



Coupling CTF with SERPENT for the thermal hydraulic and neutronic simulation of the NuScale SMR

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DECLARATION

I, Sufiyan Mohamed Daulath, hereby declare that the dissertation titled "Coupling CTF with SERPENT for the thermal hydraulic and neutronic simulation of the NuScale SMR" is my own work and has not been submitted to any university before. I have adequately cited and referenced the original sources. I declare that I have adhered to all the university's policies on plagiarism and have not misrepresented or fabricated any work in my submission.

Signature

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ABSTRACT

South Africa's severe energy crisis has prompted a shift towards diversifying the country's energy mix, with the Integrated Resource Plan specifying that a nuclear new-build programme to the extent of 5200 MW will be implemented to add to the energy mix. Although conventional PWRs will be suitable for this deployment, light-water small modular reactors such as the NuScale SMR can also be deployed. Significant benefits over larger nuclear reactors would be cost-effectiveness and advanced safety features. To enable the deployment of such a reactor design, a safety analysis report must be developed for licensing purposes. Multiple reactor analyses including neutronic and thermal hydraulic analyses are required to complete this report. Since neutron behaviour directly influences heat generation and thermal-hydraulic conditions affect neutron moderation and reactivity, neutronic and thermal hydraulic calculations are strongly interdependent. Hence for best-estimate calculations, coupled neutronic thermal hydraulic calculations are used. This study presents a coupled neutronic and thermal hydraulic simulation of the NuScale SMR using the Monte Carlo neutron transport code Serpent and the thermal hydraulic code CTF together with the North-West University Reactor Code Suite (NWURCS) Version 3 as the code coupler.

Initially, a benchmark CTF input model by Avramova was compiled and run successfully with no errors. The Avramova reactor core was modelled as a quarter core with subchannels. The model was then geometrically translated—first to an intermediate 16x16 fuel assembly layout, and finally to the specific 17x17 NuScale fuel assembly geometry. Thorough verification of geometric sub-channel quantities was done, ensuring that flow areas, wetted perimeters and gap lengths accurately reflected the NuScale core design as per Chapter 4 of the NuScale Safety Analysis Report (SAR). The rest of the NuScale CTF base model was built using values obtained from Chapter 4 of the NuScale SAR and input into their specific card groups in CTF. Steady-state conditions were assumed. The guide tubes were modelled as a solid rod. The CTF base model was built and run successfully with no errors.

To ensure reliable power profile data, source convergence was verified by monitoring Shannon entropy until it stabilized during inactive cycles. Consequently, only active cycles reflecting a converged fission source were utilized to generate the power profiles required for the Serpent-CTF coupling.

NWURCS served the purpose of input generation for Serpent and CTF and the coupling. System level coupling was done by NWURCS where Serpent power profiles were mapped to CTF, and the resulting fuel and moderator temperatures were returned to Serpent to update the neutronic state. This process was repeated through several iterations until convergence was achieved.

Convergence was monitored visually since stability was also monitored. Establishing convergence using a computer algorithm could lead to false convergence, since the oscillations in the solutions had bounding values larger than 5 °C. To ensure accuracy and reliability, post-coupling verification was performed on key parameters including the effective multiplication factor (k_{eff}), detector data, fuel and moderator temperatures and power fields, confirming that the coupled simulation produced stable and consistent results before the base case coupling calculation was conducted.

The base case coupling calculation was initiated using well guessed values for boundary conditions to establish numerical stability over 30 iterations. To ensure reliable results, the boundary conditions were then adjusted step by step to match NuScale specifications. Inlet temperature, mass flow rate, pressure, and power were updated in separate steps. These progressive steps allowed for the isolation of any errors and confirmed that convergence was obtained as it approached the final base NuScale model.

The final base case coupling calculations were executed for 42 iterations, and convergence was visually confirmed through the uniform distribution of data points between boundary lines. Statistical analysis over the iterations revealed that the percentage difference for maximum heat structure and moderator temperatures remained below 1%, while maximum power was within an acceptable 5%. The heat structure (fuel) temperature standard deviation was at 1.5 K. Moreover, the standard deviation of the multiplication factor was consistent with the statistical uncertainty of the Monte Carlo Serpent simulation, confirming that the coupled results fall within the expected stochastic range. Finally, the heat structure temperatures were verified by confirming that the axial profiles correctly reflected the sinusoidal like power distribution, with peak temperatures aligning with the maximum neutron flux as dictated by reactor physics.

The effect of increasing active cycles on accuracy was evaluated. The results demonstrated that while higher cycle counts reduced the standard deviation (implying improved statistical precision) the impact on the mean values was negligible, with differences remaining below 0.035%. Upon visual inspection no significant effect had been noticed from changing the active cycles.

A comprehensive sensitivity analysis further tested the model's reliability, examining its response to changes in inlet enthalpy, mass flow rate, power, and pressure within a range of $\pm 10\%$. The results indicated that the model is most sensitive to changes in power and inlet enthalpy, both of which produced statistically significant deviations exceeding the coupling standard deviation. Theoretical analysis using fundamental heat transfer equations confirms this behaviour, as power is the primary source term directly influencing fuel and cladding temperatures, while inlet enthalpy sets the starting moderator temperature. Conversely, variations in mass flow rate and pressure

resulted in differences that fell within the statistical standard deviation of the coupling, meaning their individual effects could not be distinguished from the statistical noise.

A difference was noticed when comparing the model's results to the NuScale specifications. This difference could be attributed to the modelling of guide tubes as solid rods (without water flowing within the guide tubes). Other possible causes for the differences were the exclusion of detailed pressure losses and a potential difference in density of water used in CTF and Serpent. Despite this difference, the study successfully verifies the coupling methodology itself. The results prove that the coupling between CTF and Serpent was successful using NWURCS.

Key terms: NuScale, Small Modular Reactor (SMR), Serpent, CTF (COBRA-TF), Multi-physics coupling, Thermal-hydraulics, Neutronics, NWURCS (North-West University Reactor Code Suite), Monte Carlo method, Sub-channel analysis

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LIST OF ABBREVIATIONS AND ACRONYMS

BWR	Boiling water reactor
CTF	Coolant Boiling in Rod Arrays-Two Fluid
DMRE	Department of Mineral Resources and Energy
FA	Fuel Assembly
HPC	High performance computer
IAEA	International Atomic Energy Agency
JFNK	Jacobian-free Newton-Krylov
LWR	Light water reactor
LWSMR	Light water small modular reactor
Mwe	Megawatts electric
NWU	North-West University
NWURCS	North-West University Reactor Code Suite
NPM	NuScale Power Module
NPP	Nuclear Power Plant
PWR	Pressurized water reactor
RPV	Reactor pressure vessel
SAR	Safety Analysis Report
SMR	Small modular reactor

CHAPTER 1 INTRODUCTION

1.1 Background and rationale

The Republic of South Africa is in the middle of a severe energy crisis. There are multiple issues, including an electricity shortage, which has resulted in load shedding, as well as over-dependence on fossil fuels, i.e. coal for energy generation. To address these issues, the Department of Mineral Resources and Energy (DMRE) developed the Integrated Resource Plan (Department of Electricity and Energy, 2025).

The plan states that the country should pursue a diverse energy mix, such as solar, gas, wind and nuclear, which would reduce its dependence on a few primary energy sources (Department of Electricity and Energy, 2025). It also states that South Africa is to prepare for a nuclear new build programme with a planned capacity of 5200 MW. It has been proven that nuclear energy produced from uranium-fuelled nuclear power plants could provide the world with clean, economical, and reliable energy well into the next century (Barry W. Brook *et al.*, 2014). There are several types of nuclear reactors, for example, light-water reactors, high temperature gas-cooled reactors and fast-breeder reactors (John R. Lamarsh & Anthony J. Baratta, 2001).

A small modular reactor (SMR) is one type that could assist in finding a viable solution to South Africa's energy crisis. According to the US Department of Energy (2021), SMRs are nuclear power plants that are smaller (300 MWe or less) than current generation base load plants (1000 MWe or higher). These smaller, compact designs can be fabricated in a factory and transported by truck or rail to a nuclear power site.

The International Atomic Energy Agency (IAEA)(2020) states that SMRs offer significant advantages over larger nuclear reactors, including:

- **Cost-Effectiveness:** The smaller size of the SMR offers a potential cost advantage over larger reactors. SMRs involve a lower manufacturing cost as they can be produced in a factory, and the modularity ensures reduced upfront capital cost as funding can be provided in stages (per module) (US Department of Energy, 2021). The shorter construction time also means that risks and additional costs associated with projects that run over a longer timeline are negated.

- Better Safety: SMRs are designed with advanced safety features that mitigate the risks associated with nuclear accidents. The smaller size also allows for better containment in the event of an accident (IAEA, 2020).
- The modular design of the SMR allows for easy installation in remote areas or for integration with existing power grids (US Department of Energy, 2021).
- SMRs are also versatile and can be used for other applications apart from electricity generation, such as water desalination, which could be useful in the coastal areas of South Africa.

Hence, the implementation of SMRs could be a solution to the energy crisis in South Africa.

At NWU, most of the research has been done on larger nuclear reactors and some on SMRs, in particular, high-temperature gas-cooled graphite moderated SMRs. Neutronic analysis was already started on a light-water SMR (SMR-LWR) as it was believed that this would add useful knowledge to the topic of South Africa's potential to implement SMR-LWRs. In this study, the work is extended to include thermal-hydraulic analysis.

The SMR-LWR chosen to do the simulations/calculations for this study was the NuScale Power Module (NPM). The NPM (Figure 1-1) is a self-contained, light-water-cooled pressurized water reactor (PWR). It is a nuclear steam supply system that comprises a reactor core, a pressurizer, and two steam generators integrated within the reactor pressure vessel (RPV) and housed in a compact steel containment vessel (NuScale Power, 2016). Each reactor is housed within its own high-pressure containment vessel, which is submerged under water in a concrete pool lined with stainless steel.

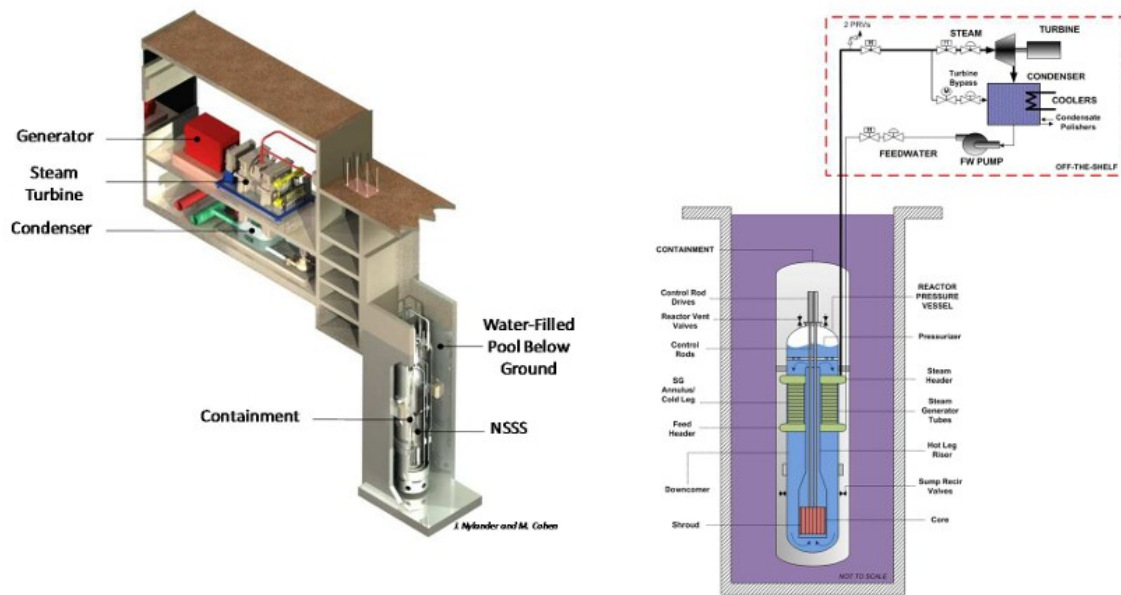


Figure 1-1: Description of a single NuScale Power unit (NuScale Power, 2016)

According to NuScale (2013), a plant consists of 1 to 12 independent modules, each capable of producing a net electric power of 45 MWe. An example of what a modular NuScale reactor would look like is shown in Figure 1-2 (NuScale Power, 2013).



Figure 1-2: Modular NuScale reactor (NuScale Power, 2013)

To enable the deployment of an SMR-LWR design, a safety case must be developed, usually in the form of a Safety Analysis Report (SAR). To compile this report, various analyses are required, including neutronic, thermal hydraulic, nuclear safety, fuel performance, radioactive waste management, and structural analysis.

In recent times, coupled calculations have been used for neutronic and thermal hydraulic best-estimate calculations. For decades, reactor analysis was divided into several distinct domains,

such as neutronic and thermal hydraulic. However, as the solution to one problem is strongly intertwined with the solution to another, various existing codes have been coupled in order to take these interactions into consideration and provide more accurate solutions for the global reactor analysis problem (A.G. Mylonakis *et al.*, 2014).

NWU has already built neutronic models using a code suite called NWURCS, Version 3. NWURCS is the acronym for North-West University Reactor Code Suite. One of the on-going efforts in developing the code is to build the thermal hydraulic models. In Version 1 of the code, a system thermal hydraulic code was implemented, and is now being rebuilt for Version 3 in another study. However, sub-channel codes have not been implemented, and this is identified as a gap in the analysis framework at the NWU. Furthermore, the updated Version 3 code suite uses a level scheme approach (V.V. Naicker, 2024) which is considered an improvement from Version 1. This work therefore used an existing neutronic model created for the Monte Carlo code Serpent by Madi (KZ Madi, 2025), and coupled it with a thermal hydraulic model for the sub-channel code CTF (Coolant Boiling in Rod Arrays-Two Fluid).

CTF is a sub-channel thermal hydraulics code designed for core analysis of light water reactors (LWR). CTF uses a two-fluid three-field modelling approach that is capable of simulating large commercial reactors with tens of thousands of fuel pins with their associated water channels (Kaiwen Li *et al.*, 2023). Serpent is a Monte Carlo neutron transport code, designed for high-precision simulations done in the field of neutron physics. It has a range of applications, including reactor physics, criticality safety analysis, and fuel cycle analysis (Leppänen, 2015).

1.2 Problem statement

One of the main reasons the NWURCS code was written was to provide a coupling system that would allow different codes to be coupled enabling comprehensive reactor evaluations including high-fidelity Nuclear Power Plant (NPP) safety analysis. Another reason was to propagate and quantify uncertainties. NWURCS Version 1 could couple MCNP with Relap5. However, substantial changes were made to the structure of NWURCS, which means that the coupling has to be re-done. This will be carried out in Version 3. Furthermore, with Relap5 being a system thermal hydraulic code, coupling of the neutronic model with a sub-channel thermal hydraulic code is required, which is identified as a gap in the research being carried out at the NWU

In this study, the research problem is therefore to couple a neutronic code with a sub-channel thermal hydraulic code. The problem of coupling a neutronic code with a system thermal hydraulic code for Version 3 of NWURCS has been reserved for a later study. Specifically, the coupling of the neutronic code Serpent with the sub-channel thermal hydraulic code, CTF, will be carried out in this study. As part of the work, stability of the calculations during the iteration process will be

evaluated, since oscillations are expected due to the used of a Monte Carlo code for the neutronic calculations.

1.3 Aim

The aim of this study is to develop a coupled neutronic–thermal hydraulic model for the NuScale SMR by first building a CTF base thermal hydraulic model and then integrating it with an existing Serpent neutronic model. With CTF being a sub-channel code, this will supplement the coupling with system thermal hydraulic models.

1.4 Objectives

The six objectives of the study were:

1. To perform a critical review of coupled neutronic and thermal-hydraulic methodologies for light water SMRs, specifically identifying the limitations in modelling the NuScale design using the Serpent and CTF codes within the NWURCS framework.
2. To verify the successful compilation and execution of CTF by reproducing the Avramova benchmark, demonstrating the code's reliability for modelling sub-channel thermal-hydraulic behaviour in a pressurized water reactor.
3. To develop and verify a representative thermal-hydraulic base reactor core model of the NuScale SMR in CTF, ensuring the model's geometric accuracy and numerical stability for its application in coupling with Serpent via the NWURCS framework. .
4. To contribute to the development of the NWURCS input model generator by verifying its functionality through rigorous debugging and stability testing, ensuring the consistent generation of error free CTF input models while implementing Shannon entropy metrics to confirm source convergence in the Serpent neutronic calculations.
5. To implement the coupling methodology within the NWURCS framework, while refining and verifying the integrity of data transfer for key variables including pressure, mass flow rate, and inlet enthalpy and to ensure the consistent exchange of power and temperature values between Serpent and CTF.
6. To evaluate the performance of the coupled Serpent-CTF calculations by assessing numerical stability, visual convergence, and the accuracy of axial and radial temperature distributions, while performing sensitivity studies on key parameters such as mass flow, inlet enthalpy, power, and pressure and also analysing the impact of the number of active cycles on solution accuracy.

CHAPTER 2 REACTOR THEORY AND LITERATURE REVIEW

2.1 Introduction to thermal hydraulics and computer code coupling in nuclear reactors

2.1.1 Basic background of thermal hydraulics

The application of thermal hydraulics for nuclear reactors constitutes the study of heat generation, distribution, and fluid flow dynamics within the reactor core and associated systems and is central for optimizing efficient power generation and safety (D'Auria, 2017). Thermal hydraulics applies the principles of thermodynamics and fluid mechanics to model how heat generated by nuclear fission is dissipated by water (the coolant) in LWRs. The key phenomena are the single-phase and two-phase flow, where the coolant either remains liquid or partly vaporizes and affects the heat transfer rate. This creates possible hurdles, such as approaching the critical heat flux, which leads to overheating if heat clearance is ineffective (D'Auria, 2017). With advanced reactor configurations, thermal hydraulics also addresses phenomena such as natural flow under transients (which could include accidents), where in failures to use pumps force a system to buoyancy-driven flow, and instabilities that would disrupt stable operation (Aksan, 2019). Research has highlighted specific regimes in which the pressure exceeds a critical point (e.g. deteriorated heat transfer in supercritical fluids), which leads to unique behaviour in heat convection that demands specialized correlation for accurate modelling (Zhang & Hassan, 2022).

2.1.2 Computer code coupling calculations

Computer code coupling calculations in water reactors refer to integrated multi-physics simulations that link neutronics—the study of neutron transport, fission reactions, and power distribution—with thermal hydraulics, which encompasses heat transfer, fluid flow, and coolant behaviour in the reactor core and systems (Hamilton *et al.*, 2016). This coupling is essential for modelling the interdependent feedback loops in LWRs accurately, such as in PWRs. This is because changes in coolant temperature or density can alter neutron moderation and absorption and thereby influence reactivity and heat generation. In steady-state operations, these calculations ensure precise predictions of power distribution and temperature profiles, while in transients or accident scenarios, they capture dynamic behaviour such as reactivity insertion or loss-of-coolant scenarios. The strong nonlinear interactions between these physics demand a high-fidelity approach to minimize conservatism in safety analysis and to optimize reactor designs.

At the core of coupling calculations is the state characterization: neutronics determines the spatial and energetic distribution of neutrons, leading to the fission heat distribution, which thermal

hydraulics then uses to compute the temperature and density fields. A consistent definition for these fields must then be obtained, i.e. the neutronic fields when applied to the thermal hydraulic calculation produce the correct temperature and density fields, and vice versa. One of the most efficient methods for obtaining this consistency is by iterative calculations between the codes until convergence of the fields is obtained. This is called code coupling.

Coupling methods are broadly classified into internal and external approaches. Internal coupling integrates neutronics and thermal-hydraulics solvers within a unified framework, which enables direct memory data transfer for efficient, high-accuracy exchanges without intermediate files (Li *et al.*, 2023). One major disadvantage of the internal approach is that it involves significant modifications in both the thermal hydraulic and neutronics codes (Ivanov & Avramova, 2007). In contrast, external coupling separates code exchange data iteratively, often via files, which can introduce approximations and increase the computational overhead. External coupling is often required because suppliers of codes do not supply the source code; hence, the internal approach cannot be applied. Furthermore, external coupling is simpler to implement if various codes (both neutronic and thermal hydraulic) are to be compared. External coupling also requires little or no modifications of the thermal hydraulic and neutronics codes (Ivanov & Avramova, 2007).

As mentioned above, iteration schemes are critical for convergence. The Picard iteration (or block Gauss-Seidel) alternates between solving each physics domain, offering simplicity but suffering from slow linear convergence and potential instability in tightly coupled systems, making it appropriate for systems that are not tightly coupled (Hamilton *et al.*, 2016). Advanced alternatives include Jacobian-free Newton-Krylov (JFNK) methods, which provide quadratic convergence and global stability by solving the nonlinear residual of the coupled system, which is appropriate for tightly coupled systems but limited by a complex implementation, and Anderson acceleration, which enhances Picard by extrapolating from prior iterates to speed up convergence, limited by the need for additional memory to store prior iterates. These are particularly effective for criticality problems (k-eigenvalue) and critical boron searches in PWRs, where on-line cross-section generation is computationally intensive.

In practice, coupling Monte Carlo-based codes for neutronics and sub-channel codes like CTF for thermal hydraulics demonstrate the advantages of internal coupling in LWRs (Li *et al.*, 2023). Deterministic methods offer computational efficiency but suffer from spatial homogenization, whereas Serpent (Monte Carlo code) provides exact 3D, sub-pin resolution at a higher computational cost. System codes (like RELAP5) utilize computationally efficient, lumped 1D models with low spatial resolution, whereas sub-channel codes provide exact, 3D pin-by-pin thermal-hydraulic data at a higher computational cost (Ivanov & Avramova, 2007). Challenges with the coupling calculations include high computational costs from iterative data exchanges and

cross-section updates; mesh incompatibility between physics domains; and ensuring convergence in nonlinear systems (Hamilton *et al.*, 2016).

Overall, coupling calculations enhance reactor safety and efficiency by providing holistic insight into multi-physics interactions, which enables better steady-state or transient modelling and design optimizations in water reactors (Li *et al.*, 2023).

2.2 Nuclear power reactors

2.2.1 The light water small modular reactor

Light water small modular reactors (LWSMRs) are a subset of SMRs that use light water—ordinary water (H_2O)—as both coolant and neutron moderator. This builds on the established technology of conventional LWRs. LWSMRs are designed to produce up to 300 megawatts electric (MWe), and offer a compact, scalable alternative to traditional large-scale nuclear power plants. This addresses challenges such as high capital cost and extended construction timelines. The modular design enables factory fabrication and transport, which could reduce construction schedules to as little as two to three years, rather than a decade, which is required for conventional reactors (Locatelli *et al.*, 2014). This makes them suitable for smaller grids, remote locations, or applications such as industrial heat supply or marine propulsion.

LWSMRs operate on the principle of nuclear fission: uranium-235 atoms in fuel rods (typically uranium dioxide, UO_2) split, and heat is released. The reactor core is housed in a compact pressure vessel (often less than 4 meters in diameter for purposes of transportability) and sustains a controlled chain reaction. Light water moderates neutrons to thermal speeds to maintain fission, while absorbing most of the generated heat. LWSMRs are divided into two main types: PWRs and boiling water reactors (BWRs). In PWR-based LWSMRs, water is kept under high pressure (15–16 MPa) to ensure it remains liquid at a high temperature (about 290–330°C). In BWR-based designs, the water boils directly in the core and produces steam (Carelli *et al.*, 2010). In PWR LWSMRs, the heated, pressurized water in the primary coolant loop transfers its thermal energy to a secondary loop via steam generators.

Many designs adopt an integral configuration, with the core, steam generators, and pressurizer housed within a single vessel, as this reduces external piping and enhances safety by minimizing the risk of leaks (Locatelli *et al.*, 2014). The secondary loop is isolated from radioactivity and produces steam to drive a turbine-generator for electricity production. In BWR LWSMRs, steam is generated directly in the core, sent to the turbine, and then condensed back to water for recirculation. Thermal efficiencies typically range from 25–33%, which is slightly lower than large

LWRs, due to the size constraints, but it is sufficient for reliable baseload power (Carelli *et al.*, 2010).

Safety is a key focus of LWSMRs, with designs incorporating passive safety systems that rely on natural processes such as convection and gravity rather than active mechanical components. Some LWSMRs also use burnable poisons in the fuel to control reactivity, which could extend the refuelling interval to several years. This is particularly advantageous for remote or marine applications (Hirdaris *et al.*, 2014).

2.2.2 NuScale reactor

Core

The NuScale core configuration consists of 37 fuel assemblies. The NuScale fuel assembly design is 17x17 and is approximately one-half the length of typical PWR fuel assemblies (NuScale Power, 2020). The assembly is supported by five spacer grids, 24 guide tubes, and a top and bottom nozzle that together provide the structural skeleton for the 264 fuel rods. Each fuel assembly has a central instrument tube. The fuel is uranium dioxide (UO_2). Figure 2-1 shows the reactor core (NuScale Power, 2020), and Figure 2-2 (Fridman *et al.*, 2023) shows the fuel assembly.

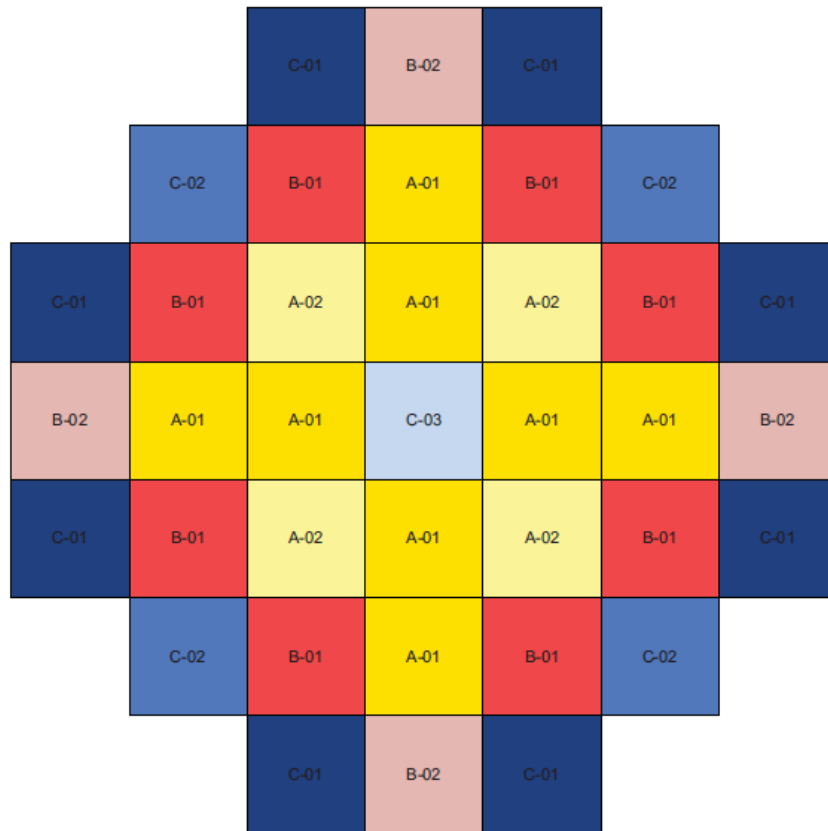


Figure 2-1: Layout of the NuScale core

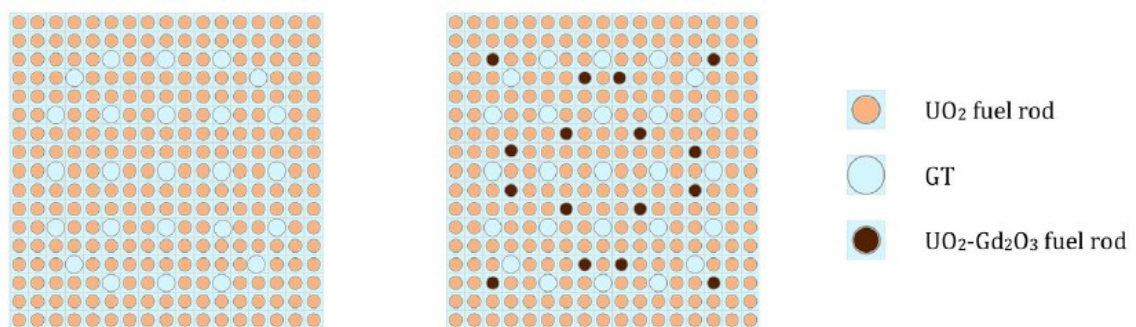


Figure 2-2: Radial layout of fuel assemblies (un-poisoned (left) and poisoned (right))

Specifications

Table 2-1 shows all the relevant NuScale specifications. (NuScale Power, 2020)

Table 2-1: NuScale specifications (NuScale Power, 2020)

Parameter	Value	Units
Core thermal output	160	MWth
System pressure	12755.3	kPa

Inlet temperature	531.483	K
Core average temperature	557.039	K
Average temperature rise in core	55.56	K
Best estimate flow	587.15	kg/s
Number of fuel assemblies	37	-
Layout dimensions in fuel assembly	17x17	
Fuel Assembly	-	-
Length	2.3876	m
Rods per fuel assembly	264	-
Fuel assembly pitch	0.21504	m
Fuel rod pitch	0.012598	m
Number of guide tubes per assembly	24	-
Number of instrument tubes per assembly	1	-
Guide tube OD	0.012243	m
Fuel Rod	-	-
Cladding outside diameter	0.0094996	m
Cladding inside diameter	0.0082804	m
Cladding thickness	0.0006096	m
Fill gas	Helium	-
Fuel pellet OD	0.00811532	m
Fuel pellet length	0.01016002	m
Fuel rod length	2.15900432	m

Fuel rod OD	0.00949962	m
Fuel rod ID	0.00828042	m
Fuel rod cladding	M5® (zirconium)	-

2.2.3 Avramova reactor

The CTF model for the NuScale reactor was developed from an existing model developed by Maria Avramova (M. Avramova et al., 2002). The PWR reactor design used in the Avramova study is referred to as the Avramova reactor in this document. It contains 121 fuel assemblies and has a 14x14 design in terms of fuel assembly layout.

Specifications

Table 2-2 provides all the relevant Avramova PWR reactor specifications. (M. Avramova et al., 2002).

Table 2-2: Avramova PWR reactor specifications (M. Avramova *et al.*, 2002)

Parameters	Value	Units
Fuel rod OD	0.0107696	m
Guide tube OD	0.0136906	m
Fuel rod pitch	0.0141224	m
Fuel assembly pitch	0.1981966	m
Fuel assembly dimensions	14x14	-
Number of fuel assemblies	121	-
Gap between fuel assemblies	0.000508	m
No. of fuel rods	179	-
No. of guide tubes	16	-
No. of instrumentation rods	1	-

Fuel active length	2.413005	m
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Core model in CTF

The Avramova reactor core was modelled in CTF as a quarter core model with sub-channels. This input file was available online. Figure 2-3 shows the sub-channel layout from sub-channels 1-7. Figure 2-4 shows the layout of the whole quarter core model, including sub-channels 8 and 9. A quarter of the fuel assembly at the centre of the reactor core makes up sub-channels 1-5 and a part of subchannel 6, as shown in Figure 2-4. In this figure, the block with the diagonal hatch shading is only a quarter of the full central fuel assembly. Subchannel 6 is also made up from parts of the three fuel assemblies surrounding the centre fuel assembly, which is also shown in Figure 2-4. The remaining part of the three assemblies makes up sub-channel 8. The rest of the quarter core is modelled as sub-channel 9 (M. Avramova *et al.*, 2002).

