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# PROGRESS REPORT ON THE DESIGN OF THE COMPACT CORE FOR UPGRADING THE MUNICH RESEARCH REACTOR

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## ABSTRACT

We are planning to modernize the research reactor FRM at Munich using a novel "compact core". This cylindrical fuel element has about 20 cm diameter and 70 cm height, is cooled by light water and surrounded by a large heavy water tank. Using the new $U_3Si/Al$ fuels with high enrichment (93%) and with an uranium density of 2.8 g/cm$^3$ a maximum thermal neutron flux $\Phi_{th}^{max}$ above $8 \cdot 10^{14}$ cm$^{-2}$s$^{-1}$ can be achieved in the $D_2O$-tank at only 20 MW reactor power. A reduction of enrichment to about 45% can be mostly compensated by an increase in uranium density up to 6.5 g/cm$^3$ and $\Phi_{th}^{max}$ is 8% smaller, then. In the case of 20% enrichment, however, the core volume must be enlarged significantly and $\Phi_{th}^{max}$ decreases by 32%. While these results have been obtained for a compact core with 18 concentric fuel plate rings, we also started to investigate an alternative version with 104 involute-type fuel plates. The first results are very promising, too.

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## CONCEPT

Our project is a major upgrade of the research reactor FRM at Munich. For that purpose we are working on the design of a particularly small, undermoderated core (with about 20 cm diameter and 70 cm height) which is cooled by light water and surrounded by a large $D_2O$ moderator tank (having both 250 cm diameter and height). This concept allows to achieve high values of the thermal neutron flux $\Phi_{th}$ outside of the core (i.e. in the $D_2O$ tank) already at modest reactor power /1-5/.

A more than 250 cm long, vertical core tube of about 20 cm inner diameter separates the core and its $H_2O$ cooling circuit from the surrounding $D_2O$. The reactor will be controlled by an absorber rod which moves in the central channel of the core. Independent from that the reactor can be shut down by absorber rods in the $D_2O$ tank which, however, are fully withdrawn during regular reactor operation. The main purpose of the $D_2O$ tank is to incorporate the user installations, i.e. horizontal beam tubes, vertical irradiation channels, and neutron spectrum modifiers (cold source, hot source, converter). Although calculations of the influence of these experimental facilities on the reactor are on the way, the following discussion always refers to the "unperturbed" situation in which the tank contains only $D_2O$.

Burnup calculations have been performed based on an earlier version of the core. The design of this "compact core 2" was similar to that to be shown later in this paper (Fig. 1a); it contained 6.99 kg of U235 /1,2/. From these calculations it was concluded, that an unperturbed value of the multiplication factor $k_{eff} \approx 1.22$ should be necessary for the cold, clean compact core 2 in order to operate the reactor for about 44 days at 20 MW under realistic conditions /3-5/. To be on the safe side we will require that $k_{eff} \geqq 1.24$ for any practicable compact core design to be discussed. This condition also reflects our feeling that from economical reasons the mass of U235 in the compact core should not be much larger than about 7 kg. On the other hand, this mass of U235 can not be much smaller than that either if we insist on a reactor cycle length of about 44 days at 20 MW. Considering the small volume of the compact core this means that the fuel packing density must be very high. It follows that the availability of the new high-density fuels, which are presently developed within the international reduced enrichment programs, is a necessary condition for a rigorous realization of the compact core. As we will see shortly, this statement is true even for the case of high enrichment, but all the more so in the case of reduced enrichment.

In what follows we present the results of two-dimensional neutronic calculations (DOT 3.5 code) for two technically different versions of the compact core, i.e. one with concentric and one with involute-shaped fuel plates. The long core tube was always assumed to consist of zircaloy of 10 mm thickness.

## COMPACT CORE WITH CONCENTRIC FUEL PLATE RINGS

An optimized version of the compact core with concentric fuel plate rings is shown in Fig. 1a. For this "compact core 5" the calculations concentrated on the case where the $U_3Si/Al$ dispersion fuel was assumed to be highly enriched (93% U235), because of the following reasons: the so obtained HEU results represent the proper reference for a comparison with other high flux reactors (which all use HEU fuel) and also for a comparison with compact core designs based on reduced enriched (MEU or LEU) fuel. Yielding the best results HEU fuel is also most attractive for the practical realization of the compact core.

