Evaluating reactivity control options for 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 of delivering this technology. The topic of the control and shut down for a zero power reactor is for the first time introduced through a literature review and the reduction of the control approaches to a limited number of basic functions with different variations. In the following, the requirements for the control and shutdown system for a reactor experiment are formulated, and based on these assessments, an approach for the shutdown – splitting the lower part of the core with reflector, and an approach for the control – a vertically movable radial reflector are proposed. Both systems will be usable for a zero-power system with a liquid as well as with as a solid core and even more importantly, both systems somehow work on the integral system level without disturbing the central part of the core which will be the essential area for the experimental measurements. Both approaches have been investigated as a singular system as well as their interactions with one another and the sensitivity of the control system. The study has demonstrated that both proposed systems are able to deliver the required characteristics with sufficient shutdown margin and a sufficiently wide control span. The interaction of the system has been shown to be manageable and the sensitivity is on a very good level. The multi-group Monte-Carlo approach has been cross evaluated by a continuous energy test leading to good results, but they also demonstrate that there is room for improvement.

Keywords:

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

Introduction

In the development of innovative reactor systems, zero or very low power experiments have historically been seen as the first step in the development of a new reactor program or a new technology [1]. Already the planning as well as the construction create a multitude of learing opportunities which will extend into the operation and the experimental program [2]. In [3] and in the first part of this publication series [4], the importance of a zero-power reactor experiment for the process of developing a new, innovative rector concept like molten salt fast reactor is worked out and the challenges, due to the homogeneous core composition (unity of coolant and fuel) of a molten salt reactor are described. In a third part the role of the reflector is discussed and analysed [5]. A zero-power reactor experiment for a molten salt reactor is significantly different to existing, heterogeneous experiments based on pins with the requirement to understand the effects of heterogeneity. On the one hand, the homogeneous nature of the reactor media will required novel approaches for the design, operation, and control. On the other hand, the experimental setup must be designed, developed and invented. To avoid disturbance of the homogeneous system is a significant, new challenge for designing an innovative approach for control and shut down of a homogeneous reactor experiment. The focus of the development is to deliver a control and shutdown system which avoids a major disturbance of the homogeneous arrangement as it would be in the case of the use of control rods in industrially operated light water reactors.

Most of the currently operated reactors rely on different approaches for the control and shutdown while very often the control system can act as an independent, diverse shut down system. A typical example is the use of control and shutdown rods in pressurized reactors which is complemented with the boric acid operated control system for burnup compensation. In boiling water reactors, the control and shutdown system based on control blades, which are complemented with operational control through the recirculation pump speed and the related void content in the core and a diverse shutdown system based on boric acid injection. In both reactor types, burnable poisons are widely used to reduce the excess reactivity of fresh fuel assemblies.

CANDU reactors have a more sophisticated control system which is required due to the large core size. The control system consists of moving adjuster rods and varying the water level in vertical cylinders [6] mainly for the control of the flux shape while burnup compensation is only required to a very small extent due to the online refuelling. “The first shutdown system is made up of rods that drop automatically and stop the chain reaction if something irregular is detected. The second system injects a liquid, or poison, inside the reactor to immediately stop the chain reaction.” [6] Technically, the option of draining the heavy water moderator for shut down would be another option which has been discussed.

Sodium cooled fast reactors are typically controlled via different sets of rod systems, safety (shutdown) rods, regulating rods, rapid shutdown rods and sometimes additional shutdown rods [7] with different types of drives and even flexible chains have been investigated in some projects. The sodium cooled fast reactor community has also been working on passively activated safety shutdown systems [8].

The German pebble bed HTGR used 36 absorber rods for power control and reactor scram, which are inserted or dropped in the side reflector via gravity and for long term shut down, 42 absorber rods with pneumatic drives could be inserted directly into the pebble bed [9]. However, other approaches like withdrawing a certain amount of pebbles from the pebble bed reactor have been investigated after problems occurred with inserting the shutdown rods into the pebble bed.

For future molten salt reactors control rods [10] and core drainage are proposed for shutdown for MSR systems and has been used in MSRE [11]. While initial studies indicate that the burnup control could be achieved through control of the core temperature, due to the strong thermal feedback effect [21] which allows to compensate a significant amount of reactivity with only a moderate change in the salt temperature. The approach of draining the salt will not work in a MSFR zero power experiment, which most probably will take place in the first step in a solid arrangement in order to reduce the complexity.

Looking into more exotic approaches in control system, tests have been performed on “Critical-Assembly Experiments on a Reflector Control System for a Boiling Reactor” [12] and reflector manipulations have already been used very early on in reactor physics experiments [13], reflector manipulation drums are often proposed in very compact space reactors [14] or training/teaching/research? reactors [15]. For critical experiments, moderator level manipulation has been used for criticality determination [17] and changing or manipulating the reflector conditions is used in critical assemblies [13], too. Splitting of the spherical core into two half spheres is another approach for shutdown which has been used in some very small education reactors. The most recent zero power experiments for accelerator driven systems YALINA [18] and GUINEVERE [19] use in accelerator beam control.

Based on this literature overview on control and shutdown mechanisms, the work provide here will aim to develop and evaluate diverse control and shutdown approaches as well as their interplay for control and shutdown of a homogeneous critical zero power experiment for a potential molten salt fast reactor through the use of a multitude of modelling and simulation results using different tools of the SCALE package.

Basic considerations for control and shutdown

In general, several basic operational principles for active reactor control can be identified:

- Increasing the absorption of neutrons
    - In the fuel (e. g. burnable poison)
    - In the moderator (e. g. liquid poison)
    - In the fuel assembly (e. g. absorber rods)
    - In the surrounding (e. g. rods in reflector)
- Reducing the fission probability for neutrons through
    - Changing the moderation (e. g. increasing the void in BWR, moderator drainage in heavy water reactors)
    - Changing the amount of fissile material in the core (e. g. withdrawing pebbles, draining molten salt)
    - adding absorber (e. g. adding poison)
- Increasing the neutron leakage form the system via
    - absorbing neutrons in surrounding (e. g. absorber rods in reflector)
    - changing the reflection (e. g. control drums)
- Manipulating an external neutron source (e. g. accelerator shutdown)

These active principles are supported in almost every well-designed reactor system by inherent control mechanisms based on the feedback effects due to temperature changes and the resulting effects (e. g. fuel temperature effect, moderator temperature effect, coolant density effect), even if these effects are not always all negative, the overall balance of all feedback effects must be negative to ensure stable reactor operation.

From the basic list above, it is already apparent that some control and shutdown approaches can act in parallel on different principles e. g. control rods in the absorber to reduce the number of neutrons and change through this the neutron leakage from the core. Interestingly, the described inherent control mechanisms of reactors act on the same underlying basic principles, e. g. the increase of the fuel temperature leads to an increase of the resonance absorption of neutrons, or the moderator density effect is affecting the fission probability of the neutrons due a change of their energy.

To understand the specific demand for the control and shutdown system to be designed, it is important to understand the specific boundary conditions. Two major points have to be mentioned here: Molten salt fast reactors typically consist of a homogeneous core configuration in contrast to typical solid fuelled reactors with a heterogeneous fuel assembly and core composition. A zero-power experiment will have the opportunity/requirement to operate under room temperature, thus with solid salt, as well as a molten salt system at a higher temperature, thus the control system should be able to cope with both conditions leading to a system with weak feedback effects at solid state and the potential for a much stronger feedback in the molten stage. In addition, in a reactor physics experiment, the control system has an additional function, the system is typically used for the exact determination of criticality which has a strong role in the validation of codes on criticality, e. g. via the determination of the control rod position in both the experiment and the calculation.

The described demand specifies the following requirements:

- Shutdown and control system should be diverse
- The systems should be able to operate independently
- Both systems should allow a safe shutdown
- The control system should not create a major inhomogeneity to avoid any impact on the experimental investigation
- The control system should deliver sufficient sensitivity for the validation of criticality, e. g. measurable and reproducible movement following a temperature change in the core
- The interaction of the systems should not impinge on their individual purpose
- Both systems should be applicable in a solid as well as in the liquid core

Based on this requirement two different systems are proposed:

- Shutdown via splitting the reflector, or a part of the core with the reflector form the main part of the core downwards. This can provide a fail-safe solution for the ultimate shutdown driven by gravity
- Control via a vertically movable radial reflector as a movable sleeve around the reactor

Both systems will be usable for a zero-power system with liquid as well as with a solid core and even more importantly, both systems should somehow work on the integral system level without disturbing the central part of the core, which will be the essential area for the experimental measurements. Both approaches should also be able to act as a singular system, as well as together. Their interaction and the sensitivity of the control system will be investigated in the following through the use of a multitude of modelling and simulation results using deterministic and Monte Carlo tools of the SCALE package.