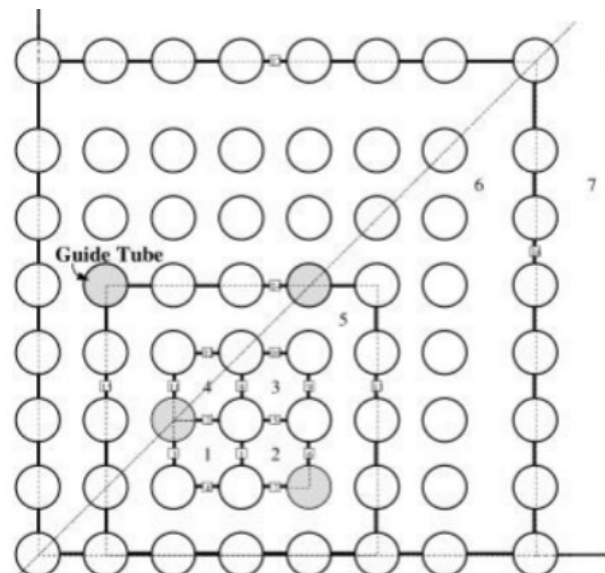


Figure 2-3: Sub-channel layout, from sub-channels 1-7

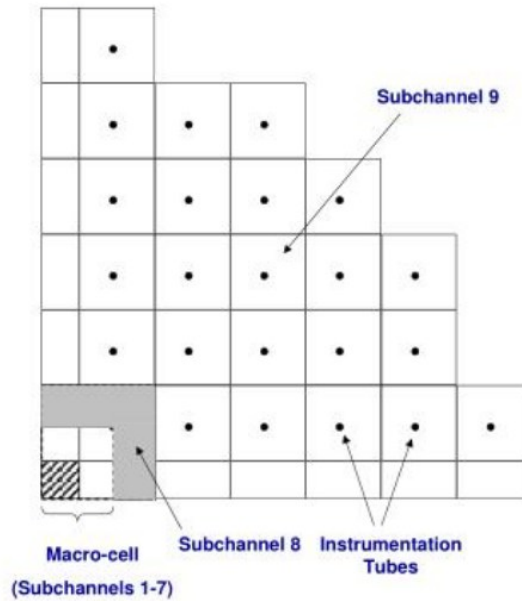


Figure 2-4: Layout of the quarter core model

2.3 Serpent

This study focussed on the thermal hydraulic modelling, with the Serpent model being developed in a previous study done by Kgomo Madi, a past student of NWU (KZ Madi, 2025). Serpent is a Monte Carlo neutronic code. The transport of neutrons in the core is carried out using the analogue method. Important aspects of the code are neutron data input and processing; stochastic modelling of the neutron transport; associated source convergence; statistics values of the output parameters, notably the multiplication factor and the neutron flux tallies. Further details can be found in the study done by Madi (2025) and on the Wiki page for Serpent (Ville Valtavirta, 2015).

2.4 NWURCS

NWURCS is a set of codes that have been in development at NWU, Faculty of Engineering, since 2011. The current version is Version 3. The main feature of the suite of codes is the level scheme distinguishing the core, fuel assemblies and fuel pins as nested levels, with lattices defining the layouts for the deeper levels nested within a given level. This level scheme facilitates the definition of units and lattices with generic input syntax for any level. The code was developed for two applications, namely code coupling at system level and uncertainty propagation. With both applications, at system level, the code also generates input files for neutronic and thermal hydraulic codes. As such, the code can be used to generate input for stand-alone applications (i.e. without coupling and/ or uncertainty propagation).

2.5 CTF

The CTF code is a modernized thermal hydraulic sub-channel analysis tool primarily designed for LWR applications, such as PWRs and BWRs (Salko *et al.*, 2022). CTF can be used in coupling calculations to enable multi-physics simulations that integrate neutronics, thermal-hydraulics, and fuel performance for improved accuracy in reactor design, safety analysis, and depletion studies (Bennett *et al.*, 2016). For instance, it is coupled with Monte Carlo neutronics codes like MCNP6, RMC, or MCS for high-fidelity pin-by-pin whole-core analyses, providing thermal hydraulic feedback (e.g. coolant density, temperature profiles), in order to refine power distribution (Li *et al.*, 2023).

2.6 Research Gap

Limited work has been done on coupling Monte Carlo neutronic codes (Serpent) with the sub-channel thermal-hydraulic codes (CTF), particularly within flexible coupling frameworks such as the North-West University Reactor Coupling System (NWURCS). Specifically in terms of the NWU, this study will attempt to close this gap in terms of the analysis sequences currently in use.

CHAPTER 3 METHODOLOGY

3.1 Introduction

This chapter describes the methodological approach that was followed to develop a thermal-hydraulic base model for the NuScale SMR using CTF, and to couple this model to an existing Serpent neutronic model (KZ Madi, 2025) within the NWURCS Version 3 framework. It also outlines the overall research design, the computational tools required, the steps taken to construct and verify the CTF input model, and the process followed to integrate it with the neutronic solution. The methodology section includes the verification approach employed to ensure the thermal-hydraulic inputs were correct before coupling was done.

3.2 Research approach and design

The research was conducted using a computational modelling and verification approach. The work required the step-by-step construction of a fully functional thermal-hydraulic representation of the NuScale SMR in CTF independent of NWURCS, the reconstruction and translation of geometric inputs for input to NWURCS, and the coupling of this thermal-hydraulic model with a neutronic model developed in Serpent using NWURCS. A few assumptions/limitations were made, namely: the model would be for a steady-state condition. Neglecting transients means the model cannot predict time-dependent behaviour, but a steady-state approach is a valid first step to get a converged baseline solution. This trade-off allows for a more rigorous check of the coupled code's stability and accuracy before adding the extra complexity of time-dependent feedback loops. One also notes that there is a difference between numerical coupling and physical coupling. This study centres around numerical coupling, which can be considered as a "snapshot" at a distinct operating state, where the aim of the coupling calculations is to get the exact match of the neutronic and thermal hydraulic parameters at the state in consideration. Physical coupling can be for example the modelling of feedback effects, which was not the focus of this study.

The water flowing through the guide tubes was not modelled, i.e., the guide tubes were modelled as a solid rod. This simplification was made to reduce computational overhead in the sub-channel mesh, as the lack of heat generation in the guide tubes should have a minimal impact on the overall core thermal-hydraulic profile for steady state calculations. However, it is recognized that this limits the model's ability to capture localized moderation effects and bypass flow distributions. Both these assumptions will be relaxed in later studies.

3.2.1 Access to computational resources

Monte Carlo simulations are computationally intensive. Thus, access to the NWU High Performance Computer (HPC) was obtained. The HPC environment was configured with what was required to execute Serpent simulations by the code developer.

3.2.2 Compilation and testing of COBRA-TF

The CTF code was obtained by means of the NWU code-sharing agreement. Before any modelling could begin, CTF was compiled. Compilation was verified using the Avramova benchmark PWR input file, which served as a reference test case. Minor compilation issues were resolved in consultation with the NWURCS code developer, and successful execution of the Avramova model confirmed that the code environment was stable.

3.2.3 Building the NuScale reactor core model on CTF

3.2.3.1 Adapting the Avramova benchmark model

The Avramova PWR input was used as a template, as it employs nine sub-channels to model a quarter-core. Since NuScale uses a 17x17 fuel assembly layout, the Avramova 14x14 layout had to be systematically converted to a 17x17 layout.

3.2.3.2 Sequential geometric translation

To avoid introducing geometric inconsistencies, a stepwise transition was followed. First, the Avramova 14x14 layout was translated into an intermediate 16x16 model. This 16x16 layout then had to be converted to a 17x17 layout, and then the NuScale-specific 17x17 model using the actual NuScale design dimensions. However, in order to do this, the input values for the following dimensions had to be calculated correctly: flow area, wetted perimeter and gap lengths in the CTF input model. Using the Avramova specifications, the values for the dimensions were re-calculated for each sub-channel, and these were verified to be the same as the Avramova values. Thereafter the transitional calculations (to 17x17) could be done accurately. The next level of transition was introduced only after the intermediate models produced stable and error-free CTF runs. Each translation was drawn out by hand to ensure that the correct number and positions of the fuel pins/guide tubes were used.

3.2.3.3 Verification of geometric sub-channel quantities

The verification process focused on ensuring that the flow area, wetted perimeter and gap lengths of each sub-channel were represented correctly. These values were manually calculated in Microsoft Excel and then compared with the computational results produced by NWURCS. The

manual and computational values were identical, which confirmed that the geometric definitions were correct. This verification confirmed that the sub-channel geometry in the 17x17 NuScale configuration matched the expected layout and that the geometric data was accurately entered into the CTF input file.

3.2.4 Implementation of CTF card groups

CTF uses 15 card groups to define the reactor system. These are as follows (M. Avramova, 2011).:

- Card group 1: Selection of the Physical Models, Global Boundary Conditions, and Initial Conditions
- Card group 2: Channel Description
- Card group 3: Transverse Channel Connection Data (Gap definition)
- Card group 4: Vertical Channel Connection Data
- Card group 5: Geometry Variation Data
- Card group 6: Channels and Gaps Affected by Variation Tables
- Card group 7: Local Pressure Loss Coefficient and Grid Spacer Data
- Card group 8: Rod and Unheated Conductor Data
- Card group 9: Conductor Geometry Description
- Card group 10: Material Properties Tables
- Card group 11: Axial Power Distribution Tables, Radial Power Distribution, and Transient Forcing Functions
- Card group 12: Turbulent Mixing and Void Drift Data
- Card group 13: Boundary Condition Data
- Card group 14: Output Options
- Card group 15: Time Domain Data

For purposes of this study, only Card groups 1, 2, 3, 4, 7, 8, 9, 10, 11, 13 and 15 were considered. This was to prevent scope creep. The remaining cards will be considered in later studies. The methodology involved populating these cards with specific NuScale input values derived from technical documentation, literature, and computed geometric data.

3.2.5 Defining the input CTF model

After confirming that the geometric parameters (Card groups 2 and 3) were correct, the remaining CTF input card groups were defined accurately. Card groups 4, 7, 8, 9, 10, 11, 13 and 15 were populated with the required parameters using data obtained from the NuScale reactor specifications and values calculated from the model geometry.

Each card group was completed as follows:

- Card group 4 (Vertical channel data): channel connections were defined to reflect the quarter core structure.
- Card group 7 (Pressure loss and spacer grid data): inputs were assigned according to the standard setup used in the Avramova model.
- Card groups 8 and 9 (Rod and conductor data): rod and guide tube dimensions, multiplication factors, and materials were entered.
- Card group 10 (Material properties): cladding properties were defined using zirconium data.
- Card group 11 (Power functions): axial power functions were defined using placeholders as these were populated by coupling with Serpent.
- Card group 13 (Boundary conditions): utilised the pressure and enthalpy - which was calculated using EES (Mahmoud *et al.*, 2023), using the inlet temperature and pressure.
- Card group 15 (Time domain data): steady state parameters were specified.

Once all card groups were correctly defined, the model was executed. The code ran successfully without errors, which confirmed that all input parameters were correctly entered and that the model was stable.

3.3 Source convergence and Shannon entropy

In Monte Carlo neutronic calculations, the accuracy of power and flux tallies depends on the convergence of the fission neutron source distribution. Because Serpent begins each simulation with an initial source guess that does not necessarily represent the true physical fission distribution of the source neutrons in the reactor, a number of inactive cycles are required for the source to spread out and stabilise. Only once source convergence is achieved can the tallies produced during subsequent active cycles be considered physically meaningful (Leppänen, 2015).

To verify source convergence in this study, the Shannon entropy was used as the monitoring metric. Shannon entropy provides a quantitative measure of the spatial distribution of the fission source by dividing the geometry into bins and evaluating how neutrons populate these bins in each cycle. At the beginning of the simulation, entropy values typically fluctuate, as the source distribution adjusts. As the fission source approaches its steady-state fundamental mode, these fluctuations diminish and the entropy trace settles into a stable plateau (Leppänen, 2015).

In this work, the Shannon entropy values generated by Serpent were plotted over the full range of inactive and active cycles. Source convergence was confirmed once the entropy curve became

approximately constant, with no systematic drift and only small statistical fluctuations about a stable mean. Only after this plateau was observed were the active cycles used for tallying the axial and pin-wise power distributions required for coupling with CTF.

Ensuring that the fission source had fully converged before extracting power data was essential to produce a reliable base case for the coupled Serpent–CTF simulations (Hamilton *et al.*, 2016).

3.4 Coupling methodology

The final phase of the methodology involved integrating the CTF input model with the input Serpent neutronic model (KZ Madi, 2025) of the NuScale core that was already built. Coupling of Serpent and CTF was performed using the NWURCS Version 3 code suite. The coupling was done through file exchange, with output data from Serpent read by NWURCS and then written into the CTF input files.

3.4.1 NWURCS

NWURCS serves the purpose of both input generation and coupling of files. In terms of input, it generates the input files for Serpent and CTF. Regarding the coupling, NWURCS extracts data from the output file of Serpent and writes this into the input file of CTF, and vice versa. This detail is provided in the next section.

3.4.2 Iterative coupling

Serpent calculates the neutron flux and produces a power distribution. The power is mapped to CTF using NWURCS. CTF calculates the temperature of the fuel pellet, gap, cladding and moderator. These thermal-hydraulic conditions are mapped and returned to Serpent via NWURCS. The unit cells in Serpent are updated with this gained information and recomputes the power. This process was repeated through several iterations until the results converged. Monitoring of the convergence was done visually, for reasons explained later. However, NWURCS does contain an algorithm for determining convergence automatically (numerically) which can be utilized for more routine calculations.

3.5 Post-coupling verification

After the coupling between Serpent and CTF was completed, several verification steps were performed to confirm that the coupled system was functioning correctly and producing consistent results. This meant ensuring that the outputs obtained from the coupled calculations were accurate and stable. The following values were verified:

- K-effective (k_{eff})

- Detector data (power fields)
- Temperature values, including that of the moderator and heat structures.
- Relaxation methods.

Thereafter, the coupled base case results were produced and analysed.

3.6 Sensitivity Analysis

Sensitivity studies were then done to determine the effect that selected input values would have on chosen output values after coupled calculations were done to evaluate the robustness of the coupled Serpent-CTF model. Sensitivity studies were done using a 10% increase and decrease on the mass flow rate, inlet enthalpy, power and pressure variables. These parameters were considered since these are the base parameters for the solution of the fluid mechanics equations. Since only the steady state solution was being considered, it was deemed that sensitivity on other fluid mechanics parameters and heat transfer parameters could be carried out in a second phase of sensitivity studies. A detailed sensitivity study of all applicable parameters would have increased the scope beyond that required for a Masters study and was therefore reserved for future studies. As mentioned above, verification of the methodology and assessment of the robustness of the method was the key focus of the current study.

10% was chosen to obtain an indication of what result to expect: it was not chosen based on empirical data, such as plant operating characteristics. Thereafter the results were analysed.

3.7 Flow Chart

The flow chart below (Figure 3-1) provides an overview of the processes and steps followed in undertaking the study.

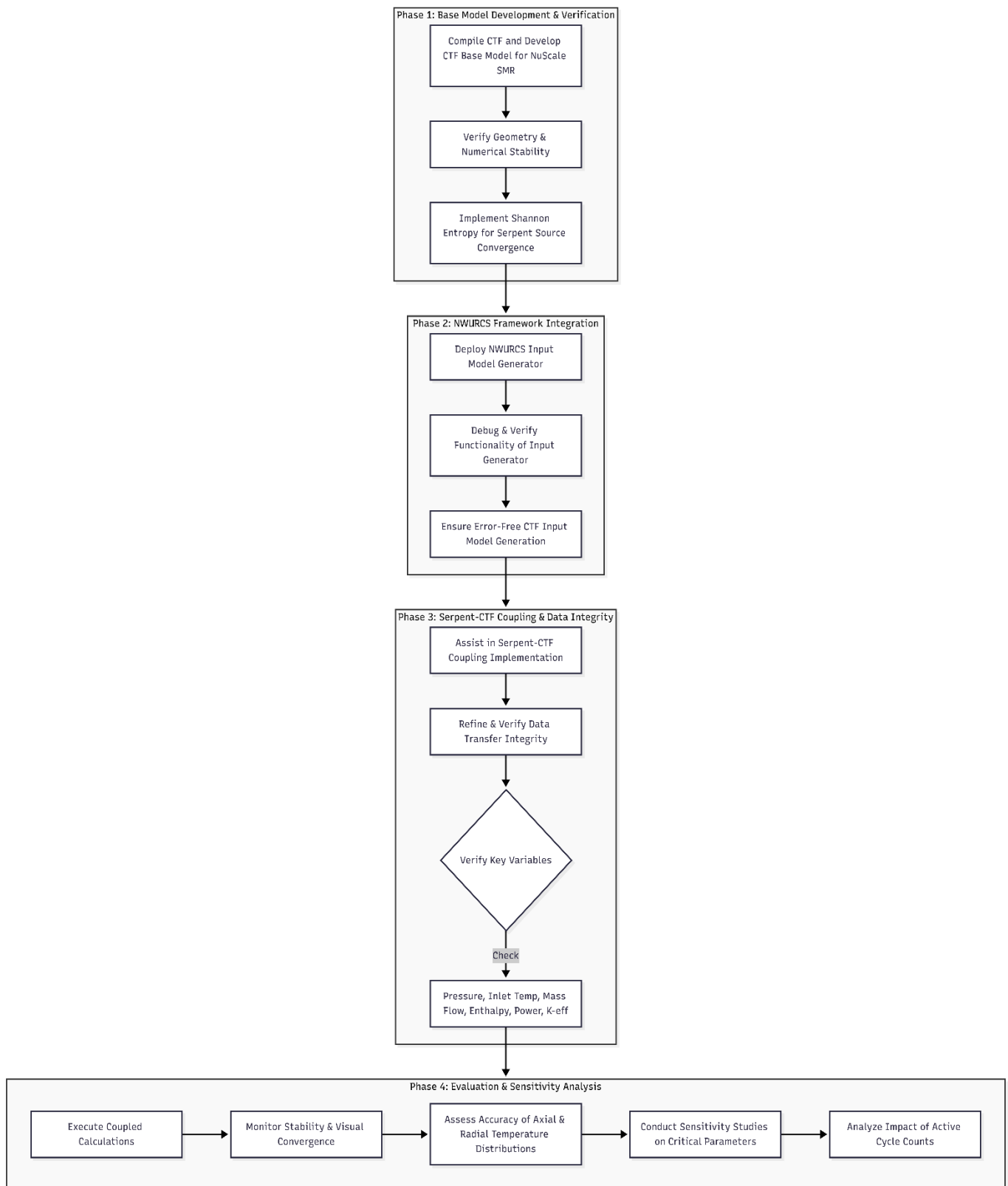


Figure 3-1: Methodology Flowchart

CHAPTER 4 BUILDING THE NUSCALE INPUT MODEL FOR CTF

4.1 Building the NuScale input model

4.1.1 Assumptions

The following assumptions were made:

- Steady-state conditions.
- No water flowing through guide tubes, i.e. model guide tubes as a solid rod (not hollow).

4.1.2 Avramova input model

The CTF code has been available at NWU since 2013 through a code exchange agreement with the code providers, and the process of compiling the code was done using the Avramova input model as the test case. Access was obtained to the Avramova base model built on CTF. The code was successfully compiled and executed after a few minor bugs were fixed. To learn how to compile CTF, the user manual for NWURCS was accessed and utilized. As stated in the literature review, Avramova modelled a quarter core, with 9 sub-channels.

4.1.3 Transitioning from the Avramova model to the NuScale model

The Avramova model has a reactor with a 14x14 fuel assembly layout, whereas the NuScale model has a 17x17 layout. Hence, the 14x14 input model had to be converted to a 17x17 model. The same 9 subchannels specified for the Avramova model was used, with the dimensions being redefined.

A step-by-step method was chosen for the translation of a 14x14 model to a 17x17 model. Firstly, the 14x14 was translated into a 16x16 model, then the 16x16 model was translated to a 17x17 model. However, in order to do this the input values for the following dimensions had to be calculated correctly: flow area, wetted perimeter and gap widths in the CTF input model, since these values affect the hydraulic diameter, which influences the pressure drop and heat transfer calculations. These calculated values were then compared to Avramova, whereafter the transitional calculations (to 17x17) could be done accurately.

4.1.3.1 Flow area

The flow area of each sub-channel was calculated using Excel as follows.

A bounding square was defined around the external boundary of the sub-channel, and the area of the square then calculated. An inner square was then drawn to separate the current subchannel from the other sub-channels inside the inner boundary square. (The first four sub-channels do not have an inner square as they do not contain a sub-channel inside the bigger square.) Thereafter the area of all the sections of fuel rods and the guide tubes in the sub-channel were subtracted from the area of the square to give the flow area. Only the area of the fuel rods and guide tubes that were inside the sub-channel's dimensions were used.

Appendix A (0) visualises and breaks down the method used to calculate the flow area (including the equation used) by using an example of how the calculation for flow area was done for sub-channel 5.

Table 3 shows that these calculations were done for all the sub-channels, and comparison with the Avramova values showed that they were identical.

Table 3: Area calculations done for each sub-channel and compared to the Avramova values (m^2)

Sub-Channel	Area Squares	Final Area	Avramova Area
1	0.000199	0.000094	0.000094
2	0.000199	0.000094	0.000094
3	0.000199	0.000108	0.000108
4	0.000199	0.000094	0.000094
5	0.0032	0.0012	0.0012
6	0.0099	0.0036	0.0036
7	0.034	0.012	0.012

8	0.08	0.028	0.028
9	0.95	0.57	0.57

4.1.3.2 Wetted perimeter

The wetted perimeter of each sub-channel was calculated via Excel as follows.

A bounding square was defined around the external boundary of the sub-channel. Then an inner square was defined to separate the current subchannel from the other sub-channels inside the inner boundary square. (The first four sub-channels do not have an inner square as they do not contain a sub-channel inside the bigger square.) Thereafter, the circumference of all the sections of fuel rods and guide tubes inside the sub-channel boundary were added together to determine the perimeter. Only the perimeter of the fuel rods and guide tubes that were inside the sub-channel's dimensions were used.

Appendix B (0) visualises and breaks down the method used to calculate the wetted perimeter (including the equation used) by using an example of how the calculation for the wetted perimeter was done for sub-channel 5.

Table 4 shows that these calculations were done for all the sub-channels, and that they were identical to the Avramova values.

Table 4: Wetted perimeter calculations for each sub-channel compared to the Avramova values (*m*)

Sub-Channel	Wetted Perimeter	Avramova Wetted Perimeter
1	0.036	0.036
2	0.036	0.036
3	0.034	0.034
4	0.036	0.036
5	0.42	0.42
6	1.13	1.13
7	4.17	4.17

8	9.4	9.4
9	189	189

4.1.3.3 Gap width

The gap width is equal to the total width for transverse flow between the two adjacent regions modelled by the sub-channels (M. Avramova, 2011). These gaps width between sub-channels need to be input in the CTF model, and to calculate these quantities the following equations were used:

For flow between fuel rods

$$G_w = FR_p - 2FR_R \quad (1)$$

For flow between fuel rods and guide tubes

$$G_w = FR_p - FR_R - GT_R \quad (2)$$

For subchannels 5 to 9:

$$G_w = FR_p + FA_G$$

or

$$G_w = FR_p - -FR_R - GT_R + FA_G \quad (3)$$

Where G_w is the gap width, FR_p is the fuel rod pitch, FR_R is the fuel rod radius, GT_R is the guide tube radius and FA_G is the fuel assembly gap width.

For example, as shown in Figure 4-1, Gap 1 (between sub-channel 1 and 2) has two fuel pins defining the gap, so the flow can only happen in the gap between the two pins. Hence the gap width was calculated using Equation 1. With gap 2 (between sub-channel 1 and 4), there is a guide tube and a fuel rod (Equation 2 is used here); therefore, the gap width is smaller and there is less space available for flow.

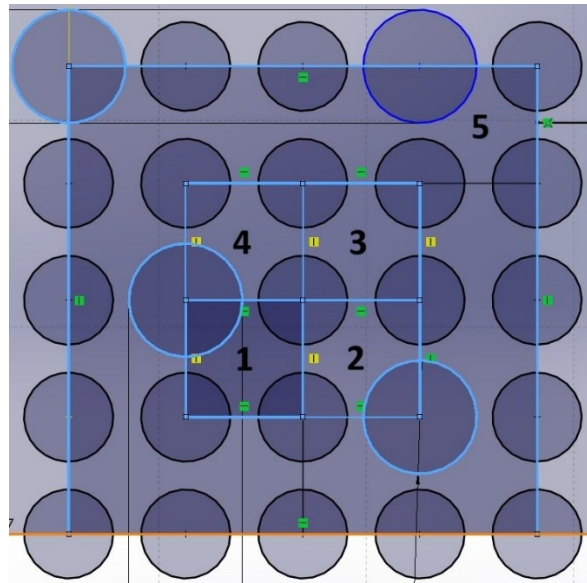


Figure 4-1: Sub-channels 1-5 14x14 Avramova model

Table 5 shows the gap widths that were calculated in Excel and the gap width inputs of the Avramova model for purposes of comparison. They were verified as being the same.

Table 5: Gap lengths calculated in Excel in m

GAP	From Sub-channel	To Sub-channel	GAP Length	Avramova GAP Length
1	1	2	0.0034	0.0034
2	1	4	0.0019	0.0019
3	1	5	0.0019	0.0019
4	1	5	0.0034	0.0034
5	2	3	0.0034	0.0034
6	2	5	0.0019	0.0019
7	2	5	0.0019	0.0019
8	3	4	0.0034	0.0034
9	3	5	0.0034	0.0034

10	3	5	0.0034	0.0034
11	4	5	0.0019	0.0019
12	4	5	0.0034	0.0034
13	5	6	0.013	0.013
14	5	6	0.009	0.009
15	5	6	0.012	0.012
16	6	7	0.024	0.024
17	6	7	0.024	0.024
18	7	8	0.044	0.044
19	7	8	0.044	0.044
20	8	9	0.067	0.067

4.1.3.4 Transition to 17x17 NuScale FA layout

The same Avramova input dimensions (M. Avramova *et al.*, 2002) were used to transform the 14x14 Fuel Assembly (FA) layout to a 16x16 FA layout using the same calculation method for the flow area, wetted perimeter and gap length. However, the values for the larger sub-channels (5-9) changed when more fuel rods were present, and the code was re-run with these new input values. The code ran successfully with no errors.

The same Avramova input dimensions (M. Avramova *et al.*, 2002) were used to transform the 16x16 model to a 17x17 model using the same calculation method. The code was re-run with the new input values, and the code ran with no errors.

The input dimensions for the 17x17 model were then adjusted to include the NuScale dimensions. Using the same calculation method and noting that the NuScale reactor has a different number of fuel rods and guide tubes per assembly, with different positions indicated for the guide tubes, the calculations were done to obtain the new input values. The code was re-run with these new input values, and the code ran successfully with no errors. Figure 4-2 shows the sub-channel layout for NuScale from sub-channel 1-8. Sub-channels 1-4 are the small squares and are labelled accordingly. Subchannels 5-8 are represented by different shades of grey i.e, the region

with the lightest shade is subchannel 8, and the slightly darker shaded region is subchannel 7 and subchannel 6 is the region darker than subchannel 7 and subchannel 5 is the region darker than subchannel 6 but excludes subchannels 1-4. The rest of the fuel assemblies were modelled as sub-channel 9 and subsequently is the largest subchannel and therefore has the largest flow area, wetted perimeter and gap length from all the subchannels. The circles are fuel pins, and the shaded circles are the guide tubes.

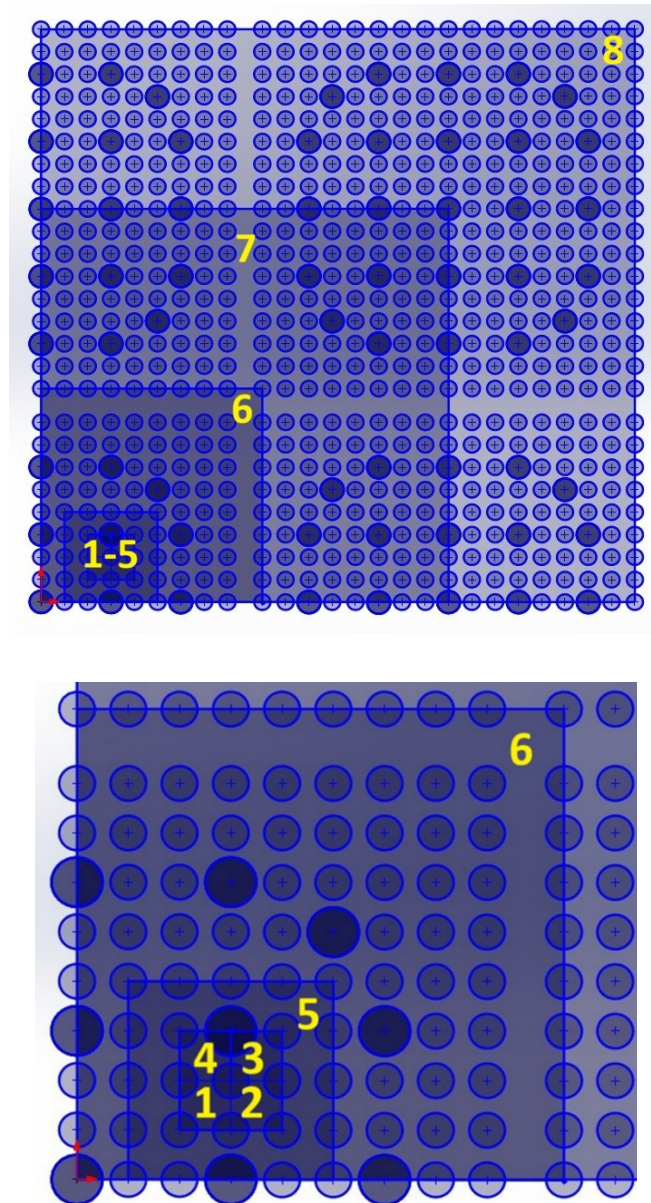


Figure 4-2: NuScale sub-channel definitions

Table 6 shows the flow area calculated per sub-channel for the 17x17 NuScale model.

Table 6: Flow area calculated per sub-channel for the 17x17 NuScale model in m^2

Sub-Channel	Final Area
1	0.000088
2	0.000088
3	0.000076
4	0.000076
5	0.0010
6	0.0056
7	0.017
8	0.033
9	0.16

Table 7 shows the wetted perimeter calculated per sub-channel for the 17x17 NuScale model.

