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A Draft Design of a Zero Power Experiment for Molten Salt Fast Reactor Studies

Bruno Merk * , Omid Noori-kalkhoran , Lakshay Jain , Daliya Aflyatunova , Andrew Jones , Lewis Powell , Anna Detkina , Michael Drury , Dzianis Litskevich , Marco Viebach , Carsten Lange

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A Draft Design of a Zero Power Experiment for Molten Salt Fast Reactor Studies

B. Merk [1,2,*], O. Noori-kalkhoran [1], L. Jain [1], D. Aflyatunova [2], A. Jones [1], L. Powell [1], A. Detkina [1], M. Drury [3], D. Litskevich [1], M. Viebach [4] and C. Lange [4]

[1] The University of Liverpool, School of Engineering, United Kingdom
[2] The University of Liverpool, School of Physical Sciences, United Kingdom
[3] UK Atomics, United Kingdom
[4] TU Dresden, Institute of Power Engineering and Environmental Technology, Germany
* Correspondence: merk@liverpool.ac.uk

Abstract: The UK government and many international experts have pointed out that nuclear energy has an important role to play in the transition towards a decarbonized energy system since it is the only freely manageable very low-carbon energy technology with 24/7 availability to complement renewables. Besides current investments in light water reactor technologies, we need innovation for improved fuel usage and reduced waste creation, like offered by iMAGINE, for the required broad success of nuclear technologies. To allow quick progress into innovative technologies like iMAGINE and their regulation, a timely investment into urgently needed experimental infrastructure and expertise development will be required to assure the availability of capacities and capabilities. The initial steps to start the development of such a new reactor physics experimental facility to investigate molten salt fast reactor technology are discussed and a stepwise approach for the development of the experimental facility is described. The down selection to the choice for a diverse control and shutdown system is described through manipulating the reflector (control) and splitting the core (shutdown). The developed innovative core design of having the two core parts in two different rooms opens completely new opportunities and will allow to manifest the request for separated operational and experimental crews, as nowadays requested by regulators into the built environment. The proposed physical separation of safety relevant operational systems from the experimental room should on the one hand help to ease the access to the facility for visiting experimental specialists. On the other hand, the location of all safety relevant systems in a now separated access-controlled area for the operational team will limit the risk of misuse through third party access. The planned experimental programme described with the major steps: core criticality experiments, followed by experiments to determine the neutron flux, neutron spectrum, and power distribution as well as experiments to understand the effect of changes in reactivity and flux as a function of salt density, temperature and composition change.

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Introduction

The important role of nuclear energy – in all forms, large as well as small – in the transition towards a decarbonised energy system of the future has been recognised by experts. This is due to nuclear energy currently being the only freely manageable, very low-carbon technology with 24/7 availability to complement renewables. It is seen as the key towards energy independence and boosting energy security in the UK. [1]. Recently, Fatih Birol, executive director, IEA also described the importance of nuclear energy in the IEA report on Nuclear Power in Clean Energy System: "Alongside renewables, energy efficiency and other innovative technologies, nuclear can make a significant contribution to achieving sustainable energy goals and enhancing energy security" [2]. Based on IEA data, nuclear power is the second-largest source of low-carbon electricity today and "Over the past 50 years, the use of nuclear power has reduced CO_2 emissions by over 60 giga tonnes – nearly two years' worth of global energy-related emissions" [2]. However, the significant reduction of CO2 emissions over 50 years is a snap-shot dated 2019. It reflects a situation which, at least in the western world, is mainly based on massive investments into nuclear done in the past. The investment into building nuclear power stations has substantially slowed down in the OECD countries, resulting in a significantly aged reactor fleet. The number of new projects is currently very limited and often suffer cost overruns and delays in delivery. Very recently, at COP28, more than 20 countries have launched declaration to triple nuclear energy capacity by 2050, recognizing the key role of nuclear energy in reaching net-zero [3]. To successfully deliver on this substantial and very challenging promise towards a net-zero future, nuclear must innovate to better deliver on the future requirements and be successful on the longer term. According to the NS-energy business [4], nuclear must improve in fuel utilisation, reducing the long construction time-frames, the damage due to mining, and the waste accumulation or its handling. An additional key for expected quick and massive delivery will be to drive down cost and complexity in construction and operation.

The role of experiments and a well defined stepwise approach has been described by General Director of NIKIET Andrei Kaplienko at the opening event of the Russian MSFR programme: "We all have to solve an extremely ambitious task - to create a research reactor here. There is no similar real object anywhere in the world. I am convinced that we will succeed, we will be the first. And although a complex of works has been included in the national project, we will go in stages. First of all, the creation of a research reactor for testing technologies. Let's move on to a large reactor with more powerful parameters, having completely understood the required technology. The path is not fast, but it [the reactor concept] is new, and it is impossible to take risks."[13]. This coincides very well with the observations on risk taking in the Manhattan Project by the lead General L. Groves who spoke about no having been aware of the chances and risks which would have to be taken that in more normal times would be considered reckless in the extreme [16] which was caused by the high pressure.

