Innovative investigation of reflector options for the control of a chloride-salt based molten salt zero power reactor

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Abstract

Molten salt reactors have gained substantial interest in the last years due to their flexibility and their potential for simplified closed fuel cycle operation for massive net-zero energy production. However, a zero-power reactor experiment will be an essential first step into the process delivering this technology. The choice of the optimal reflector material is one of the key issues for such experiments since on the one hand it offers huge cost saving potential due to reduced fuel demand, on the other hand an improper choice of the reflector material can have negative effects on the quality of the experiments. The choice of the reflector material is for the first time introduced through a literature review and a discussion of potential roles of the reflector. The 2D study of different potential reflector materials has delivered a first down selection with SS 304 as representative for stainless steel, lead, copper, graphite, and beryllium oxide. A deeper look identified in addition iron-based material with high Si content. The following evaluation of the power distribution has shown the strong influence of the moderating reflectors creating a massively disturbed power distribution with a peak at the core boundary. This effect has been confirmed through a deeper analysis of the 2D multi-group flux distribution which lead to the exclusion of the BeO and the graphite reflector. The most promising materials identified have been SS 304, lead, and copper. The final 3D Monte-Carlo study demonstrated that all three materials have the potential to reduce the required amount of fuel by up to 60% compared NaCl which has been used in previous studies and is now taken as reference A first cost analysis has identified the SS 304 reflector as the most attractive solution. The results of the 2D multi group deterministic study and the 3D multi group Monte-Carlo study have been confirmed through a continuous energy Monte-Carlo reference calculation showing only minor differences.

Keywords:

Nuclear; Nuclear Reactors; Reactor Physics; Nuclear Experiments; Zero-Power Reactors; Modelling & Simulation; Molten Salt Reactors

Introduction

Zero or very low power experiments are recognized as the first step into a new reactor technology, historically [1] as well as in the recently published new development process [2] and in recently initiated programs [3]. The major point in the past has been to test new configurations in safe settings and to use opportunity of these highly flexible experiments to create an accelerated learning curve at the beginning of a new technology. In new programs, there is the additional demand to provide safety demonstrations and to validate code systems to assure the quality of the predictions for the next step, while using this multi-fold opportunity for learing in manufacturing and educating future reactor physics experts. [4]

The first part of this current series of publications on zero-power studies delivers on the importance of a zero-power reactor experiment for the process of developing a new, innovative reactor concept in the form of a molten salt fast reactor and the challenges, due to the homogeneous core composition (unity of coolant and fuel) are worked out [5]. The second part delivers on new approaches for the control and shutdown of a homogeneous core experiment [6]. This will be complemented with this study of the choice of the neutron reflector as an essential part for efficiently operating small reactor cores, especially in the case of the fast neutron spectrum.

The reflector is an essential part of all operating reactors, as well as for a wide variety of reactor experiments. However, the reflector sometimes fulfils completely different demands in different reactors, e. g. protecting essential components versus improving the neutron economy and can be formed easily out of coolant, normal structural materials of the reactor, or from a special material.

In light water reactors, the reflector is just provided by the light water coolant and the core barrel and partly the outer row of the low leakage loading could also be seen as a kind of reflector. The major function of the reflector materials in LWRs is to protect the pressure vessel from high energy neutron flux to keep the fluence on the vessel within an acceptable limit over the lifetime [7]. In high temperature reactors such as the AVR [8] and the THTR [9] the major aim of the reflector is to improve the neutron economy; thus, graphite is used as the reflector and it is also used as a structural material.

It is interesting to recognize that the relative size of the reflector is significantly decreasing with increasing core size. This just demonstrates that the relevance of the reflector is decreasing with decreasing surface to volume ratio. An interesting and relatively new approach is the proposed use of BeO reflector. In the micro reactor concept U-Battery, this approach has been proposed to reduce the core size. In comparison to the classical graphite reflector a clear size reduction can be achieved, however this size reduction comes with a significant cost due to the more exotic reflector material [10].

Sodium cooled fast reactors are significantly different in the design of the reflector, due to the closed system and the high energy fast neutron flux, resulting in different approaches. The reflector in a SFR like the pool type PFBR [10], comprises several rings, starting with the breeding blanket to improve neutron economy while breeding fresh fissile material, followed by a steel reflector and a B4C shield which can be seen as the core. This area is followed by the internal vessel storage for the fuel, required due to the high decay power of the fuel assemblies when unloaded from the core. The internal storage is surrounded again by a stainless-steel reflector and finally a large B4C shielding to prevent the heat exchanger containing secondary sodium from the high energy neutron flux which could otherwise lead to activation of this secondary coolant. New investigations have been recently delivered with the aim to replace a part of the reflector with more advanced material like ferroboron [12]. It is impressive to see the dimensions, while the Core consists of the ~9 inner rings, the described outer structure consists of 14 rings leading through the increase of the size of the rings to ~200 core assemblies compared to ~1300 assemblies in the outer structure.

The very significant role of the reflector in critical experiments is maybe best demonstrated with the last documented criticality accident at Sarov (Arzamas-16) in 17 June 1997 [13]. This accident was caused when reproducing an experimental setup which had been already used in the 1970ies. "He [the experimenter] had taken the dimensions for all of the system components from the original 1972 logbook. However, when he copied down the inside and outside dimensions of the copper reflector (167 and 205 mm, respectively) he incorrectly recorded the outside dimension as 265 mm." When assembling the experimental setup this change in the reflector led to a prompt critical spike and the ~6.5 day excursion. In general, in most of the nuclear experiments, the reflector is an essential piece to improve the neutron economy leading to a reduced demand of fissile material and thus to reduce the cost. However, the reflector has the potential, not only to reduce cost, but also to influence the results of future experiments which can lead to significant problems, e. g. in YALINA experiments the idea to support the fast reactor configuration by a decoupled thermal system with the aim to boost criticality has lead to some really surprising and hard to explain results [14] caused by the penetration of thermal neutrons into the fast region [15], thus an improper decoupling of the fast system from thermal system has finally taken place in the real experiment.

An additional challenge for future projects is the required and requested flexibility of a multi-purpose facility for reactor physics of advanced, molten salt-based reactor systems which may need different reflectors for each technology considered, which in turn may have contrasting neutron spectrums. The primary focus of this work is on a fast system, but with a clear outlook into flexible multi-purpose operation for the long term. This forms a secondary focus to keep in mind the view and the requirements of the reflectors that are suitable for a potential future experimental investigation of a thermal core. The investigation will start from a generic reflector which has been used in the previous studies [5, 6] and will proceed into an investigation to support the right choice of the ideal reflector for a molten salt zero power reactor answering the research question "Which reflector material will assure the best possible performance in a fast reactor experimental configuration?"

The investigation will start with the discussion of the different roles of the reflector followed by a broad investigation of different potential materials and a refined investigation of a down selected number of attractive materials. It will be finished by a verification of the results with alternative calculation methods and a test of the stability of chosen material for the control and shutdown proposals of [6].

The role of the reflector

A part of the different roles a reflector can play in a nuclear reactor and in nuclear experiments has already been discussed in the review of existing solutions in the introduction. However, it is important to collect all functions of the reflector and all requests to the reflector in the case of a zero-power experiment, both points will be delivered in this section.

Theoretically, the main aims of a reflector that surrounds a nuclear reactor or experiment are:

- Saving neutrons by improving neutron economy
- Protecting the environment from radiation
- Protecting the experiments from the environmental influence
- Potential control moving reflector, carrying of control system through rod or drums

- Possibility for massive saving in cost

The potential savings of adding a reflector to a zero power reactor core has been investigated using a NaCl reflector for two different systems, one system based on a eutectic NaCl-UCl_x fuel 42.5% NaCl- 40.5 UCl_4- 17% UCl_3 (denoted 42.5% NaCl) and a second heavy metal rich system with 20%NaCl-56.35%UCl_4-23.65%UCl_3 (denoted 20% NaCl) [24]. For both salt systems the volume gain of adding a 30 cm thick NaCl reflector has been determined and is given in Figure 1. There is a clear trend that the gain will increase with decreasing core size, which seems to be natural while the gain for the heavy metal rich system is not very pronounced and can may even be explained by the slightly reduced core size. However, it is clear from the figure that the volume of the fuel required for the experiment can be reduced by between 30 and 45% when a 30 cm thick NaCl reflector is applied.

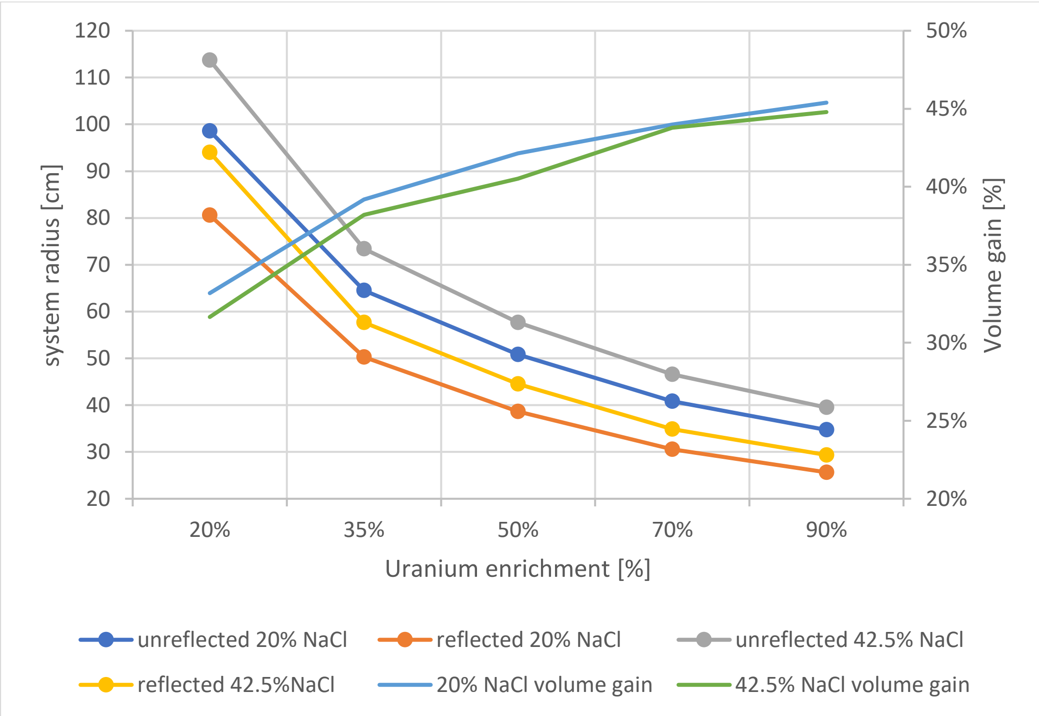


Figure 1: Generic 2D calculated system size depending on the fuel enrichment for the eutectic and the heavy metal rich system and the fuel volume reduction achieved through a 30 cm thick NaCl reflector calculated with SACLE/POLARIS [24]

In addition to the potential gain and the protection effect of the reflector in nuclear reactors, some very specific demands on the reflector have to be kept in mind for a zero-power experiment, with some additional specifics for a molten salt reactor experiment:

- The reflector should save as many neutrons as possible – reducing cost and reducing the core size or enrichment
- The reflector should only have limited effect on the neutron spectrum which will have influence on the power production/neutron flux at the core boundary in the spatial as well as the energy distribution
- The reflector should be usable for all temperature ranges of the experiment
- The reflector should not disturb potential kinetic experiments – long life of neutrons e. g. in graphite or neutron production in the YALINA experiment
- The reflector should cause only limited disturbance of the natural neutron flux distribution of a homogeneous fast system

- The reflector could act as a moderator for the thermal system or could provide additional neutrons, e. g. a hybrid system like in the YALINA experiments

The core study will focus on the experiments for the fast system as envisaged for iMAGINE [2], a system operating on spent nuclear fuel without prior reprocessing [16], but some outlook will be given on the multi-purpose use for future investigations of a thermal system.