Codes & General Modelling

The salt system is based the density versus temperature curve data from Russian literature [1], see table 1. The data is used for the analysis based on a reference temperature of 980 K with changes by ± 50K for the analysis of feedback effects. The data should be seen as starting point for initial studies with the limits already discussed in [7].

Table 1: Concentration dependent densities for the system NaCl-UCl_3-UCl_4 with the Uranium salt composition 30% UCl_3+70% UCl_4 and varying NaCl concentrations part reprinted form [1]. The experimental error in the density measurements is given with max ± 1.5%

Concentration % NaCl	ΔT [K]	a	b 10^3	std dev 10^3
20.0	934 – 1018	5.3995	1.8646	4
30.0	934 – 1020	4.9360	1.5276	2
45.0	939 – 1029	4.2368	1.0256	3
60.0	872 – 1037	3.8237	0.8774	2
80.0	985 – 1119	3.2382	0.8012	2

Based on the coefficients given in Table 1, the temperature dependent density is calculated based on the following formula:

$$\rho\left[\frac{g}{cm^3}\right] = a - bT[K] \quad (1)$$

Based on the given salt system investigation [21] and the first investigations on the required dimensions for a zero-power experiment [4], the heavy metal rich case with 20%NaCl-56.35%UCl_4-23.65%UCl_3 is used for the following investigations of control and shut down options.

The main part of the simulations for this initial study of zero-power reactor control and shut down approaches have been performed using the Keno VI module of the SCALE code system [26] to analyse the 3D system. “KENO-VI uses the SCALE Generalized Geometry Package, which provides a quadratic-based geometry system with much greater flexibility in problem modelling but with slower runtimes. Both versions of the KENO perform eigenvalue calculations for neutron transport primarily to calculate multiplication factors (k_{eff}) and flux distributions of fissile systems in both continuous energy (CE) and multi-group (MG) modes. They are typically accessed through the integrated SCALE sequences. KENO’s grid geometry capability extends region-based features for accumulating data for source or biasing parameter specifications, as well as for tallying results from a calculation for the visualization or communication of data into or out of a calculation.”[23]. The serial studies on enrichment variation and the analysis of the effect of the removal of the reflector is based on another code of the SCALE package – POLARIS [22] which normally that provides a 2D lattice physics analysis capability that uses a multigroup self-shielding method called the Embedded Self Shielding Method (ESSM) and a transport solver based on the Method of Characteristics (MoC). This code has been meanwhile compared to different Monte Carlo solvers [24,] besides the validation performed by the developer Oak Ridge National Laboratory. The analysis is extended for creating a deeper understanding of the neutron spectrum by using the multi-group deterministic S_n transport calculation sequence TRITION/NEWT.

The multi group Keno VI analysis is based on the v7-252 cross section set (based on ENDF/B 7.1) of the SCALE package [26] which is also the basis for the TRITON/NEWT as well as the POLARIS calculations while the continuous energy version of Keno IV uses the ce_v7.1_endf library of the SCALE package.

For the study, a general 3D Keno-VI model has been built (see Figure 1) representing a cylindrical core surrounded by a thin vessel and a reflector on all surfaces, which will be successively modified in dimension and organization for the simulation of the proposed control and shut down approaches. For completeness the used POLARIS model is given in Figure 2 and the used NEWT model for the neutron spectrum analysis in Figure 3 has already been used in the previous study [4].

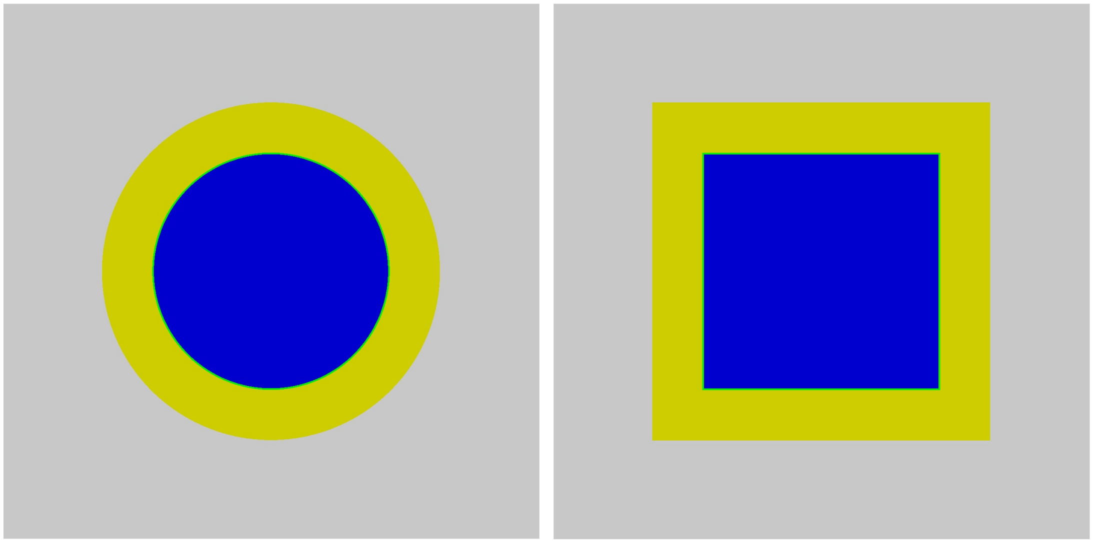

Figure 1: General 3D Monte-Carlo model of the configuration with molten salt fuel core – blue, stainless steel vessel – light green, reflector – yellow, and vacuum - grey developed as basis for the 3D studies of the proposed control and shutdown approach

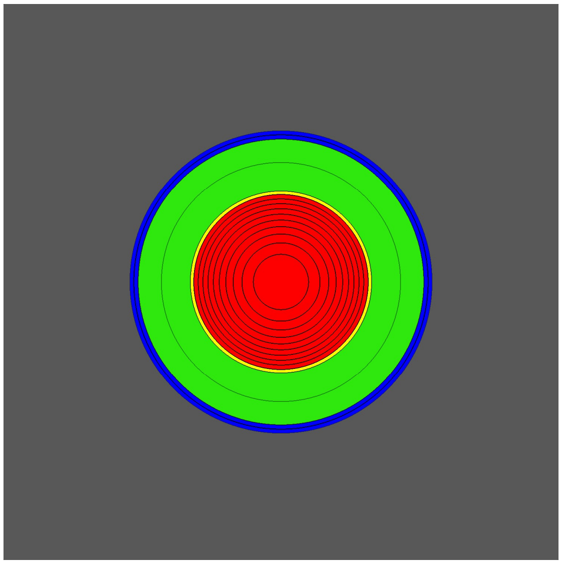

Figure 2: 2D SCALE/POLARIS model (molten salt fuel core – red, stainless steel – yellow, NaCl reflector – light green, vacuum – blue, absorber material – dark grey) used for the general analysis

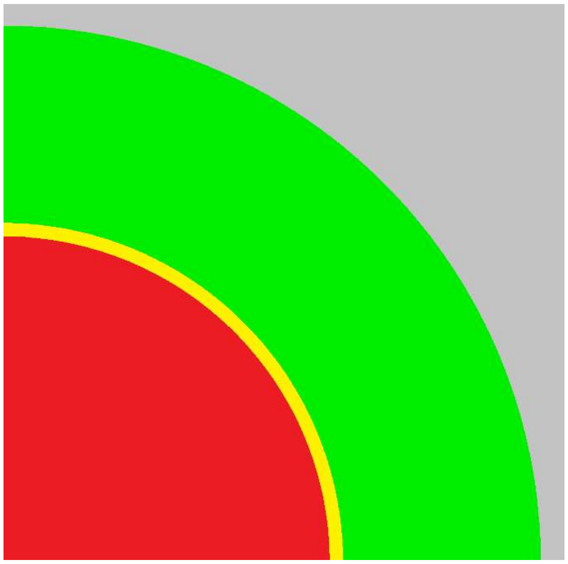

Figure 3: 2D SCALE/TRITON/NEWT model (molten salt fuel core – red, stainless steel – yellow, NaCl reflector – light green, vacuum – grey) used for the analysis of the neutron flux distribution

All Monte-Carlo simulations a setting of 2000 generations with 20000 particles have been used and the source convergence has been checked. This setting leads to an accuracy of ±30 pcm and below at 95% confidence, which is more than sufficient for the current level of the investigation of the control and the shutdown system as well as their interplay.