Although there is a definite need for innovative nuclear reactor technologies, there are almost no low power experimental facilities available anymore. However, these facilities have been one of the fundamental drivers of nuclear reactor development, existing in the world. It must be mentioned here that current commercial nuclear technologies are still based on the initial developments of the 1950s and '60s. At this time, many countries built and operated a large number of such experimental facilities, which were used to study different things and drive rapid development. A search in the IAEA research reactor database for facilities with a thermal power between 1 kW and 1MW in Western Europe gives the following results: 51 reactors at different stages of shutdown or decommissioning, 5 operational reactors (4 of them are TRIGA reactors), and none are planned or under construction. In fact, only 3 such reactors are under construction or planned across- the world with none in OECD countries [5].

These numbers clearly indicate that most of the facilities created in the 1950s and '60s have been closed, mainly due to a lack of demand as a result of the significant slow-down of nuclear development in the late 1970s and 1980s. The new regulatory requirements introduced in reaction to the accident at Fukushima-Daichi in 2011 also led to the closure of long existing facilities, since many of them could not fulfil the enhanced regulations. In the past, these flexible low power experimental facilities, which included zero power reactors (ZPRs), criticality-safety assemblies and shielding facilities, produced essential experimental evidence and large quantities of physics data, which were needed to ascertain the reliability and accuracy of calculational techniques which are still used for current reactor designs. However, there was no urgent need for a change of direction since there was only limited demand or at least no plan for a rapid growth of nuclear energy production. However, this has drastically changed now. Nowadays, nuclear technologies face a strong demand for innovation and rapid development again, like in the early days. Innovation and rapid development will be the only way to fulfil the expectations and the promises announced at COP28 [3]. Unfortunately, one key stepping stones, experimental facilities is missing to deliver testing as well as proofing the quality and reliability of the modelling and simulation (M&S) systems to be used for the detailed design. There are a very limited number of available experimental facilities which will surely not be sufficient to fulfil the broad demand providing a sufficient number of highly specialized

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experiments for new reactor types which is required to deliver the experimental basis to create the innovation required to make nuclear fit for the expected/promised massive contributions to net-zero. Additionally, even if some facilities will be available, the question will be: Can these existing experimental facilities deliver experiments relevant to the required new technologies?

Typically, an experimental zero power facility is the first essential step into the development of a novel nuclear technology, allowing a stepwise growth of capabilities and capacities in building and operating an innovative facility in a smaller scale project which can feed into the following steps [12]. Key advantage would be the relatively low cost, low risk (small and relatively simple), and quick response (< 5 years) of this reduced complexity project for fast preparation and learning. An additional aim is to qualify subject matter experts in design, construction, commissioning, and operation for the development and delivery of the required, often new technologies and the later larger scale facilties as well as to qualify design tools as well as the interaction with the regulator. Such a facility will allow to gain relevant experience in reduced complexity systems to avoid costly and time-consuming mistakes in expensive large-scale projects like the recent delivery of large scale light water reactors. Thus, a zero-power experiment is the essential first step to research a game-changing technology in a safe setting, to advance knowledge, capabilities and capacities required to grow the skills base for designers and, operations as well as for the regulatory bodies. Zero power experiments aim at demonstrating innovative safety features and, proofing the quality and reliability of the modelling and simulation (M&S) systems including improving the tools and models. It will allow a substantiated response to regulatory requests for safety demonstration and code testing and quality assurance, and will provide the urgently needed skilled workforce for a nuclear renaissance as it has been decided at COP28. A zero-power facility serves on many levels, see Figure 1, from manufacturing/delivering (designing, licensing, constructing, commissioning) and operation of a new reactor, through the experiment (upskilling new experts for an experimental program), to taking a scientific leadership role (being recognized as scientific super power for advanced reactors). In addition, a new facility will be a fresh start, designed and constructed under the current regulatory rules which will assure improved operational safety as well as increased quality of the built structures which hopefully will create the basis for long term operation as it was for the facilities of the 1950s and '60s.