Codes and Data

Based on the given salt system investigation [17] for iMAGINE and the dimensions study [5], the applied standard salt composition for the study for the nominal case, is the heavy metal rich composition 20%NaCl-56.35%UCl_4-23.65%UCl_3. This composition has originally been studied for the required thermo physical properties by [25]. In addition, some comparative studies are based on the eutectic 42.5% NaCl- 40.5 UCl_4- 17% UCl_3.

The simulations for this step of the study of the zero-power reactor configurations have been mainly performed using TRITON/NEWT sequence of the SCALE code system [19]. Applying TRITON for the preparation of the shielded multi-group cross section set and NEWT for the 2-D transport solutions for the core part of the study. This is complemented with the use of Keno VI (multi-group as well as continuous energy) for creating 2-D cross checking solutions as well as for the following 3-D studies using the multi-group solver and the continuous energy solver for cross testing. For TRITON the v7-252 cross section set of the SCALE package has been used, which is based on ENDF/B 7.1. The sequence and the cross section set is also the basis for the multi-group cross section preparation for the multi-group (MG) Keno VI calculations while the continuous energy version uses the ce_v7.1_endf library of the SCALE package

For the TRITON/NEWT study, two specific 2-D models for a fast molten salt reactor have been built for the simulation, Figure 2. Both NEWT models, reflect a 2-D quarter of the core with x-y discretization consisting of the ring core (with added ring shaped discretization for the evaluation of the power distribution), the steel vessel surrounded by reflector while the rest of the cell is filled with vacuum using reflective boundaries at the bottom and the right side and vacuum boundaries at the other two sides. The 2-D and 3-D Keno VI models shown in Figure 3, reflecting a cylindrical core surrounded by a vessel and a reflector on all sides for the 3D model and reflective boundary conditions at top and bottom for the 2-D model were used for cross testing with the NEWT results.

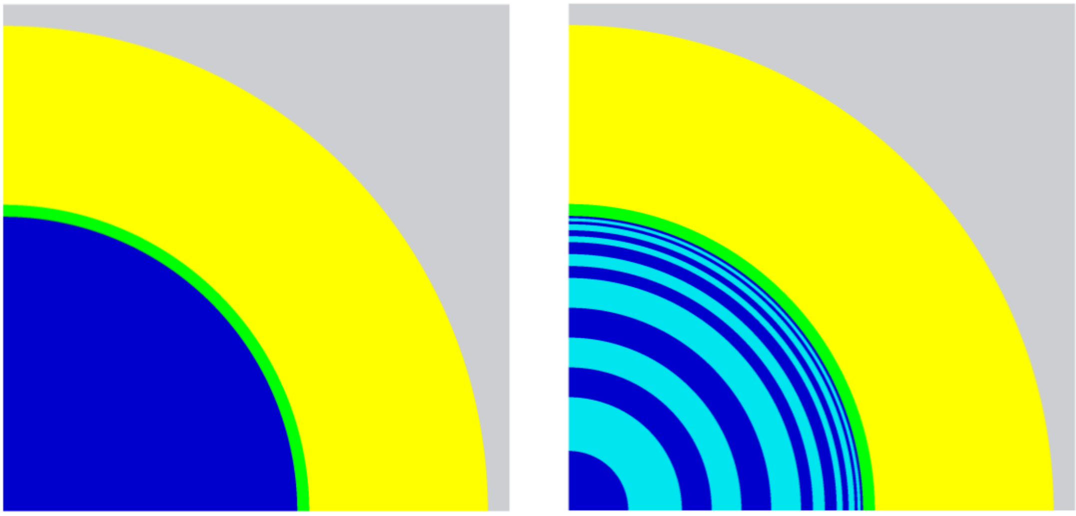


Figure 2: TRITON/NEWT model for the 2D study of reflector materials (left) and for the analysis of the variation of the effect of different reflector thickness (the thickness of the green reflector region is varied). The evaluation of the power distribution in the 2D system is based on a ring structure in the core (right); molten salt core – blue, steel vessel – light green, reflector – yellow, surrounded by vacuum - grey

Figure 3: General 2D (left and centre) Monte-Carlo model of the configuration (left, top view x-y, centre front view x-z) and 3D (left and right) Monte-Carlo model of the configuration (left, top view x-y, right front view x-z) with molten salt fuel core – blue, stainless steel vessel – light green, reflector – yellow, and vacuum - grey used for the validation of the results and the 3D studies

Test of different materials

The study of the optimization of the reflector is in the first step based on the 2D critical reference system with the following dimensions, core radius 49.4 cm in a 2 cm thick SS 304 vessel surrounded by a 30 cm thick NaCl reflector, see arrangement given in Figure 2, and calculated using TRITON/NEWT. In the first analysis typical materials used in nuclear reactors and experiments are investigated and the change in criticality is shown in Figure 4. The big influence of the reflector on the system criticality is just visible through the between the Helium case (reference for a non-reflected system) with k_{eff} = 0.743393 and the graphite case with k_{eff} = 1.190281, which would at the end reflect in a massive difference in the required amount of fissile material for the experiment leading ultimately to massive cost savings. Beside graphite, the investigated high density metals lead to a clear increase in criticality while the low density light metal sodium as well as water and the shielding material ferroboron [12] lead to a reduction of criticality compared to the reference material NaCl.

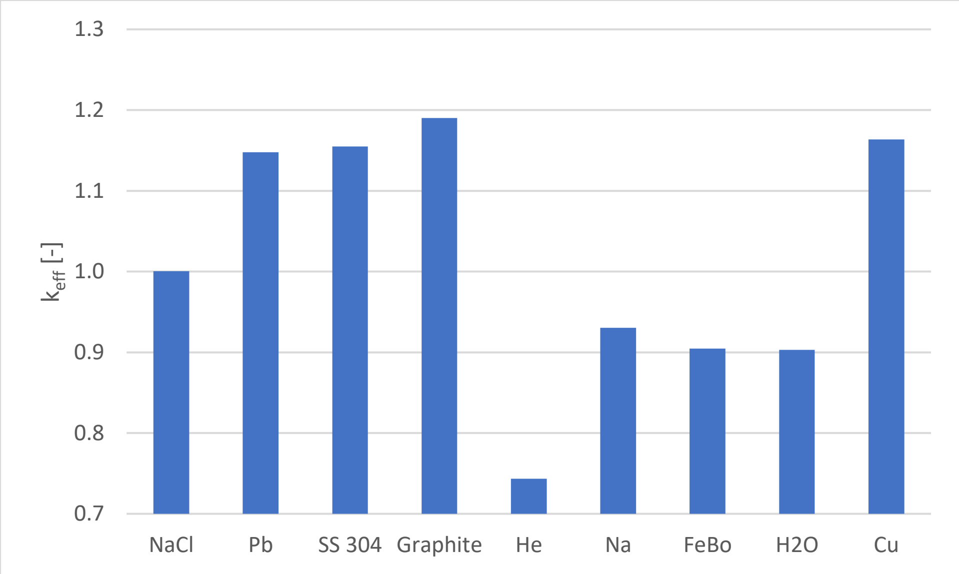


Figure 4: Analysis of the effect of a 30 cm thick reflector made from different materials used in nuclear reactors and experiments on the criticality of the studied 2D test core

In the next step the study has been widened on the one hand to more exotic materials for reactor use which are sometimes proposed for future reactor systems, or for very specific issues in reactors. On the other hand, a more in-depth analysis is performed to understand the big difference between carbon steel containing 99% iron, 1% carbon, k_{eff} = 1.127055 and stainless steel SS304, k_{eff} = 1.155004. This is achieved by systematically studying the separate effect of the main alloying elements: chrome, nickel, manganese, silicon, each singled out in a composition with 20% of the alloying element in 80% iron. The results of this single effect study are shown in Figure 5. The study of the alloying elements indicates a strong influence appearing in the case of the addition of silicon. In addition, the study of alternative reflector materials indicate a very high k_{eff} for using BeO as reflector material. Two other often proposed hydrogen rich reflector materials, polyethylene and ZrH_2 do not deliver the expected improvement of criticality when used as reflector material.

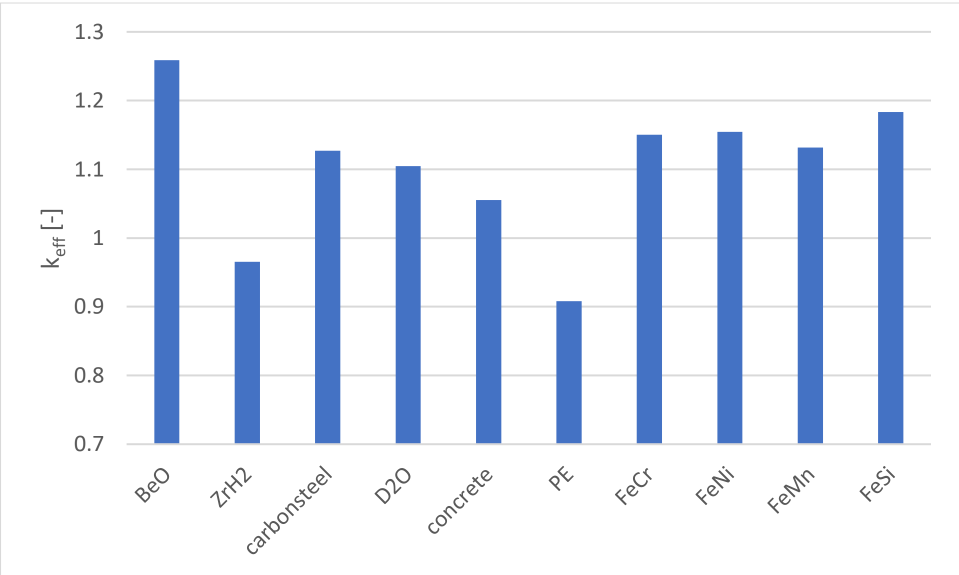


Figure 5: Analysis of the effect of a 30 cm thick reflector made from different, more exotic materials on the criticality of the studied 2D test core

Based on the finding of the very strong influence of silicon on the effect of the reflector, some existing typical high silicon materials have been investigated in the last step of the materials study with very positive results for cast iron with high (GJS-XSiMo 5.1 - https://www.brechmann-guss.de/wp-content/uploads/2016/07/Datenblatt-SiMo.pdf) and very high silicon content (Hi Si cast - https://inis.iaea.org/collection/NCLCollectionStore/_Public/35/066/35066186.pdf , see Figure 6. For comparison two artificial materials have been added – SS304 with an additional 10% of Si and an artificial ferrocarbon replacing boron by carbon while using the other data from FeBo [12]. Note that the data for SS304 is given on the left end of the figure for comparison. Based on these results Hi Si cast could be an interesting alternative to stainless steel, but only in the case that it would be financially more attractive; thus it must be cheaper or on the same level as SS304, which seems to be doubtful taking into account the amounts of stainless steel used in the modern world.

