COUPLED 3D NEUTRONIC AND THERMOHYDRAULIC CALCULATIONS FOR A COMPACT FUEL ELEMENT WITH DISPERSE UMo FUEL AT FRM II

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ABSTRACT

The newly developed X² program system is intended to be used for high-detail 3D calculations on compact research reactor cores. Using this system, the efforts to calculate scenarios for a new fuel element for FRM II using disperse UMo (8wt% Mo, 50% enrichment) are continued. By now, a radial symmetric core model with averaged built-in components for the D_2O tank is used.

Two different scenarios are compared: The minimum fuel density of 7.5 g U/cm³ and 8.0 g U/cm³ with 60 days cycle length. In addition, two “flux loss compensating” scenarios based on 8.0 g U/cm³ with 10% higher power / longer reactor cycles are regarded.

1. Introduction
1.1 FRM II, Disperse UMo

The core of FRM II consists of only one single fuel element, a compact core with 113 evolute shaped fuel plates. Currently, a disperse U_3Si_2-Al fuel with densities up to 3.0 g U/cm³ is employed. The degree of enrichment is 93% (HEU). In terms of the RERTR program, cores with a higher uranium density and consequently lower enrichment are studied. For this, disperse UMo-Al (8 wt% Mo) is a promising candidate. For the particular geometry of the FRM II compact core, this would allow a decrease of the enrichment down to 50% (MEU).

FRM II performed general feasibility calculations for a compact core of this type [13] and is also engaged on the experimental side of the development of the new fuel [3].

The general conditions for the fuel conversion of FRM II are:

- In all aspects the new core has to be as save as the current one
- The achievable cycle length must be at least 60 days at 20 MW power (today’s value)
- The neutron flux and quality have to be as high as currently (only marginal losses)
- Any conversion to lower enrichment has to be economically reasonable, i.e. operation costs increase only marginally

In the framework of this paper, it will be discussed how some of these requirements can be met using disperse UMo. The approaches are straight-forward, all design parameters are inherited directly from the current fuel element. In addition, two hypothetical scenarios to compensate the flux loss by a higher reactor power or a longer cycle length are given.

1.2 The X² program system

The X² program system is a new, coupled calculation system developed at FRM II. It couples the Monte Carlo code MCNPX (currently version 2.7.B) [1], the CFD code CFX (ANSYS, version 12) [2] and the burn-up program MonteBurns [4]. It is specialised on the simulation of compact research reactor cores.

The code system was validated by a code-to-code comparison on the results of the current fuel element of FRM II as calculated by [7,8,9] as well as comparisons to measured data as far as available [10]. All calculations are conducted in 3D as far as possible. Oxide layers, burn-up and heat distributions can be considered. The principal program flow of X² is shown in fig. 1. More details on the implementation in X², the choice of codes and the application to FRM II can be found in [11,12].