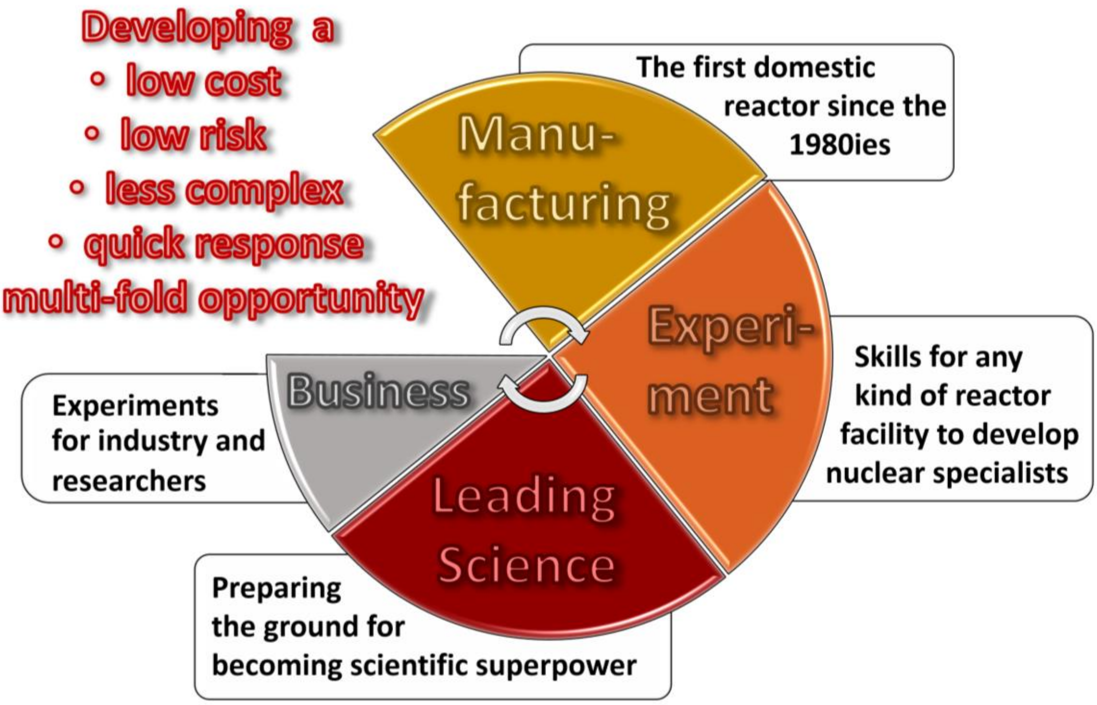

Figure 1. Opportunities created through the development of a zero power facility in the case of the UK [12].

One of the innovative ideas for a nuclear system optimized for closed fuel cycle operation and waste burning is iMAGINE [7]. The proposed iMAGINE concept – a highly innovative nuclear system based on a molten salt fast reactor in conjunction with an integrated salt clean-up system using the principles of reverse reprocessing [23]. The aim is to operate on existing spent nuclear fuel from light water reactors (LWRs) without the demand for prior reprocessing to deliver waste management [4] and power production [5] in parallel. This approach is planned to be significantly more efficient than the traditional closed fuel cycle approaches based on solid fuel [6].

A future facility for studying iMAGINE has to be developed within the constraints of the 2020s, expecting significantly higher cost and a demanding, time intensive, new regulatory process. This will limit the number of potential facilities and thus creates the demand for much higher flexibility and a wider range of the operational envelope to deliver on substantially different challenges in a single facility. The basic parametric investigation based on modelling and simulation (M&S) has already been published in previous publications: [6] regarding salt composition, enrichment and salt volumes, [10] regarding generic control and shutdown options, and [11] regarding the choice of potential reflector materials.

Aim of this publication is to deliver design principles and proposed facility design for a room temperature solid salt core to support the development of future molten salt reactors with a potential later step to move to elevated temperatures and investigate a molten core. In a first step we will provide a methodological overview on potential design choices for the control and shutdown system design including a down selection to the for us most promising options. Followed by defining a preliminary experimental programme, 'What has to be measured?', 'How can it be measured?'. The design choices are consolidated in this first step through scoping calculations on core size, reflector dimensions and achievable control and shutdown margins [6,10,11]. The publication is documenting the results and discussions of a series of workshops within the EPSRC funded "Defining a Draft for a Zero Power Reactor Experiment for Molten Salt Reactors" project. The provided theoretical discussion and the design choices will be followed by a follow-up publication consolidating the design choices including details on the dimensions required for the shutdown and control to achieve the design targets for core subcriticality.

What characterizes a Zero-Power Experimental Facility?

A zero power experimental facility is a highly specialised setup for neutron physics and, potentially, safety related experiments. It is typically characterized as follows:

- Multi-purpose facility
- Small scale experiment
- Low power system (< 10kW)
- Room temperature operation
- No requirement of a dedicated heat removal system
- Negligible power-induced reactivity feedback
- Negligible burnup and poisoning due to fission products
- No new fuel requirements after the initial core loading
- Reduced safety challenge due to the elimination of dedicated heat removal systems
- Low radiation level system
- Highly accessible system
- Flexible reactor operation
- Flexible adjustment of experimental conditions according to the validation criteria/requirements

Such zero-power facilities are typically used to carry out experiments for measuring different parameters required to fulfil regulatory requirements and/or validation of codes/calculations. These include the following:

- core criticality;
- neutron flux, energy, and power distribution;
- reactivity coefficients;
- changes in reactivity and flux as a function of salt density, temperature and composition change (in case of molten-salt reactors)
- kinetic parameters such as the Rossi-Alpha

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- safety relevant effects (shutdown through core drainage)

Opportunities

Zero power reactor experiments are typically the start into new reactor programmes [12] since they offer low complexity designs without heat transfer systems, thus greatly simplifying the licensing procedure. Such a project also provides the opportunity to create the regulation specific to the new technology in a collaborative process between the developers and the regulator. A zero power experimental facility provides a low radiation development ground for quick experiments and feedback, and thus an opportunity for rapid learning in a safe setting. It opens "spaces for creativity" and has in addition a platform which can serve for education and training. The development of a new facility will in addition allow testing of advanced manufacturing techniques and will create a platform to (re-)build regulatory know-how during its designing, commissioning, and operation [12]. From the experimental point of view, the zero-power experiments allow delivering many experiments in a short time due to the low radiation levels and high accessibility of the core. This, along with the low neutron loads on the instrumentation allows the use of a large number of diverse techniques.