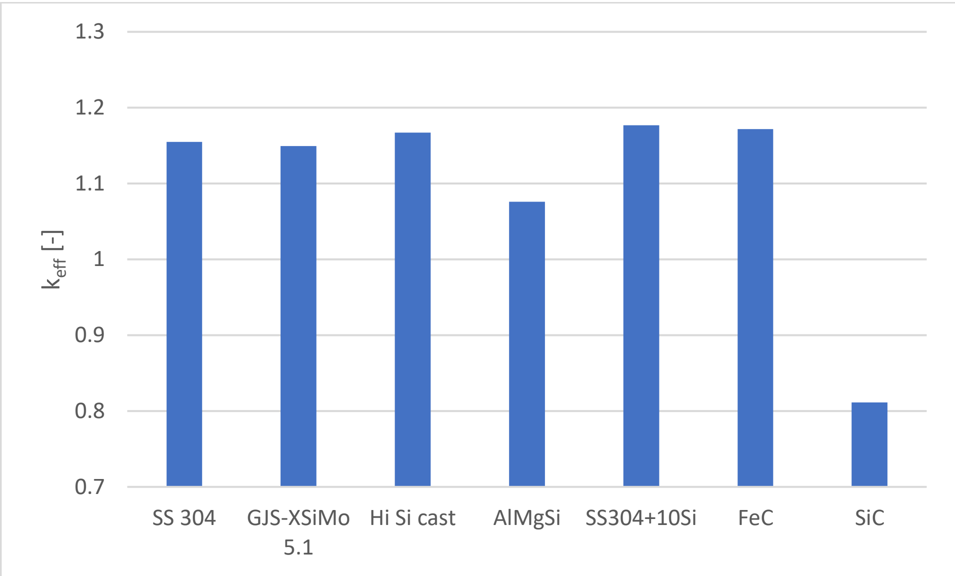


Figure 6: Analysis of the effect of a 30 cm thick reflector made from different silicon and carbon rich materials on the criticality of the studied 2D test core

Finally, it is important to understand the effect of the reflector temperature on the efficiency of the reflector, since most probably a zero-power reactor experiment will be operating at room temperature in the first stage of the tests, while in the longer term it could be of interest to operate at higher temperatures up to the potential maximum operation temperature of ~800 K to see the operational conditions and behaviour in real molten salt instead of solid salt. Even if the reflector itself will not be directly in contact with the salt, there will be an elevated temperature level in the whole system. It is important to understand that a potential material would work properly for the first stage of the test on room temperature as well as for the later hot tests. In Figure 7, a very systematic final check for the effect of materials is given for scoping for different materials at room temperature as well as at the standard investigation temperature based on the maximum temperature of 800 K for the reflector. The results show only a very weak dependence of the reflector effect on the criticality of the temperature seething of the reflector for the metal-based materials. A more pronounced effect is only visible in the case of a hydrogen rich reflector such as PE.

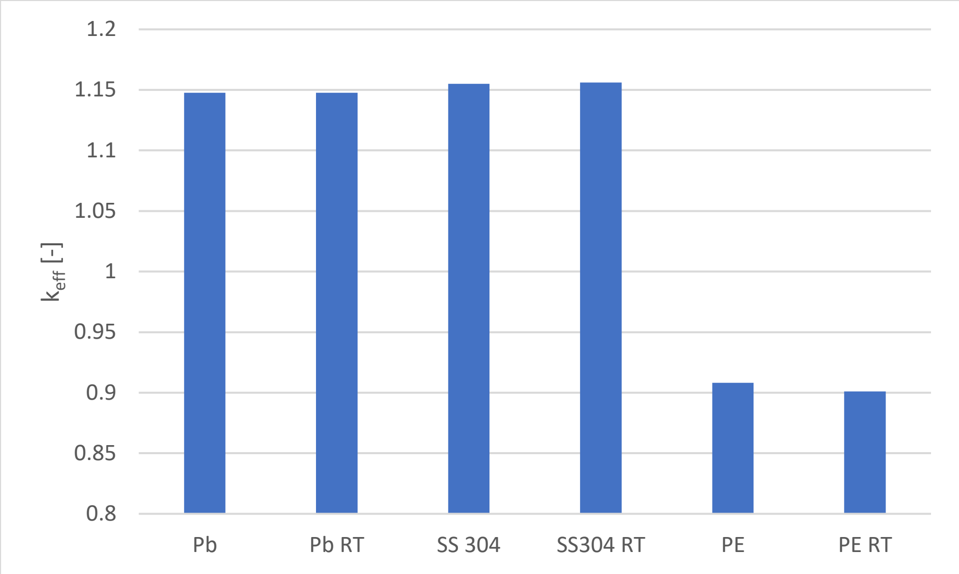


Figure 7: Scoping analysis of the effect of the operational temperature (800 K versus room temperature, RT) of the 30 cm thick reflector using metal based as well as hydrogen based materials on the criticality of the studied 2D test core

After the analysis of the effect of the reflector material on criticality the study will focus on another key point for the down selection of potential reflector candidates for a zero power reactor physics experiment supporting molten salt fast reactors. This point is the effect of the reflector on the neutron flux distribution in the core of the fast system. Experiments like YALINA have shown that fast reactors can be very sensitive to thermal neutrons entering into the fast system leading to a massive and absolutely not desired distortion of the detector readings [15, 20] and thus on the power distribution.

The radial power distribution has been calculated for a set of chosen, attractive materials and some reference cases using the model given in the right part of Figure 2. Figure 8 demonstrates the massive influence of the choice of the reflector material on the radial power distribution in the analysed core. The use of highly reflective light materials, e. g. BeO, H_2O or graphite lead to a very strong power increase in the outer area which completely disturbs the natural power distribution in the core as given by the green curve for the pseudo unreflected system. Thus, these materials would not be a good choice as a reflector in a fast system. However, it should be kept in mind that this decision maybe would have to be revised when a thermal system would be analysed, since there the effect is expected to be not relevant – thus materials like BeO, H_2O or graphite are very attractive choice due to their high efficiency in neutron reflection (a strong increase in the k_{eff} of the system), and they should be analysed in more detail for their application in an experimental setup for the investigation off a thermal core.

Comparing the heavier materials, even here it is clear that each of these reflectors has a strong influence on the power distribution when compared with the Helium case, even the use of a shielding material with a strong neutron absorption potential like Ferroboron (dark blue versus green). However, even in all heavy reflector material cases, the power distribution will be massively flattened due to the reflector, but in the ideal case the spatial form of the power distribution (cosine like) is kept as natural as possible with a clear peak in the centre of the system and ideally only a very limited increase of the power at the boundary.

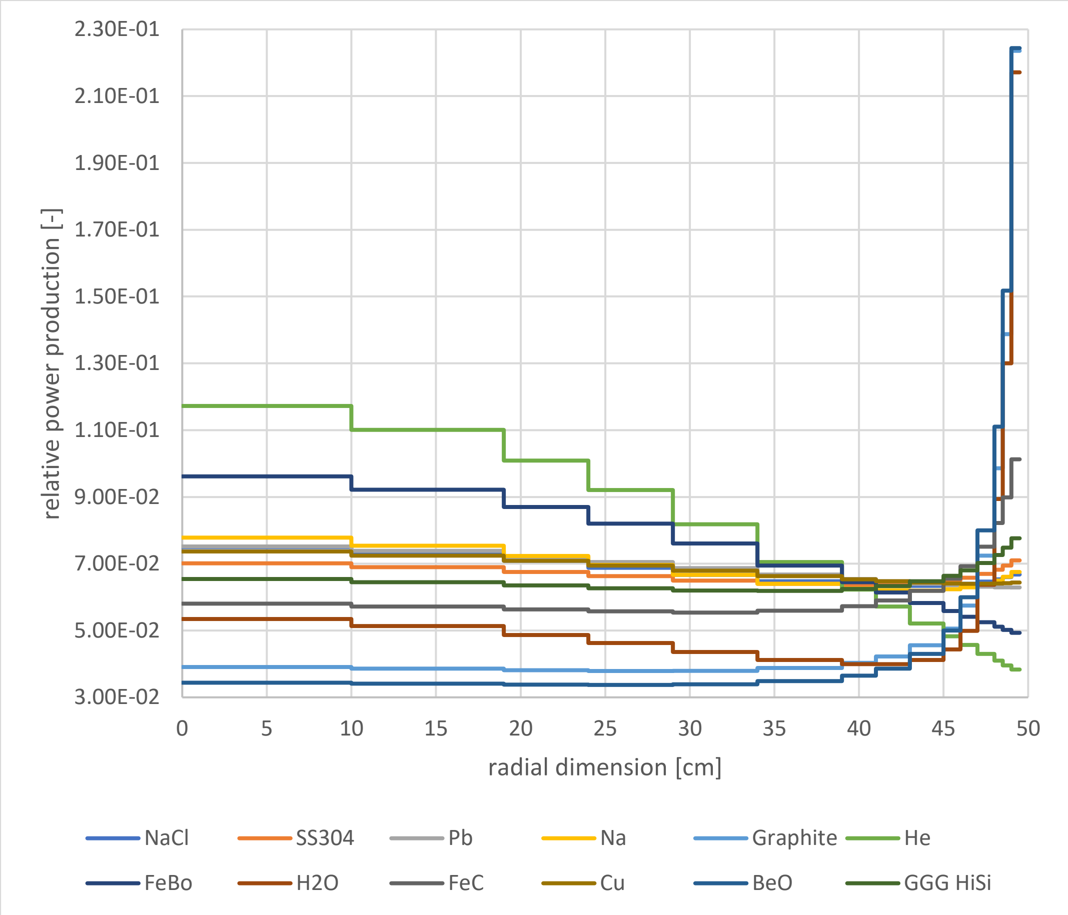


Figure 8: Radial power distribution investigated in a 2D system for different reflector materials for a zero power experimental core

For a more detailed insight, Figure 9 shows a narrowed down selection to the most interesting materials which all show a natural (cosine like) power distribution in the inner part of the core while delivering a reasonable increase in the system k_{eff} study above. In this figure it is obvious that all reflectors lead to an increase of the power in the outermost ring, but while this increase is stronger for the silicon containing materials, Hi Si cast and SS 304, it is moderate for the sodium containing materials, pure Na and NaCl, and it is very limited for heavy materials like lead and copper. In addition, lead and copper show a very nice power distribution with a clear peak in the centre, which is slightly lower than for the unreflected system but with a comparable shape.