Shut down system study

The currently proposed configuration for a molten salt fast reactor experiment will be based on a homogeneous core composition with the heavy metal rich salt composition containing 20%NaCl-56.35%UCl_4-23.65%UCl_3 a salt composition as it has been investigated for the breeding [24] and feedback [21] studies for iMAGINE.

Such a homogenous system is in strong contrast to the classical zero-power reactor studies which are in most of the cases designed to investigate heterogeneous configurations having the aim of understanding the effect of the heterogeneity. In a homogeneous system the investigation of the undisturbed system will be of high interest, thus a shutdown system which introduces a perturbation in the homogeneous structure would be a penalty. Looking into the study of homogeneous critical systems, these systems are often controlled via neutron leakage. In addition, the system should ideally be applicable in the solid state at room temperature for a first operational stage as well as for the liquid core in a higher temperature operation at a later stage of the experiments. A first guess of such a shutdown system is given in Figure 4. In this approach the bottom reflector of the core will be removed. Two different approaches are investigated, in case 1 only the bottom reflector is removed while the side reflector is not changed – thus only a gap is created, while in case 2 the side reflector will be limited to the bottom of the core – thus a streaming path for neutrons to leave the system will be opened. Case 3 replicates case 1 but with an opening of 50 cm compared to the 30 cm in case 1. Case 4 follows the same principle it replicates case 2 but with 50 cm opening instead of 30 cm. All 4 cases have been calculated based on the identical Monte-Carlos settings and delivered the following outcome: case 1, -1855 ± 33 pcm; case 2, -2737 ± 33 pcm; case 3, -2596 ± 30 pcm; and case 4, -3181 ± 33 pcm, all with a 95% confidence interval which indicates that the statistics of the Monte-Carlo calculation does not have a significant influence. The change from case 1 to case 2 aims to limit the influence of the side reflector, and increase the shutdown margin by almost 50%.

Increasing the opening from 30 to 50 cm increases the shutdown margin by ~40 % when the side reflector is not reduced, but only by a bit more than 15% when the side reflector is cut. Thus, creating a wider opening is only of interest when it creates an additional streaming path for neutrons as in case 3. However, all cases demonstrate that the achievable shutdown margin is only in the area of two to three thousand pcm which is maybe not sufficient.

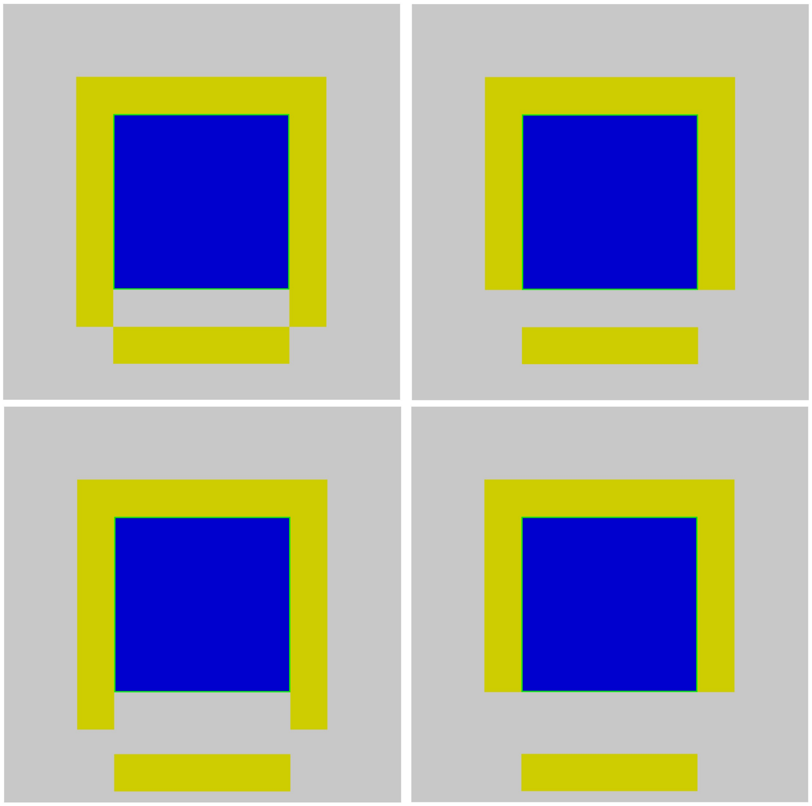

Figure 4: Different cases investigated for the study of the shutdown system moving the bottom reflector away from the core (top left – case 1 (reference), top right – case2, bottom left – case 3, bottom right – case 4)

Based on the above achieved results, it would be of interest to enhance the effect of the removal of the bottom reflector. A promising approach could be to remove not only the reflector but in addition a limited layer of the core. A comparable strategy has been implemented in the teaching reactor SUR-100 which is based on a structure of polyethylene plates with homogeneously distributed fuel. The investigation of this strategy is given in the models created for the analysis and shown in Figure 5. For illustration, the base case is given in the left top corner, it is identical to case 2 of Figure 4. In the following steps a slice of 10 cm (top right), of 20 cm (bottom left), and of 30 cm (bottom right) is moved with the reflector away from the core. This exercise has been performed for all 4 cases defined in Figure 4.

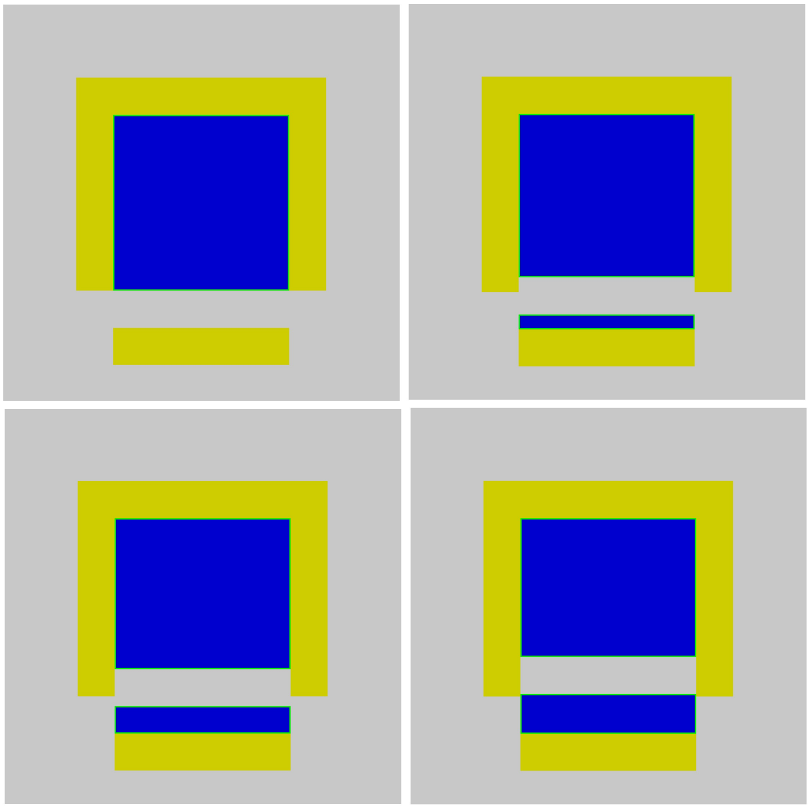

Figure 5: Different cases for the investigation of the shutdown efficiency between only moving the reflector (left top) and moving the reflector with increasing sized layers (10 cm right top, 20cm left bottom, and 30 cm right bottom) of the core contained in a separated vessel

An overview on the combined result for all cases is given in Figure 6 for the 30 cm opening for all cases. The general tendency is for all 4 cases comparable. The 10 cm slice increases the shutdown margin by ~50%, the 20 cm slice by ~100% and the 30 cm slice by slightly more than 150%. The gain, in form of shutdown margin, is slightly weaker in case 2 where the reference case (case 1 in Figure 4) has the strongest shutdown margin. Considering all the results shown, it is apparent that the removal of the bottom reflector has the potential to be used as a shutdown system and the negative reactivity margin can be tailored to the demanded shutdown reactivity, which will have to be discussed and agreed with the regulator on a more detailed design level.