According to Fig. 1a the 18 fuel plate rings are fastened to 6 aluminium supports and are characterized by fuel and cladding thicknesses of 0.55 mm and 0.33 mm, respectively. The relatively large width of the $H_2O$ cooling channels, 2.2 mm, leads to a sufficiently large fraction of neutrons thermalized whithin the core volume and so to a high enough value of $k_{eff}$ /3-5/. The inner and outer core radii are $R_i$ = 3.51 cm and $R_o$ = 9.87 cm, respectively, as defined by the dimensions of the 6 supports (which are 5.6 mm thick). The innermost guide tube consists of 2.5 mm aluminium. The active core height is H = 70 cm, but the fuel plates are extended on each end by 6 cm aluminium plates. After subtraction of the fuel-free regions around the 6 supports, the active core volume is $V_a$ = 16.4 liter and the total heat exchange surface $S_a$ = 9.31 $m^2$. It follows that at P = 20 MW the average power density is $P/V_a$ = 1.22 MW/l and the average heat flux density $q = P/S_a$ = 215 $W/cm^2$, which both are values already obtained or even surpassed at other high flux reactors.

Using high enriched (93%) fuel a relatively modest value of the uranium density, $\rho_u$ = 2.8 $g/cm^3$, is sufficient for obtaining a U235-mass within the limits discussed above, 6.66 kg. The results of our two-dimensional neutron transport calculations for this version of the compact core 5 are shown in line (a) of Table 1. One can see that $k_{eff}$ = 1.271 is safely above the required value and that the maximum thermal neutron flux in the $D_2O$ tank is $\phi_{th}^{max} = 6.63 \cdot 10^{14}$ $cm^{-2}s^{-1}$. Due to the self-shielding of the active core region the neutron absorption is increased close to the (inner and outer) core surface and so is the heat flux density in the core yielding a maximum value $q_{max}$ = 600 $W/cm^2$.

It is an inherent advantage of the concentric compact core that its power density profile can be flattened by simply varying the uranium density $\rho_u$ from ring to ring. Assigning to the 18 fuel plate rings values of $\rho_u$ = 1.65/2.3/14 x 2.8/2.3/1.65 $g/cm^3$ the total U235-mass slightly decreases to 6.22 kg, but line (b) of Table 1 shows that $q_{max}$ is drastically smaller now.

Due to the relatively small central $H_2O$ channel (Fig. 1a) the compact core 5 can not be controlled by one central absorber rod alone, but only by the combined action of control rod and burnable poison. So we have homogeneously mixed 5 g of B10 (25 g of natural boron in the form of $B_4C$) to the fuel and the results for this core are shown in line (c) of Table 1. If we additionally include a hafnium control rod of 3.15 cm outer radius and 5 mm thickness, we obtain the results