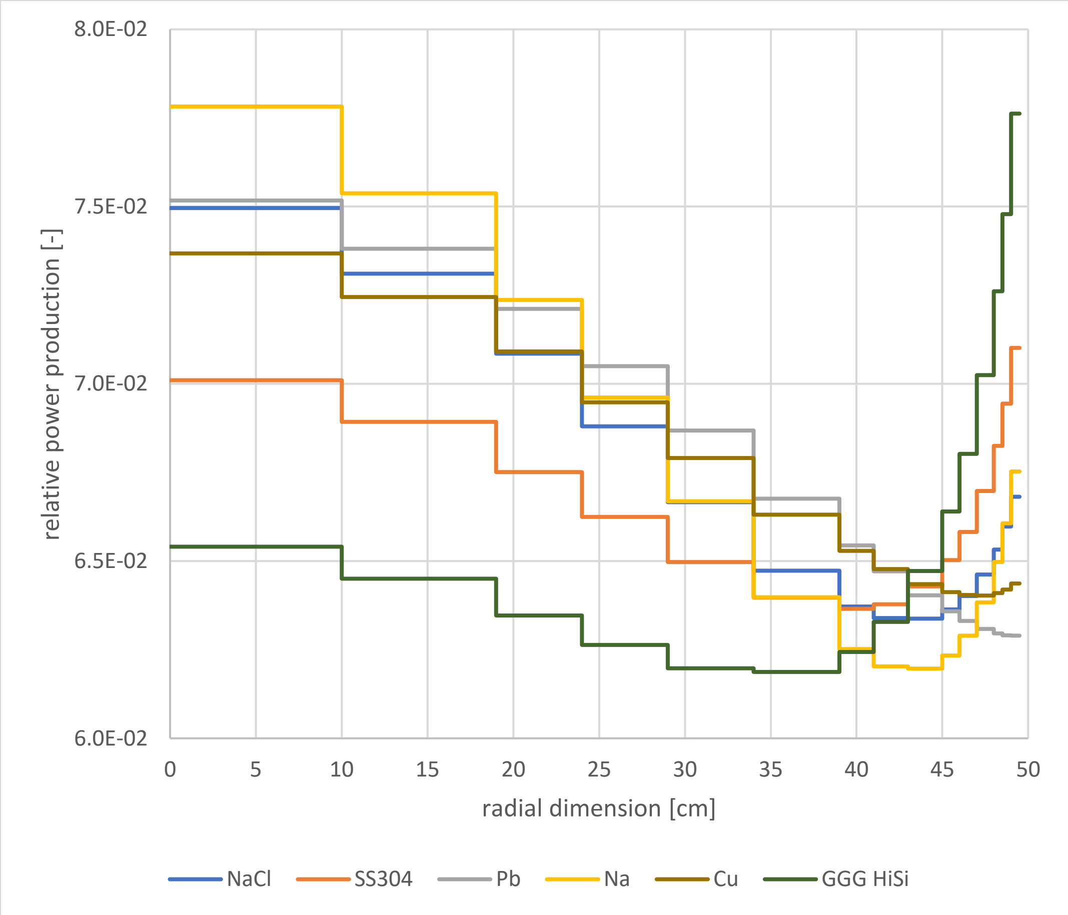


Figure 9: Narrowed down choice of materials for deeper investigation of the radial power distribution investigated in a 2D system for different reflector materials for a zero power experimental core

The results up to now favour the use of a copper or lead reflector. For further investigation, these two materials will be compared with the original NaCl reference, with stainless steel and partly with graphite.

Reflector dimension

In this section the effect of the reflector on the critical size of the core and the efficiency of the reflector depending on its thickness will be investigated to get a better understanding of the potential reduction of the demand on fissile material. This will also allow the determination of the ideal reflector thickness depending on the chosen reflector material.

The core dimension and thus the required amount of fissile material is strongly dependent on the choice of the reflector material, see Figure 10. The first comparison is between the heavy metal rich core and the eutectic core. The eutectic core requires a ~15% larger radius to achieve criticality when the same dimension of reflector is chosen. However, when comparing the required heavy metal amount in the analysed 2D core, the eutectic composition requires about 9% less heavy metal, which means that the additional core volume or even slightly more volume is just filled by NaCl. Thus, in the case where the core dimension itself is not a limiting value, the choice of the eutectic composition could be favourable, even if the demand on the infrastructure (reflector material, potential control system [6], core housing) will depend on the absolute core size. Therefore, this opportunity should be recognized and investigated in a future optimization process required for the design of a new type of zero power reactor. The use of the chosen reflectors reduces in all cases the core dimension, the use of a 30cm reflector consisting of lead reduces the radius by 23%, the use of the SS 304 reflector by 26%, the copper reflector by 27% and the graphite reflector by 35%. The same reduction in the required core size could be achieved by a 50cm thick lead reflector. Thus, all investigated metal reflectors, which deliver a reasonable power distribution have a strong potential to reduce the required core size for a critical system, but the gain is only weakly dependent on the material. This opens a wide opportunity for choosing and analysing different optimization parameters in the future core design.

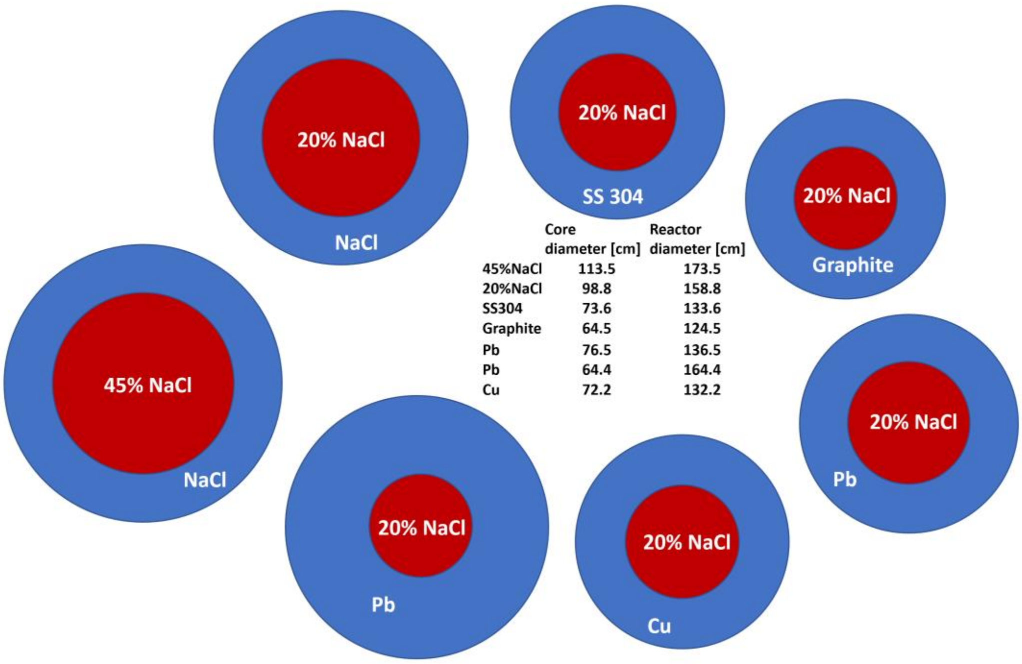


Figure 10: Variation of the 2D core dimension required to achieve a critical configuration for a zero power system

Recognizing the great potential that the right choice of the reflector has in reducing the amount of fuel required to form a critical system, the next step is to obtain a deeper understanding of the options. Is there a saturation effect and is the applied first guess of using a 30cm thick reflector really the ideal choice? The analysis is based on the comparison of the core criticality curve depending on the thickness of the reflector and the different reflector materials, while all cases are normalized on the critical system with the 30 cm thick reference reflector as calculated above.

Figure 11 depicts the variation of k_{eff} with reflector thickness for five reflector materials, and the trends shows some different effects. First of all, all reflector arrangements tend to deliver the to be expected asymptotic behaviour which confirms that at a certain thickness, the addition of more reflector has only a very marginal effect. However, it is very interesting to recognize that the asymptotic behaviour sets in at very different reflector thicknesses for the different materials with copper not showing a reasonable gain after increasing the reflector to more than 30 cm while there is still a reasonable increase in criticality even for 80 to 120 cm in lead. Looking at the other end of the x-axis, the different criticality states with almost no reflector (1 cm) reflect the different core sizes required for the reference solution, while all curves intersect at the reference point 30 cm reflector. The structure of the curves can help to identify the ideal reflector thickness depending on the materials which tends to the outcome that for lead, a thicker reflector could be very promising (see the added 50cm case in Figure 10), while for copper and most probably SS 304 a thinner reflector would be sufficient, which in turn would provide better value for money.

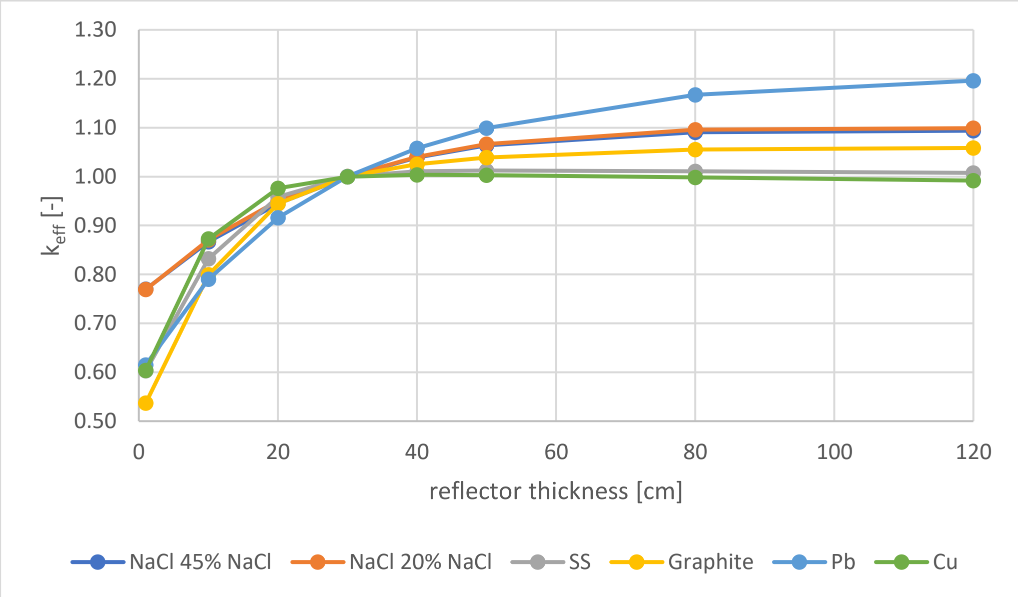


Figure 11: Criticality of the studied 2D system for different reflector thickness normalized on the critical core diameter for each reflector material with a 30 cm reflector

The very strong influence of the reflector on the system criticality and thus on the required system size and fuel demand has been demonstrated so far in the current study. In addition, a strong influence of the reflector material on the power distribution has been found and a first optimization on the required 2D core diameter for different reflectors materials has been performed. This approach is enriched with a study on the efficiency of the reflector thickness given in Figure 11. However, all these results have been achieved using TRITON/NEWT only. To improve the trust into the results a comparison using the 2D KENO VI model given in Figure 3 has been performed. For this evaluation the multi-group approach as well as in the continuous energy approach has been used and the results are given in Table 1. The system diameters vary between all three approaches slightly with the strongest variations for the SS 304 reflector, while the results for the Pb and the Cu reflector are much closer. Anyway, it is clear that the dimensional changes are small and captured with sufficient accuracy for the aim of this study. Further investigation will be required as soon as a reasonable geometry has been designed for a potential core configuration of a zero power set-up.

Table 1: Systematic comparison of the TRITON/NEWT multi-group results with KENO VI in the multi-group approach as well as in the continuous energy approach.