On a more technological view, the thickness of the layer to be moved should be as thin as possible. On the one hand, the whole design of the control system will be more challenging with increasing weight of the piece to be moved which creates the demand for a thin layer. On the other hand, the core part to be moved will limit the opportunity for the insertion of instrumentation and the thicker the layer is, the less undisturbed core volume will be left at the top which will be used for the investigation of the behaviour of the homogeneous system. Thus, finally the dimension of the layer used for the shutdown system will be a typical optimization problem to create sufficient shutdown reactivity while limiting the disturbance on the experimental performance.

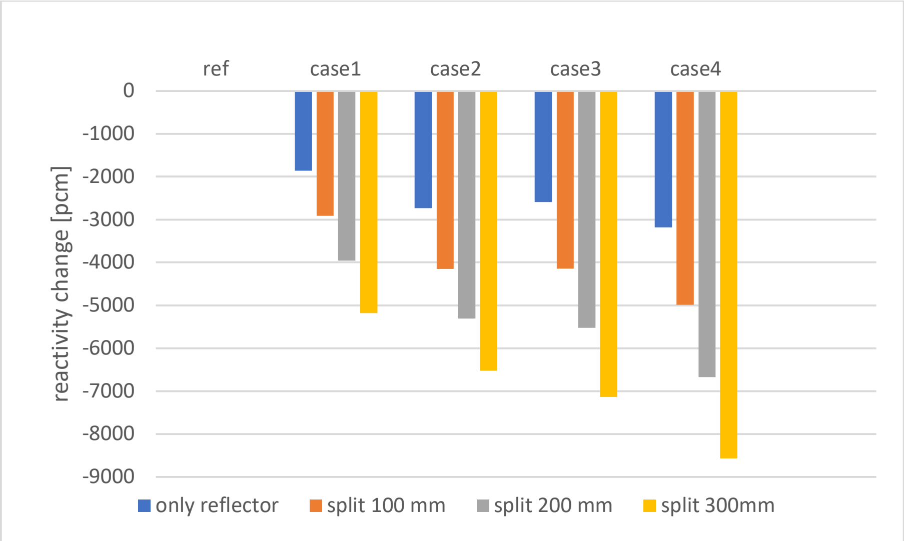

Figure 6: Negative reactivity effect (shutdown reactivity) caused by moving the reflector and different sized layers of the core away from the main core for the 4 described cases

Control System Study

The boundary conditions of ideally not disturbing the homogeneous arrangement of the core described for the shutdown system are even more important for the control system which will be used to start-up the reactor as well as to keep the reactor in the critical state. The additional request on the applicability for the solid as well as for the hot liquid state is essential for the control system, too. Based on these requirements, the control of the criticality via the movement of the radial reflector seems to be a promising option, especially if the system would be efficient enough to assure that most of the core can stay reflected to get good opportunities for the evaluation of the reflected configuration. However, this way of control could in addition allow the investigation of the neutron flux distribution in the un-reflected core (the reflector space in the model is filled with vacuum), too. The potential core criticality change, investigated in the two-dimensional system is given in Figure 7 as a function of the fuel enrichment. From this evaluation of the criticality change the limitation of the radial reflector control is obvious. The system using the reflector for control will strongly increase in efficiency with decreasing reactor core size. The reactor size coincides in the investigated system with the uranium enrichment while the effect of the salt configuration, thus the amount of NaCl carrier salt has only a very minor effect. The figure indicates that a sufficient criticality change by removing the radial reflector can only be achieved for systems with at least 20% enrichment and thus an estimated 2-D system radius of about 80 cm. For the chosen system with a 35% enrichment, the expected value of this initial investigation will be in the range of more than 20000 pcm. Thus, a broad range of configurations and even a significant temperature range with the resulting reactivity change due to the strong feedback effects, [4], can be evaluated/compensated with the proposed radial control reflector holding the reactor in a critical status.

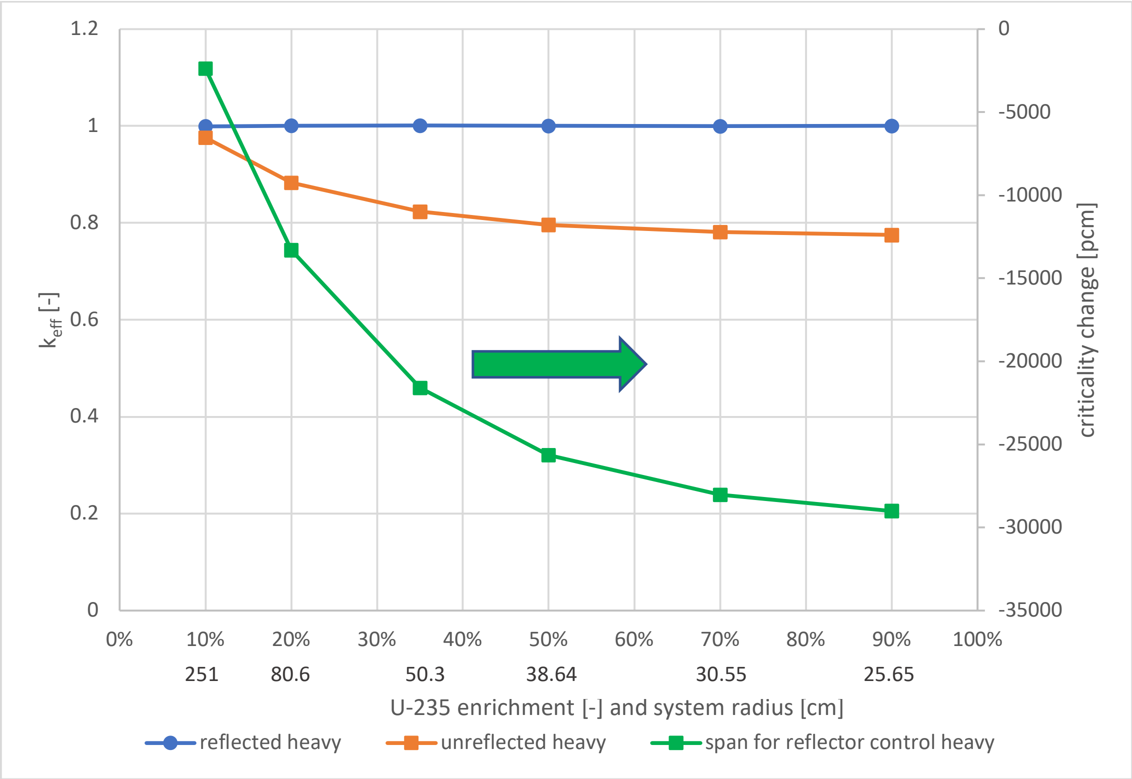

Figure 7: Criticality versus U-235 enrichment for the reflected and the unreflected 2D system demonstrating the increase of the control potential span with increasing U-235 enrichment and correlated reduced core size

Based on this initial 2-D evaluation, the approach of a control system using a vertically moving radial reflector will be investigated in more detail in a three-dimensional analysis using Keno VI. The first step for the 3-D analysis is to determine the appropriate 'slightly over critical' configuration – a cylinder with a diameter of 140 cm and a core height of 140 cm delivers in the Keno VI multi-group calculation a k_{eff} of 1.02033. The used core model is given in the left upper corner of Figure 8 using a 10 mm thick stainless-steel wall and a 30 cm layer to split off for the shutdown system. The following images from left to right in the upper and then the lower row visualize the concept of the radial reflector control accomplished by moving the radial reflector stepwise downwards. The visualized pictures are only a few of the used steps investigated for the analysis of the control effect curve of the control system. The radial reflector in the undisturbed reference system reaches at the top and the bottom 6 cm further than the core to assure that the effect of moving the reflector on core criticality starts already after a limited amount of movement.