Approach to the problem

Facility/core design

Design of the general facility and the core is based on a step by step effort to investigate a fast molten salt reactor system. Main characteristics will be the fuel and carrier salt in itself, ideally NaCl-UCl3-UCl4 with a higher enrichment than for a power reactor core. Up to now, the initial studies point to an ideal enrichment of 35%, but depending on the location of the experimental facility, non-proliferation requirements could limit the uranium enrichment to 19.9% on the cost of a larger core size. Fast molten salt reactors typically have a homogenous core. Thus, it would be ideal to replicate this in the experimental facility which would lead to a completely new challenge [12], since most of the leading experimental reactors built in the past have been, at least partially, designed to understand the effects of heterogeneity in the core. This is also one of the reasons why we expect that a new experimental setup for molten salt fast reactors (MSFRs) would be more preferable as compared to carrying experiments in one of the few zero power experimental facilities still existing. There is a core difference which requires new thinking and exploration, since MSRs are unique in comparison to other reactor technologies (which have significant heterogeneity due to the use of solid fuels), it is not only essential to properly understand the behaviour of a homogeneous core but also to innovatively plan what needs to be measured and how it can be measured in this fundamentally distinct system. There is also a strong need to consider the different experimental opportunities available for such a system, since unlike other fast reactors which are based on solid fuels and typically consider either MOX or metal fuels, a wide variety of fuel compositions are being considered for future molten salt reactors.

Modern development approaches proposed are nowadays often characterized through a multi-stage, step by step approach [7,13]. The same is planned for the proposed MSFR experiment. The first step is based on starting with a solid core at room temperature. The experiments at room temperature conditions will be much easier to handle and will allow testing of the equipment and procedures for core characterization, as well as other relevant experiments under direct access to the core like in other zero power experiments [14,15]. The results from this step can be used for experimental demonstrations and the initial code validation, which will support the regulation of the next step of the experiments in a molten core at elevated temperature. The experiments in this configuration will then be based on the experiences and measurements from the first step. This will be required to assure a higher confidence – of the designers, regulators, operators and experimentalists. It has to be kept in mind that the regulation of a homogeneous system like an MSFR, with unity of fuel and coolant, will be fundamentally different from other designs which have gone through regulation up to now. Thus, there will be a need for active development of the regulatory framework in a safe setting and it will be easier with the proposed step-wise approach from room temperature to higher operational temperatures. In the absence of such a multi-step development paradigm for risk reduction, an approach like the one used in the Manhattan project would have to be taken for any breakthrough

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technology. General Groves the military lead of the project described the late learning during the Manhattan project: "Not until later it would be recognized that chances would have to be taken that in more normal times would be considered reckless in the extreme. Not until later it would become accepted practice to proceed vigorously on major phases of the work despite large gaps in the basic knowledge" [16]. It should be noted that in the modern times, these risks would be inacceptable during the development of innovative nuclear technologies. Although innovation, especially of breakthrough technologies, would certainly involve some unknowns lying outside existing basic knowledge and thus require experimental proofs, a multi-stage step-wise approach will reduce risks through active risk mitigation. Bigger the steps, greater will be the unknowns as well as the opportunities. Thus, developers must aim to reduce risks by tackling unknowns in a safe setting and in reasonable chunks, which is the core basis for developing a zero power experimental facility like the one proposed here.

Core control

Before looking into specific solutions, a general overview into the physical principles for controlling a reactor and their limitations has been given. Based on these, a set of potential control and shutdown systems have been discussed, followed by narrowing down the choices based on various advantages and disadvantages to give the reader insight into the decision-making process.

Principle methods for control and shut down of a reactor are typically based on modifying one of the broad terms of the neutron balance equation:

neutron leakage + neutron absorption = 1/k * fission source

A. Increasing the absorption of neutrons through the addition of neutron absorbers into the core, like the insertion of control rods into a reactor core, or the addition of boron into the coolant of a light water reactor.
B. Increasing leakage of neutrons through removing a part of the neutron reflector which helps scatter back neutrons into the core. This technique has also been proposed for small sized reactors like space reactors through the use of control drums which can combine reflecting and absorbing properties [17]
C. Decreasing the fission source by removing fuel from the core through the use of control rods with a combination of absorber and a fuel follower. When the control rod is removed, the fuel follower moves into the core adding fissile material and when the control rod is inserted, the fuel follower moves out of the core reducing the amount of fuel in the core. This approach has been used in some reactors in the past to increase the efficiency of the control system [18]. In addition, this effect has been studied in the core disassembly phase in sodium cooled fast reactors [19] and it is used in some small education and teaching reactors like AKR-2 where the core is split into two halves for the shutdown [20]
D. Changing the neutron spectrum into energies with lower fission cross sections and increased leakage. This approach can be particularly interesting in thermal reactors where the hardening of the neutron spectrum though the removal of the moderator can significantly reduce the fission reaction rate. As a side effect the neutron leakage also increases. This approach is possible in heavy water moderated reactors through moderator drainage [21], or it can be seen as a natural phenomenon occurring during a large break loss of coolant accident when all moderator has been pushed out of the core

Each of the above-mentioned mechanisms has its advantages as well as limitations and challenges. The optimum choice(s) is also governed by the following factors:

- Applicability – is the proposed method compatible with the system. For eg., the insertion of absorber like boron into the moderator works only in a system with liquid moderator like for PWRs or PHWRs
- Sufficient margin – does it provide sufficiently large changes. For eg., the control system has to be powerful enough to compensate the reactivity changes during a full cycle of an LWR
- Sufficient sensibility – does it provide the sensibility needed for experiments. For eg., for any reactor experiment, it is essential to be able to measure the critical steady state operational point with enough precision even after small changes in the core