Material	System radius [cm]			Deviation [%]	
Code	newt	mg MC	ce MC [ref]	newt	mg MC
SS 304	36.8	35.5	37.9	-2.9%	-6.3%
Pb	38.25	37.65	38.1	0.4%	-1.2%
Cu	36.1	35.45	36.05	0.1%	-1.7%

Analysis of the influence of the reflector material on the neutron flux

Neutron spectrum

To create a deeper understanding of the effects of the different reflector materials, the neutron spectrum of the whole system and the spatial neutron flux distribution of 5 energy groups will be analysed. The 5 energy groups have been mainly chosen in a way to reflect the neutron energy *distribution of a fast system. The first insight into the global neutron spectrum indicates that the highly reflective materials BeO and graphite lead to a neutron spectrum close to a light water reactor spectrum with a significant thermal peak, while metal reflectors Cu, Pb, and SS304 lead to a typical fast reactor spectrum, which are similar to the spectrum of the absorber containing reflector, Ferroboron, and the unreflected system using He to fill the reflector region, see*

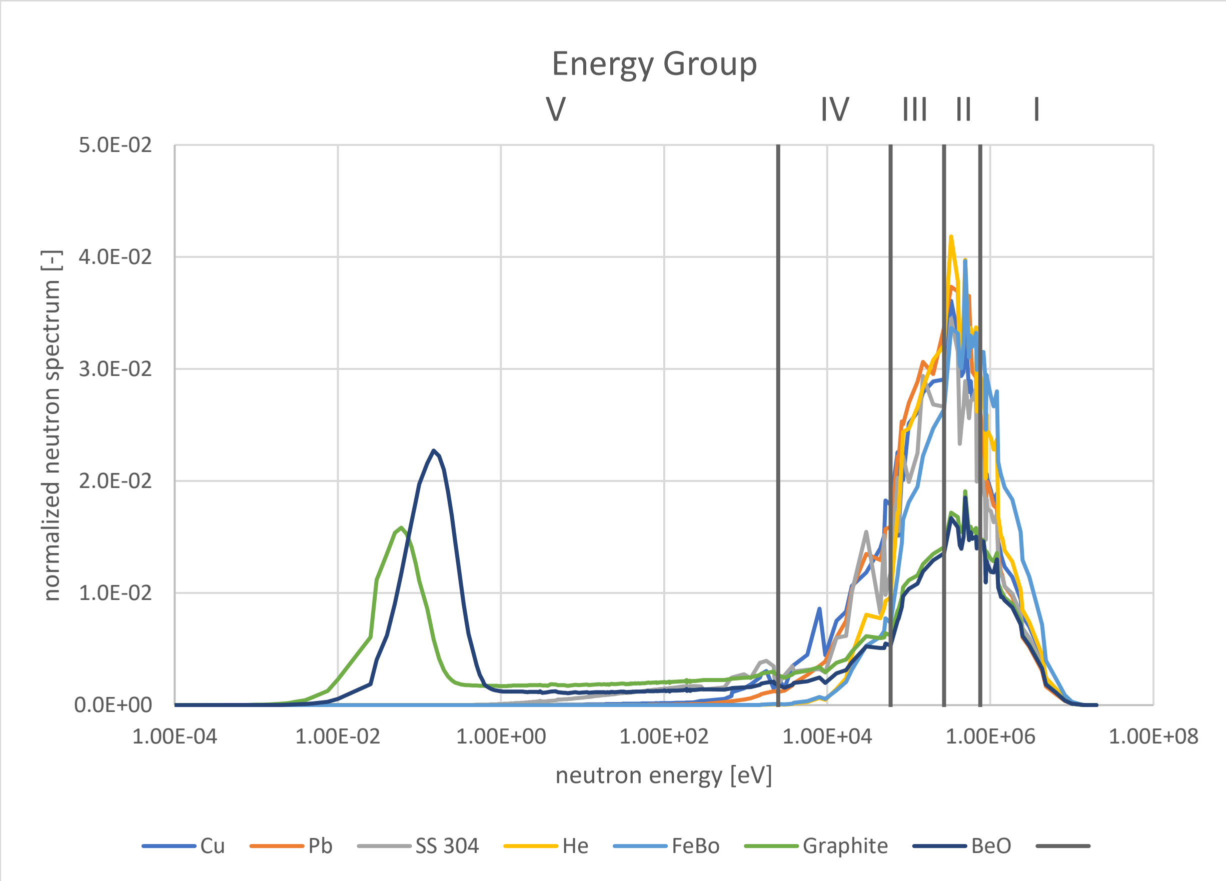


Figure 12. The insight into the neutron spectrum for BeO and graphite correlates very well with the observations for the power distributions, see Figure 8. Even if the fuel in the core represents a fast reactor configuration, there is a strong thermal peak which is formed in the strongly moderating reflector. The thermal neutrons then penetrate back into the fast reactor core, having a very high importance due to the significantly higher reaction cross section in the low energy range – thus, these neutrons very efficiently undergo fission reactions in U-235. This leads to the undesired power peaking at the boundary of the core caused by a strong self-shielding effect which limits the depth of the penetration of the thermal neutrons. Thus, these moderating reflectors are not promising for fast reactor investigations, but they would have to be investigated in more detail for a later stage when thermal configurations could be investigated in a multi-purpose facility.

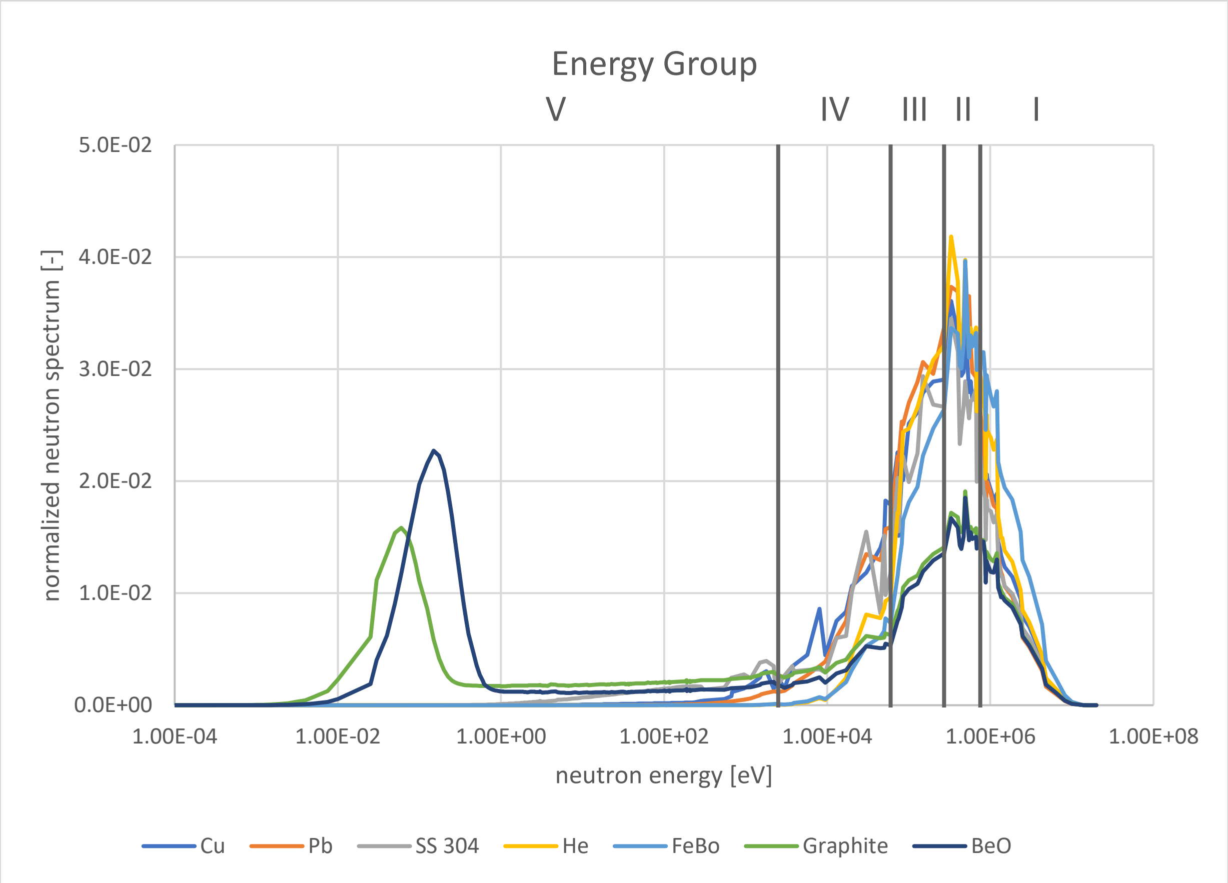


Figure 12: 252 energy group neutron spectra in the 2D system dependent on the reflector material

For a more detailed look into the effects of the metallic reflectors,

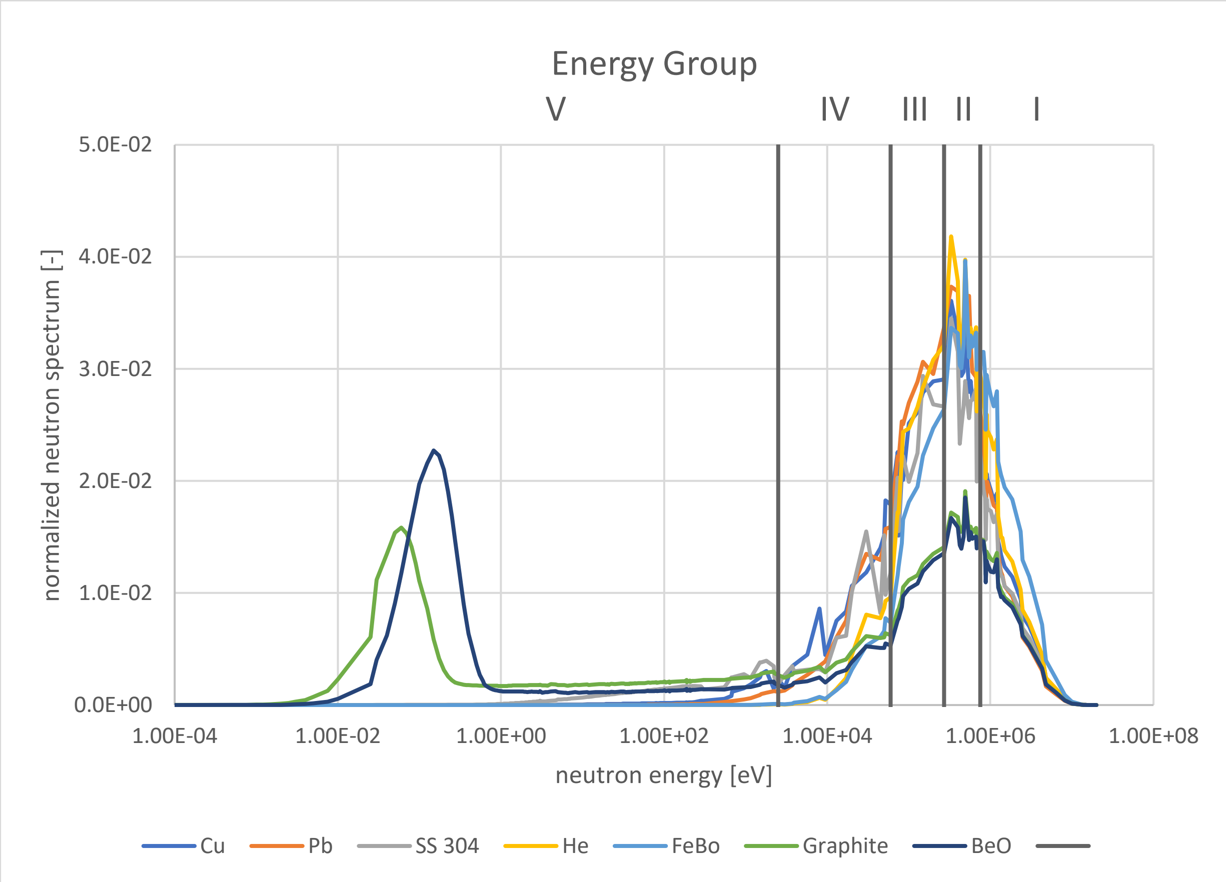


Figure 12 is narrowed down in the energy range that is relevant to the neutron energies expected in a fast reactor. The resulting plot, Figure 13, shows some really important details created by the different metallic reflectors, which correlate once again very well with what is shown for the power distribution in Figure 9. Obviously, SS304, Cu and Pb form a small low energy tail in the system, too and the interesting point is that this low energy tail exactly coincides with the power increase at the boundary which is highest for SS304 and lowest for lead. All metal reflectors tend to soften the neutron spectrum slightly with an increase of the number of neutrons below ~200 keV and a decrease of the number of neutrons above ~500 keV. In contrast to this, the use of a reflector containing a strong absorber for low energy neutrons, like Ferroboron tends to harden the neutron spectrum, even compared to an unreflected system by reducing the leakage of fast neutrons above 1MeV, while there is no effect on low energy tail below 10 keV.