Table 7: Wetted perimeter calculated per sub-channel for the 17x17 NuScale model (*m*)

Sub-Channel	Wetted Perimeter
1	0.030
2	0.030
3	0.032
4	0.032
5	0.37
6	1.98
7	6.37
8	11.8

9	59.4
---	------

Table 8 shows all the gap widths calculated for the 17x17 NuScale model.

Table 8: Gap widths calculated for the 17x17 NuScale model (*m*)

GAP	From Sub-channel	To Sub-channel	GAP width
1	1	2	0.0031
2	1	4	0.0031
3	1	5	0.0031
4	1	5	0.0031
5	2	3	0.0031
6	2	5	0.0031
7	2	5	0.0031
8	3	4	0.0031
9	3	5	0.0031
10	3	5	0.0017
11	4	5	0.0031
12	4	5	0.0017
13	5	6	0.012
14	5	6	0.012
15	5	6	0.012
16	6	7	0.029
17	6	7	0.029
18	7	8	0.040
19	7	8	0.040
20	8	9	0.082
21	8	9	0.082

4.1.3.5 Verification of the 17x17 NuScale input model

The 17x17 NuScale input model was built independently by the NWURCS code developer as well, and the inputs were calculated and generated using NWURCS. The student's calculations (done manually) were then compared to the code developer's calculations (done computationally). This is also an acceptable method for verification.

Table 9 shows the comparison between each flow area value (per sub-channel) calculated manually and by computational methods.

Table 9: Flow area values calculated manually and computationally

Sub-channel No.	Flow Area - Student [m^2]	Flow Area Code - Developer [m^2]
1	0.000088	0.000088
2	0.000088	0.000088
3	0.000076	0.000076
4	0.000076	0.000076
5	0.0010	0.0010
6	0.0056	0.0056
7	0.018	0.018
8	0.033	0.033
9	0.16	0.16

Table 9 shows that the results show strong agreement with the reference data, thereby verifying the model. The minor discrepancy in the flow area for sub-channel 7 between Table 6 (0.017) and Table 9 (0.018) is attributed to differences in rounding precision during the data extraction phase.

Table 10 shows the comparison between each wetted perimeter value (per sub-channel) calculated manually and by computational methods.

Table 10: Wetted perimeter values calculated manually and computationally

Sub-channel No.	Wetted Perimeter - Student [m]	Wetted Perimeter - Code Developer [m]
1	0.030	0.030
2	0.030	0.030
3	0.032	0.032
4	0.032	0.032
5	0.37	0.37
6	1.98	1.98
7	6.37	6.37
8	11.8	11.8
9	59.4	59.4

Table 10 shows that the results show strong agreement with the reference data, thereby verifying the model.

Table 11 shows the comparison between each gap width value calculated manually and by computational methods.

Table 11: Gap width values calculated manually and computationally

GAP No.	From Sub-Channel	To Sub-Channel	GAP Width – Student [m]	GAP Width - Code Developer[m]
1	1	2	0.0031	0.0031
2	1	4	0.0031	0.0031
3	1	5	0.0031	0.0031
4	1	5	0.0031	0.0031

5	2	3	0.0031	0.0031
6	2	5	0.0031	0.0031
7	2	5	0.0031	0.0031
8	3	4	0.0031	0.0031
9	3	5	0.0031	0.0031
10	3	5	0.0017	0.0017
11	4	5	0.0031	0.0031
12	4	5	0.0017	0.0017
13	5	6	0.012	0.012
14	5	6	0.012	0.012
15	5	6	0.012	0.012
16	6	7	0.029	0.029
17	6	7	0.029	0.029
18	7	8	0.040	0.040
19	7	8	0.040	0.040
20	8	9	0.082	0.082
21	8	9	0.082	0.082

Table 11 shows that the results show strong agreement with the reference data, thereby verifying the model.

Tables 9, 10 and 11 show that the NWURCS calculations were correct and verified and from this point onwards the dimensional inputs used were the computational values. This ensured that the calculations to be performed would have higher numerical precision and this would also reduce/eliminate the risk of human error and maintain the data integrity and reproducibility

required for reliable multi-physics coupling. The remainder of the Card group 3 inputs were derived from the diagram of the 17x17 fuel assembly of NuScale and from the code developer.

The final version of the Card group 2 and 3 inputs used are shown in Figure 4-3 and Figure 4-4, respectively. Note that the gap numbers for Card group 3 are not the same as those in Table 11. This was because the code developer and student used different numbering/labelling methods/styles. However, the gaps are still defined correctly and are related to the correct sub-channels and are in the correct locations.

```
* Group 2 - Channel Description
*****
*NGRP
  2
* ---CARD 2.1 -----
*NCHA NDM2 NDM3 NDM4 NDM5 NDM6 NDM7 NDM8 NDM9 |
  9  0  0  0  0  0  0  0  0  0  0  0  0  0  0
* ---CARD 2.2 -----
*  I      AN      PW      ABOT  ATOP  NMGP
  1 8.782760E-05 2.984510E-02      0      0      0
  2 8.782760E-05 2.984510E-02      0      0      0
  3 7.612190E-05 3.199865E-02      0      0      0
  4 7.612190E-05 3.199865E-02      0      0      0
  5 1.007108E-03 3.667554E-01      0      0      0
  6 5.634771E-03 1.980849E+00      0      0      0
  7 1.761522E-02 6.369297E+00      0      0      0
  8 3.315235E-02 1.181925E+01      0      0      0
  9 1.642556E-01 5.939206E+01      0      0      0
```

Figure 4-3: Final Card Group 2 input

```

*****
* Group 3 - Transverse Channel Connection (Gap) Data
*****
*NGRP
  3
* NK NDM2 NDM3 NDM4 NDM5 NDM6 NDM7 NDM8 NDM9 NM10 NM11 NM12 NM13 NM14
  21  0  0  0  0  0  0  0  0  0  0  0  0  0
***** Group 3.2
*K IK JK GAPN LNGT WKR FWAL IGPB IGPA FCT IGP JGP IGP JGP IGP JGP
  1  5  6 0.012392 0.025196 1.5 0.0  0  0  1.0  8 -1  2 -1  3 -1
  4.0  0.0
  2  1  5 0.003098 0.025196 1.5 0.0  0  0  1.0  4  1  0  0  0  0
  1.0  0.0
  3  4  5 0.003098 0.025196 1.5 0.0  0  0  1.0  5  1  0  0  0  0
  1.0  0.0
  4  1  2 0.003098 0.025196 1.5 0.0  0  0  1.0  2  6  0  0  0  0
  1.0  0.0
  5  3  4 0.001727 0.025196 1.5 0.0  0  0  1.0  7  3  0  0  0  0
  1.0  0.0
  6  2  5 0.003098 0.025196 1.5 0.0  0  0  1.0  4  8  0  0  0  0
  1.0  0.0
  7  3  5 0.003098 0.025196 1.5 0.0  0  0  1.0  5  8  0  0  0  0
  1.0  0.0
  8  5  6 0.012392 0.025196 1.5 0.0  0  0  1.0  1  9  6  9  7  9
  4.0  0.0
  9  6  7 0.028535 0.025848 1.5 0.0  0  0  1.0  8 10 -1 10  0  0
  9.0  0.0
 10  7  8 0.039826 0.025196 1.5 0.0  0  0  1.0  9 11 -1 11  0  0
 17.0  0.0
 11  8  9 0.082071 0.025848 1.5 0.0  0  0  1.0 10 -1 -1 -1  0  0
 26.0  0.0
 12  1  5 0.003098 0.012598 1.5 0.0  0  0  1.0 14 -1  0  0  0  0
  1.0  0.0
 13  2  5 0.003098 0.012598 1.5 0.0  0  0  1.0 15 -1  0  0  0  0
  1.0  0.0
 14  1  4 0.003098 0.012598 1.5 0.0  0  0  1.0 12 16  0  0  0  0
  1.0  0.0
 15  2  3 0.003098 0.012598 1.5 0.0  0  0  1.0 13 17  0  0  0  0
  1.0  0.0
 16  4  5 0.001727 0.012598 1.5 0.0  0  0  1.0 14 18  0  0  0  0
  1.0  0.0
 17  3  5 0.001727 0.012598 1.5 0.0  0  0  1.0 15 18  0  0  0  0
  1.0  0.0
 18  5  6 0.012392 0.012598 1.5 0.0  0  0  1.0 -1 19 16 19 17 19
  4.0  0.0
 19  6  7 0.028535 0.013033 1.5 0.0  0  0  1.0 -1 20 18 20  0  0
  9.0  0.0
 20  7  8 0.039826 0.012598 1.5 0.0  0  0  1.0 19 21 -1 21  0  0
 17.0  0.0
 21  8  9 0.082071 0.013033 1.5 0.0  0  0  1.0 20 -1 -1 -1  0  0
 26.0  0.0
*NMGP
  0

```

Figure 4-4: Final Card Group 3 input

4.1.4 Initial conditions (Card Group 1)

An inlet pressure of 127553 [kPa], an inlet temperature of 531.483 [K] and a mass flow rate of 1267.21 [kg/s] were used. The pressure and temperature data were obtained from the NuScale SAR (NuScale Power, 2016). The inlet enthalpy was calculated using EES yielding a value of 1126 [kJ/kg]. An inlet mass flow rate of 1267.21 [kg/s] was chosen as this was the value inherited

from an earlier model produced by NWURCS. This value was later changed – see Chapter 8, where its significance is discussed in detail. Note that the CTF code calculates the sub-channel mass flow rates according to the sub-channel flow areas, as specified in Card group 2.

4.1.5 Vertical channel data (Card Group 4)

Card 4 of CTF requires the vertical channel data, so 12 axial sections were defined, with each section's size being 0.2 metres to total 2.4 metres. The active height of the fuel assembly was 2.000 meters. Axial sections 1 and 12 are the upper and lower boundary cells; axial sections 2 to 11 define the active height of the FA assembly.

Figure 4-5 shows the final input for Card Group 4.

```
* ---CARD 4.2 -----
*ISEC NCHN NONO      DXS IVAR
1  9 10  2.00000E-01 12
* ---CARD 4.3 -----
1  2.00000E-01
2  2.00000E-01
3  2.00000E-01
4  2.00000E-01
5  2.00000E-01
6  2.00000E-01
7  2.00000E-01
8  2.00000E-01
9  2.00000E-01
10 2.00000E-01
11 2.00000E-01
12 2.00000E-01
```

Figure 4-5: Final input for Card Group 4

A simplified pressure loss-co-efficient of 1.00 was used for axial section 2, and 0.90 for the rest of the sections. Due to the defined scope of this study, detailed calibration of these pressure loss co-efficients and consideration of the pressure drop in terms of these values is deferred to future work.

Figure 4-6 shows the final input for Card group 7.

```

*****
* Group 7 - Local loss coefficient and Grid spacer data *
*****
*NGRP
7
* NCD NGT IFGQ IFSD IFES IFTP GTMP NFBS NDM9 NM10 NM11 NM12 NM13 NM14
25 0 0 0 0 0 0 0 0 0 0 0 0 0
* CDL J ICDM ICDM ICDM ICDM ICDM ICDM ICDM ICDM ICDM ICDM ICDM ICDM
1.00 2 1 2 4 0 0 0 0 0 0 0 0 0
1.00 2 3 7 0 0 0 0 0 0 0 0 0 0
1.00 2 5 0 0 0 0 0 0 0 0 0 0 0
1.00 2 6 0 0 0 0 0 0 0 0 0 0 0
1.00 2 8 9 0 0 0 0 0 0 0 0 0 0
*
0.90 3 1 2 4 0 0 0 0 0 0 0 0 0
0.90 3 3 0 0 0 0 0 0 0 0 0 0 0
0.90 3 5 0 0 0 0 0 0 0 0 0 0 0
0.90 3 6 0 0 0 0 0 0 0 0 0 0 0
0.90 3 7 8 9 0 0 0 0 0 0 0 0 0
*
0.90 5 1 2 4 0 0 0 0 0 0 0 0 0
0.90 5 3 0 0 0 0 0 0 0 0 0 0 0
0.90 5 5 0 0 0 0 0 0 0 0 0 0 0
0.90 5 6 0 0 0 0 0 0 0 0 0 0 0
0.90 5 7 8 9 0 0 0 0 0 0 0 0 0
*
0.90 7 1 2 4 0 0 0 0 0 0 0 0 0
0.90 7 3 0 0 0 0 0 0 0 0 0 0 0
0.90 7 5 0 0 0 0 0 0 0 0 0 0 0
0.90 7 6 0 0 0 0 0 0 0 0 0 0 0
0.90 7 7 8 9 0 0 0 0 0 0 0 0 0
*
0.90 9 1 2 4 0 0 0 0 0 0 0 0 0
0.90 9 3 7 0 0 0 0 0 0 0 0 0 0
0.90 9 5 0 0 0 0 0 0 0 0 0 0 0
0.90 9 6 0 0 0 0 0 0 0 0 0 0 0
0.90 9 8 9 0 0 0 0 0 0 0 0 0 0
*

```

Figure 4-6: Final input for Card group 7

4.1.6 Rod and unheated (guide tube) conductor data (Card group 8)

Each sub-channel was labelled (1 to 9) and assigned its own fuel rod number. For example, sub-channel 6 had fuel rod 6 assigned to it. Each was assigned its own guide tube number as well. Only seven unheated conductors are defined, as two sub-channels do not have a guide tube present in them (sub-channels 1 and 2). Hence sub-channel 3 was assigned an unheated conductor number of 1, sub-channel 4 was assigned number 2, and so forth. In terms of defining a fuel rod and possibly an unheated rod for a sub-channel, one then notes that this fuel rod, and possibly an unheated rod, are then composite rods. They are not actual fuel or unheated rods, but a combination of rods within or in direct contact with the sub-channel. For example, the single composite fuel rod attached to sub-channel one as shown in Figure 4-1 is actually composed of the four fuel rods at the corners of the sub-channel. Based on the geometry, each of these rods should contribute a quarter of its physical property to the composite rod, according to the parameters being modelled, for example the power. This mapping was carried out by NWURCS and also verified manually.

4.1.6.1 The gap conductance (HGAP)

Thermal resistance is the temperature difference (ΔT), at steady state, between two defined surfaces of a material or construction that induces a unit heat flow rate through a unit area, in $\text{K}\cdot\text{m}^2/\text{W}$ (C-Therm Technologies Ltd., 2022). The value of the thermal resistance (R) can be determined by dividing the thickness (L) by the thermal conductivity (k) of the specimen.

$$R = \frac{\Delta T}{q} = \frac{L}{k} \quad (4)$$

q is the heat flow rate.

Thermal conductance is defined as the steady-state rate at which heat flows through a material or assembly per unit area, resulting from a unit temperature difference between its two surfaces. It is measured in watts per square metre per kelvin ($\text{W}/\text{m}^2\cdot\text{K}$) (C-Therm Technologies Ltd., 2022). The conductance value is the reciprocal of the thermal resistance value, which can be expressed as follows in Equation 5 and consequently, the value of the thermal conductance can be calculated by dividing the thermal conductivity by the thickness of the specimen.

$$C = \frac{q}{\Delta T} = \frac{1}{R} = \frac{k}{L} \quad (5)$$

$$C = \frac{k}{L}$$

CTF requires the thermal conductance as input, rather than the thermal resistance or thermal conductivity. A value of $k = 0.211 \left[\frac{\text{W}}{\text{m}\cdot\text{K}}\right]$ was found for helium at $T = 531.5 \text{ K}$ using the interpolation shown in Table 12. The thermal properties for helium are shown in the table in Appendix D (Engineers Edge, 2020).

Table 12: Interpolation for thermal conductivity

Temperature (K)	Thermal Conductivity $\left[\frac{\text{W}}{\text{m}\cdot\text{K}}\right]$
477.15	0.197
531.483	0.211
589.15	0.225

The thickness was calculated using the NuScale fuel pin dimensions shown in Figure 4-7 (Fridman *et al.*, 2023).

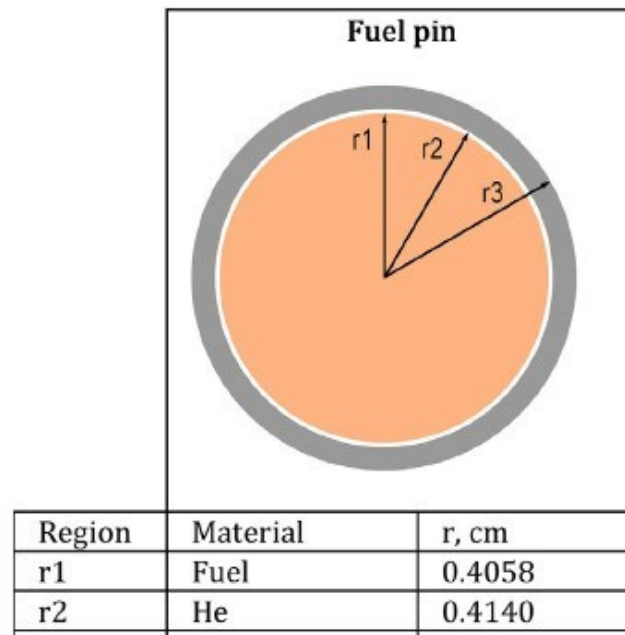


Figure 4-7: Fuel pin dimensions

$$\text{Gap thickness} = r2 - r1$$

$$\text{Gap thickness} = 0.4140 \text{ [cm]} - 0.4058 \text{ [cm]}$$

$$\text{Gap thickness} = 0.000082 \text{ [m]}$$

Hence:

$$C = \frac{k}{L}$$

$$C = \frac{0.211}{0.000082}$$

$$C = 2573.17 \left[\frac{W}{m - K} \right]$$

The gap conductance value was approximated to 2600 and used for the rest of the work. The sensitivity of this value will be investigated in a follow-up study.

$$C \approx 2600.00 \left[\frac{W}{m - K} \right]$$

4.1.6.2 Rod multiplication factor

The rod multiplication factor (RMULT) defines the number of rods modelled in each composite rod N (N is the index of rods.) Each N refers to a specific sub-channel, as indicated in Table 13, with the number of rods also indicated in the table.

Table 13: Number of rods modelled in each N, for each sub-channel

Sub-Channel	N (Index)	No. of Rods
1	1	1
2	2	1
3	3	0.75
4	4	0.75
5	5	11
6	6	60.25
7	7	189.25
8	8	355.75
9	9	1764.50

4.1.6.3 Wetted perimeter of each guide tube

The wetted perimeter of each guide tube (HPERIM) is the circumference of the guide tube, i.e.:

$$\text{Guide tube circumference} = 0.0384 [m]$$

4.1.6.4 Unheated conductor multiplication factor

The unheated conductor multiplication factor (RMULS) defines the number of unheated conductors modelled in each subchannel, as indicated in Table 14

Table 14: Number of unheated conductors modelled in each N for each subchannel

Sub-Channel	N (Index)	No. of Unheated Conductors
3	1	0.25
4	2	0.25
5	3	1
6	4	4.75
7	5	18.75
8	6	31.25
9	7	175.00

Figure 4-8 shows the final inputs for Card group 8

```

*****
* Group 8 - Rod and Unheated Conductor Data *
*****
*NGRP
8
* ---CARD 8.1 -----
*NRRD NSRD NC NRTB NRAD NLTY NSTA NXF NCAN RADF W3 NM12 NM13 NM14
9 7 1 1 0 0 0 0 0 0 1 0 0 0
*---CARD 8.2 & 8.3
* N IFTY IAXP NRND DAXMIN RMULT HGAP ISEC HTMB TAMB
*NSCH PIE NSCH PIE NSCH PIE NSCH PIE NSCH PIE NSCH PIE NSCH PIE NSCH PIE
1 1 1 0 0.000 1.000 2600.000 1 0.000 0.000
1 0.7440 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000
2 2 2 0 0.000 1.000 2600.000 1 0.000 0.000
2 0.7450 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000
3 3 3 0 0.000 0.750 2600.000 1 0.000 0.000
3 0.9890 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000
4 4 4 0 0.000 0.750 2600.000 1 0.000 0.000
4 0.7470 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000
5 5 5 0 0.000 11.000 2600.000 1 0.000 0.000
5 0.8330 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000
6 6 6 0 0.000 60.250 2600.000 1 0.000 0.000
6 0.9620 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000
7 7 7 0 0.000 189.250 2600.000 1 0.000 0.000
7 0.8920 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000
8 8 8 0 0.000 355.750 2600.000 1 0.000 0.000
8 0.9190 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000
9 9 9 0 0.000 1764.500 2600.000 1 0.000 0.000
9 0.9130 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000 0 0.0000
*---CARD 8.5 -----
* N ISTYP HPERIM HPERIMI RMULS NOSLCH NSLCHC HTAMBS TAMBS
1 10 3.84593E-02 0.00000E+00 0.25 3 0 0.0 0.0
2 11 3.84593E-02 0.00000E+00 0.25 4 0 0.0 0.0
3 12 3.84593E-02 0.00000E+00 1.00 5 0 0.0 0.0
4 13 3.84593E-02 0.00000E+00 4.75 6 0 0.0 0.0
5 14 3.84593E-02 0.00000E+00 18.75 7 0 0.0 0.0
6 15 3.84593E-02 0.00000E+00 31.25 8 0 0.0 0.0
7 16 3.84593E-02 0.00000E+00 175.00 9 0 0.0 0.0
*---CARD 8.6
* I NRT1 NST1 NRX1
1 9 7 2
*---CARD 8.7
* *IRTB
1 2 3 4 5 6 7 8 9
*---CARD 8.8
* *ISTAB
1 2 3 4 5 6 7
***** Group 8.9 Initial heater rod temperature profile
* AXIALT TRINIT
0.0 280.00
2.413 280.00
*****
* END GROUP 8 *

```

Figure 4-8: Final input for Card group 8

4.1.7 Conductor geometry (Card group 9)

4.1.7.1 Nuclear fuel pin data

Table 15 shows the input values used in CTF for the nuclear fuel pin.

Table 15: Input values used in CTF for nuclear fuel rod

Outside rod diameter (DROD) [m]	0.009499619
Fuel pellet diameter (DFUEL) [m]	0.008116
Number of radial nodes in the fuel pellet (NFUEL)	5
Clad material properties	Material no.1 in Card group 10
Clad thickness [m] ($r_3 - r_2$)	0.0006096
Theoretical density of fuel [%]	96

4.1.7.2 Data for unheated conductors (guide tubes)

Table 16 shows the input values used in CTF for the guide tubes.

Table 16: Input values used in CTF for guide tubes

Outside diameter (DROD) [m]	0.012242824
Number of radial regions in the conductor (NFUEL)	2
Coolant (water) thickness [m]	0.005715
Zr-4 thickness [m] ($r_2 - r_1$)	0.000406
Theoretical density of fuel [%]	96

The final inputs for Card group 9 are shown in section 0 in Appendix C.

4.1.8 Material properties of zirconium (clad)

The material properties for zirconium were defined as indicated below.

The specific heat capacity and thermal conductivity tabulated in terms of temperature levels were obtained from IAEA (IAEA, (1997)). The specific heat capacity and thermal conductivity values required were interpolated from these tables. Table 17 shows the inputs in CTF. (Note that the values were input in Celsius, but the table shows the values in Kelvin.)

Table 17: CTF input for zirconium

Temperature(K) (TPROP)	Specified heat capacity (kJ/kg-K)	Thermal conductivity (W/m-K)
423	0.304931	13.90
523	0.316949	14.66
773	0.344068	17.37
973	0.363945	20.35
1073	0.373035	22.11
1123	0.602928	23.06
1173	0.816025	24.06
1223	0.544068	25.10
1300	0.355932	26.50
1400	0.355932	27.89

The final inputs for Card group 10 are shown in section 0 of Appendix C.

4.1.9 Modelling power functions

The axial power functions were initially defined using placeholder values (as the input for the power profiles was taken from Serpent during coupling), with each sub-channel having its own axial power function with 12 axial sections of which only 10 were the active core sections. The time for the power forcing function was set to 21.8 seconds (in 25 intervals) and a power factor of

1 was used. Radial power functions were also defined using placeholder for each sub-channel to be later updated using Serpent data. This meant that the power was kept constant as a function of time for the calculation, to ensure modelling a steady state plant.

The final inputs for Card group 11 are shown in section 0 of Appendix C.

4.1.10 Boundary conditions

The inlet boundary conditions used were mass flow rate and enthalpy. EES was used to calculate the enthalpy at the inlet, with an inlet temperature of 531.483 [K] and a pressure of 12755 [kPa]. The enthalpy was calculated to be 1126 [kJ/kg]. With the total mass flow given, the inlet mass flow rate for each sub-channel was calculated by CTF using the sub-channel flow areas defined in Card group 2.

The outlet boundary conditions were defined using the NuScale pressure of 12755 [kPa]. Note that CTF uses [bar] as the unit. The inlet enthalpy should have been calculated using the inlet pressure. However, since the pressure drop across the core was reserved for a later study (due to scope constraints), and is most probably a second order effect, the outlet pressure was used to calculate the inlet enthalpy.

The final inputs for Card group 13 are shown in section 0 of Appendix C.

4.1.11 Time domain data

A time domain of 21.8 seconds was chosen, with the data printed out every 0.2 seconds.

The final inputs for Card group 15 are shown in section 0 of Appendix C.

This concluded the building of the CTF input model using the NuScale parameters.

4.2 Coupling

NWURCS serves both the purpose of input generation and the coupling of files. In terms of input, it generates the input files for Serpent and CTF. Regarding the coupling, NWURCS extracts from the output file of Serpent and writes this into the input file of CTF, and vice versa. This is called system level coupling.

In terms of the output from Serpent, the data extracted was the power profile of the reactor core. This power profile was then broken up into its constituent parts, according to each sub-channel for the CTF input. In other words, the flux was mapped onto the nine sub-channels of the CTF input. Also, the axial discretization was considered, i.e. the axial power profile in the reactor core

at the corresponding positions of each sub-channel was axially mapped. Therefore, the input file of CTF contained the relevant power profiles.

In terms of the output from CTF, the data extracted were the temperatures for each sub-channel, specifically that of the fuel pellet, gap, cladding and moderator (water). These temperatures were mapped onto the relevant spatial positions in the reactor core, and the spatial mapping was then used to define the unit cells of the Serpent input.

The CTF model was a quarter core, and the Serpent model was a full core. Using symmetry considerations, the data from the CTF model was therefore converted from a quarter core to a full core. Similarly, the data from the Serpent model was converted from a full core to a quarter core.

The density of water was not transferred from the CTF model to the Serpent model, as is normally the case; instead, a lookup table was used in NWURCS as a function of temperature to define density. The effect of not using the CTF density for the Serpent model needs to be considered in a future study.

The data was transferred from Serpent to CTF by means of a series of codes in the code suite of NWURCS. This was also done to transfer data from CTF to Serpent. The source code of NWURCS is not discussed in this work, but details can be obtained from the code developer if needed (V.V. Naicker, 2024).

The Serpent calculations were run on the HPC host, and the CTF calculations were run on a Windows laptop. The data was transferred between these systems using codes in NWURCS. The convergence of the coupling was carried out visually, not internally by the code. As can be seen in Figure 5-8, the values at the start of the coupling were not very far from the coupled values. If an internal algorithm had been used to determine the convergence of the coupling, the coupling could have stopped at, for example, the fifth iteration, when the convergence criteria were met. Since the study was concerned with methodology development, it was important to ensure that the calculations were stable after many iterations. Therefore, the calculations were allowed to continue to about 15 iterations beyond the point at which they could have been considered converged by an internal algorithm. The stability of the iterations was assessed by confirming that the data was well bounded. This is illustrated by the red lines shown in Figure 5-8. To assess the convergence visually, the data points were visually checked to see if they were uniformly distributed between the boundary lines.

To obtain a numerical test for convergence, the percentage difference between the maximum and minimum values was calculated, as well as the standard deviation of the data points considered

to be converged. As a guide, a percentage difference of less than 1% would be acceptable and a percentage difference of less than 4% would be accepted with caution.

However, an internal calculation for convergence is recommended for routine calculations. These are built in with NWURCS, and the details can be found in the NWURCS User Guide (V.V. Naicker, 2024).

The actual calculations were run using a batch file for the Windows system and a shell script for the HPC host.

The flow chart for the coupling process is shown in Figure 4-9.

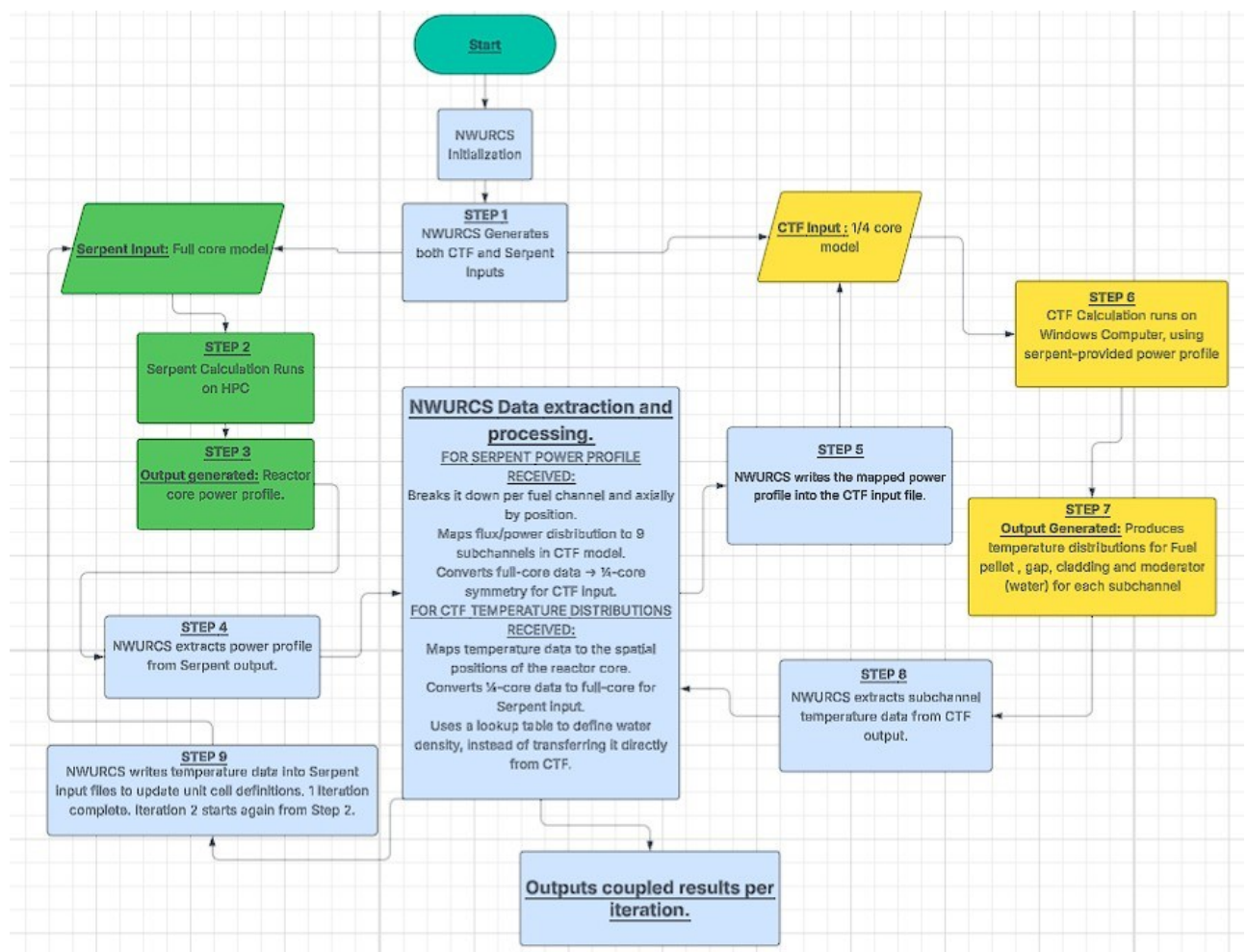


Figure 4-9: Flow chart for the coupling process

When carrying out coupling iterations, relaxation and acceleration techniques are normally used. Relaxation methods assist with coupling convergence and acceleration techniques are normally used to speed up the convergence. Relaxation is discussed in more detail in section 4.9 on verification of relaxation. Consideration of acceleration will be implemented in further studies after the methodology for coupling has been tested on several systems.