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- Agility of action – does it act quickly enough in a transient. For eg., several passively acting shutdown systems have been proposed for fast reactors, but their actuation time is not sufficient to avoid accident progression
- Moving mass – can the engineering challenges be handled. For eg., a large component like a reflector or a part of the core could be too heavy to be moved precisely and quickly, thus splitting of the core has only been used in very small cores until now
- Disturbing the homogeneity – does it cause perturbations in the surroundings of the measurements. For eg., if experiments in a homogenous material configuration will be required, the local insertion of control rods could have strong influence on the experimental outcome

Based on the aforementioned principles, we have identified the following potential systems for shutdown and control of a future zero power experimental core for the iMAGINE project [7,22] representing a homogeneous fast reactor core configuration:

1. In-core control or shutdown absorber rod [principle A]
2. Moving radial reflector up or down [principle B]
3. Splitting the core [principle B and C]
4. Absorber rod/drum in the reflector [principle B]
5. Moving rod with reflector material in the reflector [principle B]
6. Core drainage – only in liquid state [principle C]
7. Moving axial reflector [principle B]
8. Inserting/removing rod of fuel inside the core [principle C]

After identifying different potential control and shutdown systems, these should now be evaluated against the operational and experimental requirements of the ZPE core. An experiment for a molten salt fast reactor is typically formed with a homogeneous core. This is in strong contrast to 'classical' zero power experiments where the investigation of the heterogeneity effects in the core is one of main parameters to be studied.

For the investigation of a homogeneous core, it would be favourable or even desirable to use control and shutdown systems which do not disturb the homogeneity of the system. This criterion is not fulfilled for the cases 1 and 8. Case 6 is eliminated due to the nature of the experiment which is planned to be in the first phase in a solid core. Removal of the axial reflector (Case 7) will likely be a challenging design task during actual construction of the system. A sideways movement of e.g. the top reflector, would create an inhomogeneous effect which would be a massive challenge for the modelling and simulation, while the vertical movement would tend to have a strongly non-linear effect on reactivity. This would require a complex linear tracking system with the challenge of dealing with the non-linear relationship between movement and reactivity effects. Thus, manipulation of the axial reflector for control does not seem to be an ideal choice. In addition, already the first, basic studies unveiled that changes in the axial reflector tend to be less effective than manipulations of the radial reflector.

However, removal of the axial reflector, or if not sufficiently efficient, the combination of moving the reflector together with a part of the core (increasing leakage combined with removing fuel) to achieve the requested shutdown margin is an attractive option for the shutdown of the core. The system is already used and approved, but only for small cores of education reactors, see eg. [20]. In the case of a zero power core for a MSFR, the masses to be moved will be substantially larger which will be a challenge to be mastered in the design. However, the characteristics seem to be promising with a strong initial effect as soon as the core split is activated as well as a homogenous effect which will cause only minor disturbance of the core characteristics. In the case of a shutdown system, the split core part will be completely attached to the core as the first step of the start-up procedure, thus only the casing of the core parts will act as minor inhomogeneity.

This leaves manipulation of neutron leakage as the optimum choice for control system of the ZPE. This could be achieved by either moving the whole radial reflector or by using drums/rods of absorber or reflector material. Decisions in greater detail have to be taken based on calculations regarding the required efficiency and sensitivity of the system. Among these, movable rods of reflector material or moving the complete reflector would be more favourable solutions, since both these approaches would allow reaching the most homogeneous configuration in the operational state (when the reflector is almost closed). The regulatory requirement of diverse solutions for the shutdown and control systems would imply that splitting of the core would be the most favoured shutdown mechanism. This will also minimise any perturbations to homogeneity of the system when the shutdown system is in the operational position.

Currently foreseen experimental programme

In general, the main characteristics to be investigated or the predetermined behaviour which has to be approved have already been given above. In this section more details have been provided on how these characteristics can be best investigated through specific experiments

- core criticality [24,25]

It is typically measured by determining the critical mass of the fuel salt in the current configuration. This is done by successively adding discrete amounts of fissile material in the case of MSRE (or fuel in the form of fuel assemblies) followed by determining the response rate to a neutron source while gradually reducing the negative control reactivity in steps before measurements are taken. This process for the molten salt ZPE will be comparable to adding fuel assemblies in a classical reactor, but the geometry for adding fuel material will most probably be different. This process will be repeated until an infinite response to the source confirms the criticality of the core at a certain position of the control system. It must be noted here that ideally, the discrete amount of fuel to be added in each step should be chosen such that the core is self-limiting, *i.e.*, it would self-stabilise with an acceptable rise in core temperature through heat-up in the case the system is becoming critical when adding new material.

- Sensitivity of the control and shutdown systems [26,27]

Once criticality has been achieved, sensitivity of the control and shut down systems will be determined. All values will be compared to extensive modelling and simulation results of pre- and post- experimental calculations to validate computational models and determine the bias between experiment and simulations. These are highly important characterization experiments, since the control rod position and the changes in the position related to changes in the core will be one of the most important pieces of information created in the following experiments.