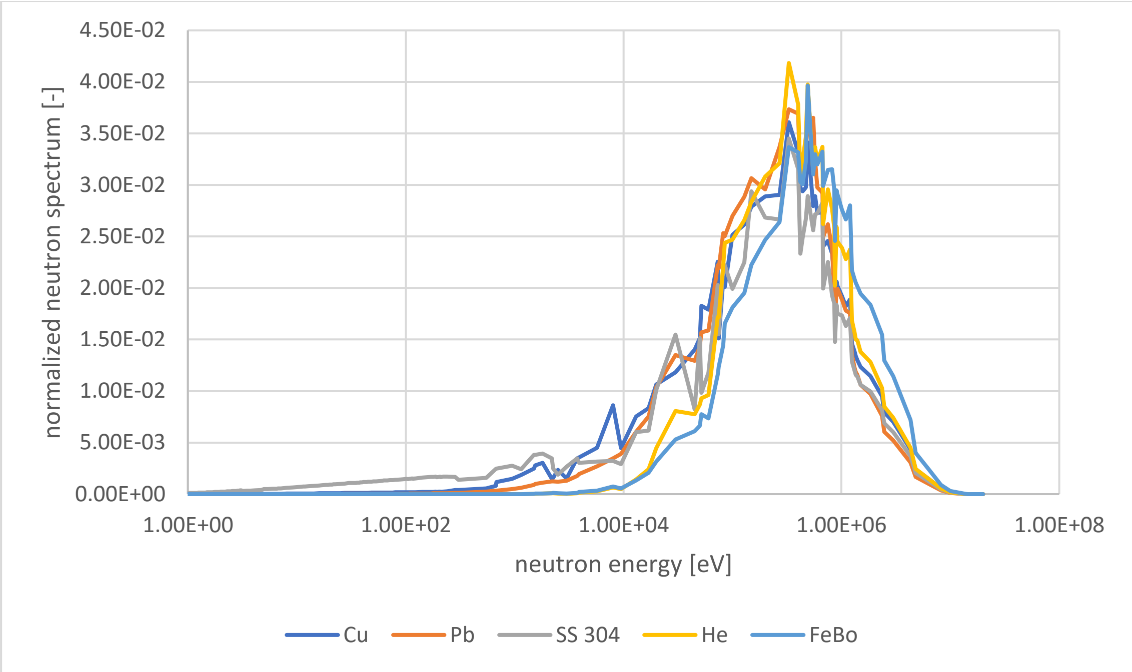


Figure 13: Selected fast reactor neutron spectra in the 2D system dependent on a selection of potential reflector materials

The spatial and energy resolved neutron flux will be investigated through comparison of two sets of neutron distributions for a 5-group neutron flux using the energy boundaries shown in

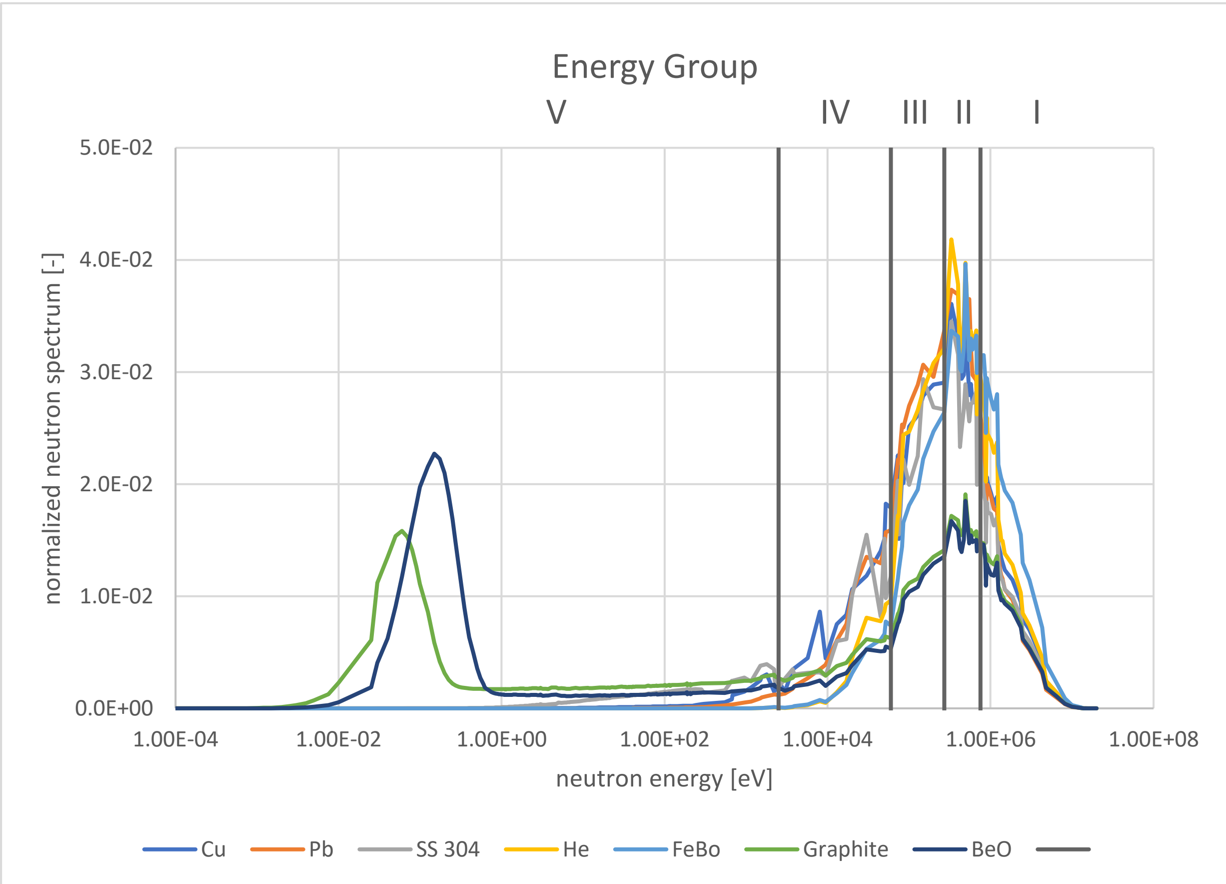


Figure 12. Comparing the group wise spatial flux distribution of the He reflected system, see Figure 14, which represents an unreflected system, with the system using FeBo as an absorbing reflector, the effect of the reflector is visible in each group. In the first three groups, the reflector leads to a

wider spread of the high flux area in the centre of the core and a very thin area of increased neutron flux outside of the steel shell of the core. This effect is more pronounced in group 4 where an almost flat flux distribution appears through the whole core, while in group 5, the flux maximum is moved to the outer area of the core, but there are only very few neutrons in this group at all. However, when looking into the absolute values of the neutron flux for the different groups given at the bottom of the figure, it is clear that the absolute number of neutrons in each group is only very slightly changed. All 5 groups show only a very small penetration depth of the neutron flux into the reflector which indicates that a much thinner reflector would most probably deliver almost the same result. This is in strong contrast to the case using a lead reflector, here the penetration depth is already high in the first group and starting from group 2 the full reflector is used – thus a thicker reflector could be promising in this case. This confirms the results given in Figure 10 and Figure 11, demonstrating that increasing the reflector thickness over the 30 cm standard has still a good influence on the criticality. The lead reflector flattens the spatial neutron flux in groups 1 to 3 significantly while it leads compared to the He and FeBo case to a decrease in the absolute number of neutrons in the first group and an increase in the second, third, and fourth group. The maximum neutron flux in the fourth and fifth group appears in the lead case already in the reflector leading to an increase of the power production at the core surface. The general tendency in the copper reflector is comparable to the lead reflector, but with a significantly lower penetration depth in the first three groups. The maximum neutron flux in the copper case is slightly lower in the groups 1 to 3, but higher in group 4 and 5, as already to be expected from Figure 13. Groups 4 and 5 indicate a spatial flux maximum in the reflector feeding back into the core leading to the slight power increase at the core boundary as shown in Figure 9 , with a slightly stronger effect than in the case using the lead reflector.