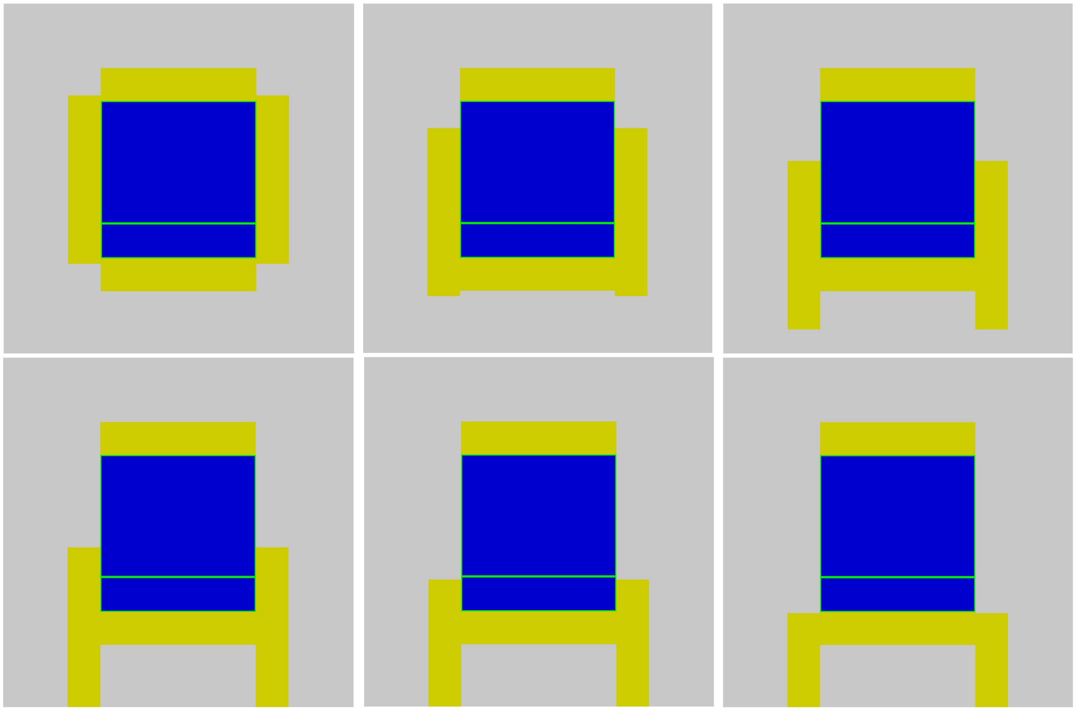

Figure 8: Different steps of reflector movement steps (top form left to right 0, -30cm, and -60cm, bottom left to right -90cm, -120cm, and -150cm) for the analysis of the reactivity curve related to the movement of the reflector

The analysis of the control reactivity curve is accompanied with the analysis of the effect of the thickness of the reflector by investigating not only the reference case with the 30 cm thick reflector, but also a case with a reflector reduced to 20 cm and one with an increased reflector thickness of 40 cm, see Figure 9. The 20 cm reflector case requires a core with 144 cm diameter and a height to assure a critical reactor with some reserve criticality margin, while the increase of the thickness of the radial reflector to 40 cm allows to reduce the core size to 136 cm diameter and height. The axial reflector is kept with a thickness of 30 cm in each of the cases.

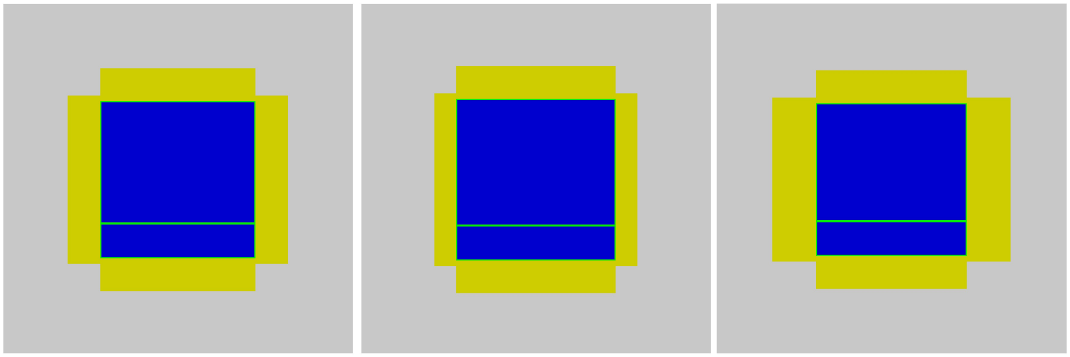

Figure 9: Cases for the investigation of the effect of different reflector thickness of the movable radial reflector on the control reactivity curve (left 30cm reflector case with 140cm diameter and 140 height, centre 20cm reflector case with 144cm diameter and 144 height, right 40cm reflector case with 136cm diameter and 136 height)

The control curves given in Figure 10 indicate a reactivity control span of ~12000 pcm for the 20 cm thick reflector, ~16000 pcm for the 30 cm thick reflector and ~20000 pcm for the 40 cm thick reflector. The curves are determined through Monte-Carlo calculations with the reflector moved downwards in 10 cm steps from the original starting position until the lower end of the core is reached. All curves show the characteristic trend with lower efficiency of the control system at the beginning and the end of the movement path. This means the control system allows at the beginning and at the end a very sensitive control since moving one increment has a smaller influence on the overall core criticality than when the control system is acting somewhere around the core centre where the neutrons typically have a higher importance. Thus, the increase of the leakage has stronger influence on criticality in this area. The control response to the thickness of the reflector is almost proportional to the thickness of the reflector, even for the 40 cm thick reflector. This indicated that there would still be an opportunity to increase the reactivity change if required, since only a very small saturation effect can be observed. In general, the criticality change which is effected by the control system is in all investigated cases very wide which will allow to compensate for the large reactivity changes which are expected for molten salt systems due to the very strong feedback effects caused by the strong effect of the density change of the salt which is acting a as coolant as well as a carrier for the dissolved fuel [24].

Finally, the decision for the thickness of the reflector and the use of the reflector for controlling the system criticality will follow different objectives since the control system design will be dependent on the weight of the component which has to be moved and the ideal system should be lightweight which points to a thin reflector. However, from core design, control, and cost point of view the objective is an as efficient as possible reflector, since as shown above the thickness of the reflector has an influence on the core size and thus on the amount of fuel required for the experiment which is one of the costliest parts in a zero-power experiment. The results for the criticality study show the influence of the reflector thickness on the required volume while the reference case with the 30 cm thick reflector leads to a volume of ~2.15 m^3, the case with the 20 cm thick reflector requires ~2.35 m^3 (+9% core volume) and the case with the 40 cm thick reflector requires only 1.98 m^3 (-8% core volume).

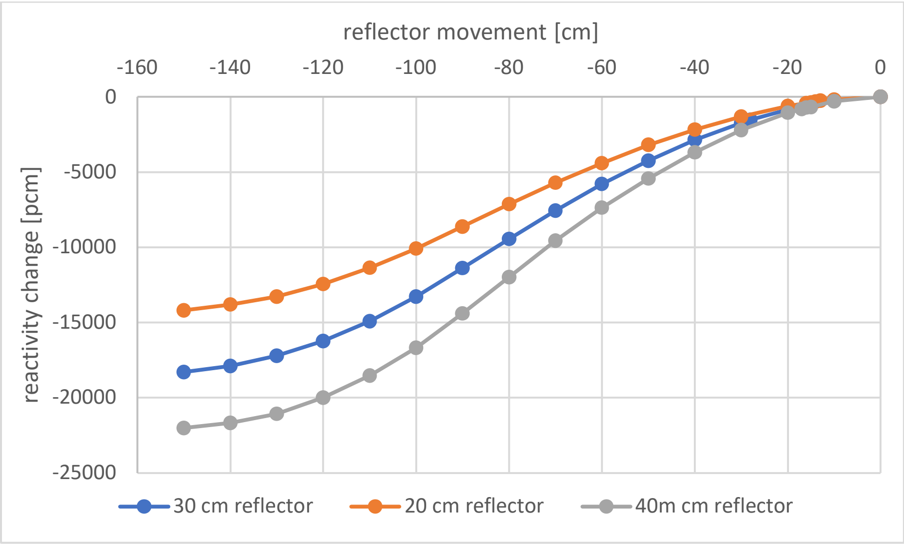

Figure 10: Control reactivity curve dependent on the stepwise downward movement of the reflector for systems with different thickness of the reflector