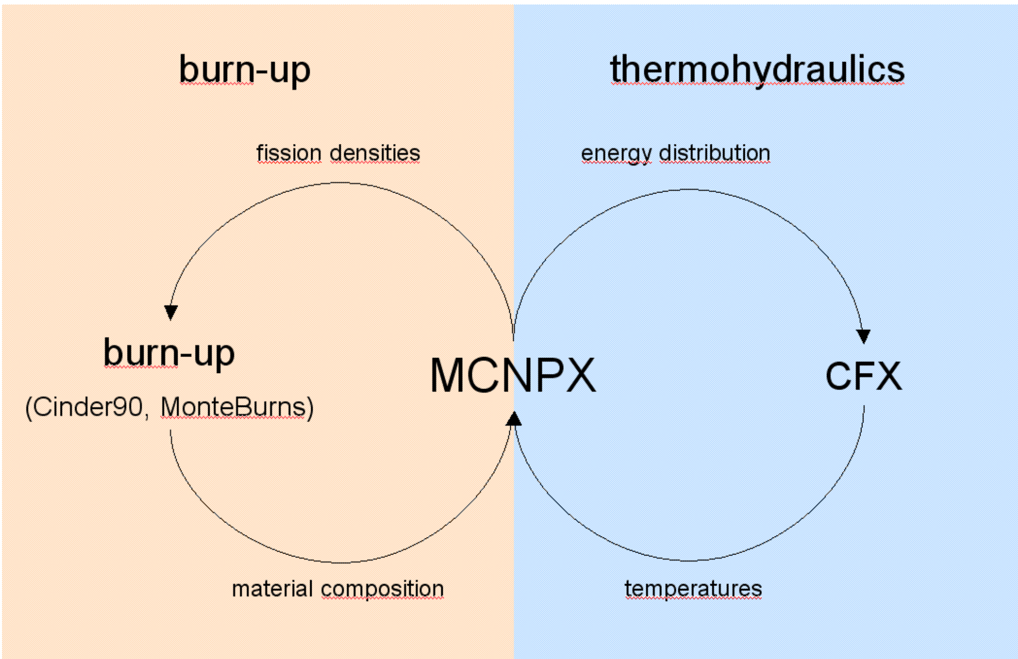

Fig 1: X² program flow

2. Scenarios

As mentioned before, two different main conversion options are considered. The minimum uranium density at 50% enrichment to guarantee a reactor cycle length of 60 days with disperse UMo is 7.5 g U/cm³. A higher density of 8.0 g U/cm³ permits further installations in the reactor or compensation for reactor degradation. It is obvious that a higher uranium density will worsen the neutronic and thermohydraulic properties of the core. Therefore, two “loss compensating” scenarios with a higher total power (22 MW instead of 20 MW) or a longer cycle length (66 d / 60 d) are discussed.

Figure 2 shows the predicted control rod driveway of FRM II for ulterior unchanged conditions compared to the current situation. The technical limit is a control rod position of +41 cm. The steeper slope at the very begin of the cycle (BOL) compared to the current situation originates from the lower excess reactivity due to the increased parasitic absorption from ^{238}U in the fuel. For the case of 8 g U/cm³ at 20

MW, the slope generally rises slower due to the higher remaining ^{235}U density during the cycle. The general steepening towards EOL is explained by the lower control rod reactivity worth as the rod position approaches it upper limit.