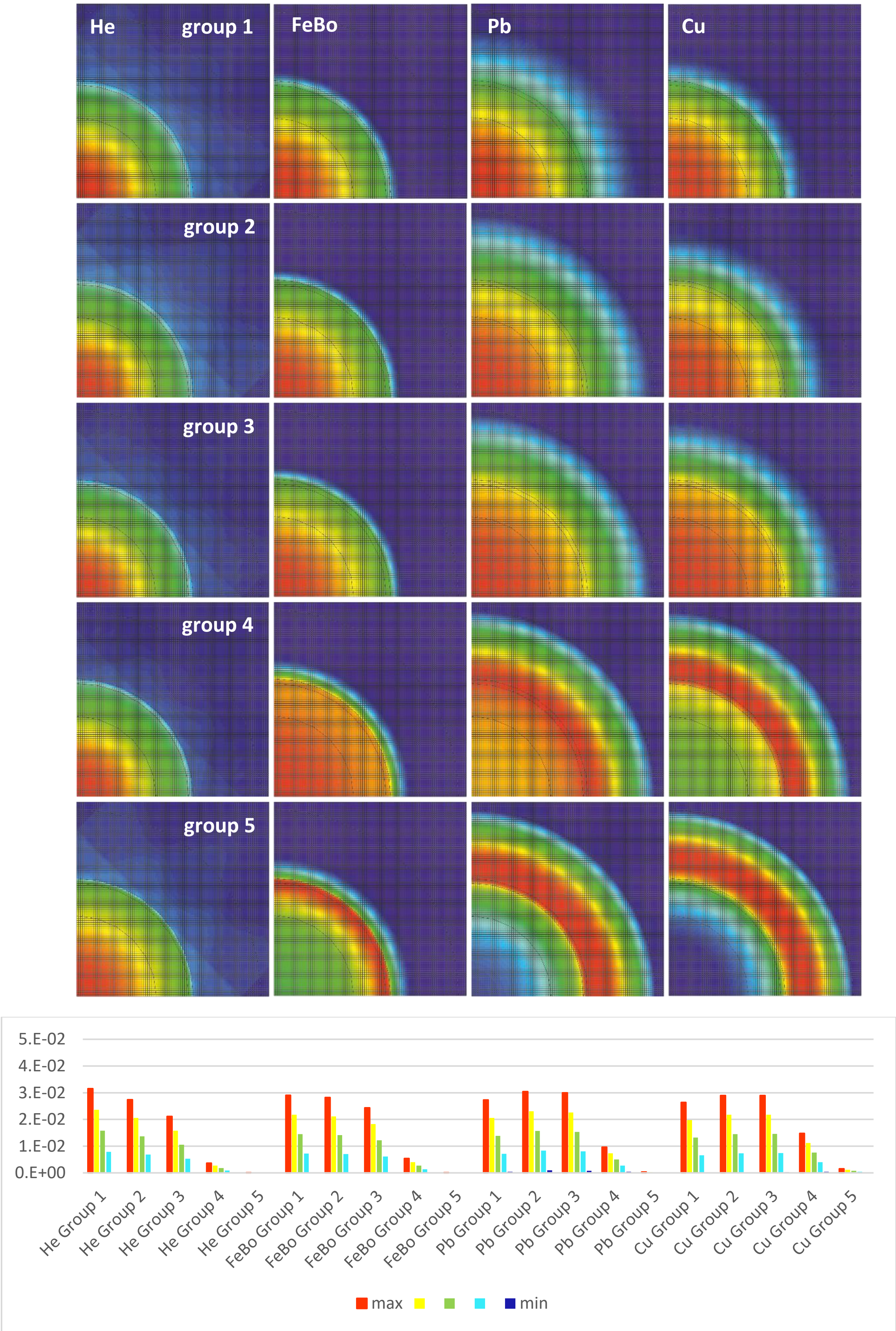
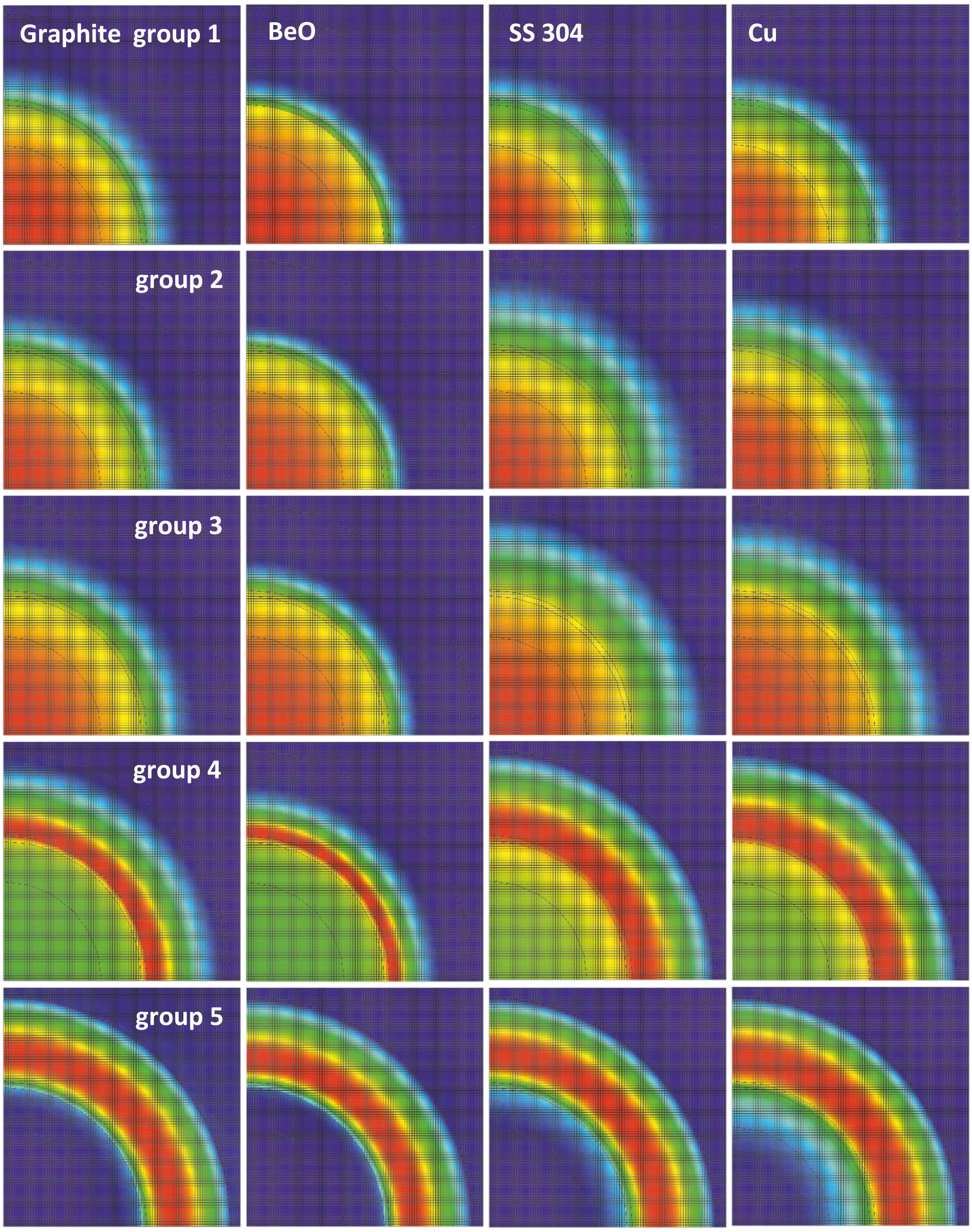


Figure 14: Group wise 2D spatial neutron flux distribution in the core for 4 different weakly reflecting materials

The group wise spatial distribution of the neutron flux for the cases with the more moderating reflectors Graphite, BeO, and SS 304 are given in Figure 15 with the case of the copper reflector added for comparison. Both strongly moderating reflectors Graphite and BeO show in the first groups there is a significantly lower penetration of the neutron flux into the reflector when compared to the metal-based reflectors. This indicates that for the BeO reflector, especially, there seems to be room for a strong reduction of the reflector thickness. The low penetration depth coincides with the clearly reduced maximum neutron flux in these three groups in the moderating reflectors. The real effect of the moderating reflector is seen in group 4 and even more in group 5. Already in group 4 the neutron flux peak is completely moved into the reflector, but in contrast to the metal reflectors, there is only a very thin outer core layer which is boosted by the lower energy neutrons from the reflector. On the one hand, this explains the increase of the neutron flux in group one and two of the moderating layer cases leading to a flatter neutron flux distribution. On the other hand, it will cause a kind of rim effect, which could be problematic in the first phase of the zero-power reactor operation as long as the core is in solid state. In addition, it will increase the fluence on the core vessel. The configuration is much more pronounced in group 5 with a significant increase of the absolute number of neutrons in this group, see the bottom row of the figure which indicates that the neutron flux in the graphite moderator in this group is about a factor of 18 higher than in the copper case and a factor of 280 higher than in the non-reflected system. In the BeO case it is even worse with a flux increase by a factor of 28 compared to the copper case and 440 compared to the unreflected case. These two results show that there is a significant amount of neutrons ‘stored’ in the reflector which do not significantly take part in the fission reaction cycle – this could lead to problematic behaviour in future zero-power reactor experiments such as rod drop or source pulse experiments [20, 21] to determine the core criticality. The comparison of the SS 304 case and the copper case shows only minor differences in the neutron flux distribution, a slightly higher penetration depth of the neutron flux into the reflector in the groups 1 to 3 and a slightly higher penetration depth of the neutron into the core when the neutron flux in the reflector is higher in group 5. In this group the major difference is shown in the number of neutrons appearing in the group, see the bar chart at the bottom of Figure 15.



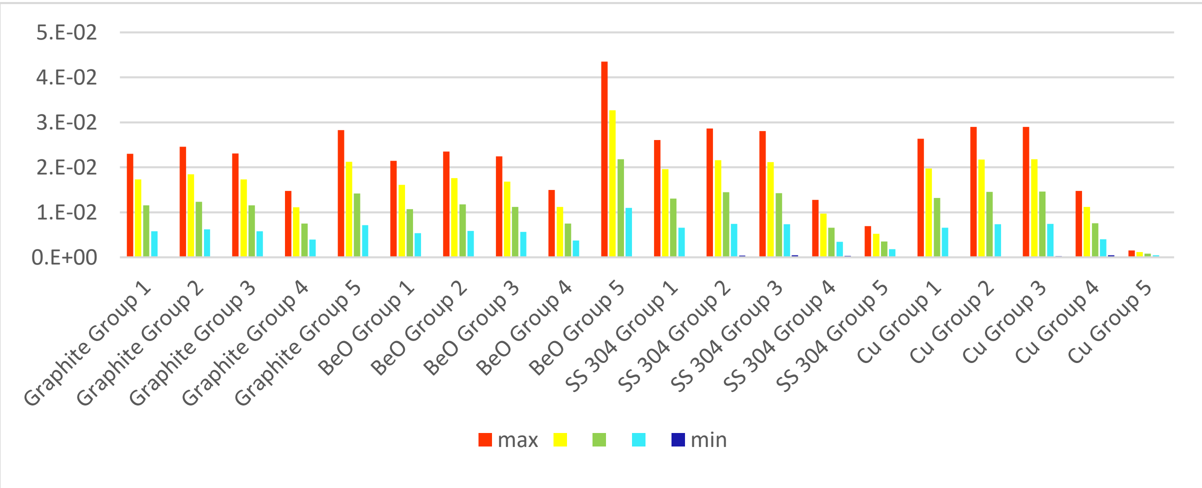


Figure 15: Group wise 2D spatial neutron flux distribution in the core for 4 different strongly reflecting materials

3-D Monte-Carlo study

The numerical study of the effect of different reflector materials will be closed using a 3D Monte-Carlo evaluation of the required volume for a critical core dependent on the chosen reflector material. The massive reduction of the required core volume for the different chosen reflectors, compared to the NaCl reflector used in the previous studies [5, 6] is given in Figure 16. While a core with a 30 cm reflector made from NaCl requires almost 2 m^3 of fuel to achieve a critical configuration, the, in this study, chosen metallic reflectors can assure core criticality with less than 1 m^3 of fuel. The exact result is a matter of optimization with the SS 304 reflector and the Copper reflector requiring ~0.85 m^3. However, the study has shown that the copper reflector could most probably be reduced in thickness to achieve the best result, while the lead reflector could deliver a better performance with a higher thickness. For confirmation of the results an additional continuous energy Monte-Carlo calculation has been performed, see right bar in Figure 16. This test indicates a difference of about 5% between the multi-group approach and the continuous energy approach, which seems to be acceptable for this kind of broad optimization study. However, for a more detailed analysis the use of a continuous energy Monte-Carlo code seems to be more appropriate.