The Serpent input file was developed by a student from NWU, Kgomo Madi, and implemented in NWURCS after the Serpent inputs were verified by the code developer (KZ Madi, 2025). The student worked on the same NuScale reactor design. The source convergence was obtained using the Shannon entropy.

In the current study, the student's technical contribution to the coupling focused on the rigorous verification and stability testing of the integrated system, specifically concerning the input generation and code coupling. The student conducted the functional verification of the NWURCS input model generator by identifying and reporting various bugs and crashes during the model development process, which ensured the consistent generation of error free CTF input models essential for numerical stability. Furthermore, the student refined and verified the accuracy of the data transfer between the solvers by performing a technical assessment of the coupling parameters to ensure that key variables—specifically pressure, mass flow rate, and inlet enthalpy—were correctly passed by the NWURCS framework.

Input values are used by NWURCS using files f004 and f005, and unit files and lattice files. Details regarding the descriptions of the unit files and lattice files and how they are used to construct the Serpent input file are given in (KZ Madi (2025)). Other projects have also been completed using NWURCS and provide further insight into the neutronic modelling (Montwedi *et al.*, 2025). The input values are processed by NWURCS and used to create the relevant input files for Serpent and CTF.

4.3 Verification of coupling variables

In order to verify the coupling variables, the following values were considered: pressure, inlet temperature, mass flow rate, inlet enthalpy and power. All values and calculations were verified to check if the same values were being passed properly by NWURCS when coupling Serpent and CTF. The same inputs were used in all verification steps. A simple verification check was initially done to check if all the files and folders were named correctly. It was successful. When running the Serpent input generation, the `serpent.input` file was used as the input, and it generated the two files `serpent.input_res.m` and `serpent.input_det0.m`. The k_{eff} values were located in `serpent.input_res.m`, and the power profiles were in the detector files `serpent.input_det0.m`.

In Serpent, the positions where fluxes are tallied are called detector positions. In a physical reactor, these could correspond to detector positions where fluxes could be measured. The `iter_conv` folder contains all four field values, namely k_{eff} , power, heat structure temperatures and moderator (water) temperatures. File names for power are named with the convention

field_2_subchannel number_00_00_xx. File names for moderator temperatures are named with the convention field_3_subchannel number_00_00_xx. File names for heat structure temperatures are named with the convention field_4_subchannel number_00_00_xx. The file name for k_{eff} is named with the convention keff_01_00_00_00. After each coupling iteration, the k_{eff} file is populated with the k_{eff} value and the other files are populated with the respective values per axial section.

For the CTF calculation, the input file used was `deck.inp`, and all the outputs (e.g. pressure temperature etc.) were found in the output file `deck.out`. In terms of the coupling, the output data for each iteration was stored in the file `iterdata`. All data was passed between the input and output deck, and all the data was coupled.

The iteration file `f216` is necessary for two reasons. First, it serves as a conduit between CTF and Serpent input and output files. Second, the data stored in this file is used for checking iteration convergence. The convergence check was done using the maxima values.

In terms of verification, it is important to check that the temperatures produced in the output of the CTF file are stored correctly in the iteration file `f216` and correctly passed to the Serpent input file. Similarly for the Serpent output, it is necessary to check that the multiplication factor and the power profile are stored correctly in the iteration file `f216`, and that the power profile is correctly transferred to the CTF file. Incorrect data transfer would be a fundamental flaw, which could result in non-convergence of the coupling, or even false convergence of the coupling.

4.4 Verification of source convergence using Shannon entropy

As explained in depth in section 3.3 on source convergence and Shannon entropy, it is important that source convergence is achieved. In this study, the monitoring metric of Shannon entropy was used to verify source convergence. Figure 4-10 shows the Shannon entropy over a period of 400 generation cycles. In cycle 1, the value is high. In terms of the Monte-Carlo calculation, as the generation cycles approach cycle 75, the data becomes statistically equal, which implies that the source is well spread out over the entire problem. Once the entropy is statistically constant, it indicates that the source is uniformly distributed in a statistical sense. To be conservative, skipped cycles (inactive) were introduced for the first 100 generation cycles, then 300 active generation cycles were used. Source convergence was confirmed once the entropy curve became approximately constant, with no systematic drift and only small statistical fluctuations about a stable mean. Once source convergence was confirmed, the coupling was started.

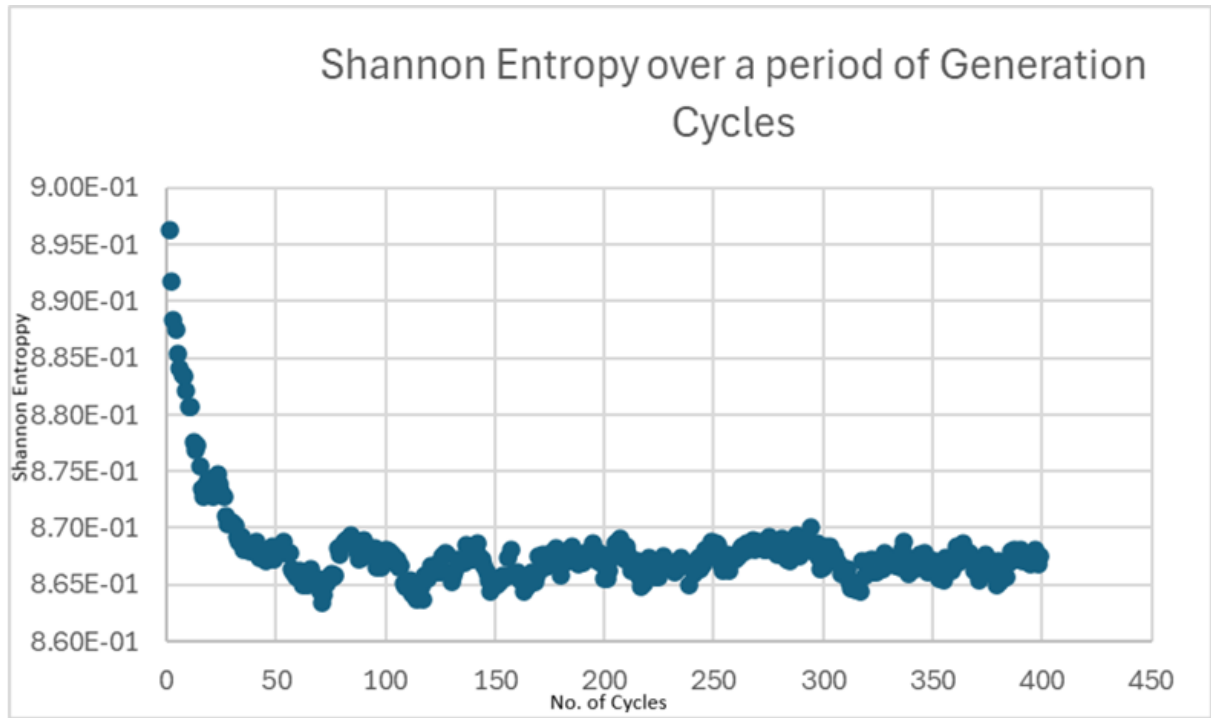


Figure 4-10: Entropy over 400 generation cycles

4.5 Verification of k effective k_{eff}

To verify if the k_{eff} values were being calculated and transferred properly, the Serpent data for k_{eff} found in the `serpent.input_res.m` file was compared to the k_{eff} values in the "iterconv" folder. This was followed by verifying the coupling output k_{eff} values found in the `iter_data` file. The figures below (Figures 4-11 to 4-13) show that the values were transferred correctly between the files. Figure 4-11 shows the k_{eff} values in the `serpent.input_res.m` file. Figure 4-12 shows the values of the k_{eff} field in the iterconv folder. Figure 4-13 shows k_{eff} values in the `iter_data` file.

```

serpent.input_res.m
241
242 SIX_FF_ETA      (idx, [1: 2]) = [ 1.74608E+00 0.00016 ];
243 SIX_FF_F        (idx, [1: 2]) = [ 7.11205E-01 0.00015 ];
244 SIX_FF_P        (idx, [1: 2]) = [ 7.00780E-01 0.00012 ];
245 SIX_FF_EPSILON  (idx, [1: 2]) = [ 1.20919E+00 0.00014 ];
246 SIX_FF_LF       (idx, [1: 2]) = [ 9.82820E-01 2.6E-05 ];
247 SIX_FF_LT       (idx, [1: 2]) = [ 9.99626E-01 3.9E-06 ];
248 SIX_FF_KINF     (idx, [1: 2]) = [ 1.05228E+00 0.00023 ];
249 SIX_FF_KEFF     (idx, [1: 2]) = [ 1.03382E+00 0.00023 ];
250
251 % Fission neutron and energy production:
252
253 NUBAR           (idx, [1: 2]) = [ 2.45721E+00 4.7E-06 ];
254 FISSE           (idx, [1: 2]) = [ 2.02525E+02 5.2E-07 ];
255
256 % Criticality eigenvalues:
257
258 ANA_KEFF        (idx, [1: 6]) = [ 1.03390E+00 0.00023 1.02665E+00 0.00024 7.16762E-03 0.00338 ];
259 IMF_KEFF        (idx, [1: 2]) = [ 1.03392E+00 0.00011 ];
260 COL_KEFF        (idx, [1: 2]) = [ 1.03393E+00 0.00020 ];
261 ABS_KEFF        (idx, [1: 2]) = [ 1.03392E+00 0.00011 ];
262 ABS_KINF        (idx, [1: 2]) = [ 1.05238E+00 0.00010 ];
263 GEOM_ALBEDO     (idx, [1: 6]) = [ 1.00000E+00 0.0E+00 1.00000E+00 0.0E+00 1.00000E+00 0.0E+00 ];
264

```

Figure 4-11: k_{eff} values in serpent.input_res.m

keff_01_00_00_00				
1	29	1.03390	0.00023	0.00030
2	28	1.03360	0.00024	-0.00023
3	27	1.03383	0.00022	0.00010
4	26	1.03373	0.00024	-0.00020
5	25	1.03393	0.00024	0.00010
6	24	1.03383	0.00024	0.00045
7	23	1.03338	0.00022	-0.00063
8	22	1.03401	0.00022	0.00012
9	21	1.03389	0.00022	0.00000
10	20	1.03389	0.00021	0.00008
11	19	1.03381	0.00023	0.00007
12	18	1.03374	0.00022	-0.00009
13	17	1.03383	0.00022	0.00014
14	16	1.03369	0.00022	0.00021
15	15	1.03348	0.00022	-0.00035
16	14	1.03383	0.00023	0.00026
17	13	1.03357	0.00023	-0.00012
18	12	1.03369	0.00021	0.00001
19	11	1.03368	0.00023	0.00018
20	10	1.03350	0.00021	-0.00054
21	9	1.03404	0.00023	0.00081
22	8	1.03323	0.00021	-0.00054
23	7	1.03377	0.00022	0.00027
24	6	1.03350	0.00023	-0.00017
25	5	1.03367	0.00022	-0.00063
26	4	1.03430	0.00021	0.00029
27	3	1.03401	0.00022	0.00021
28	2	1.03380	0.00022	-0.00035
29				

Figure 4-12: k_{eff} values in iterconv


```

DET110X = [
1.88970E+00  3.14950E+00  2.51960E+00
];

DET110Y = [
6.29900E-01  1.88970E+00  1.25960E+00
];

DET110Z = [
1.13650E+01  3.13650E+01  2.13650E+01
3.13650E+01  5.13650E+01  4.13650E+01
5.13650E+01  7.13650E+01  6.13650E+01
7.13650E+01  9.13650E+01  8.13650E+01
9.13650E+01  1.11365E+02  1.01365E+02
1.11365E+02  1.31365E+02  1.21365E+02
1.31365E+02  1.51365E+02  1.41365E+02
1.51365E+02  1.71365E+02  1.61365E+02
1.71365E+02  1.91365E+02  1.81365E+02
1.91365E+02  2.11365E+02  2.01365E+02
];

```

Figure 4-15: Co-ordinates for the detectors

When the verification process was conducted for the first time, there was an overlap of detectors, which meant that values were being recorded twice, which results in an incorrect flux value being used in the calculations. The error was then forwarded to the code developer, and the error was fixed. In Figure 4-16, the picture on the left shows the overlap that occurred (the darker shade means it was overlapping) and the picture on the right shows the overlap after it was fixed.

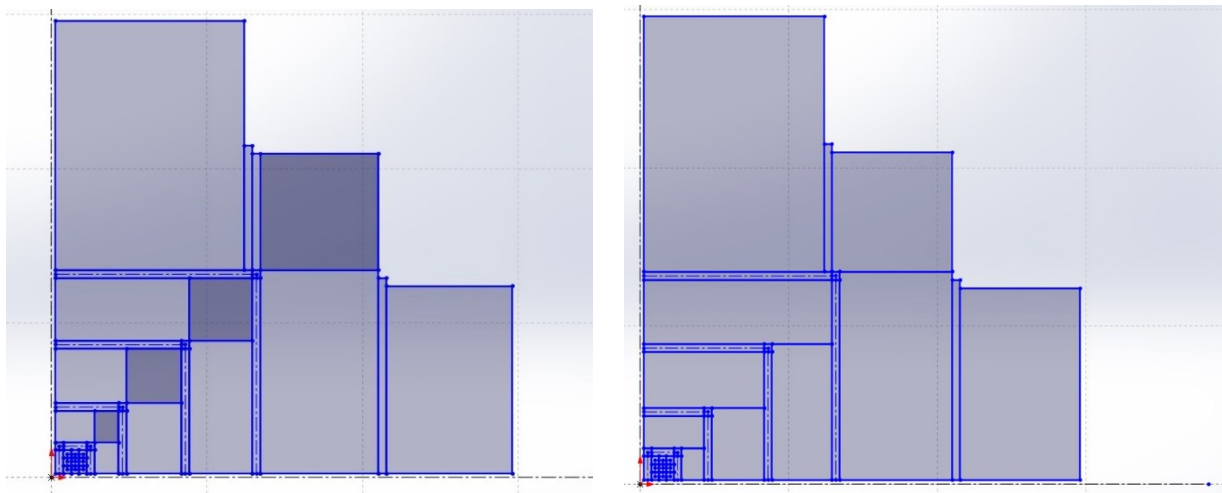


Figure 4-16: Detectors overlapping (left), and after the overlapping was fixed (right)

4.7 Verification of temperature values in f216

File `f216` has the temperature values of the nuclear fuel rods in three regions: the fuel (region 1); the gap (region 2); and the cladding (region 3). It also has the temperature values for the guide tubes. To verify if file `f216` had the same values that CTF outputs for these temperatures, an

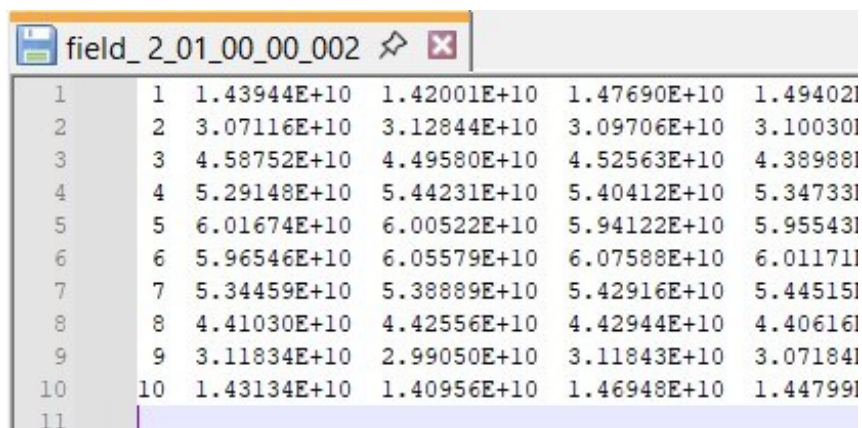
Excel spreadsheet was used to verify the temperature for each sub-channel at each region of the fuel rods.

The output values taken from CTF are under 'Surface' and 'Centre'. The average is calculated and converted to $^{\circ}\text{K}$ (under the heading in Kelvin) and compared to the `f216` value. It is clear that the numbers are the same. Each table is labelled, for example: "Pipe 1, Region 1, nuc rod or hsrod". The labels correspond to the pipe number in file `f216`, the region and the nuclear fuel rod or guide tube at which the temperature values are. The values are for temperatures at each of the 10 axial sections. All values were successfully verified. Appendix E shows an example of one section of the spreadsheet used to verify the temperature values.

4.8 **Verification of power, moderator (water) and heat structure temperature values from files 'iterconv' and 'f216'**

File `f216` also contains the power, moderator (water) temperatures and heat structure temperatures. These needed to be verified as the same corresponding values in the field files (e.g. `field_2_01_00_00_002`) in the folder 'iterconv'. To do this, an Excel spreadsheet was created, and the two values were compared, and each found to be the same. This was done for the power, moderator (water) temperature and heat structure temperature. Appendix F shows an example of the Excel verification for each of these parameters.

Figure 4-17 provides an example of what the field table looks like.



1	1	1.43944E+10	1.42001E+10	1.47690E+10	1.494021
2	2	3.07116E+10	3.12844E+10	3.09706E+10	3.100301
3	3	4.58752E+10	4.49580E+10	4.52563E+10	4.389881
4	4	5.29148E+10	5.44231E+10	5.40412E+10	5.347331
5	5	6.01674E+10	6.00522E+10	5.94122E+10	5.955431
6	6	5.96546E+10	6.05579E+10	6.07588E+10	6.011711
7	7	5.34459E+10	5.38889E+10	5.42916E+10	5.445151
8	8	4.41030E+10	4.42556E+10	4.42944E+10	4.406161
9	9	3.11834E+10	2.99050E+10	3.11843E+10	3.071841
10	10	1.43134E+10	1.40956E+10	1.46948E+10	1.447991
11					

Figure 4-17: Field table example

4.8.1 **Maximum values**

The maximum values for power, water temperature, and heat structure temperature were all recorded in an Excel spreadsheet. They were compared to the maximum values in the `iterdata`

file and were found to be the same and hence were verified. Table 18 shows an example of a section of the Excel file used to verify the maximum value.

Table 18: Example section from Excel file used to verify maximum values

MAX in iterdata	MAX in Excel
1.13369E+15	4.00E+11
	3.69874E+11
	3.73E+11
	3.99074E+11
	3.77854E+12
	2.18338E+13
	5.70991E+13
	1.30358E+14
	1.13369E+15

4.9 Verification of relaxation

The relaxation method was verified successfully using Excel. The unrelaxed values of iteration i and $i - 1$ were taken, and each was multiplied by a chosen relaxation factor of 0.5, then added together to obtain the final value. The final value was compared to the output value given by the code in f216 and was seen to be correct and hence verified. Table 19 shows an example of one of the verifications done between iteration 10 and iteration 9.

Table 19: Example of relaxation verification done between iteration 10 and 9

Iteration 10 Unrelaxed	Iteration 09 Unrelaxed	Factor	Answer	f216 Output
725.12	732.61	0.5	728.87	728.87
729.55	737.03	0.5	733.29	733.29
734.52	741.99	0.5	738.26	738.25
739.5	746.97	0.5	743.24	743.24
744.5	751.96	0.5	748.23	748.23
749.52	756.97	0.5	753.25	753.25
754.55	762	0.5	758.28	758.27
759.61	767.04	0.5	763.33	763.33

764.67	772.1	0.5	768.39	768.38
769.22	776.64	0.5	772.93	772.93

CHAPTER 5 RESULTS AND DISCUSSION

5.1 The coupled base case

5.1.1 Introduction

After the successful verification of the coupling process, the coupling calculation was run successfully using a set of placeholder values for the pressure, inlet temperature (inlet enthalpy in single phase flow), mass flow rate and the power whereby no crashes or bugs were present. These values were input into NWURCS, which generated the input files for Serpent and CTF and consequently the coupling process was conducted and run for 30 iterations until satisfactory visual convergence was achieved. Thereafter, the values were changed one by one to bring the input values closer to the NuScale definitions and run. This was done in order to make it easier to fix computer code crashes as they appeared and to test if convergence was achieved at each step. The visual convergence method was used for the reasons discussed in section 4.2. Convergence and stability were confirmed visually as the data points were uniformly distributed between the red boundary lines. Firstly, the inlet temperature and enthalpy were changed in calculation 2 to that of NuScale (531.483 K). Thereafter, the mass flow in calculation 3 was set to 5128 [kg/s], which NWURCS calculated and generated 1267.21 [kg/s] as the input in CTF (explained in section 4.1.4) and then pressure (12.7553 MPa) in calculation 4. Calculation 5 changed the power (explained in calculation 5 section). The NWURCS input values for each calculation are shown in Table 20.

Table 20: Input NWURCS values for each calculation

	Pressure (MPa)	Inlet Temperature (K)	Mass flow rate (kg/s)	Enthalpy (kJ/kg)	Power (W)
Calculation 1	15.5	580	3018.83	1250	6e+04
Calculation 2	15.5	531.483	3018.83	1126	6e+04
Calculation 3	15.5	531.483	5128	1126	6e+04
Calculation 4	12.7553	531.483	5128	1126	6e+03
Calculation 5	12.7553	531.483	5128	1126	4.53e+04

5.1.2 Calculation 1 results

The maximum power for 30 iterations was plotted. The results are shown in Figure 5-1.

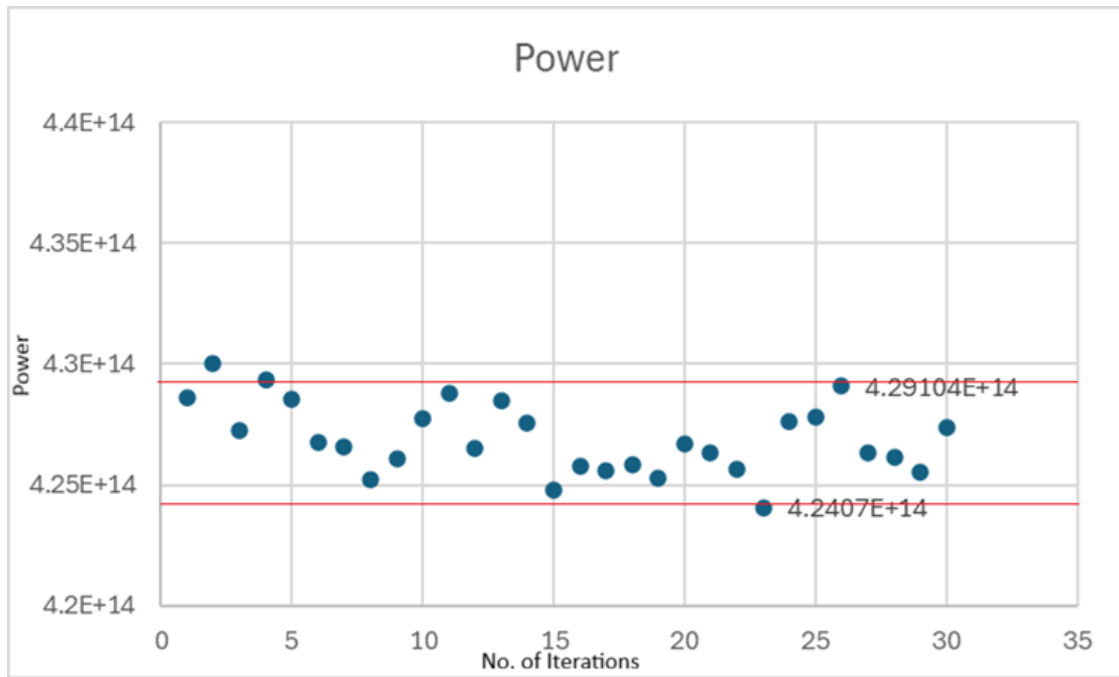


Figure 5-1: Calculation 1, maximum power

Convergence was confirmed visually as the data points are uniformly distributed between the boundary lines. The percentage difference between the minimum and highest power values was calculated using Equation 6 (with the first five iterations being ignored, as the calculation was still settling after using initial guess values and this will be done for the rest of the work). It was found to be 1.982%.

$$\%diff = 100 \times \frac{(Y_{max} - Y_{min})}{Y_{ave}} \quad (6)$$

Where: Y is the parameter being considered (in this case, power); and Y_{ave} is the average of Y_{min} and Y_{max} .

An important observation is that the mean is horizontal. This then gives confidence that the result is fluctuating about a mean, and the standard deviation can be calculated.

Table 21: Calculation 1 - power

% Difference between highest and lowest	Standard Deviation	Average (Mean)
1.982%	1.45136E+12	4.26916E+14

The maximum heat structure temperature for 30 iterations was plotted. The results are shown in Figure 5-2.

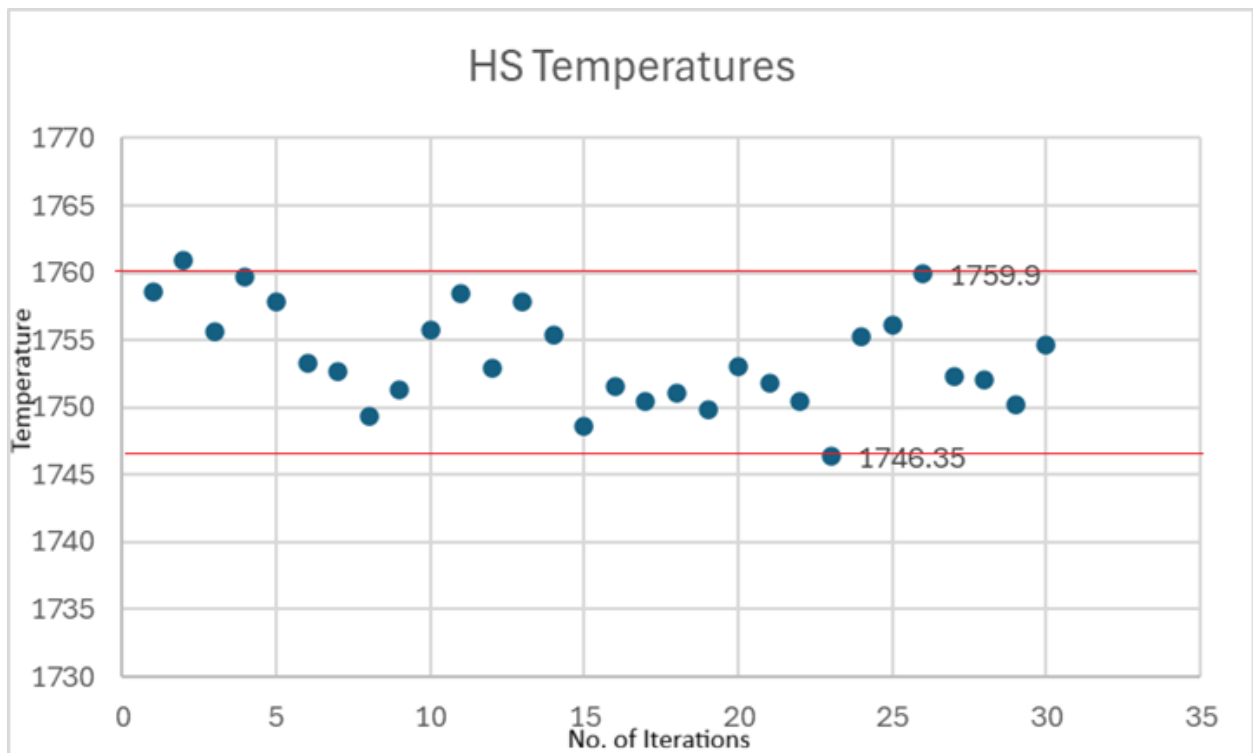


Figure 5-2: Calculation 1 - maximum heat structure temperatures

Convergence was confirmed visually as the data points are uniformly distributed between the boundary lines. The percentage difference between the highest and lowest temperature values using Equation 6 was found to be 0.776%

Table 22: Calculation 1 - heat structure temperature results

% Difference between highest and lowest	Standard Deviation	Average (Mean)
0.776%	3.66738902	1753.776667

The maximum k_{eff} for 30 iterations was plotted. The results are shown shown in Figure 5-3.

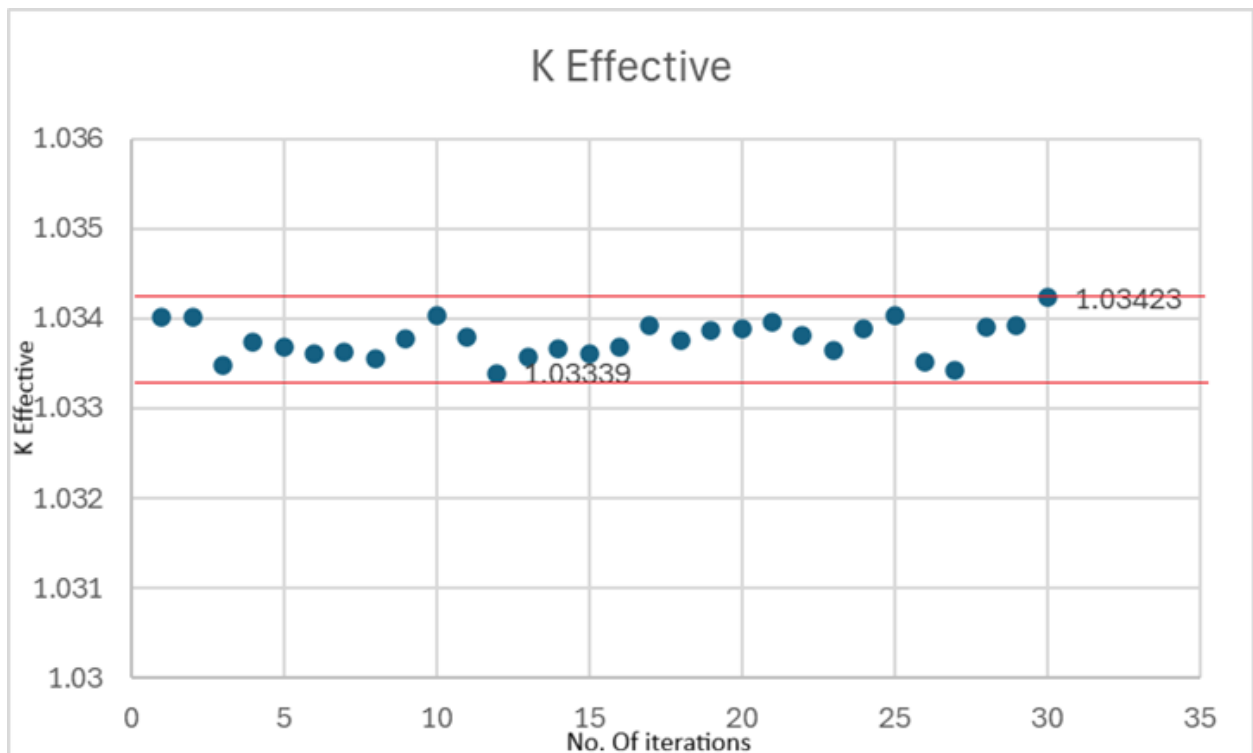


Figure 5-3: Calculation 1, maximum k_{eff}

Convergence was confirmed visually as the data points are uniformly distributed between the boundary lines. When using Equation 6, the percentage difference between the highest and lowest k_{eff} values was found to be 0.0813%.