- neutron flux, energy, and power distribution;

The neutron flux distribution in space and energy is one of the main characteristics of any reactor system. It is mainly determined through the fuel characteristics (enrichment, density, matrix) and the presence or absence of specific moderating materials. The spatial neutron flux is either measured through moving an instrument for flux measurement through different positions of a core (sequential) or through the use of a set of identical instruments in parallel. Generally, in an experiment for a typical heterogeneous core, the main parameter to be investigated will be the effect of heterogeneity in the system. This will not be the case in a fast molten salt reactor with a homogeneous core. However, the neutron flux distribution in the core is still of high interest for the code validation. It must be noted here that a homogeneous core allows substantially more flexibility in the choice of location as well as size of the instrumentation channels. The energy distribution is typically measured through a set of threshold reactions based activation foils and this will be used as a standard for molten salt reactors too. The more innovative approach using instruments with different threshold materials will allow to acquire additional insights, since the activation foil approach is rather complex, thus the number of spatial measurement points will be limited. For certain applications, also a spectrometer consisting of a set of proton recoil detectors (e.g., gas-filled proportional counters and organic scintillation detectors) can be used, see [28].

- reactivity coefficients;

The reactivity coefficients are of fundamental importance for stable reactor operation and thus, are among the most relevant safety related parameters. In traditional zero power experiments the reactivity coefficients are hard to determine since in most cases, their measurement involves temperature changes of specific components, e.g. the fuel to determine the fuel temperature coefficient, or the matrix material (replica of the coolant)/moderator to determine the coolant or moderator temperature coefficient for the power reactor. For this kind of experiments, molten salt

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fast reactors would provide better opportunities due to unity of the coolant and fuel in the system. This will allow that conclusions can be drawn from uniform temperature changes. However, in molten salt reactors additional changes are imaginable which will require a larger number of parameters to be measured, as explained in the following point.

- changes in reactivity and flux as a function of salt density, temperature and composition change

Temperature and density changes will most probably be correlated in a molten salt fast reactor due to the operation around atmospheric pressure as well as unity of the fuel and coolant. As already mentioned, this will simplify the experiments since a uniform, non-nuclear, external heating would be easily possible for both the solid and molten fuel. This will allow clear observation of the effect of temperature and density changes due to expansion on core criticality. In the liquid phase, it will be of high interest to demonstrate the difference between a core with a free surface and a core with a limited volume which should provide different quality of feedback in the real core compared to the pre-calculated value.

The investigation of reactivity effects due to compositional changes will be the most challenging experiment since these effects are not seen in conventional solid-fuelled reactors besides the compositional changes due to burnup. However, such burnup dependent effects cannot normally be investigated directly in a zero power facility. This is because of the negligible burnup at low-powers associated with ZPE operation and that any high-power operations would undermine the idea of experiments in a very limited radiation field. For these studies novel innovative methods will be needed either through transforming techniques which have been used for the investigation of burnup effects in the past zero power experiments for LWRs or through the development of new instrumentation. It must be recognized that changing the salt composition in a solid experimental setup for these investigations will be almost impossible or at least very challenging – at most some small probes of different salt compositions could be inserted into the core, or a pile oscillator experimental setup could be applied. The situation in the liquid core would be easier.

The changes in flux distribution can be directly measured for different core temperatures and compared to the reference values. However, the effect of compositional changes on the flux distribution will be an up to now not observed “unknown” problem which will require a detailed investigation in itself to identify methods to study these effects.

- Kinetic parameters such as the Rossi-Alpha [29];

In the context of reactor design, a new configuration of a multiplying medium and the setup of experiments that influence the core and reflector configuration, understanding how a particular design or change of the reactor configuration influences the kinetic or dynamical behaviour of the underlying system is important to guarantee safe reactor operation [31]. To this end, the estimation of kinetic parameters [30] such as effective multiplication factor k_{eff}, the effective delayed neutron fraction β_{eff} and the neutron generation time Λ is common practice in both simulation and experiments. These quantities provide an appropriate measure of how the system will behave in terms of the point kinetic approximation and are thus, commonly used for validating reactor codes. Furthermore, the fraction β_{eff} of delayed neutron precursors gains even more relevance in view of using the fuel in liquid state with circulation possibly partly out of the core. Examples of typical experiments include zero power measurements such as Rossi-Alpha and Feynman-Alpha measurements, as well as the measurement of the zero power transfer function (ZPTF). These methods make use of the fact that in multiplying media, which are operated under zero power conditions, all mechanical and hydraulic fluctuations and their influence on reactivity can be assumed to be negligibly small. Fluctuations in such reactors are primary caused by the nature of the fission chain reaction and associated stochastic fluctuation in the neutron multiplying process. As a consequence, kinetic parameters can be measured reliably with high precision, and zero power reactors are very sensitive to small variations in their underlying core and reflector design. These variations will be reflected by corresponding changes in the kinetic parameters.

- potentially safety relevant effect studies

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One of the main challenges will be to confirm whether the strong reactivity effects seen in modelling and simulation are really observable in the developed core design as it is developed [6,23]. It must be noted that classical lattice calculations use very specific approximations which have been tailored for the accurate modelling of solid fuelled, min most of the cases light water cooled and moderated reactors. More generally, the zero power experiments can be used to support safety cases for subsequent power producing systems by delivering experimental proofs for the regulators to substantiate the calculation results from computational models.

- Potential additional experimental opportunities

Time of flight measurements to determine the neutron spectrum of a neutron beam outside of the reactor for a diverse method to determination of the neutron spectrum.

Use of threshold fission chambers to create spectral dependent count rates at different positions as a diverse approach to confirm the above threshold share of the neutron energy spectrum in different areas of the core, eg. core centre versus a position close to the reflector.

Rod drop and source jerk experiments are conducted as an alternative method for determining kinetic parameters. Pile oscillation method is applied to investigate in detail the material and nuclear properties of probes.