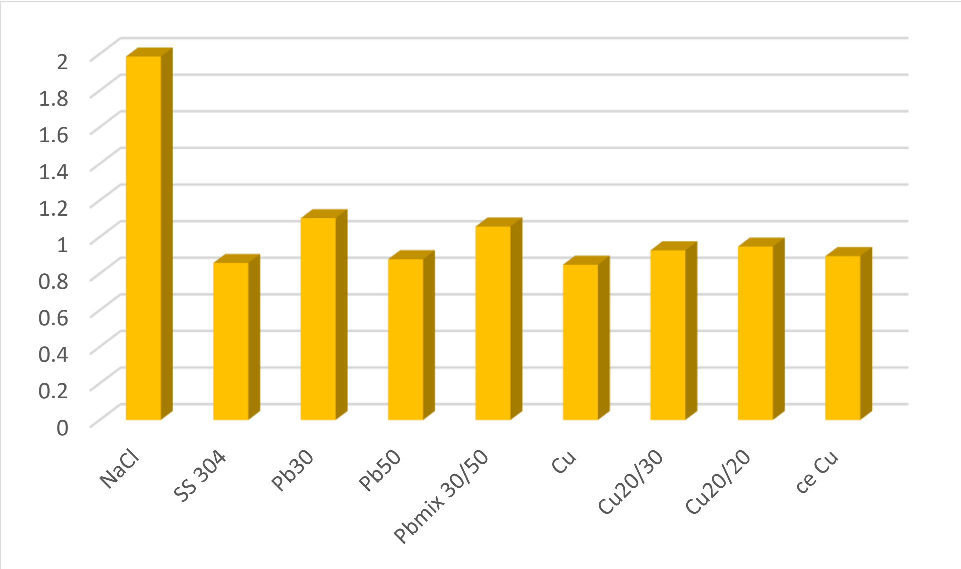


Figure 16: Evaluation of the required core volume to achieve a critical core, dependent on the chosen reflector material

A first cost analysis for different reflector approaches identifies the SS304 reflector as the cheapest solution based on the pure reflector cost, see Table 2with the data source in the footnote. In general, there is still some optimization potential when considering the cost of the fuel, the cost of the reflector and potentially the cost of the required core and reflector support. Especially in the case of applying the approach of using a moving reflector for reactivity control. In addition, the effect of the reflector on the quality of the experiments should be added to the consideration.

Table 2: Cost comparison for different reflector configurations

Reflector	Cost [$/ton]	Density [ton/m³]	Cost [$/m³]	Cost estimate [$]
SS 304 30cm[1]	4380	7.390	34733	88372
Lead 50 cm[2]	2026	11.343	22980	132728
Copper 20 cm[3]	7735	8.94	69150	105458

An initial step to create a deeper understanding of the potential saving in core volume and the role of the changes in the axial as well as in the radial reflector, some cases have been investigated for the copper and the lead reflected core. From Table 3, it is obvious that the increase in size in the radial reflector is much more efficient than increasing the size of the axial reflector. The effect can be observed with both materials independently.

Table 3: Study of potential volume savings resulting form the increase of the reflector thickness at different places

	Volume saving	case
all reflector	20.3%	Pb 30 cm to 50 cm
	10.4%	Cu 20 cm to 30 cm
axial reflector	4.1%	Pb 30 cm to 50 cm
	2.2%	Cu 20 cm to 30 cm
radial reflector	16.9%	Pb 30 cm to 50 cm
	8.5%	Cu 20 cm to 30 cm

Control curve and shutdown

In a final step the consequences of the change of the reflector on the reactor control and shutdown system as developed in [6] has to be evaluated to assure that the changed reflector still allows the application of the envisaged control and shutdown approach. The use of the smaller core with the copper reflector leads to a significant increase of the control span compared to the original larger core with the NaCl reflector, see Figure 17. The increase of the control span can be explained with the significantly stronger effect of the reflector on core criticality which is finally reflected through the opportunity to decrease the size of the core while the core still stays critical. Thus, the control approach cannot only be kept when using the copper reflector, the approach will even become more efficient and the control span will become wider which allows a higher flexibility of the reflector control and the core design.

[1] https://www.stindia.com/stainless-steel-304-316l-price-per-kg-india.html#price_per_kg
[2] https://markets.businessinsider.com
[3] https://markets.businessinsider.com

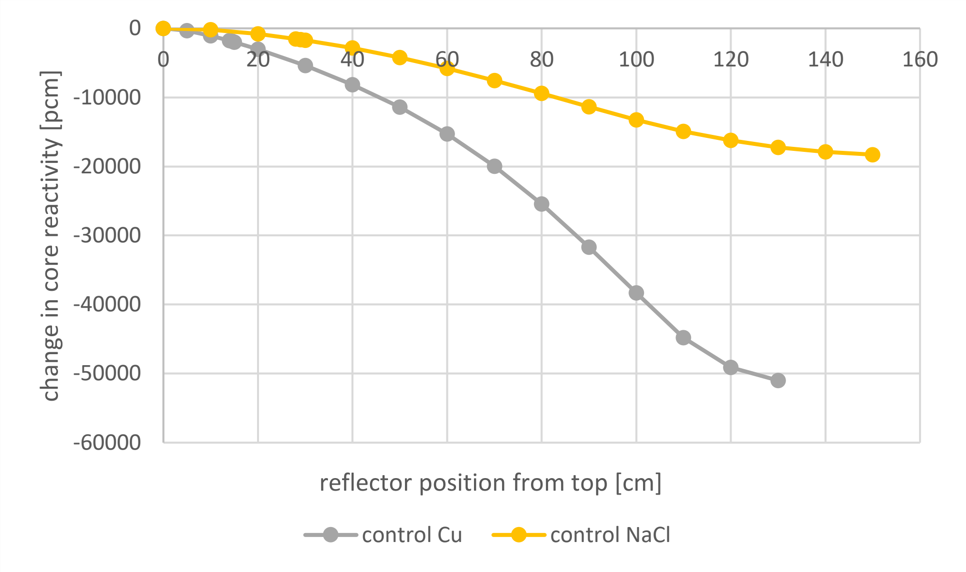


Figure 17: Comparison of the control curve caused by moving the reflector made of NaCl and copper

The evaluation of the consequences of changing to a significantly more effective reflector material on the shutdown system is given in Figure 18. The splitting of a 30 cm this layer of the core including the reflector delivers in the smaller core a significantly higher shutdown reactivity than in the reference case with the NaCl reflector. Thus, the envisaged shutdown approach is not negatively influenced by the change to a much more efficient reflector material. It would even allow a potential reduction of the core layer which has to be split away. This optimization should be carried out when a definitive decision has been taken regarding the reflector material and the final core design.

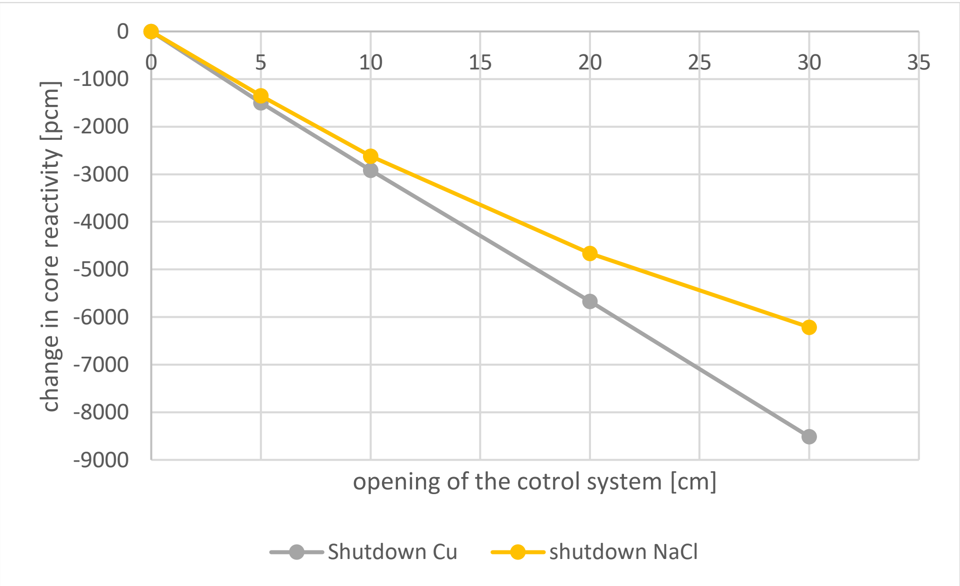


Figure 18: Comparison of the shutdown curve caused by moving the bottom part of the core for the reflector made of NaCl and copper

Conclusions and Next Steps

The relevance of the neutron reflector in core design is discussed in the introduction with a view into power reactors as well as into neutronic experiments where the role of the reflector has a much higher importance. In the following the theoretical roles of the reflector for any kind of neutron physical installations is discussed. The investigation of the effect of different reflector materials regarding the achievable k_{eff} and power distribution for a given reference configuration has been performed. The study of a set of classical reactor materials and more exotic choices led to a first down selection based on the gain in k_{eff}, with SS 304 as representative for stainless steel, lead, copper, graphite, beryllium oxide and iron based material with high Si content identified as promising. The following investigation of the power distribution highlighted that the strongly moderating reflectors based on graphite and Beryllium oxide have a strong influence on the power distribution within the core and will deliver a non-natural power distribution with a peak at the reactor boundary instead of the reactor centre.

Based on this first down selection, the 2-D critical core dimension was evaluated for the chosen reflector materials identifying stainless steel and copper as the most attractive solutions with lead as potential backup and graphite as attractive candidate in case of a future thermal system. The study of the optimal reflector dimension identified that the reference approach of a reflector thickness of 30 cm was a good approach, but especially in the case of copper a thinner reflector could be sufficient, while in the case of lead a thicker reflector could be more promising.

The analysis of the influence of the reflector material on the neutron flux spectrum confirmed the expected effect of the moderating reflectors BeO and graphite, while the difference in the neutron spectrum in the cases of the metal based reflectors has been found to be very small. The investigation of the 2-D flux distributions split in 5 energy groups confirmed the expectation that there is a significant amount of neutrons stored in the moderating reflectors which lead to a number of very well thermalized neutrons streaming back into the core explaining the power increase at the core boundary observed in the study of the 2-D power distribution. In addition, this insight highlighted the results that the penetration depth in the lead reflector is very high, while the penetration depth in the copper reflector is very low, confirming the result that a thicker lead reflector could be promising while a thinner copper reflector could be sufficient.

Following all 2-D studies, a 3-D Monte-Carlo study to investigate fuel volume savings has been performed which highlighted the potential fuel savings possible through a good choice of the reflector. There is a potential of up to a 60% reduction in the fuel volume compared to the reference case using a NaCl reflector with the best results for stainless steel and copper or a thicker lead reflector.

The final cost comparison for different reflector configurations identified that the stainless steel reflector as the most cost efficient solution. However, this reflector has the strongest influence on the power distribution. In general, there is some additional optimization needed to make a final choice between the three most promising reflector materials SS 304, lead, and copper.

The study was closed with a test confirming that the control curve and shutdown approach developed earlier is not influenced, or even partly improved through the choice of the efficient reflector material.

For future more detailed studies, investigations at room temperature would be the next step required. For this study, an urgent need for data for the fuel in the solid state at RT has been identified which will definitively be required to study this case. A next step should be, looking into a multi-purpose machine. The current study has concentrated on the fast system, but many conclusions can be drawn for the thermal system too. However, the thermal system would be worth an independent study maybe for different published core configurations e.g. Terrestrial Energy and the Chinese TMSR project.

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