Moving the reflector for the control of the reactor will have some strong influence on the neutron spectrum since the core leakage will significantly change. The analysis of the neutron spectrum based on a 2-D calculation using the deterministic TRITON/NEWT sequence of the SCALE package is given in Figure 11. The general neutron spectrum is typical for a fast reactor with the majority of the neutrons between 10 keV and 2 MeV with almost no thermal neutrons appearing in the system. The two different neutron spectra are both calculated independently and could be interpret as the neutron spectrum in the upper core part – unreflected in the case the reflector is moved downwards, and the neutron spectrum in the lower core part – reflected since there the reflector will still enwrap the core. Both of the neutron spectra shown can be seen as the two extrema since they are calculated for an axially infinite system. Thus, in the region where the top end of the reflector is located some mix of both spectra will appear. The spectrum for the unreflected case is somewhat harder than for the reflected case where some lower energy neutrons are reflected back into the core after they have lost energy in the reflector. The appearance of neutrons with energies around 1 keV has been indicated in [4] as neutrons which almost solely exist in the reflector where no fission events take place. As soon as these neutrons penetrate back into the core they will be absorbed and have a high probability to create fission reactions. Thus, the fission density in the outer core area will be slightly higher in the reflected core part. When the instrumentation for the zero power core is designed well, this change will hopefully be recognizable. Thus, a neutron flux distribution can be measured for the reflected and the unreflected core to identify the effect of the reflector onto future reactor operation where the reflector will be a design feature to improve the neutron economy in the core, even if it is expected that the effect of the reflector will be lower with increasing core size as already visible in Figure 7.

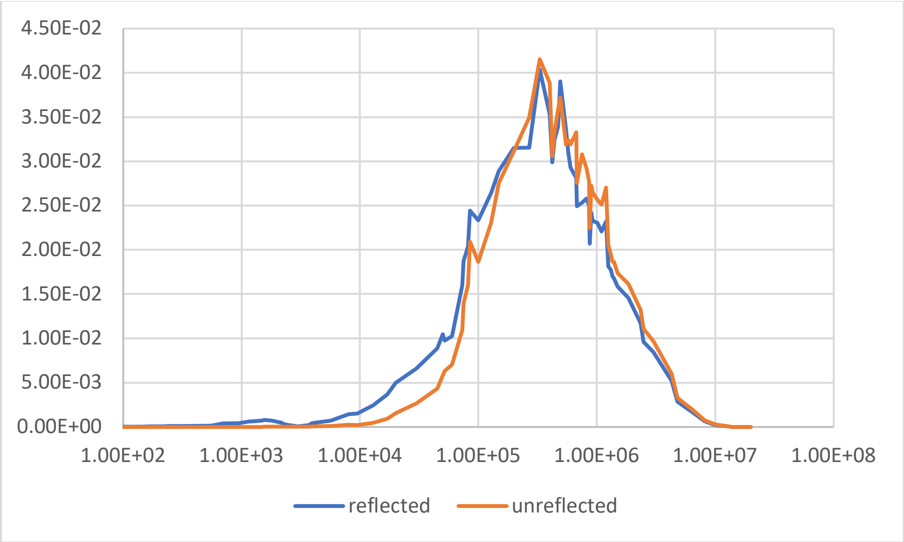

Figure 11: 2D study of the differences in the neutron spectrum caused by the control system for the 35% enriched reflected (lower core part) and un reflected (upper core part) core configuration using the heavy metal rich salt system

Following the separate study of a potential reactor shutdown system and a reactor control system, the next chapter will deliver the analysis of the interplay between both systems which will be relevant for the operation. That there will be a clear interplay between the systems is clear when analysing the results given in Figure 6 where the effect of the presence or absence of the side reflector has strong influence on the shutdown reactivity.

Control and shut down system interaction

The basic approach for this study will be taken by initiating the shutdown from the critical state of the three cases with varying reflector thickness at the appropriate reflector position. The configuration of the critical state core with 30 cm thick reflector with the reflector positioned on -29 cm from the original position leads to a k_{eff} of 1.0003 and different openings of the shutdown system is given in Figure 12. From the stepwise figures it is clear that the combination of the control and the shutdown system always tend to lead to a configuration as given in case 1 and 3 in Figure 4 with the streaming path for the neutrons to the side mostly or completely blocked by the side reflector.

The efficiency of the shutdown system will be evaluated regarding the different openings of the shutdown system as well as regarding the influence of the thickness of the side reflector on the shutdown reactivity.

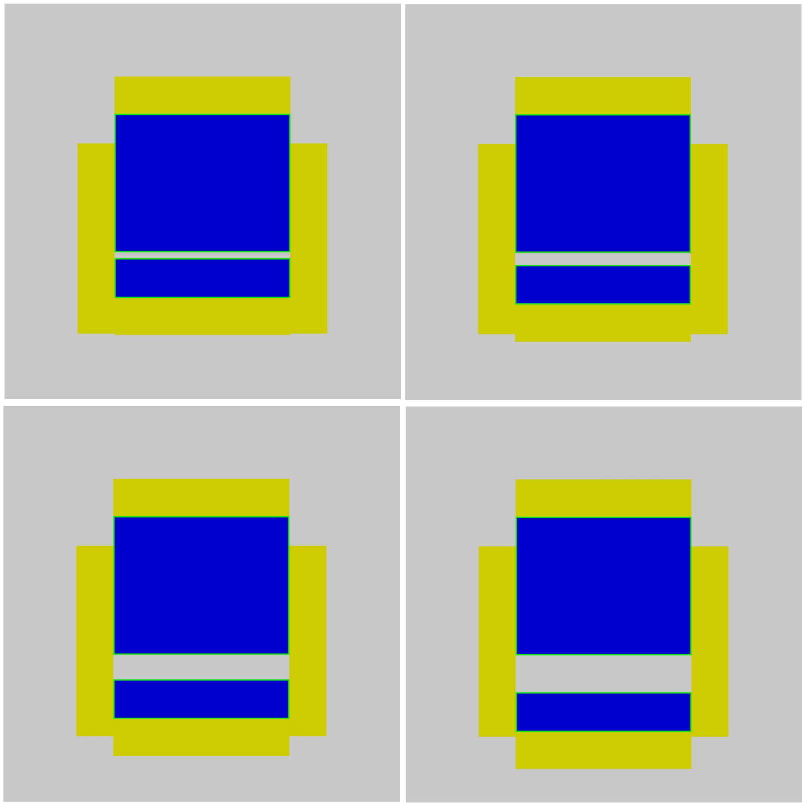

Figure 12: Shut-down system opening steps (top left 5cm, top right 10cm, bottom left 20cm, and bottom right 30cm) analysing the critical system (30cm case with 140cm diameter and 140 height, reflector position -29 cm)

The shutdown reactivity for the three different openings combined with the critical side reflector position is given in Figure 13. On the first glance, the reactivity change follows the expected pattern with increasing negative reactivity effect when the width of the opening is increased. The other effect, the increase of the negative reactivity effect caused by the increase of the core slice split off form the core from a 10 cm thick slice to a 30 cm thick slice coincides with the results given in Figure 6. For a better evaluation of the absolute values for the 30 cm opening for the cases 1 and 2 of Figure 6 are given on the left axis. These markers indicate that the combined shutdown and control case can be seen as a kind of intermediate solution between the two cases, with the 30 cm thick core layer split tending to be closer to case 2. In general, the influence of the radial reflector positions does not seem to have a very strong influence on the efficiency of the shutdown system. This finding will be very helpful for the future core design, but to deliver convincing results to the regulator, a study of a wider variety of combinations between the shutdown and the control system position will be required to demonstrate the efficiency of the shutdown system under all possible operational circumstances.

Figure 13: Shut-down reactivity from critical system dependent on the opening width of the shut-down system based on the 30cm case with 140cm diameter and 140 height

It is essential to understand the interaction of the control system and the shutdown system for any consideration of the safety of the zero-power reactor. However, for reactor design, it is also important to understand, in addition, the effect of the thickness of the reflector on the efficiency of the shutdown system as given in Figure 14. From this figure it is clear that the reflector thickness does not have a major influence on the shutdown reactivity, thus there seems to be only a weak interdependence which is important to know, to guide future investigations and to create freedom for the design of a future zero-power reactor core. The most important information is that there is almost no influence of the small openings on the reactivity change. Thus, the shutdown system characteristics shortly after initiation of the shutdown are not affected by the reflector thickness and even at the very large opening, the effect of the reflector thickness on the shutdown margin is very limited.

