mathrm{K}$ and $1.2\,\mathrm{cm}$ or less at $600\,\mathrm{K}$), the highest power density occurs in the outer fuel assembly. For larger p_p, the highest power density pin shifts to the central fuel assembly but remains at the periphery due to the slightly larger gap between assemblies, which diminishes as the pitch increases to $p_p = 3.00\,\mathrm{cm}$ or more. This effect will be explored further in future studies.

To summarize the constraints for potential core design, criticality and effective moderation at $600\,\mathrm{K}$ set the pin pitch range between $1.1\,\mathrm{cm}$ and $1.8\,\mathrm{cm}$. The temperature feedback effect sets an upper limit at $1.8\,\mathrm{cm}$, where the moderator temperature feedback coefficient becomes positive for larger p_p values. To achieve a hot rod peaking power factor between 1.5 and 1.75 at $600\,\mathrm{K}$, p_p should be between $1.1\,\mathrm{cm}$ and $1.4\,\mathrm{cm}$.

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