Table 23: Calculation 1 - k_{eff} results

% Difference between highest and lowest	Standard Deviation	Average (Mean)
0.0813%	0.000201745	1.033767

The maximum water temperature for 30 iterations was plotted. The results are shown in Figure 5-4.

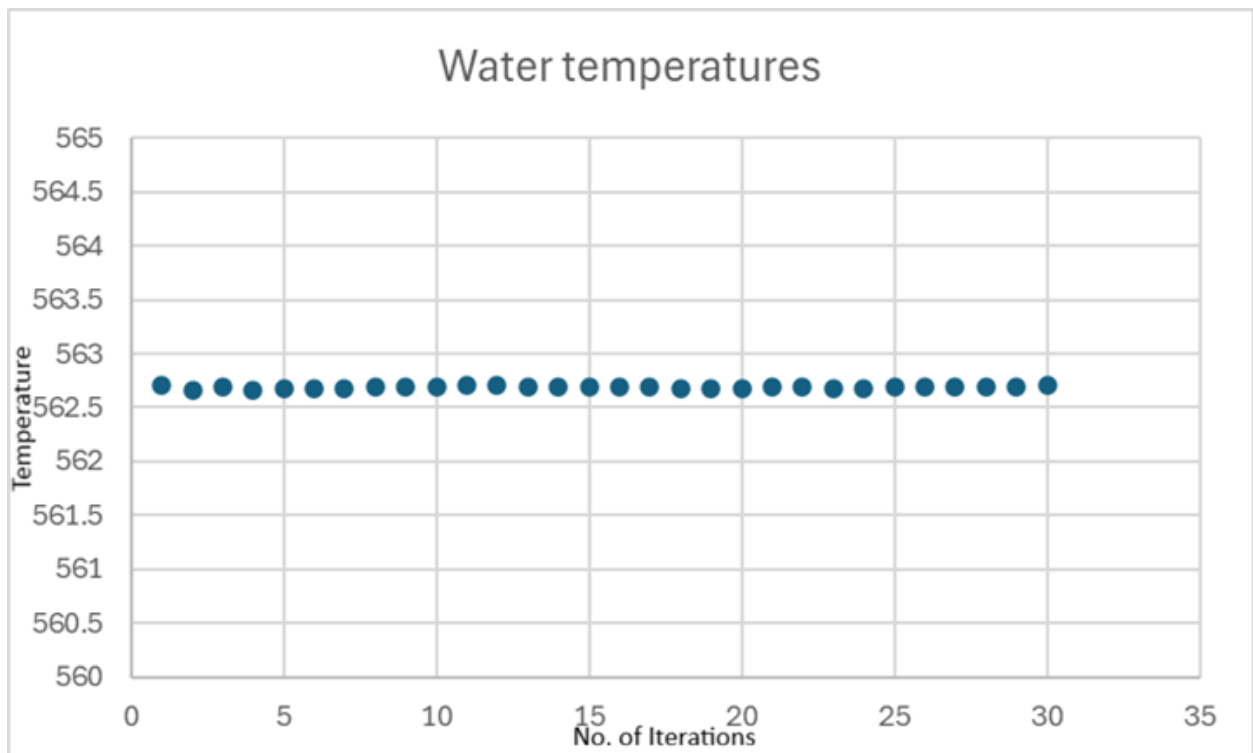


Figure 5-4: Calculation 1 - maximum water temperature

Convergence was confirmed visually as the data points are uniformly distributed. The percentage difference was minimal and was found to be 0.0082%, using Equation 6.

Table 24: Calculation 1 - water temperature

% Difference between highest and lowest	Standard Deviation	Average (Mean)
0.0082%	0.011706076	562.6883667

Temperature Distribution of Heat Structures.

The heat structures present in a fuel rod as defined previously were the fuel pellet, helium gap and cladding.

In a fuel rod, the heat is generated in the fuel pellet, and the heat generation rate is proportional to the local neutron flux, which closely follows that of a sinusoidal shape axially when there is not significant poisoning or control rods insertions to affect the profile axially. The middle of the curve has the highest neutron flux, hence the highest power and the most heat generated. The ends have lower neutron flux due to neutron leakage, hence less power and lower heat generated. So

at the middle of the rod, more heat must be conducted away radially through the cladding and into the coolant.

Figure 5-5 plotted the axial temperature distribution curve for the fuel rod and showed this phenomenon to be true, hence the results are accurate.

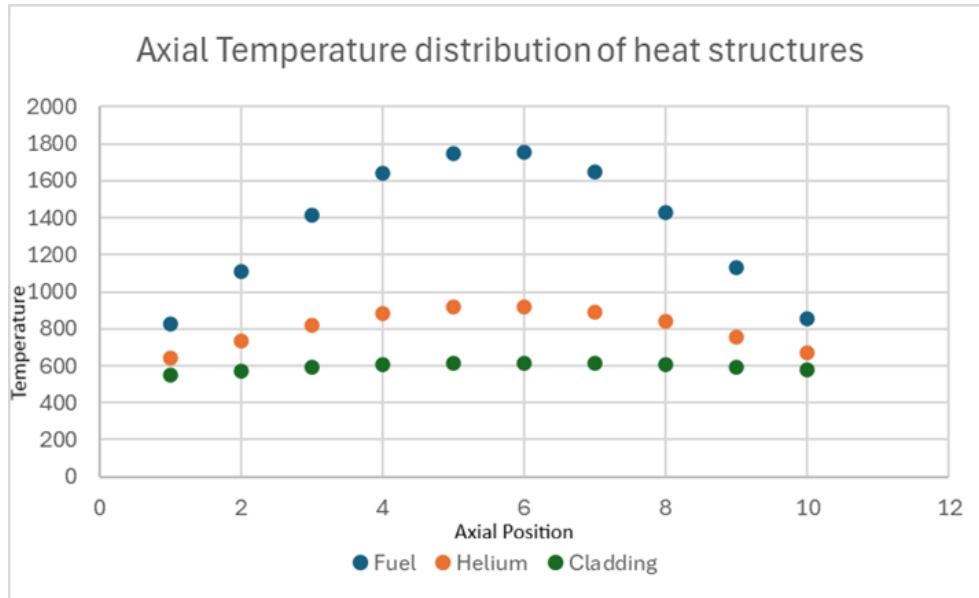


Figure 5-5: Axial temperature distribution of heat structures

The radial profile is shown in Figure 5-6. Three distinct regions are shown, that of the fuel pellet, the gap, and the cladding. The pellet region contains a source, and there the solution of the heat transport equation in cylindrical co-ordinates give the shapes of the curve. The shape of the curves for the gap and the cladding is the solution of the heat transfer equation without a source. It is noted that a larger jump in temperature occurs for the gap compared to the cladding due to the higher thermal conductivity of the cladding. Section 5.3 discusses the equations required to calculate these temperatures.

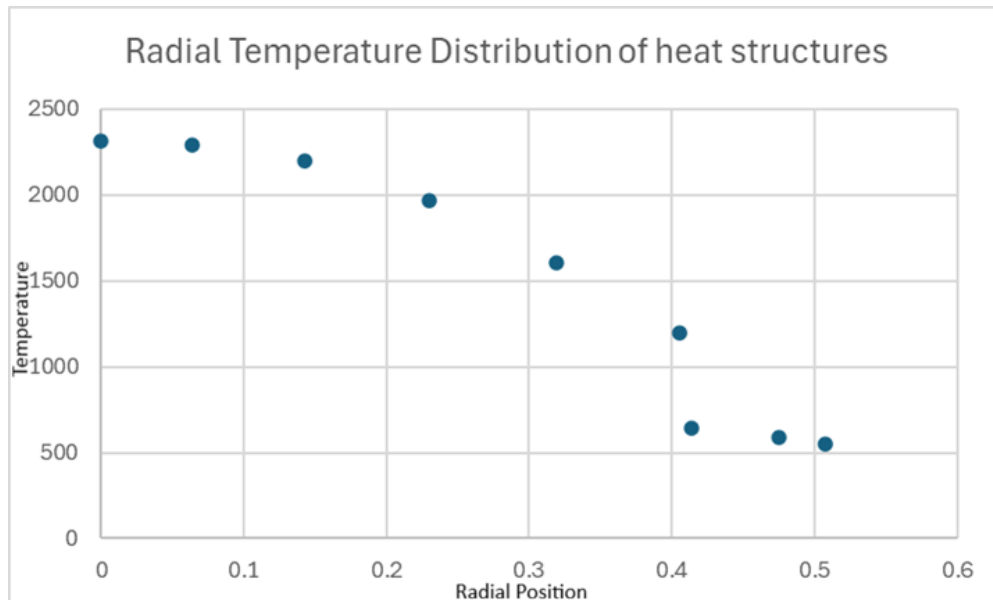


Figure 5-6: Radial temperature distribution

5.1.3 Calculations 2 to 4: Intermediate cases

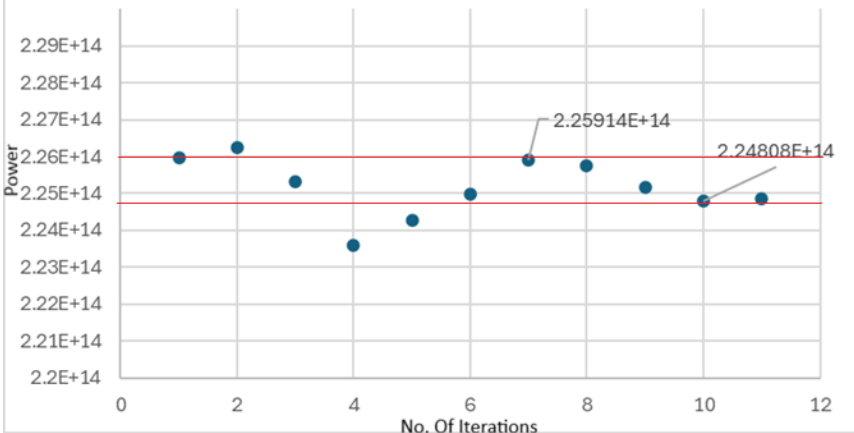
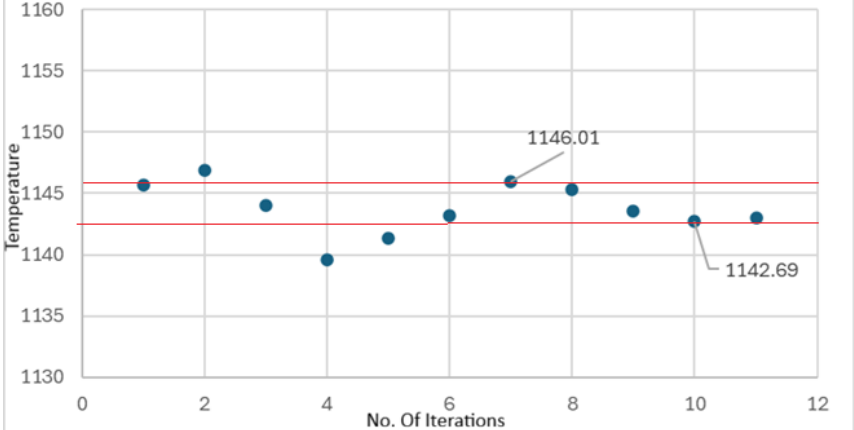
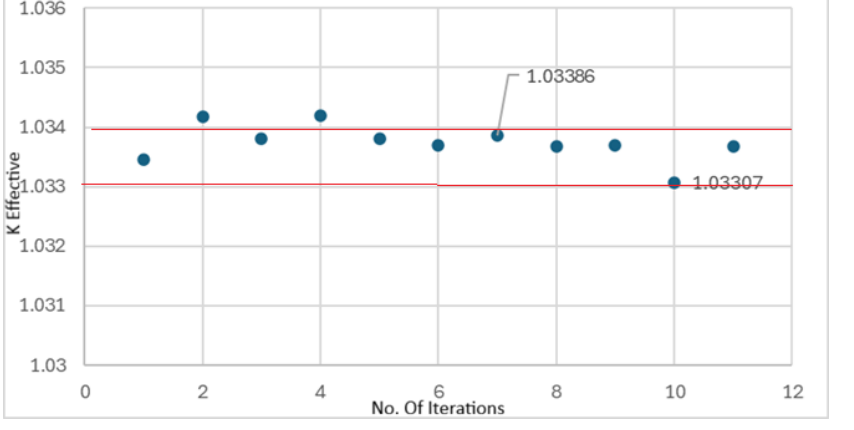
Calculations 2 to 4 were carried out, with the individual state parameters changed to those required for the NuScale reactor. This was done so that if the calculations were unsuccessful, the input parameter that had been changed could be examined and a solution sought, and the calculation then completed successfully. If all the parameters had been changed in one step, tracing the errors would have proven difficult.

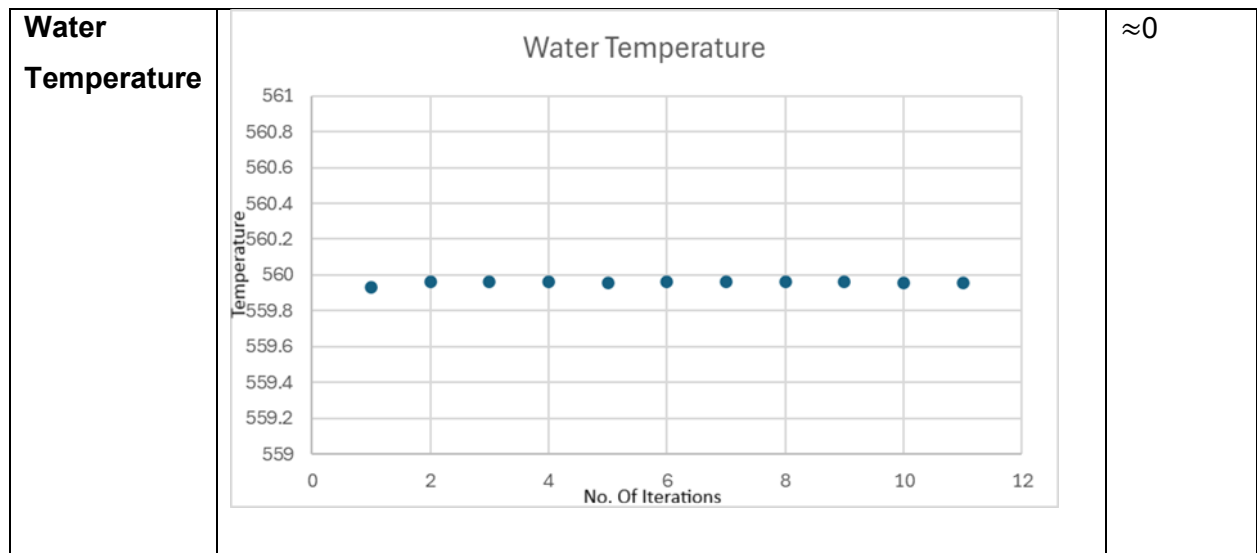
In calculation 2, 3 and 4, the inlet enthalpy (inlet temperatures), mass flow rate and pressure were changed, respectively.

Table 25 shows the maximum values for Power, Heat structure temperature, k_{eff} and Water temperature for 11 iterations plotted with the percentage difference between the highest and lowest values. The values for the first five iterations were ignored when looking for the highest and lowest values, since the values became more stable after five iterations (will be done for the rest of the calculations). Convergence was confirmed visually, as the data points were uniformly distributed between the boundary lines.

Table 25: Calculation 2 plots

<u>Value</u>	<u>Plot</u>	<u>%d</u>

Power	Power <table><caption>Approximate data points for Power vs. No. Of Iterations</caption><thead><tr><th>No. Of Iterations</th><th>Power (E+14)</th></tr></thead><tbody><tr><td>1</td><td>2.258</td></tr><tr><td>2</td><td>2.261</td></tr><tr><td>3</td><td>2.254</td></tr><tr><td>4</td><td>2.235</td></tr><tr><td>5</td><td>2.242</td></tr><tr><td>6</td><td>2.250</td></tr><tr><td>7</td><td>2.259</td></tr><tr><td>8</td><td>2.257</td></tr><tr><td>9</td><td>2.252</td></tr><tr><td>10</td><td>2.248</td></tr><tr><td>11</td><td>2.248</td></tr></tbody></table>	No. Of Iterations	Power (E+14)	1	2.258	2	2.261	3	2.254	4	2.235	5	2.242	6	2.250	7	2.259	8	2.257	9	2.252	10	2.248	11	2.248	0.49
No. Of Iterations	Power (E+14)																									
1	2.258																									
2	2.261																									
3	2.254																									
4	2.235																									
5	2.242																									
6	2.250																									
7	2.259																									
8	2.257																									
9	2.252																									
10	2.248																									
11	2.248																									
Heat structure temperature	HS Temperatures <table><caption>Approximate data points for HS Temperatures vs. No. Of Iterations</caption><thead><tr><th>No. Of Iterations</th><th>Temperature</th></tr></thead><tbody><tr><td>1</td><td>1145.5</td></tr><tr><td>2</td><td>1146.8</td></tr><tr><td>3</td><td>1144.2</td></tr><tr><td>4</td><td>1139.5</td></tr><tr><td>5</td><td>1141.5</td></tr><tr><td>6</td><td>1143.2</td></tr><tr><td>7</td><td>1145.8</td></tr><tr><td>8</td><td>1145.2</td></tr><tr><td>9</td><td>1143.5</td></tr><tr><td>10</td><td>1142.8</td></tr><tr><td>11</td><td>1143.2</td></tr></tbody></table>	No. Of Iterations	Temperature	1	1145.5	2	1146.8	3	1144.2	4	1139.5	5	1141.5	6	1143.2	7	1145.8	8	1145.2	9	1143.5	10	1142.8	11	1143.2	0.29
No. Of Iterations	Temperature																									
1	1145.5																									
2	1146.8																									
3	1144.2																									
4	1139.5																									
5	1141.5																									
6	1143.2																									
7	1145.8																									
8	1145.2																									
9	1143.5																									
10	1142.8																									
11	1143.2																									
k_{eff}	K Effective <table><caption>Approximate data points for K Effective vs. No. Of Iterations</caption><thead><tr><th>No. Of Iterations</th><th>K Effective</th></tr></thead><tbody><tr><td>1</td><td>1.0334</td></tr><tr><td>2</td><td>1.0342</td></tr><tr><td>3</td><td>1.0338</td></tr><tr><td>4</td><td>1.0342</td></tr><tr><td>5</td><td>1.0338</td></tr><tr><td>6</td><td>1.0337</td></tr><tr><td>7</td><td>1.0338</td></tr><tr><td>8</td><td>1.0337</td></tr><tr><td>9</td><td>1.0337</td></tr><tr><td>10</td><td>1.0330</td></tr><tr><td>11</td><td>1.0337</td></tr></tbody></table>	No. Of Iterations	K Effective	1	1.0334	2	1.0342	3	1.0338	4	1.0342	5	1.0338	6	1.0337	7	1.0338	8	1.0337	9	1.0337	10	1.0330	11	1.0337	0.077
No. Of Iterations	K Effective																									
1	1.0334																									
2	1.0342																									
3	1.0338																									
4	1.0342																									
5	1.0338																									
6	1.0337																									
7	1.0338																									
8	1.0337																									
9	1.0337																									
10	1.0330																									
11	1.0337																									

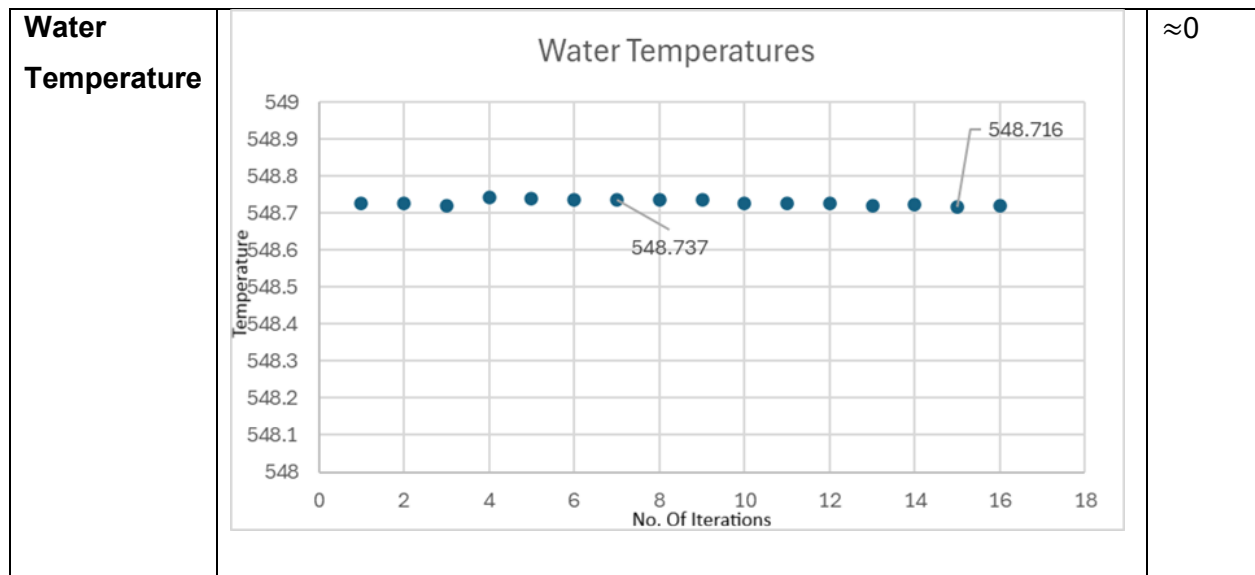


In calculation 3, the mass flow rate was changed in the input deck.

Table 26 shows the maximum values for Power, Heat structure temperature, k_{eff} and Water temperatures for 16 iterations plotted. The table also includes the percentage difference between the highest and lowest values for each parameter. Convergence was confirmed visually, as the data points are uniformly distributed between the boundary lines.

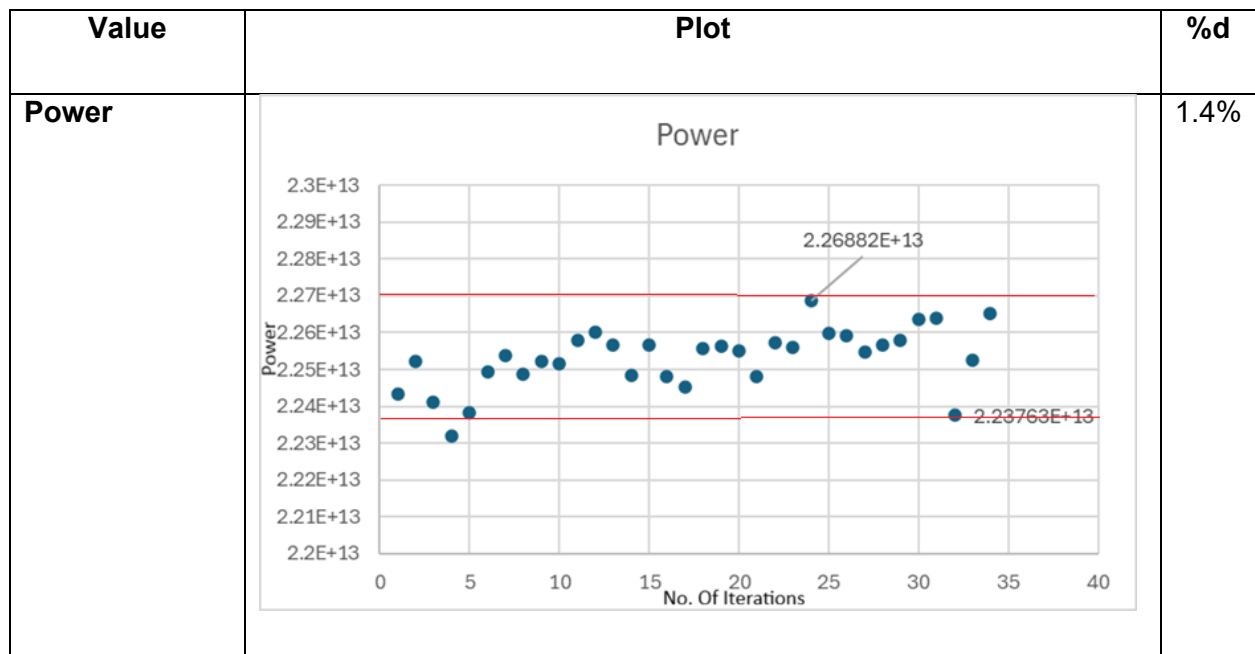
Table 26: Calculation 3 plots

Value	Plot	%d
Power	Power 2.26226E+14 2.24228E+14	0.89
Heat structure temperature	HS temperatures 1128.84 1124.26	0.41
k_{eff}	K Effective 1.03402 1.03331	0.069

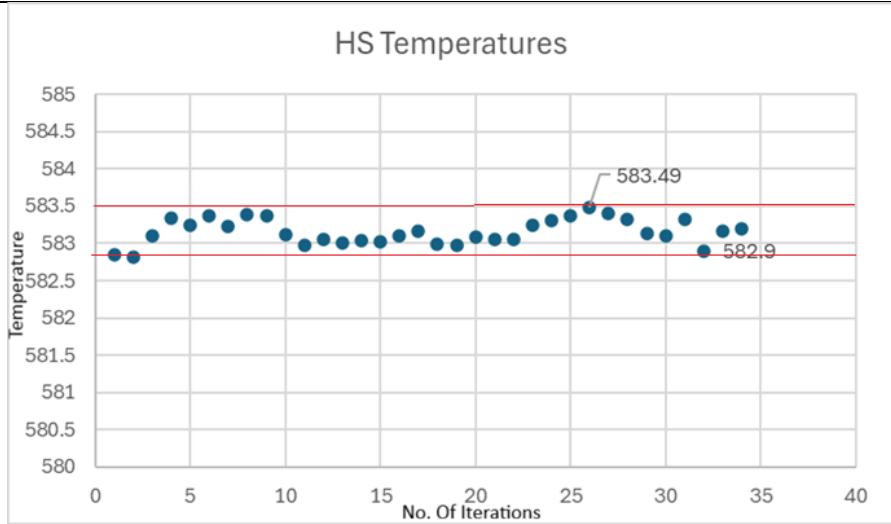


In calculation 4, the pressure was changed in the input deck. Table 27 shows the maximum values for Power, Heat structure temperature, k_{eff} and Water temperature for 34 iterations plotted. The table also includes the percentage difference between the highest and lowest values for each parameter. The values for the first five iterations were ignored when looking for the highest and lowest values, since the values became more stable after five iterations. Convergence was confirmed visually as the data points are uniformly distributed between the boundary lines.

Table 27: Calculation 4 plots

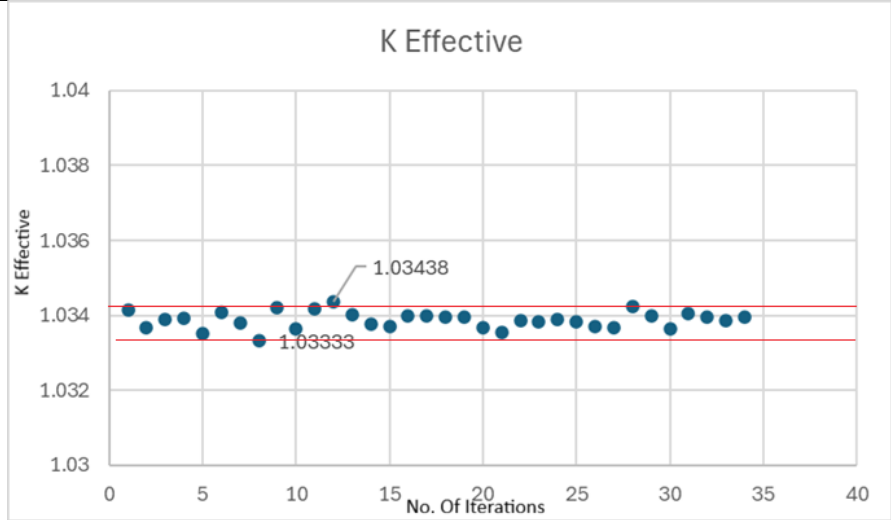


**Heat structure
temperature**



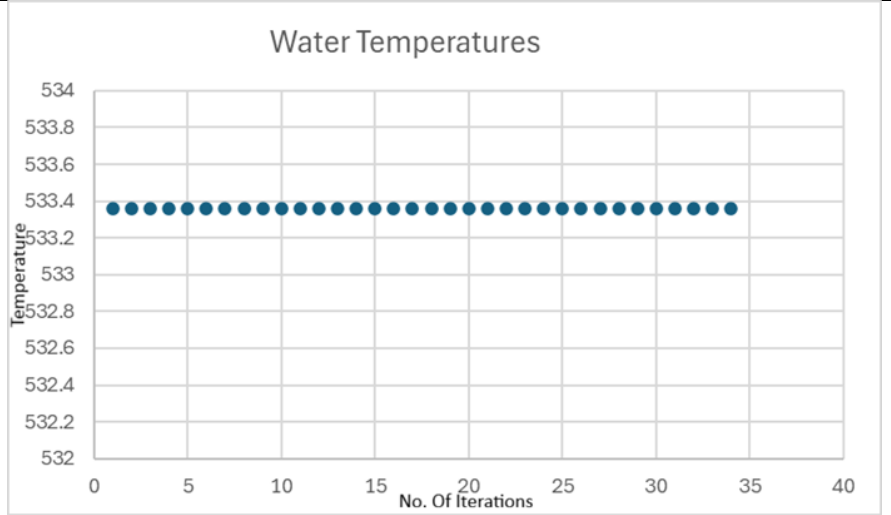
0.1

k_{eff}



0.1

**Water
Temperature**



≈ 0

5.1.4 Calculation 5: Final base case (NuScale)

A computer bug was found in the NWURCS code where the value input for the power did not appear as the correct value in the CTF file generated by NWURCS. It was not considered to be a fundamental flaw since it is a constant of the calculation and can be adjusted to a set value in the input file to NWURCS to give the correct and consistent value in the CTF input file. However, the code developer will fix this bug in due time. To calculate the correct value to be input into CTF, a placeholder value for the power A_{ph} was input. The calculation with the placeholder value A_{ph} was then run on CTF, and the parameters mass flow rate and inlet and outlet enthalpies were used in Equation 7 to calculate the actual power P_{CTF} . The calculated value P_{CTF} was then compared to the NuScale Power ($1.60 \text{ E}+08 \text{ W}$). The placeholder value A_{ph} was repeatedly changed and using trial and error, the correct power P_{CTF} (one that closest matches NuScale value of $1.60 \text{ E}+08 \text{ W}$) was found.