Investigations of the effect of removing parts of the reflector to study an unreflected core.

Creating moderated inserts in the reflector to investigate salts under thermal neutron flux to provide experimental evidence for salts used in thermal molten-salt reactors.

- Potential core design

The potential core design, including the arrangement of experimental channels as well as the control and shutdown systems, had been developed in December 2023 following several workshops to discuss various possibilities and shortlist the most attractive ones, as given above.

Basic design features of the proposed system are as follows (see Figure 2):

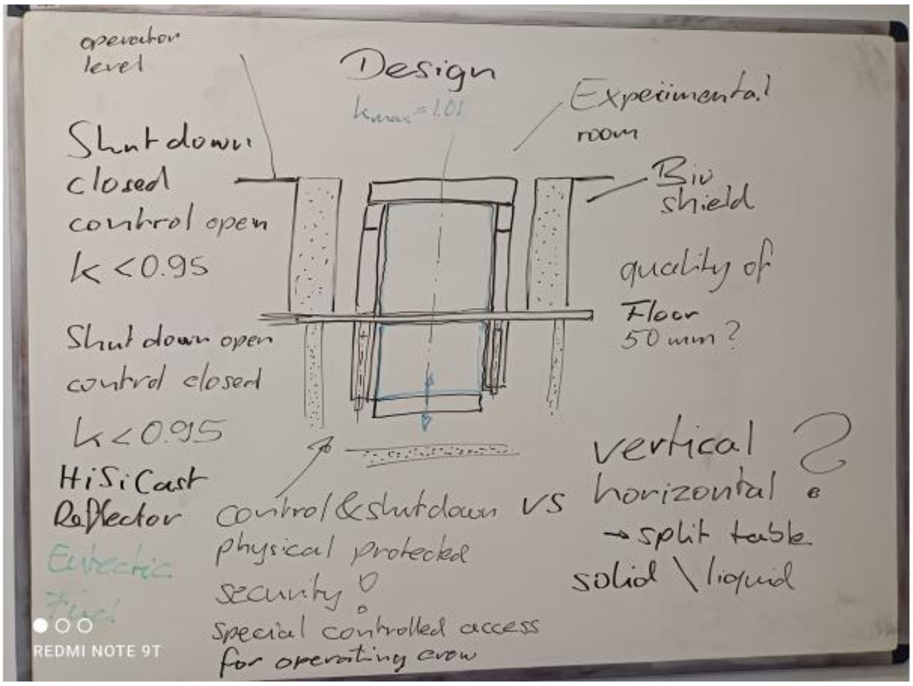

Figure 2. Draft sketch of the core design for a solid salt experimental core, drawn during the workshop.

- A split core design with a movable lower part as shutdown mechanism - share of the core has to be determined based on regulatory requirements with the first objective being to achieve k ≤ 0.95.

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- Moving reflector or parts of the reflector – choice has to be confirmed through modelling and simulation depending on the achievable versus the requested control margin and sensitivity
- Both parts of the core separated through a stainless steel floor to exclude the possibility of the upper part accidently dropping onto the lower part when the core is in a shutdown configuration.
- Core arranged in two separate rooms, one for the experimental crew conducting experiments and the other for operational, control and shutdown systems. Such physical separation of the operational and experimental areas will ensure that operational areas can be access-controlled while the experimental hall is more easily accessible for different experimental teams as well as equipments .
- High silicon cast iron reflector has been chosen based on its suitable performance amongst different reflector materials investigated earlier [11] as well as for ease of manufacturing.

The novel design choice of splitting the core into two physically separated rooms (see Figures 2 and 3) takes into account current regulatory requirement that any experimental reactor facility must have independent operational and experimental crews. The proposed innovative design incorporates this demand even at the hardware/building level. This approach should would help ease the access to the facility for visiting experimental specialists and would be one of the key features of a future international experimental facility, as envisaged by the NEA Zero power reactor task force [32]. On the other hand, the placement of all safety related systems in a strictly access-controlled area accessible only to the operational team will limit the risk of misuse through unauthorised third-party access. Additionally, the core arrangement with a steel floor in the centre will eliminate the largest potential accident initiator, the inadvertent dropping of upper part of the core onto the lower portion due to failure of the core anchoring. However, the feasibility of the proposed split-core design, as well as dimensions of the two parts in separate rooms must be investigated and confirmed through deailed modelling and simulation studies, which will be provided in a follow up publication.