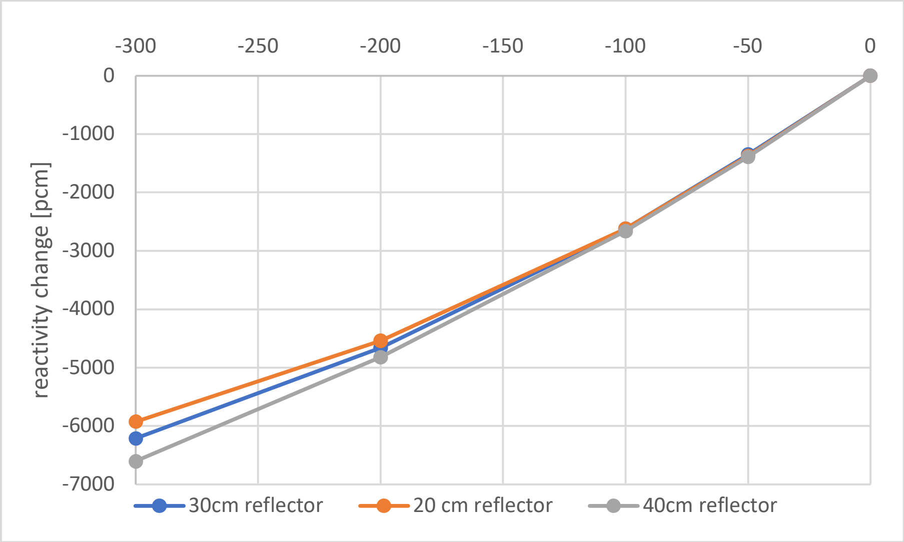

Figure 14: Shut-down reactivity from the critical state for systems with different reflector and system size

Following the investigation of the interaction of the control and shutdown system, two final points will be investigated in for completeness to answer the following questions: Is the control system sensitive enough to compensate for small reactivity changes with a sufficient movement of the reflector? Can the results gained with the multi-group Monte-Carlo be trusted, even if the master library of SCALE has been developed for light water reactor use?

Sensitivity of the control system

The first test for the sensitivity of the control system is based on compensation of the thermal feedback when the core temperature will be changed by ± 50 °C. The three reflector positions for the investigated reference case as well as for the reduced and increased temperature case are shown in Figure 15 with the detailed numbers given in Table 2. When the temperature of the core is increased from the reference temperature by 50 °C, the reflector has to be moved upwards to compensate for the reduced density of the fuel as well as for the increased absorption through the Doppler Effect. The reflector has to be moved 24 cm upwards for compensation of the increased temperature, which means based on a first guess that a temperature change of 2°C will be compensated by a movement of 1 cm within the calculation accuracy of the criticality iteration (± 30 pcm) and the accuracy of the Monte-Carlo method (± 33 pcm at a confidence of 95%). This seems to be a reasonable position change, which can be easily controlled through a modern movement system (comparable to a control rod drive in a LWR), as detected by modern measurement technologies for the determination of the reflector position. However, it has to be kept in mind that the weight of the reflector will be significantly higher than for a control rod group moved by one drive.

The compensation of the cool down of the core works in a similar manner. When the fuel temperature is reduced, the density of the salt will increase and the absorption in the fuel will decrease both leading to a higher criticality of the reactor. To compensate this criticality change, the reflector must be moved downwards by ~14 cm. The required movement is less strong than for the heat up since the efficiency of the control system is higher at a position closer to the centre of the core, see discussion of the control reactivity curve in Figure 10. Thus, in this case a temperature change of 2 °C will be compensated by a movement of the reflector y ~0.6 cm or 6 mm, which is still a value that is reliably detectable. In addition, it should not be forgotten that the temperature in this system is strongly negative, that the reactor will self-stabilize due to the feedback effect. However, the results shown are for a system with molten salt at a temperature level of ~700 °C. A real reactor physics experiment would most probably be operated in a first instance at room temperature where the feedback effects in the solid salt will be substantially different. Thus, a study based on the effectiveness of the proposed control system at room temperature should be performed as soon as reliable data on the thermal expansion coefficient of the proposed fuel salt in the room temperature range will be available.

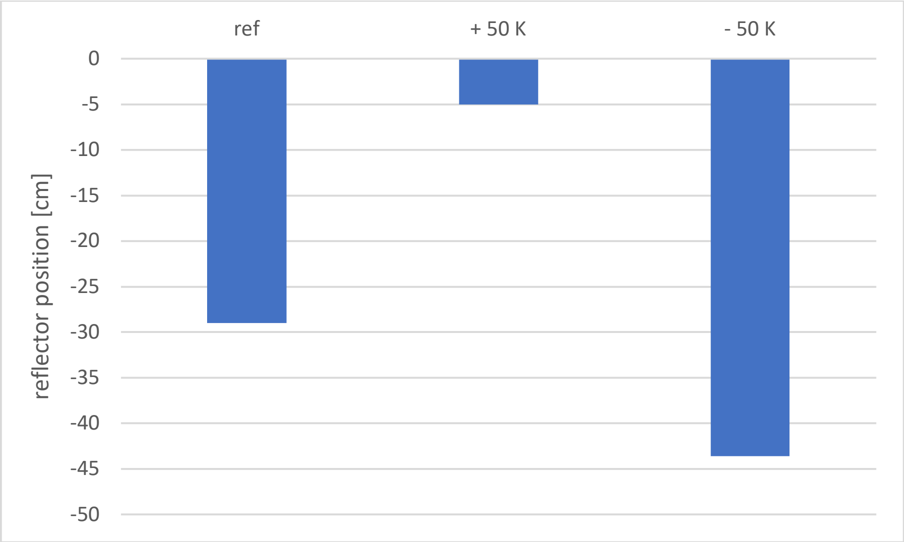

Figure 15: Study of the reflector position required to compensate for the system temperature change

Table 2: Exact criticality data and reflector position for the reference system and a postulated temperature change of ± 50 K

case	reflector position [cm]	Multiplication factor	Std dev
ref	-29	1.0003	0.0001
+ 50 K	-5	1.00001	0.00011
- 50 K	-43.6	1.00017	0.0001

Consistency check of the multi-group Monte-Carlo results

To assure the quality and reliability of the results delivered by the multi-group version of Keno VI using the v7-252 cross section set of the SCALE package [26] as master library for the CSAS-MG cross section generation procedure the result for the critical reference case will be compared to a reference continuous energy Monte-Carlo solution. The results for the comparison are given in Table 3. The application of the continuous Monte-Carlo approach delivers a slightly different critical reflector position at -22 instead of -29 cm. The results demonstrate that the use of the weighted master library has some influence on the results, but the influence seems to be limited and the use of the significantly faster multi-group Monte-Carlo approach can be confirmed as sufficiently accurate for the current level of this feasibility study. Nevertheless, for future application a two-fold strategy seems to be indicated using the multi-group approach, with deterministic as well as Monte-Carlo approaches, for serial studies to improve the systematic understanding of the system which should be backed up with several continuous energy calculations to justify the absolute values. In general, the envisaged zero-power experiments will deliver the validation basis for the future code application to assure a good validation level of the code systems foreseen for the design of future molten salt reactor systems. However, first modelling and simulation results will be required for the design of a zero-power experiment, thus the careful use of different tools and databases as well as the critical analysis of the differences will be required in the same way as the improvement of the thermo-physical data as input for the modelling and simulation tools.

Table 3: Consistency check between the multi-group Monte-Carlo result as used for the study with a continuous energy Monte-Carlo result using the same cross section basis of SCALE

Reflector position	Multiplication factor	Std dev	
-22	1.00052	0.00011	CE Monte-Carlo
-29	1.0003	0.0001	MG Monte-Carlo

Summary and Conclusions

The topic of control and shutdown is introduced through a literature review and the reduction of the control approaches to a limited number of basic functions with different variations. In the following the requirements for the control and shutdown system for a reactor experiment are formulated and based on these an approach for the shutdown – splitting the lower part of the core with the reflector, and an approach for the control – a vertically movable radial reflector are proposed. Both systems will be usable for a zero power system with a liquid as well as with a solid core and even more important, both systems somehow work on the integral system level and do not require the central part of the core to be disturbed, which will be the essential area for the experimental measurements. Both approaches as singular system as well as their interaction and the sensitivity of the control system will be investigated in the following through the use of a multitude of modelling and simulation results using deterministic and Monte Carlo tools of the SCALE package.