The equation used to calculate the power assuming steady flow state was:

$$P_{CTF} = Q = \dot{m}(h_{out} - h_{in}) \quad (7)$$

Where:

Q = heat transfer rate (energy transfer)

$\dot{m}$ = mass flow rate

h_{out} = specific enthalpy at the outlet

h_{in} = specific enthalpy at the inlet

Table 28 shows the calculations when using a placeholder value A_{ph} of **6E+03**. The calculated power P_{CTF} was found to be $2.15\text{E}+07 \text{ W}$ which was lower than the required value.

Table 28: Output values for placeholder power 6E+03

Sub-channel	$\dot{m}$ (kg/s)	h_{in} (J/kg)	h_{out} (J/kg)	$h_{out} - h_{in}$ (J/kg)	$\dot{m}(h_{out} - h_{in})(W)$
1	0.27	1125993.34	1130808.16	4814.82	1309.18
2	0.27	1125993.34	1130831.42	4838.08	1315.58
3	0.23	1125993.34	1130924.46	4931.12	1143.66

4	0.23	1125993.34	1130854.68	4861.34	1127.60
5	3.11	1125993.34	1130784.9	4791.56	14901.0025
6	17.49	1125993.34	1130808.16	4814.82	84198.21
7	54.43	1125993.34	1130482.52	4489.18	244339.86
8	102.67	1125993.34	1131808.34	5815	597036.30
9	507.23	1125993.34	1134715.84	8722.5	4424363.54
Total for a quarter core					5369734.94
Total for a full core (multiplied by 4)					2.15E+07

Several other values for A_{ph} were also tested with the results shown in Table 29. Table 29 also shows the percentage difference between the target value (NuScale) and the calculated values for the different placeholder values.

Table 29: Percentage difference between NuScale and placeholder power

Placeholder Value inputted in CTF A_{ph}	Calculated Power value in W P_{CTF}	Target Power value (NuScale) in W	% difference
6E+03	2.15E+07	1.60 E+08	152.66
6E+04	2.11E+08	1.60 E+08	27.42
4E+04	1.41E+08	1.60 E+08	12.31
4.53E+04	1.60E+08	1.60 E+08	0.0298

The placeholder value to be inputted in CTF for the power was **4.53E+04**, since the % difference value was 0.0298%.

The coupled iterative calculations were carried out with these final set of input parameters for the mass flow, enthalpy and power. The data for 42 iterations was plotted. The results are shown in Figure 5-7, Figure 5-8, Figure 5-9 and Figure 5-10 for the maximum power, maximum heat structure temperature, moderator temperature and k_{eff} , respectively.

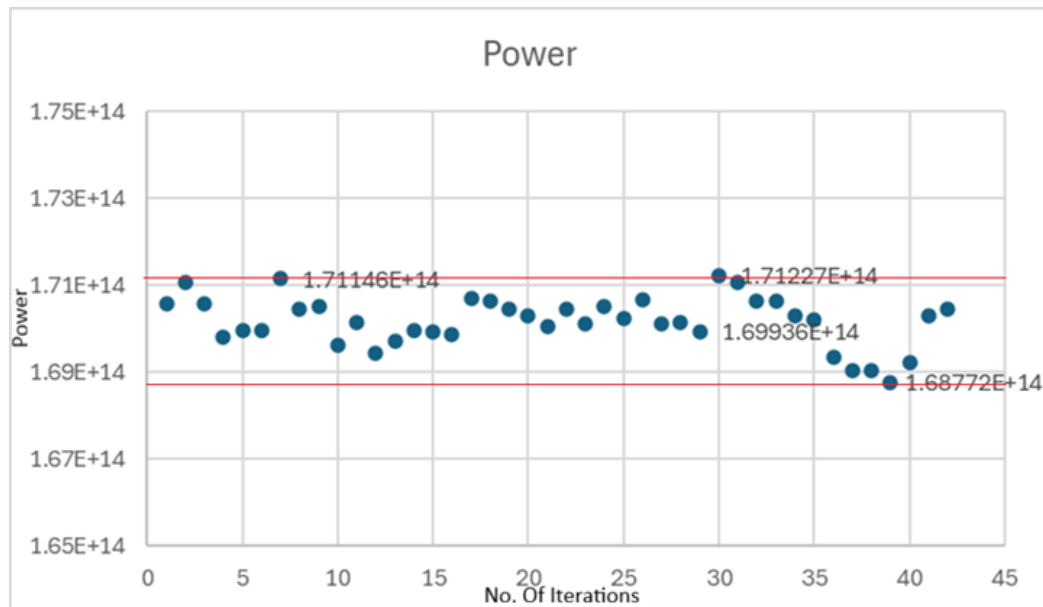


Figure 5-7: Calculation 5 - maximum power

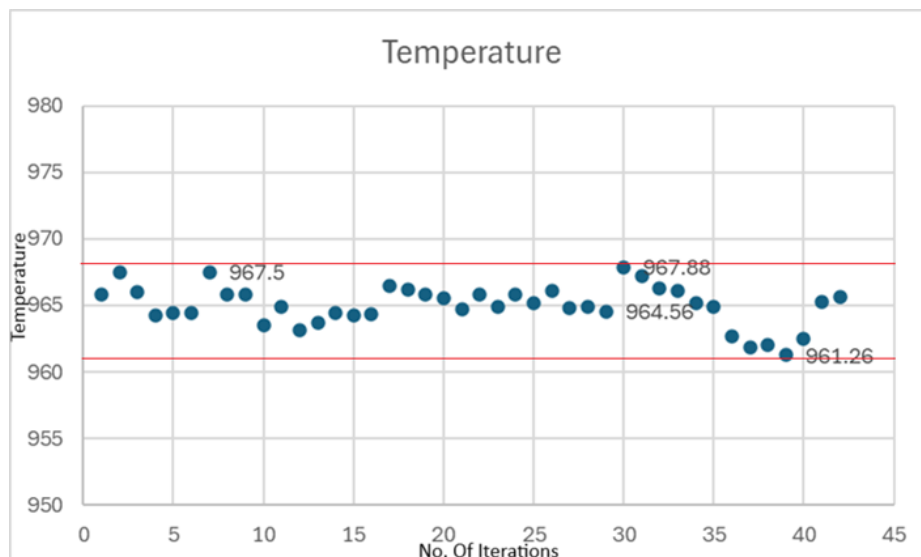


Figure 5-8: Calculation 5 - maximum heat structure temperature

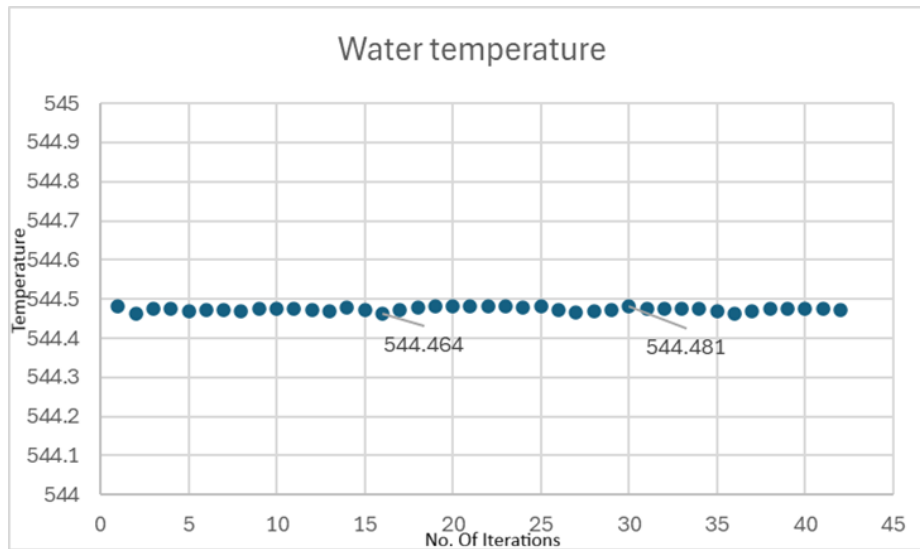


Figure 5-9: Calculation 5 - maximum water temperature

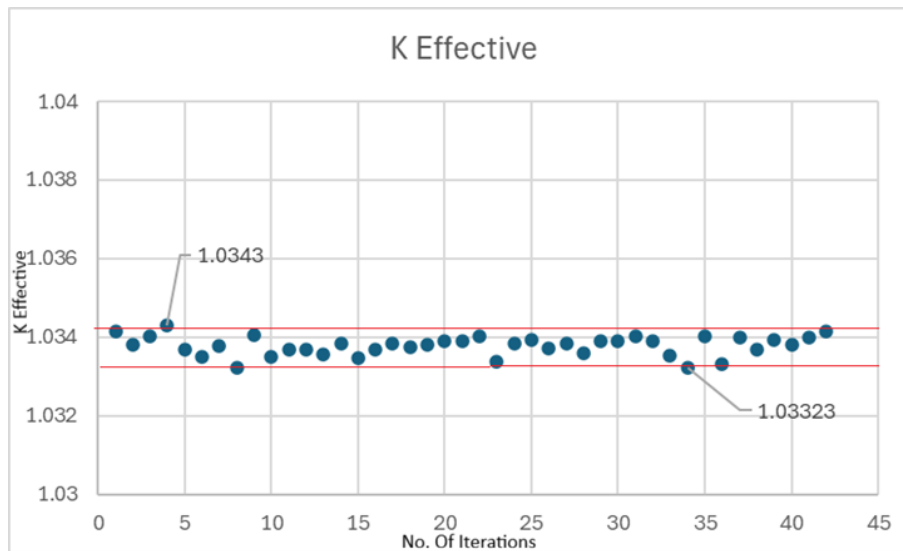


Figure 5-10: Calculation 5 - maximum k_{eff}

Convergence and stability were confirmed visually as the data points are uniformly distributed between the boundary lines.

The percentage difference between the highest and lowest power values using Equation 6 for maximum power, maximum heat structure temperature, moderator temperature and k_{eff} are shown in Table 30. It shows that the percentage differences are below 1% for all the parameters except maximum power, which could be considered a good result. Maximum power is below 5% and just above 1%, which could also be considered acceptable. The standard deviation in temperature is 1.5 K, and this can also be considered a good result. Finally, the standard deviation of the multiplication factor is 0.00024. The statistical uncertainty σ of the Serpent Monte Carlo calculation was 0.00011. It can be seen that 0.00024 is within 3σ (0.00033) of the Serpent

calculation. Given the stochastic nature of the Monte Carlo calculation, it can therefore be concluded that the standard deviation of the multiplication factor in the coupling analysis lies in the range expected due to the stochastic Serpent calculation.

Table 30: Percentage differences, standard deviation and mean - calculation 5

Parameter	% Difference between maximum and minimum	Standard Deviation	Average (Mean)
Maximum power	1.45%	5.67E+11	1.70E+14
Maximum heat structure temperature	0.69%	1.5 K	964.99 K
Moderator temperature	0.0031%	0.0052 K	544.47 K
k_{eff}	0.1%	0.00024 24 pcm	1.03378

5.1.4.1 Axial temperature distribution of heat structures

The heat structures defined previously were fuel (the fuel pellet), helium (in the gap) and cladding. In a fuel rod, the heat generation rate is proportional to the local neutron flux, which closely follows that of a sinusoidal shape axially for a system which does not contain burnable poisons for axial flux shaping. The middle of the curve has the highest neutron flux, hence the highest power and the most heat generated. The ends have lower neutron flux due to neutron leakage, hence less power and lower heat generated.

At the middle of the rod, more heat must be conducted away radially through the cladding and into the coolant. Figure 5-11 is a plot of the axial temperature distribution curve for the fuel rod. It shows this phenomenon to be true, hence the results were also verified using a physics argument.

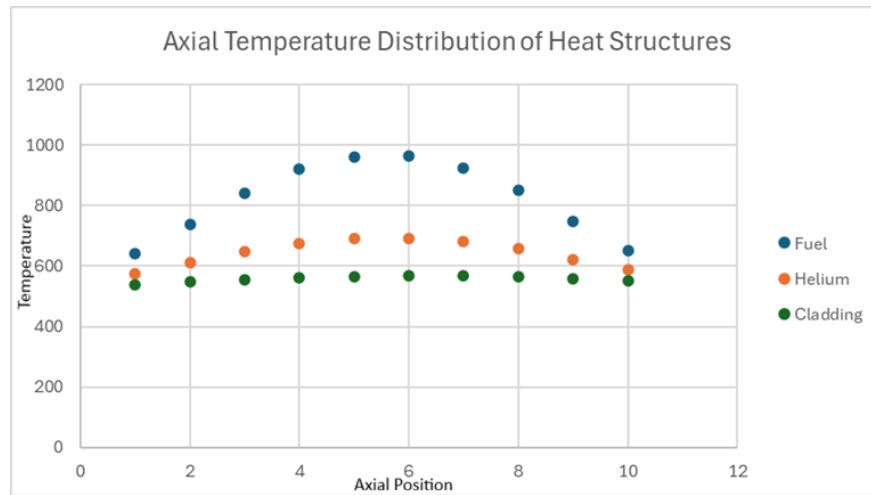


Figure 5-11: Axial temperature distribution of heat structures

The radial profile is shown in Figure 5-12.

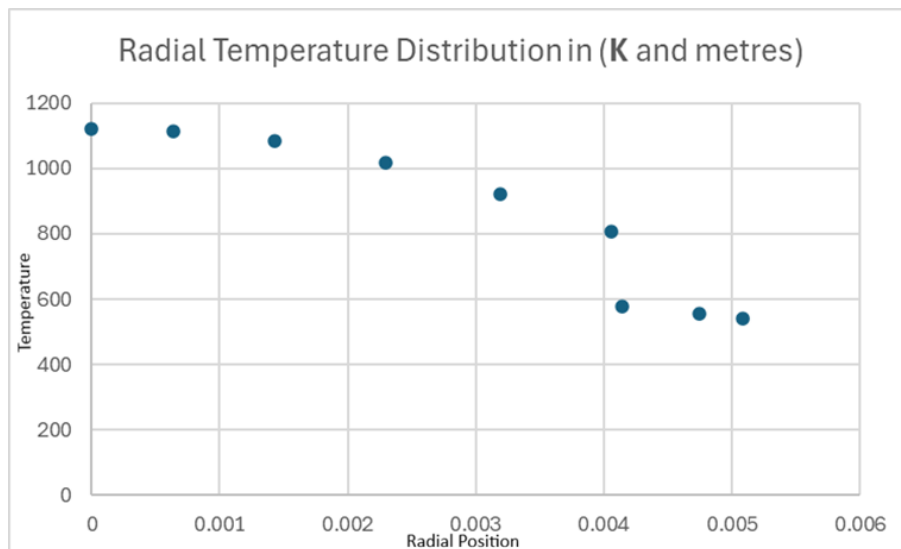


Figure 5-12: Radial temperature distribution

5.2 Effect of number of cycles on accuracy

5.2.1 Introduction

As shown in 5.4, the inlet and outlet enthalpies of calculation 5 (the previous calculation) corresponds with an axial temperature rise across the core of 11.24 K. The target value was 55.56 K (as discussed in 5.4). It is noted however that this larger value of 55.56 would correspond to fluid conditions of two-phase flow. This could introduce code coupling instability that would have to be addressed before meaningful interpretations and insight could be obtained. It was therefore decided to carry out a few tests on the model with a temperature rise of 11.24 K across the core,

and to reserve these test studies for the larger temperature difference for a later study. This was to keep the scope of the present study manageable.

In this chapter, a study was done to check if there exists a relationship between accuracy of temperature and power with an increase in the number of active cycles / more time steps.

With the current active cycles being 300, two coupling calculation sets were run with 600 and 900 active cycles for 40 iterations, with the calculation 5 values used as input.

5.2.2 Comparison

Table 31 shows the averages and standard deviations for the heat structure temperature, water temperature, power, and k_{eff} for 300, 600 and 900 active cycles. It was noticed that the average values for the different active cycles were very similar for the heat structure temperature, water temperature, power, and k_{eff} and had a 0.021%, 0.001%, 0.0035% and 0.0018% difference between them, respectively. Upon inspection it was seen that the standard deviation got lower with the higher number of active cycles (as would be expected with more statistics). This meant that, with increasing active cycles, the values were more clustered closely around the mean, which indicates less variability. It also meant that the calculation reached better convergence within 40 iterations. However, visual inspection of Figure 5-13 to Figure 5-16 showed that not much had changed; hence no significant effect had been noticed after changing the active cycles.

Because of the Monte Carlo method used in Serpent, the statistical standard deviation σ was obtained from the Serpent output file and compared to the coupling standard deviation. Normally, if differences are less than 3σ , then the two values being compared are considered to be statistically equal. In this case, not two values, but a set of values with a resultant standard deviation are compared to the statistical standard deviation. Since the coupling standard deviations are less than 3σ , the values are considered to be statistically equal.

It was also noted that the Serpent σ decreases as the number of active cycles increase. This is because the Monte Carlo method is based on probability (stochastic). The results are thus statistical estimates that include some expected fluctuation, rather than the fixed, exact answers provided by deterministic methods (Leppänen, 2015). To reduce this uncertainty, the simulation relies on the principle that the calculated average approaches the true physical value as the sample size grows. Therefore, by increasing the number of active cycles, the total number of neutron histories increases which mathematically forces the standard deviation to decrease, giving a more precise result (Lux & Koblinger, 2018).

Table 31: Averages and standard deviations for the heat structure temperature, water temperature, power, and k_{eff} for 300, 600 and 900 active cycles

Active Cycles	300	600	900
Average Heat Structure Temperatures [K]	964.99	965.13	965.2
Standard Deviation Heat Structure Temperatures [K]	1.5	1.23	0.78
Average Water Temperature [K]	544.47	544.47	544.47
Standard Deviation Water Temperature [K]	0.0052	0.0034	0.0032
Average Power	1.7017 E+14	1.7022 E+14	1.7023 E+14
Standard Deviation Power	5.67 E+11	5.0016 E+11	3.14 E+11
Average k_{eff} over 40 iterations	1.03378	1.03376	1.03377
Standard Deviation for coupling	0.00024 = 24 pcm	0.00015 = 15 pcm	0.00016 = 16 pcm
Standard Deviation Monte Carlo (σ) (Serpent)	0.00011 = 11 pcm	0.000076 = 7.6 pcm	0.000065 = 6.5 pcm
3σ	0.00033 = 33 pcm	0.00023 = 23 pcm	0.000195 = 19.5 pcm

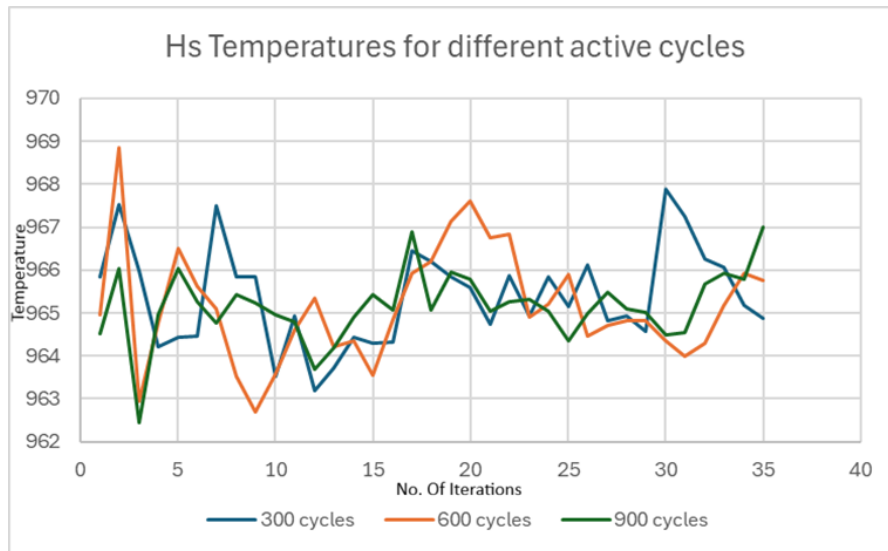


Figure 5-13: Heat structure temperature - 300, 600 and 900 active cycles

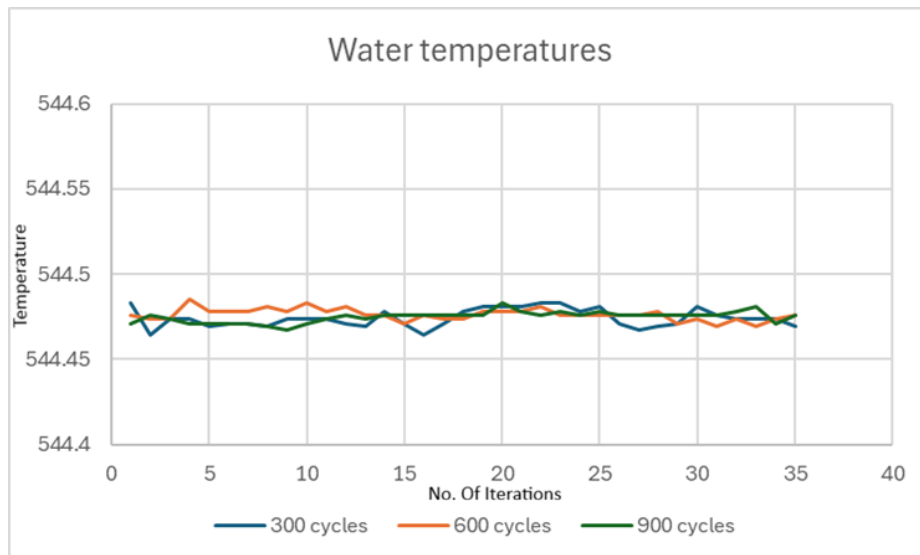


Figure 5-14: Water temperature - 300, 600 and 900 active cycles

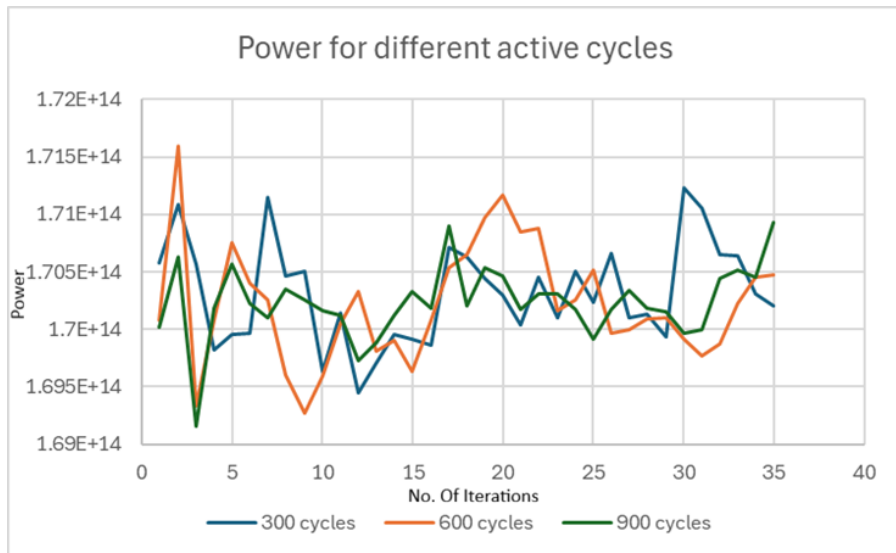


Figure 5-15: Plot of power - 300, 600 and 900 active cycles

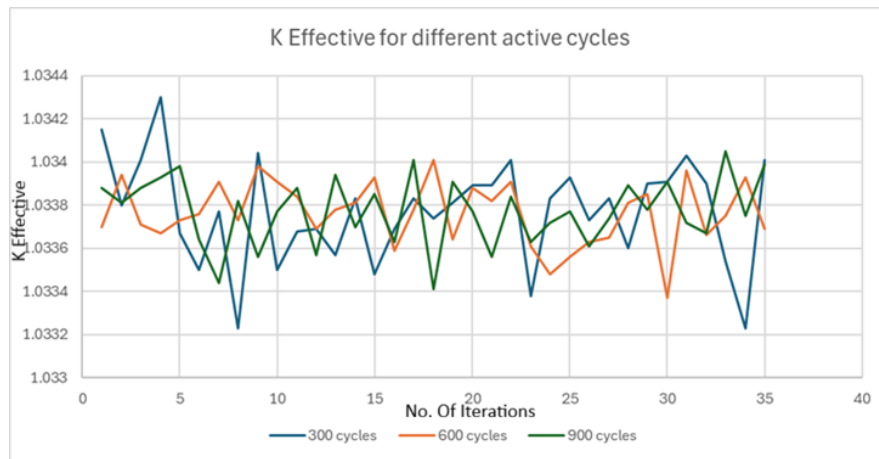


Figure 5-16: Plot of k_{eff} - 300, 600 and 900 active cycles

5.3 Sensitivity calculations

5.3.1 Introduction

Sensitivity studies were done to determine the effect that selected input values would have on chosen output values after coupled calculations were done. Sensitivity studies were done using a 10% increase and decrease on the mass flow rate, inlet enthalpy, power and pressure variables. 10% was chosen to obtain an indication of what result to expect: it was not chosen based on empirical data, such as plant operating characteristics.

As mentioned earlier, these parameters were considered since these are the base parameters for the solution of the fluid mechanics equations. Since only the steady state solution was being considered, it was deemed that sensitivity on other fluid mechanics parameters and heat transfer parameters could be carried out in a second phase of sensitivity studies.

Table 32 shows the values that were used in the sensitivity study.

Table 32: Values used in the sensitivity study

Variable	Original (calculation 5)	+10%	-10%
Inlet Enthalpy	1126	1238.6	1013.4
Mass Flow Rate	5128	5640.8	4615.20
Power	4.53E+04	4.983 E+04	4.077E+04
Pressure	12.7553	14.03083	11.47977

For the sensitivity study, each change was done individually, and every other value left the same as the original (calculation 5). For example, when running the calculation for +10% inlet enthalpy, only the inlet enthalpy value was increased, and every other value remained the same as the original NuScale. The calculation was run to 40 iterations for each change (results and graphs in Appendix G), and the results were compared to the original results.

5.3.2 Sensitivity

Table 33, Table 34, Table 35, Table 36 show how each variable change by +10% and -10% affected the average HS temperature, water temperature and k_{eff} value after 40 iterations. The values were compared to the original values, with the difference and percentage difference being calculated.

The percentage differences were calculated using Equation 8:

$$\%diff = 100 \times \frac{[Y_2 - Y_1]}{\left[\frac{(Y_2 + Y_1)}{2}\right]} \quad [8]$$

Where: Y_1 is the base value; Y_2 is the +10% or -10% value.

Table 33: Change in power

	Average value after 40 Iterations	Difference	% Difference
HS Temperature			

Base	965.0		
+10%	1013.7	48.7	5
-10%	917.2	-47.8	-5
Water Temperature			
Base	544.5		
+10%	545.7	1.2	0.2
-10%	543.2	-1.3	-0.2
k_{eff}			
Base	1.03378		
+10%	1.03369	-0.00009	-0.0085
-10%	1.03374	-0.00004	-0.0035

Table 34: Change in inlet enthalpy

	Average Value after 40 Iterations	Difference	% Difference
HS Temperature			
Base	965.0		
+10%	989.3	24.3	2.5
-10%	940.9	-24.1	-2.5
Water Temperature			
Base	544.5		
+10%	566.2	21.7	4

-10%	521.3	-23.2	-4
k_{eff}			
Base	1.03378		
+10%	1.03375	-0.00003	-0.0032
-10%	1.03379	0.00001	0.0014

Table 35: Change in mass flow rate

	Average Value after 40 Iterations	Difference	% Difference
HS Temperature			
Base	965.0		
+10%	963.2	-1.8	-0.2
-10%	967.6	2.6	0.3
Water Temperature			
Base	544.5		
+10%	543.3	-1.2	-0.2
-10%	545.9	1.4	0.3
k_{eff}			
Base	1.03378		
+10%	1.03380	0.00002	0.0021
-10%	1.03369	-0.00009	-0.0088

Table 36: Change in pressure

	Average Value after 40 Iterations	Difference	% Difference
HS Temperature			
Base	965.0		
+10%	963.7	-1.3	-0.1
-10%	963.5	1.5	0.2
Water Temperature			
Base	544.5		
+10%	544.6	0.1	0.01
-10%	544.4	-0.1	-0.01
k_{eff}			
Base	1.03378		
+10%	1.03383	0.00005	0.0044
-10%	1.03378	0.00000	0.0003

Tables 33 to 36 show that the change in power and inlet enthalpy show the larger differences with the change in power showing the largest. Furthermore, power and enthalpy show differences which are larger than the coupling standard deviation, so these differences are statistically significant. For mass flow and pressure, the differences lie below the standard deviation of the coupling standard deviation. Therefore, changes for these parameters cannot be discussed, since the differences are not above the statistical noise in terms of the standard deviation. In addition,

the differences for k_{eff} are lower than the Serpent statistical error, so discussing the changes is not possible.

To understand how these various parameters interact with each other, one needs to consider two physics phenomena. The first is that of heat transfer through solid media (termed conduction), and the second is that of heat transfer from a solid surface to a fluid and then the transport of this energy out of the fluid. This second process of heat transfer from a solid to a liquid and then transport by the liquid away from the solid is called convection.

The steady-state conduction of energy inside the pellet of a fuel pin can be understood in terms of the formalism given in “Fundamentals of Heat and Mass Transfer” (Bergman, Theodore *et al.*, 2011). Using Equation 3.58 in this reference, the temperature at any position r_1 within the fuel pellet, assuming a homogeneous heat source $\dot{q}$, is given as:

$$T_1 = \frac{\dot{q}r_2^2}{4k_{FP}} \left(1 - \frac{r_1^2}{r_2^2}\right) + T_2 \quad (9.1)$$

Where: r_2 and T_2 are the outer surface radius and temperature of the fuel pellet, respectively; and k_{FP} is the thermal conductivity of the fuel pellet, assumed to be constant in the derivation. If one considers the centreline temperature of the fuel T_{CL} , then with $r_1 = 0$ the equation becomes:

$$T_{CL} = \frac{\dot{q}r_2^2}{4k_{FP}} + T_2 \quad (9.2)$$

Or

$$\dot{q} = \frac{4k}{r_2^2} (T_{CL} - T_2) \quad (10)$$

This equation is an approximation due to the assumption of constant k and $\dot{q}$.