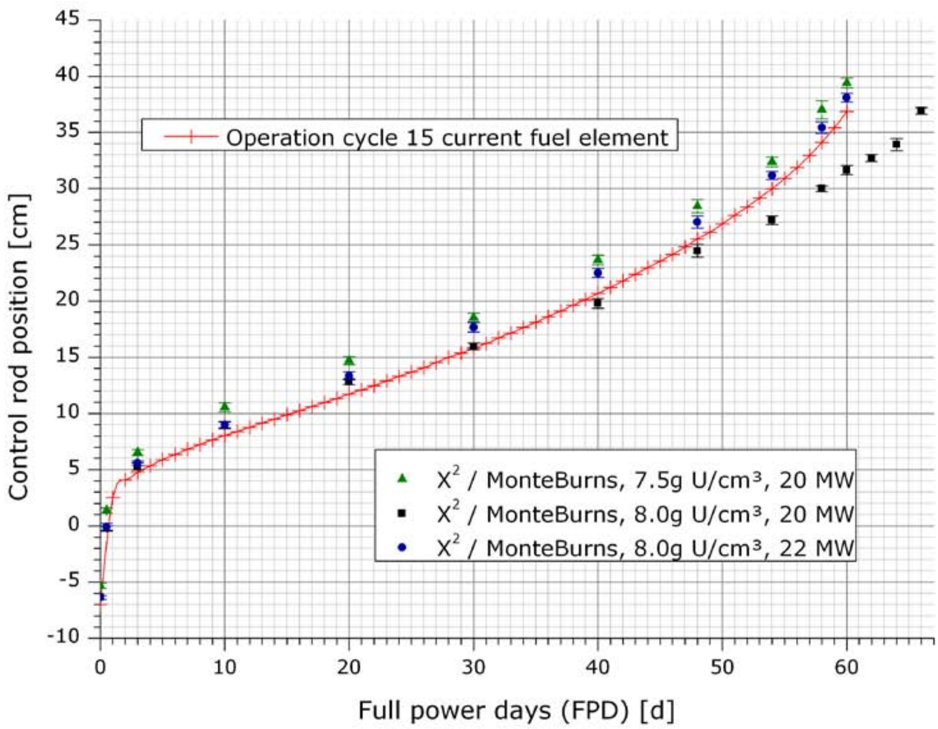

Fig 2: Predicted control rod driveway for different scenarios

An overview of the results of all four conversion scenarios and a comparison to the current situation can be found in table 1.

2.1 7.5 g U/cm³

Earlier calculations [13] already identified 7.7 g U/cm³ as the density to reach the same $\Delta\rho$ after 52 days of operation. Now, in a series of calculations, 7.5 g U/cm³ were identified as the minimum uranium density of disperse UMo to achieve a cycle length of 60 days. Despite the fact that the use of this minimum density leaves no room for optimisation of the reactor usage or compensation of the flux loss and reactor degradation, it has the less disadvantageous neutronic and thermohydraulic properties:

The maximum heat flux density rises to 401 W/cm² (up 5% from calculation for current situation), the maximum power density in the active zone rises by 7%. The maximum wall temperature rises only slightly by 1.5 K. The main drawback is a drop of the maximum neutron flux by 6.7%, as well as a drop of 6.2% of the cycle neutron yield in the BOL thermal flux maximum, $CNY(\vec{r}) = \int_0^T \phi(\vec{r},t) \cdot dt$.

However, experience with the current fuel element has shown that it is not only beneficial but necessary to have some reactivity reserve at the end of the cycle, which would not be the case with 7.5 U g/cm³.

2.2 8.0 g U/cm³

FRM II has always regarded 8.0 g/cm³ U-density as the most realistic solution for 50% enriched disperse UMo [13]. Therefore this scenario was analysed in greater detail and two options to compensate the resulting flux loss were studied. It is obvious that the flexibility gained by a higher uranium density has to be paid-off by less fortunate thermohydraulic and neutronic properties, amongst others a higher flux loss.

2.2.1 20 MW / 60 d

20 MW power and 60 days cycle length is the current situation at FRM II and the targeted minimum after the conversion of FRM II.

In the case of 8 g/cm³ uranium, the maximum heat flux density rises 6.5% to 407 W/cm². Wall and fuel temperatures are slightly higher than in the 7.5 g U/cm³-case but comparable. The maximum flux drops even more, -7.7%, as well as –7.1% for the cycle neutron yield in the flux maximum. The higher fuel density causes considerably higher local burn-up, $2.13 \cdot 10^{21}$ fissions/cm³. This is 7.6% higher than in the current situation and 4.4% higher than in the 7.5 g U/cm³-case.

2.2.2 20 MW / 66 d

Increasing the cycle length is one option to compensate the flux loss caused by the higher uranium densities. However, an increase in the cycle length is limited by the maximum burn-up the fuel can handle.

Obviously, thermohydraulic properties remain unchanged from the 60 days case. The 10% extra cycle length overcompensates the loss in the cycle neutron yield by about 2%. However, a 8% higher local burn-up than with 60 days cycle length has to be handled, now $2.30 \cdot 10^{21}$ fissions/cm³ in the maximum. Considering the present developments, it is rather unlikely that the fuel can withstand such a high a burn-up.

2.2.3 22 MW / 60 d

The third option, an increased reactor power while the cycle length is kept at 60 days, is of course the most welcome option but poses by far the highest burdens. As before, the very high burn-up has to be handled, but in addition higher demands on the cooling system have to be satisfied. The power increase would also require additional time- and labour-intensive licensing procedures for the reactor.