The investigation of the shut-down efficiency between only moving the reflector and moving the reflector with increasing sized layers of the core up to 30 cm. The comprehensive study indicates a variety of solutions with a shutdown reactivity effect of -2000 to up to -8000 pcm dependent on the configuration.

The analysis of the proposed control approach is evaluated against the U-235 to indicate the control span with increasing U-235 enrichment which is followed by the investigation of the control curve for the standard system delivering a control span of -18000 pcm. The sensitivity investigation is based on a variation of the reflector thickness by ±10 cm, which leads to a variation of ~±20% in the control span, based on the slight core size variations resulting from the effect of changes to the reflector thickness. A control reactivity curve dependent on the stepwise downward movement of the reflector for systems with different thickness of the reflector is provided for all cases and the neutron spectrum change between the core with reflector (lower core part) and without reflector (upper core part).

The interaction between both systems is analysed by introducing a shutdown with different openings in conjunction with the reflector control system in the position for a critical system delivering a shutdown reactivity curve with a maximum between -3500 pcm for a 10 cm layer and -6200 pcm for a 30 cm layer. The dependence of the shutdown system on the system size change due to the change in the reflector thickness has been found to be marginal. A sensitivity study based on a system temperature change of ± 50K lead to a reflector movement of +24 cm for + 50K and -14.6 cm for -50K to compensate for the related reactivity change induced by the temperature change.

Finally, a consistency check between the multi-group Monte-Carlo result as used for the study with a continuous energy Monte-Carlo result using the same cross section basis of SCALE is delivered which indicates a small change in the predicted control position. This inter-comparison of codes of the SCALE package with good agreement between them creates trust in the results obtained, but indicates that there is room for improvement and demonstrates the need for validation experiments to assure the best possible results for future modelling and simulation of molten salt reactor systems.

The current analysis is only applied for a very narrow window of operational temperature in molten salt, which is related to the limited data availability. Thus, a much more comprehensive study will be required as soon as the relevant thermo-physical properties are available down to room temperature.

References

1. Government and Industry Roles in the Research, Development, Demonstration, and Deployment of Commercial Nuclear Reactors: Historical Review and Analysis. EPRI 2017. 3002010478
2. B. Merk et al: A zero-power facility as multi-fold opportunity to support quick progress in innovative reactor development, atw 66 (3) 2021
3. B. Merk et al: "iMAGINE - A disruptive change to nuclear or how can we make more out of the existing spent nuclear fuel and what has to be done to make it possible in the UK?", atw 6/7 2019
4. B. Merk, A. Detkina, S. Atkinson, D. Litskevich, G. Cartland-Glover (2020) On the dimensions required for a Chloride-Salt based molten salt zero power reactor, Applied Science special edition Nuclear Waste Management
5. B. Merk, A. Detkina, S. Atkinson, D. Litskevich, G. Cartland-Glover: Innovative investigation of reflector options for the control of a Chloride-Salt based molten salt zero power reactor, Applied Science special edition Nuclear Waste Management 2020
6. Canadian Nuclear Safety Commission, Nuclear Power Plant Safety Systems, available: https://nuclearsafety.gc.ca/eng/reactors/power-plants/nuclear-power-plant-safety-systems/index.cfm#:~:text=%20Controlling%20the%20reactor%20%201%20Normal%20operation.,restarted%20by%20the%20operators%20in%20the...%20More%20, accessed 25/11/2020
7. Fast Reactor Database 2006 Update, IAEA-TECDOC-1531, available: https://www-pub.iaea.org/MTCD/Publications/PDF/te_1531_web.pdf, accessed 25/11/2020
8. S Kubo: Safety design approach featuring Severe accident countermeasures for GEN-IV SFR, International Workshop on Prevention and Mitigation of Severe Accidents in SFRs, 11th - 13th June, 2012 in Tsuruga, JAPAN, available: https://www.jaea.go.jp/04/turuga/internationalworkshop/presentationPDF/201206121630_Shigenobu%20Kubo_Japan.pdf, accessed 26/11/2020
9. THTR 300 MWe Prototype Reactor - Safety Assessment, available: https://www.nrc.gov/docs/ML0219/ML021920350.pdf, accessed 25/11/2020
10. G. M. Tolson and A. Taboada: MSRE, CONTROL ELEMENTS: MANUFACTURE, INSPECTION, DRAWINGS, AND SPECIFICATIONS, ORNL-4123, JULY 1967

11. MSRE Design Features, available: https://msrworkshop.ornl.gov/wp-content/uploads/2017/10/presentation-session-3-Greenwood.pdf, accessed 25/11/2020

12. Dingee, D. A., Hogan, W. S., Wilson, R. G., Ballowe, W. C., Jankowski, F. J., and Chastain, J. W. CRITICAL-ASSEMBLY EXPERIMENTS ON A REFLECTOR CONTROL SYSTEM FOR A BOILING REACTOR. United States: N. p., 1957. Web. doi:10.2172/4291125.

13. Hugh C. Paxton George A. Jarvis Cleo C. Byers: Reflector-Moderated Critical Assemblies, LA-5963, 1975, available: https://fas.org/sgp/othergov/doe/lanl/lib-www/la-pubs/00374353.pdf, accessed 27/11/2020

14. Ames Technology Capabilities and Facilities, available: https://www.nasa.gov/centers/ames/research/technology-onepagers/autonomous_nuclear_contr14.html, accessed 25/11/2020

15. Erdenechimeg Suvdantsetseg, Janne Wallenius, Sara Bortot: "Optimization of the reactivity control drum system of ELECTRA", Nuclear Engineering and Design, Volume 255, February 2013, Pages 376
16. Training Reactor AKR-2, available: https://tu-dresden.de/ing/maschinenwesen/iet/wket/ressourcen/dateien/akr2/Lehrmaterialien/experiments_at_akr2.pdf?lang=en< accessed 17/06/2021
17. A.D. KNIPE, B.M. FRANKLIN, B.L.H. BURBIDGE, M.F. MURPHY, A.S.DAVIES, and D. HANLON, "The DIMPLE Cruciform Assembly Benchmark Series," AEA-RS-1072 (1981)
18. Kiyavitskaya, H., Bournos, V., Fokov, Y., Martsynkevich, B., Routkovskaia, C., Gohar, Y., Persson, C.-M., Gudowski, W., 2007. YALINA-Booster Benchmark Specifications for the IAEA Coordinated Research Projects on Analytical and Experimental Benchmark Analysis on Accelerator Driven Systems and Low Enriched Uranium Fuel Utilization in Accelerator Driven Sub-Critical Assembly Systems, IAEA.

19. GUINEVERE: Generator of Uninterrupted Intense Neutron at the lead VEnus REactor, available: https://science.sckcen.be/en/Projects/Project/GUINEVERE, accessed 25/11/2020

20. Desyatnik, V.N., & Katyshev, S.F. (1980). Volumetric and surface properties of the NaCl-UCl3-UCl4 melts. Zhurnal Fizicheskoj Khimii, 54(6), 1606-1610.

21. Merk, B.; Detkina, A.; Litskevich, D.; Atkinson, S.; Cartland-Glover, G. The Interplay between Breeding and Thermal Feedback in a Molten Chlorine Fast Reactor. *Energies* 2020, *13*, 1609.

22. M. A. Jessee, J. J. Jarrell, W. A. Wieselquist, M. L. Williams, K. S. Kim, T. M. Evans, S. P. Hamilton, C. A. Gentry: POLARIS - 2D LIGHT WATER REACTOR LATTICE PHYSICS MODULE, in SCALE Code System edited by B.T. Rearden, M.A. Jessee, February 2017

23. SCALE 6.2: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design; Includes ORIGEN and AMPX., **RSICC CODE PACKAGE CCC-834**

24. B. Merk, A. Detkina, S. Atkinson, D. Litskevich, G. Cartland-Glover: Evaluation of the Breeding Performance of a NaCl-UCl-Based Reactor System, Energies 2019, 12(20), 3853; https://doi.org/10.3390/en12203853

25. J. LEPPÄNEN et. al. "The Serpent Monte Carlo code: Status, development and applications in 2013." Ann. Nucl. Energy, 82 (2015) 142-150.

26. B. T. Rearden, M. A. Jessee, Ed.: SCALE CODE SYSTEM, ORNL/TM-2005/39 Version 6.2.2, February 2017