Steady-state heat transfer through the fuel pin gap and then the cladding, assuming conduction for both cases, can be given by the equations (derived from (Bergman, Theodore *et al.*, 2011)):

$$T_2 = R_G q_r + T_3 \quad (11)$$

$$T_3 = R_C q_r + T_4 \quad (12)$$

Where: q_r is the rate at which heat is transferred through the surface per unit length; T_3 and T_4 are the outer surface temperatures of the gap and cladding respectively; $R_G = \frac{\ln \frac{r_3}{r_2}}{2\pi k_G}$ and $R_C = \frac{\ln \frac{r_4}{r_3}}{2\pi k_C}$ with k_G ; k_C are the gap and cladding thermal conductivity respectively.

The steady-state heat transfer from the surface of the cladding to the water is through convection, and can be given by (Bergman, Theodore et al., (2011)) :

$$q_s'' = h(T_A - T_B) \quad (13)$$

Where: q_s'' is the heat flux through the surface; h is the convective heat transfer coefficient; and T_B is the fluid bulk temperature. This can be approximated as:

$$T_B = \text{average}(T_i, T_o) = \frac{1}{2}(T_i + T_o) \quad (14)$$

Where: T_i and T_o are the inlet and outlet temperatures of fluid in the channel.

Finally, the amount of heat transported by the water in the channel surrounding the fuel pin can be given by:

$$Q = \dot{m}C(T_o - T_i) \quad (15)$$

Where: Q is the heat flow rate [W] into the channel; $\dot{m}$ is the mass flow rate [kg/s]; C is the specific heat capacity [J/kg/K].

This equation applies for single phase flow. For two phase flow, Equation 7 must be considered. The equations presented above is a simplified view given for brevity in the discussion. In the real case, one must also consider other aspects such as gap conductivity, nucleate boiling and turbulence.

In the equations above, $\dot{q}$, q_s'' and Q all represent the energy that is produced by the fission source but are defined in terms of the equations used. (Bergman, Theodore et al., (2011)) provide a discussion on how these quantities are defined.

Equations 9 to 15 indicate that the power produced by fission, the mass flow rate and the inlet temperature are used to calculate the various temperatures. Pressure also effects the calculations through the material properties dependence on pressure, and as a dependent variable for the solution of the fluid mechanics equations. The influence on the neutronics k_{eff} arises from the nuclear data dependence on temperature.

The equations therefore provide valuable information on how the parameters influence the calculations and therefore become important when considering uncertainty propagation.

The heat structure (fuel) temperature is sensitive to power because power is the source of the thermal energy.

The inlet enthalpy defines the starting temperature of the water since for single phase flow, Equation 7 and 16 are equivalent. With Equations 9 to 15, increasing the inlet temperature results in all temperatures shifting upwards, and vice versa with a decrease in inlet enthalpy.

In order to understand how the power influences the temperatures more than the mass flow rate, one realizes that the mass flow rate appears only in Equation 15 whereas the power appears in Equations 9 to 13 and Equation 15.

If the mass flow rate is changed, then T_o will change in terms of Equation 15. This will change the temperature of T_B . Excluding the inlet temperature, all the other temperatures will be shifted by the change that effected T_B . This is because the mass flow rate does not appear explicitly in Equations 9 to 13.

However, the power does appear explicitly in Equations 9 to 13 and therefore these temperatures will be calculated with the new value for the power in its appropriate form. It is therefore seen that the power is directly used in the equations calculating temperature. The power therefore influences the set of calculations more than the mass flow rate.

Another aspect can also contribute. Due to the reciprocal nature of the power with the mass flow in Equation 15, by changing the power by a factor f_1 , the change in the temperature across the channel will increase by a factor f_1^2 compared to the change affected by changing the mass flow rate by the same factor in the opposite direction.

Furthermore, the effect of the mass flow rate changes and pressure changes yields differences lower than the statistics of the coupling. Given the Monte-Carlo nature of the neutronic calculation, meaningful interpretation of the effects of these parameters should not be made, and the discussion on the effects of changing pressure was not pursued. It is sufficient to comment that the effect of changing the pressure is not statistically significant.

The case studied is not that of the actual NuScale case, since the delta T across the core was about 25% of that required. However, this placed the state to be that of single-phase flow and removed the possible problems associated with coupling instability due to the Monte-Carlo method and numerical code algorithms. The water temperature was calculated as 544.5 K, but at a pressure of 12.7553 MPa, the saturation temperature should actually be 602.5 K (after interpolation using the saturated-water table A-5 in (Cengel & Boles (2015))). There is clearly a difference of 58 K. However, the above results do provide insight into which parameters to focus on in the correct NuScale model.

5.4 Final NuScale model

5.4.1 Change in temperature

The equation for specific heat is as follows:

$$Q = \dot{m}C(\Delta T) \quad (16)$$

Equation 16 is used to calculate the amount of energy that is transferred to the fluid as it moves up through the reactor core. It is the same as equation 15. $Q = \dot{m}C(T_o - T_i)$

(15)

The expected temperature change for NuScale from the inlet to outlet was required to be 55.56 [K], but the output results showed only a temperature change of 11.24 [K]. In Section 5.1.4, the power supplied to the reactor core was adjusted and set to have the NuScale value of 1.6E+08 W. This is Q of Equation 16 and needs to be kept constant. In this equation, C is a property of the fluid, and for a given fluid state, the value of C will also be constant. Equation 16 therefore stipulates that either $\dot{m}$ or ΔT can be set to have the value defined in the specifications of NuScale. Both cannot be set according to the specifications of NuScale with the expectation that Equation 16 will be satisfied. This is because CTF is based on a physics model with numerical implementation, and exact agreement with reality, although appreciated, cannot be expected.

If the change in temperature, ΔT , is larger than the specified value, it could create instability in the calculations, due to the flow regime that would result, i.e. two-phase flow. Therefore, it was prudent to set ΔT to the specified NuScale value, and to adjust $\dot{m}$ so that Equation 16 could be satisfied. (Equation 16 was calculated implicitly in the algorithms of CTF).

Hence to bring the change in temperature to the specified NuScale value, the mass flow rate was adjusted. For each mass flow rate, the temperature difference was calculated as shown in Table 37 and plotted as shown in Figure 5-17.

Table 37: Mass flow rate and temperature change

Temperature change [K]	Mass flow rate [kg/s]
11.24	1267.21
14.10	1000
18.61	750

27.12	500
35.05	375
49.50	250
55.54	216.02
57.67	200

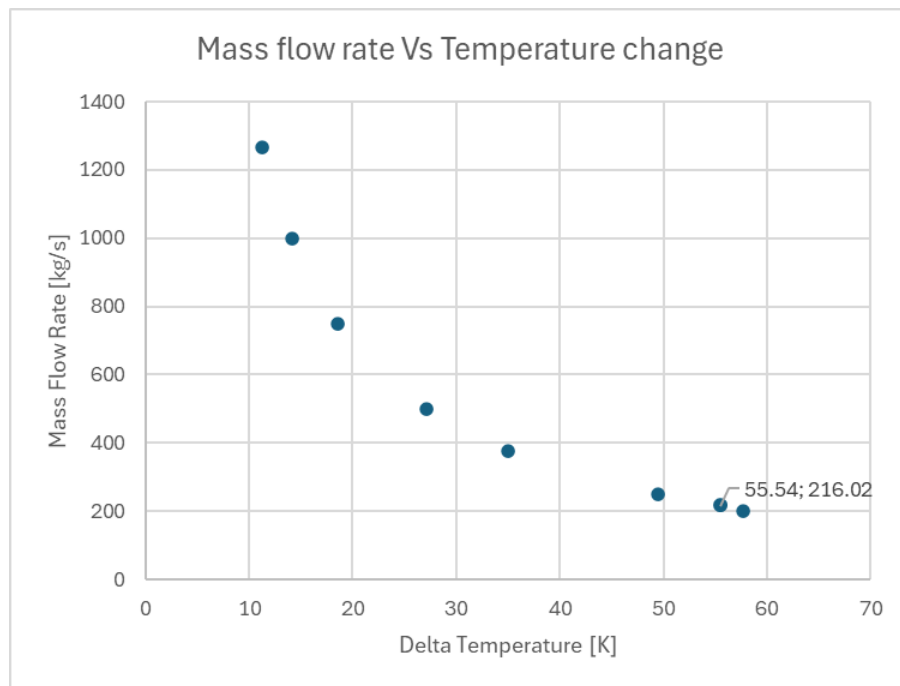


Figure 5-17: Mass Flowrate vs Temperature difference

It can be seen that as the mass flow rate value decreases, the temperature change increases, which is the mathematical consequence of Equation 16. From the results, a mass flow rate of 216.02 [kg/s] yielded a temperature change of 55.54 [K]. If we compare this to the specified NuScale data, the mass flow rate was expected to be 146.79 [kg/s] at a temperature change of 55.556 [K]. This means that the results for the mass flow rate differed by 38.16%. One reason for this difference can be attributed to the fact that the NuScale values (shown in section 2.2) were calculated with the guide tubes being modelled with water flowing through them. The present study modelled guide tubes as solids, with no water/mass flowing through them. This study also did not model the pressure losses accurately as it was decided to be reserved for a future study as the purpose of the study was to develop and verify the methodology of the coupling process. The pressure losses could also contribute to the difference.

A third reason could be that the density used in CTF used an inbuilt lookup table in CTF for the calculations, whereas the Serpent calculation used a lookup table inbuilt in NWURCS. Further effort is required to establish that these two lookup tables were identical to the required precision. However, the CTF lookup table is within the source code and would require much effort to access, whereas the NWURCS lookup table is an input file, which is simpler to access.

Another reason for the difference could be that the NuScale specifications were obtained using different design analytical tools for the calculations, namely MCNP6.1, SIMULATE5 and VIPRE-01 compared to those used in this study, namely Serpent, CTF and NWURCS.

5.5 Verification and Validation

Verification in terms of this project was carried out extensively as described in Chapters 4 and 5.

Validation requires the comparison of the code results with plant or experimental data. Such data was not available due to the following reasons. The NuScale reactor has not yet been operated and therefore no plant data is available. To build an experimental rig to validate the results is not feasible due to cost and safety regulatory considerations.

However, in applying nuclear codes, another form of validation is also acceptable when code to code comparisons are made, with one of the codes being a validated code. The results used in comparing the temperature and mass flow rates of Section 5.4. were obtained from the NuScale Safety Analysis Report (NuScale Power, 2020). These values were obtained from calculations using the code VIPRE-01 (NuScale Power, 2020). It is a validated code confirmed by the United States National Regulatory Commission (United States Nuclear Regulatory Commission, 1986). Given this, the process of validating the CTF model developed in this work for the NuScale reactor can be considered as started.

CHAPTER 6 CONCLUSION

The primary aim of this study was to develop and evaluate the methodology to build a CTF base model and to couple it with an existing Serpent model for the NuScale SMR using the NWURCS framework. This was supported by the functional verification of the NWURCS input model generator and the refinement of data transfer parameters to ensure system stability. The results confirm the coupling methodology is accurate and reliable. By verifying source convergence via Shannon entropy during inactive cycles, reliable power profiles were generated for the coupled iterations. The base case calculation achieved visual convergence over 42 iterations with no systematic drift. Statistical analysis of the base case confirmed the accuracy of the results. The percentage difference for maximum heat structure and moderator temperatures between iterations remained below 1%, while the maximum power was within an acceptable 5%.

The standard deviation of the heat structure temperature was 1.5 K. The statistical uncertainty σ of the Serpent Monte Carlo calculation was 0.00011. The standard deviation of the multiplication factor k_{eff} in the coupled calculation was 0.00024 and was well within 3σ . The axial temperature profiles correctly reflected the sinusoidal power distribution, with peak temperatures aligning with the maximum neutron flux as dictated by reactor physics, which verified the fuel temperatures. The radial temperature profile was also accurate. Upon visual inspection, and supported by a systematic analysis of Monte Carlo statistics, the effect of increasing the number of active cycles had no significant effect on accuracy.

Sensitivity analysis results showed that the model was most sensitive to power and inlet enthalpy, whilst mass flow rate and pressure had no significant effect as their differences fell within the statistical standard deviation of the coupling. The fundamental heat transfer equations confirmed these results to be valid. A more broader sensitivity study inclusive of more parameters is planned for a later study.

The calculation successfully matched the target temperature rise of 55.56 K; however, it required a mass flow rate of 216.02 kg/s to do so. The NuScale design mass flow rate was 146.79 kg/s which was a difference of 38.16%. This difference could be attributed to the modelling of guide tubes as solid rods, pressure losses not modelled correctly, a potential difference in density of water used in both CTF and Serpent and different codes used in this analysis as compared to those used for the comparison.

For future studies, the model needs to be corrected to include the water flowing inside the guide tubes, to model correctly for pressure losses, to check that the density of water used in both CTF and Serpent are the same to the required accuracy and to align the look-up tables across the

codes. Overall, the results prove that the coupling between CTF and Serpent was successful using NWURCS and provides a robust foundation for future high-fidelity SMR research.

REFERENCES

- A.G. Mylonakis, M. Varvayanni, N. Catsaros, P. Savva & D.G.E. Grigoriadis. 2014. Multi-physics and multi-scale methods used in nuclear reactor analysis. *Annals of Nuclear Energy*. 72:104–119.
- Aksan, N. 2019. An overview on thermal-hydraulic phenomena for water cooled nuclear reactors; part II: ALWRs and SCWRs. *Nuclear Engineering and Design*. 354.
- Barry W. Brook, Agustin Alonso, Daniel A. Meneley, Jozef Misak, Tom Blees & Jan B. van Erp. 2014. Why Nuclear Energy is sustainable and has to be part of the energy mix. *Sustainable Materials and Technologies*. 1–2:8–16.
- Bennett, A., Avramova, M. & Ivanov, K. 2016. Coupled MCNP6/CTF code: Development, testing, and application. *Annals of Nuclear Energy*. 96.
- Bergman, Theodore, L., Lavine, Adrienne, S., Incropera, Frank, P., Dewitt, D. & P. 2011. *FUNDAMENTALS OF HEAT and MASS TRANSFER SEVENTH EDITION*. Vol. 11. *Analytical Biochemistry*. John Wiley & Sons, 2011. <http://link.springer.com/10.1007/978-3-319-59379-1%0Ahttp://dx.doi.org/10.1016/B978-0-12-420070-8.00002-7%0Ahttp://dx.doi.org/10.1016/j.ab.2015.03.024%0Ahttps://doi.org/10.1080/07352689.2018.1441103%0Ahttp://www.chile.bmw-motorrad.cl/sync/showroom/lam/es/>.
- Carelli, M.D., Garrone, P., Locatelli, G., Mancini, M., Mycoff, C., ... Ricotti, M.E. 2010. Economic features of integral, modular, small-to-medium size reactors. *Progress in Nuclear Energy*. 52(4).
- Cengel, Y.A. & Boles, M.A. 2015. *Thermodynamics: an Engineering Approach 8th Edition*. McGraw-Hill.
- C-Therm Technologies Ltd. 2022. *Thermal Resistance and Thermal Conductance*. <https://ctherm.com/resources/helpful-links-tools/thermalresistanceandconductivity/>.
- D'Auria, F. 2017. *Thermal-Hydraulics of water cooled nuclear reactors*. *Thermal-Hydraulics of Water Cooled Nuclear Reactors*.
- Department of Electricity and Energy. 2025. *Integrated Resource Plan (IRP) 2025*. Pretoria.

- Engineers Edge. 2020. *Thermal Conductivity of gases chart*. Engineers Edge: https://www.engineersedge.com/heat_transfer/thermal-conductivity-gases.htm.
https://www.engineersedge.com/heat_transfer/thermal-conductivity-gases.htm Date of access: 05 Nov. 2024.
- Fridman, E., Bilodid, Y. & Valtavirta, V. 2023. Definition of the neutronics benchmark of the NuScale-like core. *Nuclear Engineering and Technology*. 55(10).
- Hamilton, S., Berrill, M., Clarno, K., Pawlowski, R., Toth, A., ... Philip, B. 2016. An assessment of coupling algorithms for nuclear reactor core physics simulations. *Journal of Computational Physics*. 311.
- Hirdaris, S.E., Cheng, Y.F., Shallcross, P., Bonafoux, J., Carlson, D., ... Sarris, G.A. 2014. Considerations on the potential use of Nuclear Small Modular Reactor (SMR) technology for merchant marine propulsion. *Ocean Engineering*. 79.
- IAEA. 1997. *Thermophysical properties of materials for water cooled reactors*. 20th ed. Vol. 28. Vienna.
- IAEA, I.A.E.A. 2020. *Advances in Small Modular Reactor Technology Developments: A Supplement to the IAEA Advanced Reactors Information System (ARIS)*.
- John R. Lamarsh & Anthony J. Baratta. 2001. *Introduction to Nuclear Engineering*. 3rd ed.
- Kaiwen Li, Shichang Liu, Juanjuan Guo, Zhen Luo, Shanfang Huang & Kan Wang. 2023. An internal coupling method between neutronics and thermal-hydraulics. *Annals of Nuclear Energy*. 187.
- KZ Madi. 2025. Developing a neutronic core model of the NuScale Power Module using Serpent. Potchefstroom: North-West University.
- Leppänen, J. 2015. *Serpent – a Continuous-energy Monte Carlo Reactor Physics Burnup*. http://montecarlo.vtt.fi/download/Serpent_manual.pdf.
- Li, K., Liu, S., Guo, J., Luo, Z., Huang, S. & Wang, K. 2023. An internal coupling method between neutronics and thermal-hydraulics with RMC and CTF. *Annals of Nuclear Energy*. 187.
- Locatelli, G., Bingham, C. & Mancini, M. 2014. Small modular reactors: A comprehensive overview of their economics and strategic aspects. *Progress in Nuclear Energy*. 73.

- Lux, I. & Koblinger, L. 2018. *Monte Carlo Particle Transport Methods: Neutron and Photon Calculations. Monte Carlo Particle Transport Methods: Neutron and Photon Calculations.*
- M. Avramova. 2011. *CTF - A Thermal-Hydraulic Subchannel Code for LWRs Transient Analyses User's Manual.* Pennsylvania.
- M. Avramova, S. Balzus, R. Mueller, K. Ivanov & L. Hochreiter. 2002. Comparative Analysis of PWR Core Wide and Hot Channel Calculations.
- Mahmoud, M., Abdelkareem, M.A. & Olabi, A.G. 2023. Modeling and simulation of geothermal energy systems. *Renewable Energy - Volume 2: Wave, Geothermal, and Bioenergy Definitions, Developments, Applications, Case Studies, and Modelling and Simulation.* (January, 1):197–211.
- Montwedi, O.E., Naicker, V. V. & Nyalunga, G.P. 2025. Neutronic uncertainty propagation for the SAFARI-1 research reactor benchmark: IAEA CRP T12029. *Nuclear Engineering and Design.* 435:113943.
- NuScale Power. 2013. *NuScale Power Modular and Scalable Reactor.*
- NuScale Power. 2020. *NuScale Safety Analysis Report- Chapter Four Reactor, Part 2- Tier 2.*
- NuScale Power, L. 2016. *NuScale Final Safety Analysis Report.*
- Salko, R., Wysocki, A., Blyth, T., Toptan, A., Hu, J., ... Pilch, M. 2022. CTF: A modernized, production-level, thermal hydraulic solver for the solution of industry-relevant challenge problems in pressurized water reactors. *Nuclear Engineering and Design.* 397.
- United States Nuclear Regulatory Commission. 1986. *Safety Evaluation Report on EPRI NP-2511-CCM VIPRE-01.* Washington D.C.
- US Department of Energy. 2021. *Small Modular Reactors.*
- Ville Valtavirta. 2015. *Input syntax manual - Serpent Wiki.* https://serpent.vtt.fi/mediawiki/index.php?title=Input_syntax_manual&action=info Date of access: 14 Oct. 2025.
- V.V. Naicker. 2024. NWURCS User Guide. Potchefstroom, South Africa: North-West University.
- Zhang, J. & Hassan, Y. 2022. Envisaged future for nuclear thermal-hydraulics. *Nuclear Engineering and Design.* 400.

APPENDICES

Appendix A: Example calculation for flow area in sub-channel 5

Figure A-1 shows sub-channel 5 and the defined square, as well as the smaller inner squares (1, 2, 3 and 4).

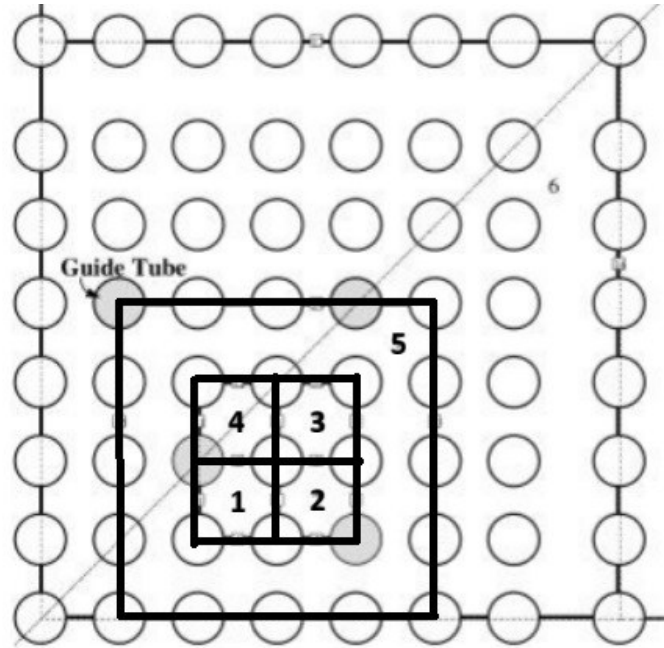


Figure A-1: Sub-channel 5

Key Values:

$$\text{Area fuel rod} = 0.0000910942 \text{ [m}^2\text{]}$$

$$\text{Area guide tube} = 0.00014721 \text{ [m}^2\text{]}$$

$$\text{Gap length between 2 fuel rods} = 0.00335 \text{ [m]}$$

$$\text{Gap length between fuel rod and guide tube} = 0.001885 \text{ [m]}$$

$$\text{Total Gap length for right side of square} = 0.009029718 \text{ [m]}$$

$$\text{Fuel rod outer diameter} = 0.010769622 \text{ [m]}$$

$$\text{Guide tube outer diameter} = 0.013690627 \text{ [m]}$$

To calculate the flow area, the area of the outer square was calculated first:

$$\begin{aligned} \text{Area of outer square} &= l^2 \\ &= (0.009019718 + 0.5(0.010769622) + 3(0.010769622) + 0.5(0.010769622))^2 \end{aligned}$$

$$\text{Area of outer square} = 0.003191088 \text{ [m}^2\text{]}$$

Thereafter, the area of the inner square was calculated:

$$\begin{aligned} \text{Area of inner square} &= \text{Area of Squares 1} + 2 + 3 + 4 \\ &= (0.010769622 + 0.00335)^2 + (0.010769622 + 0.00335)^2 + (0.010769622 + 0.00335)^2 \\ &\quad + (0.010769622 + 0.00335)^2 \end{aligned}$$

$$\text{Area of inner square} = 0.000797455 \text{ [m}^2\text{]}$$

Next, the area of the outer fuel rods and guide tubes were calculated, starting with the sections of the fuel rods and guide tubes that touch the outer square and are inside the outer square:

$$\begin{aligned} \text{Area of outer fuel rods \& guide tubes} \\ &= 0.25 \times 0.0000910942 + 0.5 \times 0.0000910942 + 0.5 \times 0.0000910942 \\ &\quad + 0.5 \times 0.0000910942 + 0.25 \times 0.00014721 + 2 \times 0.0000910942 \\ &\quad + 1.5 \times 0.0000910942 + 1 \times 0.0000910942 + 0.5 \times 0.00014721 \end{aligned}$$

$$\text{Area of outer fuel rods \& guide tubes} = 0.000679746 \text{ [m}^2\text{]}$$

Next, the area of the inner fuel rods and guide tubes were calculated, starting with the sections of the fuel rods and guide tubes that touch the inner square and are outside the inner square:

$$\begin{aligned} \text{Area of inner fuel rods \& guide tubes} \\ &= 0.0000910942 + 0.5 \times 0.00014721 + 0.0000910942 + 0.5 \times 0.00014721 \\ &\quad + 0.75 \times 0.0000910942 + 0.25 \times 0.00014721 + 0.0000910942 \end{aligned}$$

$$\text{Area of inner fuel rods \& guide tubes} = 0.000525615 \text{ [m}^2\text{]}$$

Thus, the total flow area is:

$$\begin{aligned} \text{Total Flow Area} \\ &= \text{Area of outer square} - \text{Area of inner square} \\ &\quad - \text{Area of outer fuel rods \& guide tubes} \\ &\quad - \text{Area of inner fuel rods \& guide tubes} \end{aligned}$$

$$\text{Total Flow Area} = 0.003191088 - 0.000797455 - 0.000679746 - 0.000525615$$

$$Total\ Flow\ Area = 0.0011882712 [m^2]$$

Figure A-2 shows the calculations that were all done in Excel.

SUBCHANNEL 5		
<u>Subchannel 5 Area Calculations Outer Square</u>		
Left side	0.056489713	
Right side	0.056489713	
Bottom side	0.056489713	
Top side	0.056489713	
Outer Square	0.003191088	m^2
Inner Square	0.000797455	m^2
<u>Outside Circles</u>		
Left side	0.000196217	
Right side	0.000182188	
Bottom side	0.000136641	
Top side	0.000164699	
Total Area=	0.000679746	m^2
<u>Inner Circles</u>		
Left side	0.000164699	
Right side	0.000164699	
Bottom side	0.000105123	
Top side	0.0000910942	
Total Area=	0.000525615	m^2

Figure A-2: Flow area calculations done in Excel

Appendix B: Example calculation for wetted perimeter in sub-channel 5

Key Values:

$$\text{Fuel rod circumference} = 0.0338337639 \text{ [m]}$$

$$\text{Guide tube circumference} = 0.0430103744 \text{ [m]}$$

The wetted perimeter of the outer fuel rods & guide tubes is calculated, starting with the sections of the fuel rods and guide tubes that touch the outer square and are inside the outer square:

$$\begin{aligned} \text{Wetted perimeter of outer fuel rods \& guide tubes} \\ &= 2 \times 0.0338337639 + 1.5 \times 0.0338337639 + 1.75 \times 0.0338337639 \\ &+ 0.25 \times 0.0430103744 + 0.0338337639 + 0.5 \times 0.0430103744 \end{aligned}$$

$$\text{Wetted perimeter of outer fuel rods \& guide tubes} = 0.243718805 \text{ [m]}$$

The wetted perimeter of the inner fuel rods & guide tubes is calculated, starting with the sections of the fuel rods and guide tubes that touch the outer square and are inside the outer square:

$$\begin{aligned} \text{Wetted perimeter of inner fuel rods \& guide tubes} \\ &= 0.0338337639 + 0.5 \times 0.0430103744 + 0.75 \times 0.0338337639 \\ &+ 0.25 \times 0.0430103744 + 0.0338337639 + 0.5 \times 0.0430103744 + 0.0338337639 \end{aligned}$$

$$\text{Wetted perimeter of inner fuel rods \& guide tubes} = 0.180639583 \text{ [m]}$$

$$\text{Total Wetted perimeter} = 0.243718805 + 0.180639583$$

$$\text{Total Wetted perimeter} = 0.424358388 \text{ [m]}$$

Figure B-1 shows the calculations were all done in Excel:

SUBCHANNEL 5	
<u>Perimeter calculations</u>	
<u>Outer Circles</u>	
Right Side	0.067667528
Bottom side	0.050750646
Left side	0.06996168
Top Side	0.055338951
	<u>0.243718805</u>
<u>Inner Circles</u>	
Right Side	0.055338951
Bottom side	0.036127917
Left side	0.055338951
Top Side	0.033833764
	<u>0.180639583</u>

Figure B-1: Wetted perimeter calculations done in Excel

Appendix C: Final Input data

Card group 9

Figure C-1 shows the final input for Card group 9.

```
*****
* Group 9 - Conductor Geometry Description *
*****
*NGRP
  9
* ---CARD 9.1 -----
*NFLT IRLF ICNF IMWR NDM5 NDM6 NDM7 NDM8 NDM9 NM10 NM11 NM12 NM13 NM14
 16  0  0  0  0  0  0  0  0  0  0  0  0  0  0
* ---CARDS 9.2, 9.6 & 9.7
 1 nucl  9.50000E-03  8.11600E-03  5  0  1  0  0.0  6.10000E-04  9.60000E-01  0  0  0
 2 nucl  9.50000E-03  8.11600E-03  5  0  1  0  0.0  6.10000E-04  9.60000E-01  0  0  0
 3 nucl  9.50000E-03  8.11600E-03  5  0  1  0  0.0  6.10000E-04  9.60000E-01  0  0  0
 4 nucl  9.50000E-03  8.11600E-03  5  0  1  0  0.0  6.10000E-04  9.60000E-01  0  0  0
 5 nucl  9.50000E-03  8.11600E-03  5  0  1  0  0.0  6.10000E-04  9.60000E-01  0  0  0
 6 nucl  9.50000E-03  8.11600E-03  5  0  1  0  0.0  6.10000E-04  9.60000E-01  0  0  0
 7 nucl  9.50000E-03  8.11600E-03  5  0  1  0  0.0  6.10000E-04  9.60000E-01  0  0  0
 8 nucl  9.50000E-03  8.11600E-03  5  0  1  0  0.0  6.10000E-04  9.60000E-01  0  0  0
 9 nucl  9.50000E-03  8.11600E-03  5  0  1  0  0.0  6.10000E-04  9.60000E-01  0  0  0
10 hrod  1.22420E-02  0.00000E+00  2  0  0  0  0  0  0  0  0
 2  2  5.71500E-03  1.02
 2  1  4.06000E-04  1.0
11 hrod  1.22420E-02  0.00000E+00  2  0  0  0  0  0  0  0  0
 2  2  5.71500E-03  1.0
 2  1  4.06000E-04  1.0
12 hrod  1.22420E-02  0.00000E+00  2  0  0  0  0  0  0  0  0
 2  2  5.71500E-03  1.0
 2  1  4.06000E-04  1.0
13 hrod  1.22420E-02  0.00000E+00  2  0  0  0  0  0  0  0  0
 2  2  5.71500E-03  1.0
 2  1  4.06000E-04  1.0
14 hrod  1.22420E-02  0.00000E+00  2  0  0  0  0  0  0  0  0
 2  2  5.71500E-03  1.0
 2  1  4.06000E-04  1.0
15 hrod  1.22420E-02  0.00000E+00  2  0  0  0  0  0  0  0  0
 2  2  5.71500E-03  1.0
 2  1  4.06000E-04  1.0
16 hrod  1.22420E-02  0.00000E+00  2  0  0  0  0  0  0  0  0
 2  2  5.71500E-03  1.0
 2  1  4.06000E-04  1.0
```