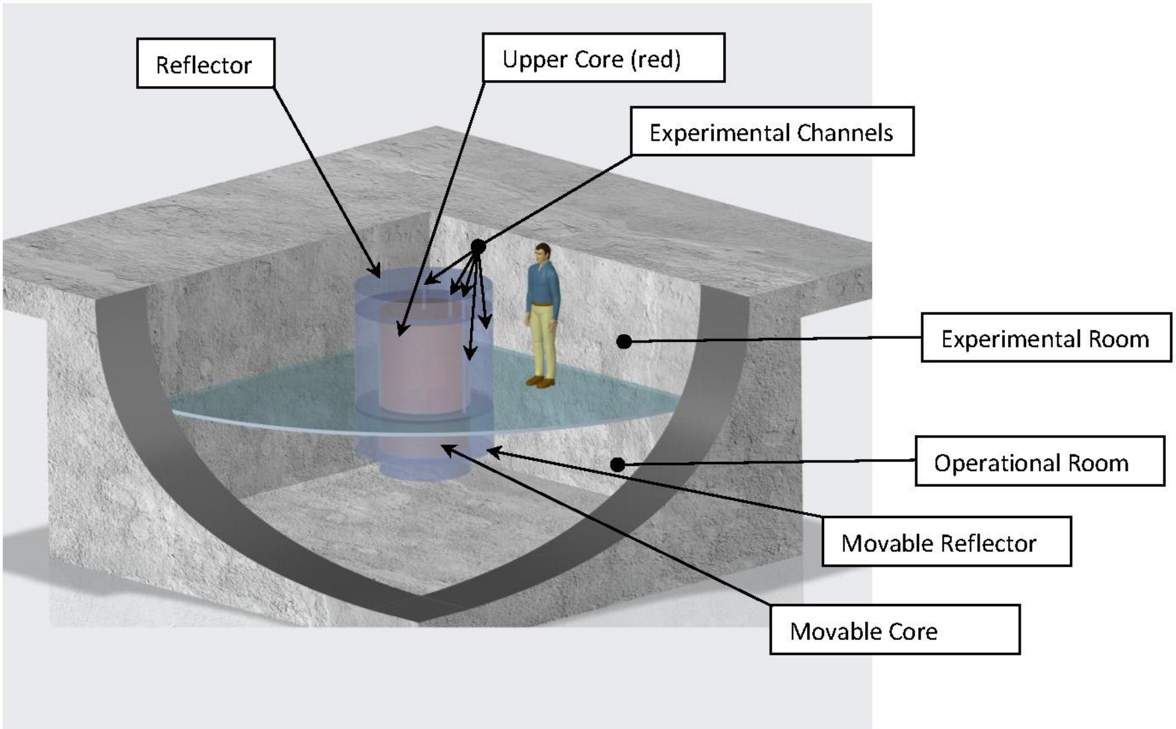

Figure 3. 3D representation of the proposed core arrangement, the experimental channels, and the separated experimatal and operational rooms for experiments and reactor control.

A major challenge of the first phase of zero power experiments with solid fuel salt will be that the experimental channels have to be defined before the core manufacturing. These will then be fixed and cannot be changed like in traditional designs with fuel assemblies which can be easily moved

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during operation. However, the high homogeneity within the system may offer the opportunity to create access for horizontal experimental/instrumentation channels which is typically challenging in a core assembled from fuel assemblies.

The major experimental channels currently foreseen are in the following locations:

- Vertical in the centre of the core
- Vertical at the core periphery
- Vertical in the reflector
- Horizontal at the top of the core
- Horizontal in the centre of the core

It should be possible to fill at least some of the experimental channels with original material to reduce potential inhomogeneities. The dimension of the channels has to be decided based on the size of the instruments to be used.

Conclusions

The UK and many international experts have made the point that nuclear energy — in all forms, large as well as small — has an important role to play in the transition into a decarbonized energy system of the future. This is because of nuclear currently being the only 24/7 available and freely manageable very low-carbon technology as a complement to the varying and weather dependent production of the renewables. More recently, at COP28, more than 20 countries announced a declaration to triple the nuclear energy capacity by 2050, recognising the undeniable importance of nuclear energy in reaching net zero. However, in order to deliver in the near future as well as to develop attractive and novel solutions, nuclear has to rapidly progress and innovate. This necessitates a timely and urgent investment into essential experimental facilities along with the development of expertise to allow quick progress into innovative technologies and ensure the availability of necessary infrastructure.

The discussions presented in this publication provide the initial steps to start the development of a new reactor physics experimental facility to investigate molten salt fast reactor technology as it is proposed within the iMAGINE project. In general, control and shutdown systems can be based on three different principles – increasing neutron absorption, decreasing the amount of fissile materials, or increasing neutron leakage, or a combination of these. The general approach is to manipulate one of the key terms of the neutron balance equation as basis for delivering a methodological overview on potential design choices for the control and shutdown. In order to ensure diverse control and shutdown systems, the following design choices have been made: manipulating the radial reflector (control) and splitting the core (shutdown).

The innovative core design has been developed through a series of workshops and consists of having the two core parts (see shutdown) separated through a stainless-steel floor plate to eliminate the potential accident scenario of inadvertent dropping of the upper part of the core onto the lower one. The novel design choice of placing the two parts of the core into physically separated rooms makes the regulatory requirement of independent operational and experimental crews inherent to the hardware/construction of the experimental reactor facility. Firstly, this approach helps ease the access of the facility for visiting experimental specialists. Secondly, the placement of all operational and safety related systems in a strictly access-controlled area for the operational team will limit the risk of misuse through unauthorised third-party access.

The planned experimental programme would consist of core criticality experiments to determine the critical mass of the innovative chlorine-based fuel salt, followed by experiments to determine the neutron flux, energy, and power distribution as well as experiments to understand the effect of changes in reactivity and flux as a function of salt density, temperature and composition change. The first phase of the experimental programme will be concluded by studies related to potential safety relevant effects and additional experimental opportunities for the analysis of detailed effects which will be important verification and validation of computational codes and models.

The theoretical discussion and design choices provided in this paper will be followed by subsequent publications consolidating the design choices including details on the dimensions of the shutdown and control systems [33] to achieve the design targets for core subcriticality as well as for the choice of the experimental programme.

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