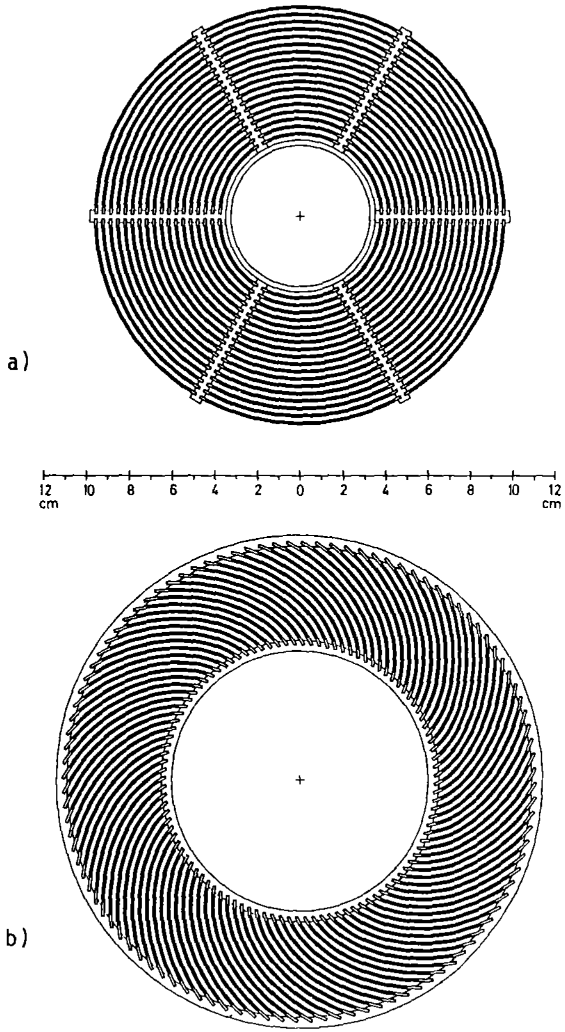

Fig. 1: The compact core with 18 concentric fuel plate rings (a, "core 5") or with 104 involute-shaped fuel plates (b, "core E5").

of line (d) of Table 1. It follows that $k_{eff}$ = 1.014, now, which means that the compact core 5 can be safely controlled if we additionally consider a constant reactivity loss $\Delta k_{eff} \approx -0.03$ due to the experimental installations in the $D_2O$ tank.

A comparison of lines (b-d) of Table 1 shows that the action of both burnable poison and control rod leads to a tolerable increase of the maximum heat flux density $q_{max}$. This behaviour is a consequence of the "shift" of the neutron flux distribution in the core more to the outer regions due to these additional absorbers. On the other hand, this effect also leads to a favourable enhancement of the thermal neutron flux in the $D_2O$-tank up to a value of $\phi_{th}^{max} = 8.67 \cdot 10^{14}$ $cm^{-2}s^{-1}$. During operation of the reactor the burnable poison will continuously be "eaten up" and the control rod slowly be withdrawn from the core, but the corresponding increase of burnup leads to a similar enhancement of $\phi_{th}^{max}$. It follows that during practical operation of this compact core 5 the (unperturbed) value of $\phi_{th}^{max}$ will always be about $8 \cdot 10^{14}$ $cm^{-2}s^{-1}$.

After 44 days of reactor operation at 20 MW about 1.10 kg U235 have been used up. For the core with density variation this leads to an average relative burnup of about 18%. Assuming a ratio of maximum to average burnup of 2.0 the local maximum burnup will be 36%. This value corresponds to a maximum fission density in the fuel of about $1.9 \cdot 10^{21}$ $cm^{-3}$ which is relatively high.

The ratio of maximum thermal flux $\phi_{th}^{max}$ (outside of the core) to reactor power P can be considered as a "figure of merit" of beam tube research reactors. For comparison purposes we have recalculated $\phi_{th}^{max}$ for the best representative of this kind of reactors, the high flux reactor HFR of the ILL Grenoble. Without both control rod and burnable poison we obtained $\phi_{th}^{max} = 1.31 \cdot 10^{15}$ $cm^{-2}s^{-1}$ at the nominal power P = 57 MW, which corresponds to a "quality factor" of $\phi_{th}^{max}/P = 2.3 \cdot 10^{13}$ $cm^{-2}s^{-1}MW^{-1}$. For the same situation line (b) of Table 1 yields a value of $\phi_{th}^{max}/P = 3.5 \cdot 10^{13}$ $cm^{-2}s^{-1}MW^{-1}$ for the compact core 5. So the quality factor of the compact core reactor is larger than that of the HFR by about 50%, which represents the essential progress inherent in the compact core concept. On the other hand, if we compare those volumina $V_{eff}$ in the $D_2O$ tank where $\phi_{th} \geqq 0.7 \cdot \phi_{th}^{max}$ we obtain that $V_{eff}$ of the compact core reactor is only about half of that of the HFR. So it is evident that a rigorously optimized compact core design certainly is the best choice for a "small" high flux reactor.