The power increase can be observed directly in all important thermohydraulic parameters: The maximum heat flux density at the plate surface has risen to

449 W/cm², 17.4% more than now. Compared to today's situation, the increase of the fuel temperature is 11.7 K, the maximum wall temperature rises by 7.1 K to 96.7°. According to 10% more power, the water heats up by 17.5 K instead of 15.9 K. The burn-up after 60 days is comparable to that after 66 days at 20 MW, $2.34 \cdot 10^{21}$ fissions/cm^3 (matching within estimated statistical uncertainty). In this scenario, the loss in CNY_{max} is overcompensated by about 2.5%. From the point of view of the users of FRM II, the situation remains unchanged from today if this scenario can be realised, which is very unlikely due to the implications discussed above.

2.3 Compact comparison

Quantity	Current	7.5g	8g	8g/66d	8g/22MW
Neutronic properties					
Max. burnup EOL [fis./cm^{-3}]	$1.98 \cdot 10^{21}$	$2.04 \cdot 10^{21}$	$2.13 \cdot 10^{21}$	$2.30 \cdot 10^{21}$	$2.34 \cdot 10^{21}$
Max. thermal flux [cm^{-2} s^{-1}]	$6.40 \cdot 10^{14}$	$5.97 \cdot 10^{14}$	$5.91 \cdot 10^{14}$	$5.91 \cdot 10^{14}$	$6.48 \cdot 10^{14}$
Cycle neutron yield [cm^{-2}]	$3.25 \cdot 10^{21}$	$3.05 \cdot 10^{21}$	$3.02 \cdot 10^{21}$	$3.31 \cdot 10^{21}$	$3.33 \cdot 10^{21}$
CNY_{max} compared to current		-6.2%	-7.1%	+1.8%	+2.5%
Thermohydraulic properties					
T_{max} fuel [°C]	102.9	108.2	108.2	108.2	114.6
T_{max} wall [°C]	89.6	91.1	91.8	91.8	96.7
T_{avg} outlet [°C]	52.9	52.9	52.9	52.9	54.5
q_{max} wall [W cm^{-2}]	382	401	407	407	449

Tab 1: Comparison of calculated neutronic and thermohydraulic properties (at BOL if not quoted otherwise)

The numbers quoted in tab. 1 apply to begin of live (BOL). The reactor model is axial symmetric and includes burn-up of the control rod. Temperatures were calculated by using UMo material data from Lee et al. [5], ranging from about 75 W/m K for 8g U/cc at room temperature to about 170 W/m K for 3.75g U/cc at 100°C. Due to lack of knowledge, no change of the thermodynamic properties of the fuel due to burn-up was included. A constant coolant inlet temperature of 37°C was assumed. Burn-up zones were chosen according to Röhrmoser et al. [6]. No oxide layer was taken into account as the data is for BOL.

3. Conclusions

It is apparent that 8g U/cc-22MW-60d is the most desirable scenario from the point of view of the scientists using the neutron source as it actually implies no change for users and instrument operators, but it is also the most demanding with respect to fuel qualification and reactor operation and very unlikely to be feasible. A scenario with 8g U/cc-20MW-60d produces the same cycle-neutron-yield without posing the burdens connected to an increase of the reactor power but still suffers from the very high burn-up of the fuel which is probably not achievable. However, if the current standard of 4 cycles per year should be kept, the shorter reactor down-times (-20%) will imply high demands on the operational team of the reactor. Accordingly, if feasible at all, only a fractional compensation of the flux loss due to the conversion seems to be a realistic option.

The two straightforward scenarios, a conversion without increase in cycle length and reactor power, deliver the most disadvantageous performance. Of those two, 8g

U/cc-20MW-60d is the most likely scenario, although it even underperforms 7.5g U/cc-20MW-60d. The latter leaves no room for increased reactor usage, neither does it contain any reactivity reserves to compensate reactor degradation due to aging or other flux depressing effects. Therefore, for a future-proof operation of FRM II using 50% enriched disperse UMo, a minimum uranium density of 8 g U/cm^3 is required.

Acknowledgements

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