Based on the results for the highly enriched compact core 5 we studied the influence of an enrichment reduction on the core performance. Line (e) of Table 1 refers to the case of medium enriched fuel (45% U235, MEU), assuming an uranium density of $\rho_U = 6.5$ g/$cm^3$ which is about the largest possible value to be achieveable with the new $U_3Si/Al$ dispersion fuels. The geometry and the other materials of this core were exactly as before. We see from Table 1 (lines e and a)

|  | U235 mass (kg) | $k_{eff}$ | $\Phi_{th}^{max}/10^{14}$ ($cm^{-2}s^{-1}$) | $q_{max}$ ($W/cm^2$) |
|---|---|---|---|---|
| compact core 5<br>($R_i$=3.51cm, $R_o$=9.87cm, H=70cm) |  |  |  |  |
| a) 93% and 2.8 $gU/cm^3$ | 6.66 | 1.271 | 6.63 | 600 |
| b) " " density variation | 6.22 | 1.254 | 6.93 | 438 |
| c) " " " + 5 g B10 | " | 1.164 | 7.34 | 476 |
| d) " " " " + 5 mm Hf | " | 1.014 | 8.67 | 540 |
| e) 45% and 6.5 $gU/cm^3$ | 7.43 | 1.228 | 6.64 | 630 |
| f) " " " but H = 80 cm | 8.49 | 1.250 | 6.12 | 571 |
| g) 20% and 6.5 $gU/cm^3$, but $R_o$ = 12.60 cm and H = 90 cm | 7.54 | 1.265 | 4.51 | 253 |
| compact core E5<br>($R_i$=6.50cm, $R_o$=10.91cm, H=70cm) |  |  |  |  |
| h) 93% and 2.8 $gU/cm^3$ | 6.64 | 1.263 | 6.54 | 515 |
| i) " " " + 5 mm Hf | " | 1.002 | 8.41 | 648 |

Table 1: Results of two-dimensional neutron transport calculations

that the mass of U235 is even larger now than in the HEU case, which means that the decrease in enrichment has actually been overcompensated by the increase in density. However, because of the higher resonance neutron absorption of U238 the value of $k_{eff}$ of this MEU core is too small and would even become smaller by the application of the density variation concept (as can be seen by comparing lines a and b of Table 1). In order to obtain a higher value of $k_{eff}$ it is necessary to increase the active core volume /3/. In line (f) of Table 1 the active core height has been increased from 70 to 80 cm leaving all the other core parameters unchanged. Considering the comparatively large mass of 8.49 kg U235, which leads to a slightly smaller rate of decrease of $k_{eff}$ during the reactor cycle, the multiplication factor $k_{eff}$ is sufficiently large now. Due to the larger core volume both the average and the maximum heat flux density (i.e. $q_{max}$) are somewhat smaller now. The most interesting quantity, the maximum thermal neutron flux $\Phi_{th}^{max}$, has decreased by about 8% with respect to the HEU case (as can be seen by comparing lines f and a of Table 1). So we conclude that a reduction of enrichment from 93% to about 45% could be realized without having too negative an influence on the performance of the compact core.

The situation becomes drastically worse, however, if we go to the case of low enrichment (20% U235, LEU), since no further increase in the uranium density $\rho_u$ is presently possible. In order to obtain sufficiently high values of $k_{eff}$ a significant increase in the active core volume can not be avoided. In line (g) of Table 1 the core height has been increased to 90 cm and the outer core radius to 12.60 cm. All the other core parameters remained as before (although a technical design would certainly provide more than 6 aluminium supports, now). These changes result in a mass of 7.54 kg U235 which is a reasonable value. Because of the large core volume the multiplication factor $k_{eff}$ is high enough and the maximum heat flux density $q_{max}$ comparatively low. This last point implies, of course, that the reactor power could be increased significantly beyond 20 MW for this core without any problems. However, since we prefer for economical reasons to keep to 20 MW, the maximum thermal neutron flux $\phi_{th}^{max}$ would be as low as $4.5 \cdot 10^{14}$ $cm^{-2}s^{-1}$, now. This penalty of a decrease of $\phi_{th}^{max}$ by about 32% with respect to the HEU case seems unacceptable to us.

Recently a 60°-segment of the compact core (in a version very similar to that shown in Fig. 1a) has been fabricated by the Nukem company. This segment is presently used for thermal hydraulic tests at the nuclear research center KfK Karlsruhe.

## COMPACT CORE WITH INVOLUTE-CURVED FUEL PLATES

An alternative possibility to realize the compact core concept is an arrangement in which the fuel plates are curved in the form of involutes, see Fig. 1b /5/. Such a design also provides a constant width of the cooling channels. Cores of this type, but with larger dimensions, are used in the high flux reactors HFR, Grenoble, and HFIR, Oak Ridge.

The design of Fig. 1b is characterized by the same active volume and by the same fuel plate lattice as the concentric core 5 (Fig. 1a), whence we may label this core version as "compact core E5" (from the German "Evolvente" for involute). If we concentrate again on the case of high enrichment (93%) with an uranium density $\rho_u$ = 2.8 g/cm$^3$, line (h) of Table 1 shows that this core E5 contains 6.64 kg U235 which is about the same as that of the concentric core 5 without density variation (line a of Table 1). The useable space between the two aluminium tubes, which both are 5 mm thick, is defined by inner and outer radii $R_i$ = 6.50 cm and $R_o$ = 10.91 cm, respectively. The shape of the involutes was obtained by the condition that, for technical reasons, the radius of curvature of the fuel plates should never be smaller than 3.5 cm (which again corresponds to the situation with core 5). The active core height was H = 70 cm as before. These dimensions seem to be about the most compact ones which can be technically realized for this type of core. The design of Fig. 1b has 104 fuel plates.

The long, vertical core tube separating the core and its $H_2O$ cooling circuit from the surrounding $D_2O$ must now have an inner diameter of nearly 23 cm, of course. It was clear from the beginning that it would be necessary to replace the strongly absorbing water in the large central channel of core E5 by some moderator of higher quality; otherwise the multiplication factor $k_{eff}$ would be too low. In the following we assumed this inner moderator to be beryllium, leaving only a gap of 9 mm $H_2O$ to the inner aluminium tube for the insertion of the control rod (not shown in Fig. 1b).

The results of our two-dimensional transport calculations for this compact core E5 (without control rod) are given in line (h) of Table 1. We see that the value of $k_{eff} = 1.263$ is safely above the required limit now. The maximum thermal neutron flux $\phi_{th}^{max}$ in the $D_2O$-tank is only slightly smaller than that of the concentric core 5 without and even with density variation (compare lines a and b of Table 1). This shows that the unavoidable small increase in the dimensions of the involute-shaped core E5 with respect to core 5 can be compensated to some extent by the better quality of the inner moderator.

If we insert a control rod of 5 mm thick hafnium into the central channel, leaving water gaps of 2 mm each on either side, we obtain the results of line (i) of Table 1. The value of $k_{eff} = 1.002$ shows that this core E5 can be safely controlled by the absorber rod alone if we again consider a constant loss of $\Delta k_{eff} \approx -0.03$ due to the experimental installations in the $D_2O$-tank. So, in contrast to the situation with the concentric core 5, additional burnable poison is not primarily necessary for the involute-shaped core E5, since the reactivity worth of the absorber cylinder is larger now as a consequence of the larger surface. The calculation yields a maximum neutron flux $\phi_{th}^{max} = 8.41 \cdot 10^{14}$ $cm^{-2}s^{-1}$ which is only about 3% smaller than that of core 5 (as follows from lines i and d of Table 1). It would, however, be more difficult to operate this core E5 at the design power of 20 MW since the maximum heat flux density $q_{max} = 648$ $W/cm^2$ is very high. What we are trying to do now is to somewhat flatten the power density profile and to improve the cooling behaviour by slightly increasing the cooling channel width as a function of radius in the outer core region, which can be achieved by a slight deviation of the fuel plate shape from the exact involute curve. For economical reasons we do not intend to vary the thickness of the fuel layer in the plates, as it is done at the HFIR reactor at Oak Ridge.

In conclusion we would like to point out that the involute-type compact core could be very attractive, too, if this cooling problem can be somewhat relaxed. There are also some fabrication aspects which have to be treated in more detail yet. The involute-type core is supposed to offer somewhat reduced fabrication costs, since all the fuel plates are identical, and also some advantages with respect to mechanical stability and control behaviour. A reduction of the thermal neutron flux being as small as in Table 1 (lines d and i) could certainly be tolerated.

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