Figure C-1: Final input Card group 9

Card group 10

Figure C-2 shows the final input for Card group 10.

```

*****
* GROUP 10 - Material Properties Tables
*****
*NGRP
  10
*Card 10.1
  2 0 0 0 0 0 0 0 0 0 0 0 0 0
*Card 10.2
  1 11 6490.000 nsbm_Zr-
*Card 10.3 T HeatCap TCond
-1.49994E-01 2.85978E-01 1.33200E+01
 1.49850E+02 3.04931E-01 1.39000E+01
 2.49850E+02 3.16949E-01 1.46600E+01
 4.99850E+02 3.44068E-01 1.73700E+01
 6.99850E+02 3.63945E-01 2.03500E+01
 7.99850E+02 3.73035E-01 2.21100E+01
 8.49850E+02 6.02928E-01 2.30600E+01
 8.99850E+02 8.16025E-01 2.40600E+01
 9.49850E+02 5.44068E-01 2.51000E+01
 1.02685E+03 3.55932E-01 2.65000E+01
 1.12685E+03 3.55932E-01 2.78900E+01
*Card 10.2
  2 11 1000.000 hrodsurface_01
*Card 10.3 T HeatCap TCond
-1.49994E-01 1.85600E+00 1.33200E+01
 1.49850E+02 1.97900E+00 1.39000E+01
 2.49850E+02 2.05700E+00 1.46600E+01
 4.99850E+02 2.23300E+00 1.73700E+01
 6.99850E+02 2.36200E+00 2.03500E+01
 7.99850E+02 2.42100E+00 2.21100E+01
 8.49850E+02 3.91300E+00 2.30600E+01
 8.99850E+02 5.29600E+00 2.40600E+01
 9.49850E+02 3.53100E+00 2.51000E+01
 1.02685E+03 2.31000E+00 2.65000E+01
 1.12685E+03 2.31000E+00 2.78900E+01

```

Figure C-2: Final input for Card group 10

Card group 11

```

*****
* Group 11 - Axial Power Tables and Forcing Functions *
*****
*NGRP
  11
* ---CARD 11.01 -----
*   NQA  NAXP  MNXN   NQ NGPF  NQR NDM7 NDM8 NDM9 NM10 NM11 NM12 NM13 NM14
*   1  9 12 33  0  1  0  0  0  0  0  0  0  0
* ---CARD 11.02 -----
* Axial Power Distribution/Forcing Functions
*   YQ
*   0.0
* ---CARD 11.03 -----
*   I NAXN
*   1 12
* ---CARD 11.04 -----
*   0.00000E+00  1.61419E-01
*   1.00000E-01  3.59779E-01
*   3.00000E-01  7.56500E-01
*   5.00000E-01  1.09322E+00
*   7.00000E-01  1.31811E+00
*   9.00000E-01  1.45341E+00
*   1.10000E+00  1.47504E+00
*   1.30000E+00  1.33777E+00
*   1.50000E+00  1.08854E+00
*   1.70000E+00  7.54765E-01
*   1.90000E+00  3.62866E-01
*   2.00000E+00  1.66917E-01
* ---CARD 11.03 -----
*   I NAXN
*   2 12

```

Figure C-3: Final input for Card group 11

```

* ---CARD 11.04 -----
  0.00000E+00    1.55827E-01
  1.00000E-01    3.58800E-01
  3.00000E-01    7.64745E-01
  5.00000E-01    1.09252E+00
  7.00000E-01    1.32965E+00
  9.00000E-01    1.45451E+00
  1.10000E+00    1.47146E+00
  1.30000E+00    1.32510E+00
  1.50000E+00    1.08901E+00
  1.70000E+00    7.49737E-01
  1.90000E+00    3.64465E-01
  2.00000E+00    1.71830E-01
* ---CARD 11.03 -----
*   I NAXN
  3 12
* ---CARD 11.04 -----
  0.00000E+00    1.54807E-01
  1.00000E-01    3.58945E-01
  3.00000E-01    7.67221E-01
  5.00000E-01    1.09578E+00
  7.00000E-01    1.32605E+00
  9.00000E-01    1.45739E+00
  1.10000E+00    1.47053E+00
  1.30000E+00    1.31985E+00
  1.50000E+00    1.09536E+00
  1.70000E+00    7.46709E-01
  1.90000E+00    3.62170E-01
  2.00000E+00    1.69900E-01
* ---CARD 11.03 -----
*   I NAXN
  4 12
* ---CARD 11.04 -----
  0.00000E+00    1.59416E-01
  1.00000E-01    3.61175E-01
  3.00000E-01    7.64693E-01
  5.00000E-01    1.09512E+00
  7.00000E-01    1.31982E+00
  9.00000E-01    1.45582E+00
  1.10000E+00    1.46742E+00
  1.30000E+00    1.33330E+00
  1.50000E+00    1.09570E+00
  1.70000E+00    7.41978E-01
  1.90000E+00    3.64977E-01
  2.00000E+00    1.76476E-01
* ---CARD 11.03 -----
*   I NAXN
  5 12

```

Figure C-4: Final input for Card group 11 (continued)

```

* ---CARD 11.04 -----
0.00000E+00 1.67295E-01
1.00000E-01 3.62701E-01
3.00000E-01 7.53512E-01
5.00000E-01 1.09301E+00
7.00000E-01 1.32849E+00
9.00000E-01 1.46031E+00
1.10000E+00 1.46717E+00
1.30000E+00 1.32888E+00
1.50000E+00 1.09361E+00
1.70000E+00 7.51505E-01
1.90000E+00 3.60822E-01
2.00000E+00 1.65481E-01
* ---CARD 11.03 -----
* I NAXN
6 12
* ---CARD 11.04 -----
0.00000E+00 1.64670E-01
1.00000E-01 3.61389E-01
3.00000E-01 7.54828E-01
5.00000E-01 1.09449E+00
7.00000E-01 1.32987E+00
9.00000E-01 1.45827E+00
1.10000E+00 1.46261E+00
1.30000E+00 1.33239E+00
1.50000E+00 1.08879E+00
1.70000E+00 7.54737E-01
1.90000E+00 3.62624E-01
2.00000E+00 1.66567E-01
* ---CARD 11.03 -----
* I NAXN
7 12
* ---CARD 11.04 -----
0.00000E+00 1.60114E-01
1.00000E-01 3.57567E-01
3.00000E-01 7.52475E-01
5.00000E-01 1.09396E+00
7.00000E-01 1.33446E+00
9.00000E-01 1.46257E+00
1.10000E+00 1.46006E+00
1.30000E+00 1.33084E+00
1.50000E+00 1.09131E+00
1.70000E+00 7.54208E-01
1.90000E+00 3.62553E-01
2.00000E+00 1.66725E-01
* ---CARD 11.03 -----
* I NAXN
8 12

```

Figure C-5: Final input for Card group 11 (continued)

```

* ---CARD 11.04 -----
0.00000E+00 1.59056E-01
1.00000E-01 3.56944E-01
3.00000E-01 7.52720E-01
5.00000E-01 1.09179E+00
7.00000E-01 1.33254E+00
9.00000E-01 1.46232E+00
1.10000E+00 1.45872E+00
1.30000E+00 1.33471E+00
1.50000E+00 1.09127E+00
1.70000E+00 7.55488E-01
1.90000E+00 3.63501E-01
2.00000E+00 1.67508E-01
* ---CARD 11.03 -----
* I NAXN
9 12
* ---CARD 11.04 -----
0.00000E+00 1.57169E-01
1.00000E-01 3.55800E-01
3.00000E-01 7.53063E-01
5.00000E-01 1.09121E+00
7.00000E-01 1.33530E+00
9.00000E-01 1.46228E+00
1.10000E+00 1.45982E+00
1.30000E+00 1.33250E+00
1.50000E+00 1.09195E+00
1.70000E+00 7.56534E-01
1.90000E+00 3.61542E-01
2.00000E+00 1.64046E-01
* ---CARD 11.05 -----
* Total Power Forcing Functions
*      YQ      FQ      YQ      FQ      YQ      FQ      YQ      FQ
      0.0      0.0000      1.0      0.1000      2.0      1.0000      10.0      1.0000
      11.8      1.0000      11.9      1.0000      12.0      1.0000      12.1      1.0000
      12.2      1.0000      12.3      1.0000      12.4      1.0000      12.5      1.0000
      12.6      1.0000      12.7      1.0000      12.8      1.0000      12.9      1.0000
      13.0      1.0000      13.1      1.0000      13.2      1.0000      13.3      1.0000
      13.4      1.0000      13.5      1.0000      13.6      1.0000      13.7      1.0000
      13.8      1.0000      14.8      1.0000      15.8      1.0000      16.8      1.0000
      17.8      1.0000      18.8      1.0000      19.8      1.0000      20.8      1.0000
      21.8      1.0000
* ---CARD 11.07 -----
* Radial Power Distribution/Forcing Functions
*      YQR
      0.0
* ---CARD 11.08 -----
*      FQR ...
0.698627 0.652558 0.869782 0.930814 0.597277 0.632088 0.530505 0.646802
1.137090
*****
* END GROUP 11
*****

```

Figure C-6: Final input for Card group 11 (continued)

Card group 13

```

*****
* Group 13 - Boundary Conditions Data
*****
*NGRP
13
* ---CARD 13.1 -----
*NBND NKBD NFUN NGBD NDM5 NDM6 NDM7 NDM8 NDM9 NM10 NM11 NM12 NM13 NM14
18 0 1 0 0 0 0 0 0 0 0 0 0 0
* ---CARD 13.2 -----
*NPTS
32
* ---CARD 13.3 -----
*ABSC ORDINT ABSC ORDINT ABSC ORDINT
0.0 0.0000 0.1 1.0000 10.0 1.0000 10.1 0.9976 10.2 0.9929
10.3 0.9867 10.4 0.9795 10.5 0.9716 10.6 0.9632 10.7 0.9547
10.8 0.9459 10.9 0.9371 11.0 0.9283 11.1 0.9196 11.2 0.9109
11.3 0.9023 11.4 0.8938 11.5 0.8855 11.6 0.8773 11.7 0.8693
11.8 0.8615 11.9 0.8537 12.0 0.8462 13.0 0.7817 14.0 0.7363
15.0 0.6960 16.0 0.6593 17.0 0.6259 18.0 0.5953 19.0 0.5672
20.0 0.5413 21.8 0.5413
* ---CARD 13.4 -----
* Inlet b.c. -----
*IBD1 IBD2 ISPC N1FN N2FN N3FN BCVALUE1 BCVALUE2 BCVALUE3 INITGAS
1 1 2 1 0 0 0.00000E+00 1.12600E+03 0.00000E+00 1
2 1 2 1 0 0 0.00000E+00 1.12600E+03 0.00000E+00 1
3 1 2 1 0 0 0.00000E+00 1.12600E+03 0.00000E+00 1
4 1 2 1 0 0 0.00000E+00 1.12600E+03 0.00000E+00 1
5 1 2 1 0 0 0.00000E+00 1.12600E+03 0.00000E+00 1
6 1 2 1 0 0 0.00000E+00 1.12600E+03 0.00000E+00 1
7 1 2 1 0 0 0.00000E+00 1.12600E+03 0.00000E+00 1
8 1 2 1 0 0 0.00000E+00 1.12600E+03 0.00000E+00 1
9 1 2 1 0 0 0.00000E+00 1.12600E+03 0.00000E+00 1
* Outlet b.c. -----
*IBD1 IBD2 ISPC N1FN N2FN N3FN BCVALUE1 BCVALUE2 BCVALUE3 INITGAS
1 12 1 0 0 0 0.00000E+00 1.12600E+03 1.27553E+02 1
2 12 1 0 0 0 0.00000E+00 1.12600E+03 1.27553E+02 1
3 12 1 0 0 0 0.00000E+00 1.12600E+03 1.27553E+02 1
4 12 1 0 0 0 0.00000E+00 1.12600E+03 1.27553E+02 1
5 12 1 0 0 0 0.00000E+00 1.12600E+03 1.27553E+02 1
6 12 1 0 0 0 0.00000E+00 1.12600E+03 1.27553E+02 1
7 12 1 0 0 0 0.00000E+00 1.12600E+03 1.27553E+02 1
8 12 1 0 0 0 0.00000E+00 1.12600E+03 1.27553E+02 1
9 12 1 0 0 0 0.00000E+00 1.12600E+03 1.27553E+02 1
*****
* END GROUP 13
*****

```

Figure C-7: Final input for Card group 13

Card group 15

```

*****
* Group 15 - TIME DOMAIN DATA                                     *
*****
*NGRPF
15
*   DTMIN  DTMAX  TEND  EDINT  DMPINT  RTWFP
0.000001  0.01  10.0   10.0   10.0   1.0
*   DTMIN  DTMAX  TEND  EDINT  DMPINT  RTWFP
0.000001  0.01  21.8   0.2   21.8   1.0
*   DTMIN (if negative stop)
      -1.0   0.0   0.0   0.0   0.0   0.0
*
*****
* END GROUP 15                                                    *
*****

```

Figure C-8: Final input for Card group 15

Appendix D: Thermal properties of helium

Temperature °C	Conductivity W/m-°C	Density kg/m ³	Specific Heat J/kg-°C	Dynamic Viscosity kg/m-s	Kinematic Viscosity m ² /s	Thermal Diffusivity m ² /s
-129.0	0.0928	0.3379	5.2×10^3	12.55×10^{-6}	37.11×10^{-6}	52.75×10^{-6}
-73.0	0.1177	0.2435	5.2×10^3	15.66×10^{-6}	64.38×10^{-6}	92.88×10^{-6}
-18.0	0.1357	0.1906	5.2×10^3	18.17×10^{-6}	95.5×10^{-6}	136.75×10^{-6}
93.0	0.1691	0.1328	5.2×10^3	23.05×10^{-6}	173.6×10^{-6}	244.9×10^{-6}
204.0	0.197	0.10204	5.2×10^3	27.5×10^{-6}	269.3×10^{-6}	371.6×10^{-6}
316.0	0.225	0.08282	5.2×10^3	31.13×10^{-6}	375.8×10^{-6}	521.5×10^{-6}
427.0	0.251	0.07032	5.2×10^3	34.75×10^{-6}	494.2×10^{-6}	666.1×10^{-6}
527.0	0.275	0.06023	5.2×10^3	38.17×10^{-6}	634.1×10^{-6}	877.4×10^{-6}

Figure D-1: Thermal properties of helium

Source: (Engineers Edge (, 2020)

Appendix E: Temperature verification example

Table 38, Table 39, Table 40 and Table 41 show an example of one section of the spreadsheet used to verify the temperature values. It can be seen that the values are equal for the ones in CTF and the ones in the f216 file.

An example of sub-channel 6, region 1 for a nuclear fuel rod is provided in Table 38.

Table 38: Verification of temperature values for sub-channel 6, region 1 for a nuclear fuel rod

Pipe 6/Region 1/nuc rod 1	Surface	Centre	Average	in Kelvin	f216 Coupling
11	873.75	1210.91	1042.33	834.44	834.44
10	868.31	1199.9	1034.105	829.88	829.87
9	862.32	1187.61	1024.965	824.80	824.8
8	856.33	1175.34	1015.835	819.73	819.72
7	850.35	1163.12	1006.735	814.67	814.67
6	844.36	1150.92	997.64	809.62	809.62
5	838.38	1138.76	988.57	804.58	804.58
4	832.39	1126.59	979.49	799.53	799.53
3	826.35	1114.37	970.36	794.46	794.46
2	820.9	1103.51	962.205	789.93	789.93

Table 39: Verification of temperature values for sub-channel 6, region 2 for a nuclear fuel rod

Pipe 6/Region 2	Surface	Centre	Average	in Kelvin	f216 Coupling
11	873.75	600.54	737.145	664.90	664.9
10	868.31	598.49	733.4	662.82	662.82
9	862.32	596.4	729.36	660.57	660.57
8	856.33	594.33	725.33	658.33	658.33
7	850.35	592.26	721.305	656.10	656.1
6	844.36	590.21	717.285	653.86	653.86
5	838.38	588.17	713.275	651.64	651.64
4	832.39	586.15	709.27	649.41	649.41
3	826.35	584.13	705.24	647.17	647.17
2	820.9	582.2	701.55	645.12	645.12

Table 40: Verification of temperature values for sub-channel 6, region 3 for a nuclear fuel rod

Pipe 6/Region 3	Surface	Centre	Average	in Kelvin	f216 Coupling
11	574.61	600.54	587.575	581.80	581.8
10	572.87	598.49	585.68	580.75	580.75
9	571.13	596.4	583.765	579.69	579.69
8	569.41	594.33	581.87	578.63	578.63
7	567.7	592.26	579.98	577.58	577.58
6	566	590.21	578.105	576.54	576.54
5	564.32	588.17	576.245	575.51	575.51

4	562.66	586.15	574.405	574.49	574.49
3	561	584.13	572.565	573.46	573.46
2	559.39	582.2	570.795	572.48	572.48

Table 41: Verification of temperature values for the guide tube, sub-channel 6

Pipe 6/ hsrod1	Surface	Centre	Average	in Kelvin	Coupling
11	555.3	555.04	555.17	563.80	563.8
10	553.78	553.55	553.665	562.96	562.96
9	552.28	552.1	552.19	562.14	562.14
8	550.81	550.65	550.73	561.33	561.33
7	549.34	549.22	549.28	560.53	560.53
6	547.89	547.79	547.84	559.73	559.73
5	546.47	546.39	546.43	558.94	558.94
4	545.05	544.99	545.02	558.16	558.16
3	543.65	543.61	543.63	557.39	557.39
2	542.25	542.22	542.235	556.61	556.61

Appendix F: Example of the Excel verification for each of the parameters (power, moderator (water) and heat structure temperature).

Figure F-1, Figure F-2 and Figure F-3 show how the Excel verification looks for the Power Values, notice how the difference between the two values is 0, hence proving verification.

Field 2/sub 1										Field 2/sub 2									
Iter	Conv	f216	Diff							Iter	Conv	f216	Diff						
9.82E+10		9.821E+10	0.00E+00							9.50E+10		9.5E+10	0.00E+00						
2.00E+11		1.997E+11	0.00E+00							1.91E+11		1.9E+11	0.00E+00						
2.97E+11		2.97E+11	0.00E+00							2.86E+11		2.9E+11	0.00E+00						
3.78E+11		3.779E+11	0.00E+00							3.45E+11		3.5E+11	0.00E+00						
4.00E+11		4.004E+11	0.00E+00							3.70E+11		3.7E+11	0.00E+00						
3.95E+11		3.955E+11	0.00E+00							3.63E+11		3.6E+11	0.00E+00						
3.56E+11		3.562E+11	0.00E+00							3.23E+11		3.2E+11	0.00E+00						
2.86E+11		2.862E+11	0.00E+00							2.67E+11		2.7E+11	0.00E+00						
1.93E+11		1.933E+11	0.00E+00							1.79E+11		1.8E+11	0.00E+00						
8.96E+10		8.963E+10	0.00E+00							8.38E+10		8.4E+10	0.00E+00						
9.82E+10	2.00E+11	2.97E+11	3.78E+11	4.00E+11	3.95E+11	3.56E+11	2.86E+11	1.93E+11	8.96E+10	9.50E+10	1.91E+11	2.86E+11	3.45E+11	3.70E+11	3.63E+11	3.23E+11	2.67E+11	1.79E+11	8.38E+10
Field 2/sub 3										Field 2/sub 4									
Iter	Conv	f216	Diff							Iter	Conv	f216	Diff						
9.33E+10		9.334E+10	0.00E+00							9.40E+10		9.4E+10	0.00E+00						
1.91E+11		1.914E+11	0.00E+00							2.06E+11		2.1E+11	0.00E+00						
2.73E+11		2.728E+11	0.00E+00							2.99E+11		3E+11	0.00E+00						
3.48E+11		3.483E+11	0.00E+00							3.74E+11		3.7E+11	0.00E+00						
3.73E+11		3.725E+11	0.00E+00							3.99E+11		4E+11	0.00E+00						
3.66E+11		3.661E+11	0.00E+00							3.89E+11		3.9E+11	0.00E+00						
3.22E+11		3.224E+11	0.00E+00							3.55E+11		3.6E+11	0.00E+00						
2.68E+11		2.679E+11	0.00E+00							2.82E+11		2.8E+11	0.00E+00						
1.85E+11		1.848E+11	0.00E+00							1.93E+11		1.9E+11	0.00E+00						
8.84E+10		8.837E+10	0.00E+00							9.23E+10		9.2E+10	0.00E+00						
9.33E+10	1.91E+11	2.73E+11	3.48E+11	3.73E+11	3.66E+11	3.22E+11	2.68E+11	1.85E+11	8.84E+10	9.40E+10	2.06E+11	2.99E+11	3.74E+11	3.99E+11	3.89E+11	3.55E+11	2.82E+11	1.93E+11	9.23E+10

Figure F-1: Excel verification of power values

Field 2/sub 5										Field 2/sub 6									
Iter	Conv	f216	Diff							Iter	Conv	f216	Diff						
9.20E+11		9.205E+11	0.00E+00							5.31E+12		5.3E+12	0.00E+00						
1.89E+12		1.887E+12	0.00E+00							1.11E+13		1.1E+13	0.00E+00						
2.85E+12		2.85E+12	0.00E+00							1.61E+13		1.6E+13	0.00E+00						
3.49E+12		3.493E+12	0.00E+00							1.99E+13		2E+13	0.00E+00						
3.78E+12		3.779E+12	0.00E+00							2.18E+13		2.2E+13	0.00E+00						
3.70E+12		3.702E+12	0.00E+00							2.14E+13		2.1E+13	0.00E+00						
3.26E+12		3.26E+12	0.00E+00							1.89E+13		1.9E+13	0.00E+00						
2.66E+12		2.66E+12	0.00E+00							1.55E+13		1.5E+13	0.00E+00						
1.82E+12		1.816E+12	0.00E+00							1.08E+13		1.1E+13	0.00E+00						
8.53E+11		8.526E+11	0.00E+00							5.13E+12		5.1E+12	0.00E+00						
9.20E+11	1.89E+12	2.85E+12	3.49E+12	3.78E+12	3.70E+12	3.26E+12	2.66E+12	1.82E+12	8.53E+11	5.31E+12	1.11E+13	1.61E+13	1.99E+13	2.18E+13	2.14E+13	1.89E+13	1.55E+13	1.08E+13	5.13E+12
Field 2/sub 7										Field 2/sub 8									
Iter	Conv	f216	Diff							Iter	Conv	f216	Diff						
1.43E+13		1.431E+13	0.00E+00							3.31E+13		3.3E+13	0.00E+00						
2.95E+13		2.952E+13	0.00E+00							6.86E+13		6.9E+13	0.00E+00						
4.25E+13		4.248E+13	0.00E+00							9.80E+13		9.8E+13	0.00E+00						
5.25E+13		5.255E+13	0.00E+00							1.21E+14		1.2E+14	0.00E+00						
5.71E+13		5.71E+13	0.00E+00							1.30E+14		1.3E+14	0.00E+00						
5.62E+13		5.615E+13	0.00E+00							1.29E+14		1.3E+14	0.00E+00						
5.07E+13		5.075E+13	0.00E+00							1.16E+14		1.2E+14	0.00E+00						
4.10E+13		4.104E+13	0.00E+00							9.48E+13		9.5E+13	0.00E+00						
2.82E+13		2.816E+13	0.00E+00							6.46E+13		6.5E+13	0.00E+00						
1.36E+13		1.355E+13	0.00E+00							3.09E+13		3.1E+13	0.00E+00						
1.43E+13	2.95E+13	4.25E+13	5.25E+13	5.71E+13	5.62E+13	5.07E+13	4.10E+13	2.82E+13	1.36E+13	3.31E+13	6.86E+13	9.80E+13	1.21E+14	1.30E+14	1.29E+14	1.16E+14	9.48E+13	6.46E+13	3.09E+13

Figure F-2: Excel verification of power values (continued)

Field 2/sub 9									
Iter	Conv	f216	Diff						
2.83E+14		2.831E+14	0.00E+00						
5.97E+14		5.966E+14	0.00E+00						
8.60E+14		8.601E+14	0.00E+00						
1.04E+15		1.043E+15	0.00E+00						
1.13E+15		1.134E+15	0.00E+00						
1.13E+15		1.125E+15	0.00E+00						
1.02E+15		1.017E+15	0.00E+00						
8.25E+14		8.254E+14	0.00E+00						
5.66E+14		5.659E+14	0.00E+00						
2.70E+14		2.705E+14	0.00E+00						
2.83E+14	5.97E+14	8.60E+14	1.04E+15	1.13E+15	1.13E+15	1.02E+15	8.25E+14	5.66E+14	2.70E+14

Figure F-3: Excel verification of power values (continued)

Figure F-4 and Figure F-5 show how the Excel verification looks for the moderator (water) temperature values. The difference between the two values is 0, which proves the verification.

Sub 1				Sub 2			
	Iter Conv	f216	Diff		Iter Conv	f216	Diff
	5.57E+02	556.95	0.00E+00		5.57E+02	556.959	0.00E+00
	5.58E+02	557.746	0.00E+00		5.58E+02	557.77	0.00E+00
	5.59E+02	558.557	0.00E+00		5.59E+02	558.592	0.00E+00
	5.59E+02	559.383	0.00E+00		5.59E+02	559.425	0.00E+00
	5.60E+02	560.225	0.00E+00		5.60E+02	560.272	0.00E+00
	5.61E+02	561.083	0.00E+00		5.61E+02	561.131	0.00E+00
	5.62E+02	561.956	0.00E+00		5.62E+02	562.004	0.00E+00
	5.63E+02	562.842	0.00E+00		5.63E+02	562.89	0.00E+00
	5.64E+02	563.743	0.00E+00		5.64E+02	563.792	0.00E+00
	5.65E+02	564.662	0.00E+00		5.65E+02	564.711	0.00E+00
Sub 3				Sub 4			
	Iter Conv	f216	Diff		Iter Conv	f216	Diff
	5.57E+02	557.028	0.00E+00		5.57E+02	556.948	0.00E+00
	5.58E+02	557.936	0.00E+00		5.58E+02	557.741	0.00E+00
	5.59E+02	558.8	0.00E+00		5.59E+02	558.557	0.00E+00
	5.60E+02	559.655	0.00E+00		5.59E+02	559.392	0.00E+00
	5.61E+02	560.515	0.00E+00		5.60E+02	560.241	0.00E+00
	5.61E+02	561.383	0.00E+00		5.61E+02	561.103	0.00E+00
	5.62E+02	562.265	0.00E+00		5.62E+02	561.98	0.00E+00
	5.63E+02	563.16	0.00E+00		5.63E+02	562.873	0.00E+00
	5.64E+02	564.068	0.00E+00		5.64E+02	563.778	0.00E+00
	5.65E+02	564.992	0.00E+00		5.65E+02	564.7	0.00E+00
Sub 5				Sub 6			
	Iter Conv	f216	Diff		Iter Conv	f216	Diff
	5.57E+02	556.937	0.00E+00		5.57E+02	556.961	0.00E+00
	5.58E+02	557.71	0.00E+00		5.58E+02	557.772	0.00E+00
	5.59E+02	558.51	0.00E+00		5.59E+02	558.59	0.00E+00
	5.59E+02	559.332	0.00E+00		5.59E+02	559.416	0.00E+00
	5.60E+02	560.17	0.00E+00		5.60E+02	560.256	0.00E+00
	5.61E+02	561.023	0.00E+00		5.61E+02	561.109	0.00E+00
	5.62E+02	561.894	0.00E+00		5.62E+02	561.975	0.00E+00
	5.63E+02	562.78	0.00E+00		5.63E+02	562.859	0.00E+00
	5.64E+02	563.679	0.00E+00		5.64E+02	563.761	0.00E+00
	5.65E+02	564.594	0.00E+00		5.65E+02	564.678	0.00E+00

Figure F-4: Excel verification of the moderator (water) temperature

Sub 7				Sub 8				
	Iter Conv	f216	Diff			Iter Conv	f216	Diff
	5.57E+02	556.904	0.00E+00			5.57E+02	556.997	0.00E+00
	5.58E+02	557.611	0.00E+00			5.58E+02	557.896	0.00E+00
	5.58E+02	558.344	0.00E+00			5.59E+02	558.833	0.00E+00
	5.59E+02	559.105	0.00E+00			5.60E+02	559.808	0.00E+00
	5.60E+02	559.891	0.00E+00			5.61E+02	560.82	0.00E+00
	5.61E+02	560.702	0.00E+00			5.62E+02	561.865	0.00E+00
	5.62E+02	561.54	0.00E+00			5.63E+02	562.946	0.00E+00
	5.62E+02	562.406	0.00E+00			5.64E+02	564.062	0.00E+00
	5.63E+02	563.296	0.00E+00			5.65E+02	565.213	0.00E+00
	5.64E+02	564.213	0.00E+00			5.66E+02	566.4	0.00E+00
Sub 9								
	Iter Conv	f216	Diff					
	5.57E+02	557.256	0.00E+00					
	5.59E+02	558.666	0.00E+00					
	5.60E+02	560.103	0.00E+00					
	5.62E+02	561.568	0.00E+00					
	5.63E+02	563.06	0.00E+00					
	5.65E+02	564.579	0.00E+00					
	5.66E+02	566.128	0.00E+00					
	5.68E+02	567.704	0.00E+00					
	5.69E+02	569.306	0.00E+00					
	5.71E+02	570.937	0.00E+00					

Figure F-5: Excel verification of the moderator (water) temperature (continued)

Figure F-6, Figure F-7, Figure F-8, Figure F-9 and Figure F-10 shows how the Excel verification looks for the heat structure temperature values. The difference between the two values is 0, which proves the verification.

Sub 1, Value 1				Sub 1, Value 2				Sub 1, Value 3			
	Iter Conv	f216	Diff		Iter Conv	f216	Diff		Iter Conv	f216	Diff
	7.26E+02	725.71	0.00E+00		6.22E+02	622.14	0.00E+00		5.68E+02	568.33	0.00E+00
	7.30E+02	730.13	0.00E+00		6.24E+02	624.24	0.00E+00		5.69E+02	569.35	0.00E+00
	7.35E+02	735.1	0.00E+00		6.27E+02	626.53	0.00E+00		5.70E+02	570.41	0.00E+00
	7.40E+02	740.09	0.00E+00		6.29E+02	628.83	0.00E+00		5.71E+02	571.48	0.00E+00
	7.45E+02	745.09	0.00E+00		6.31E+02	631.14	0.00E+00		5.73E+02	572.57	0.00E+00
	7.50E+02	750.12	0.00E+00		6.33E+02	633.47	0.00E+00		5.74E+02	573.67	0.00E+00
	7.55E+02	755.17	0.00E+00		6.36E+02	635.8	0.00E+00		5.75E+02	574.78	0.00E+00
	7.60E+02	760.23	0.00E+00		6.38E+02	638.14	0.00E+00		5.76E+02	575.9	0.00E+00
	7.65E+02	765.31	0.00E+00		6.40E+02	640.49	0.00E+00		5.77E+02	577.03	0.00E+00
	7.70E+02	769.87	0.00E+00		6.43E+02	642.66	0.00E+00		5.78E+02	578.14	0.00E+00
Sub 2, Value 1				Sub 2, Value 2				Sub 2, Value 3			
	Iter Conv	f216	Diff		Iter Conv	f216	Diff		Iter Conv	f216	Diff
	7.41E+02	741.31	0.00E+00		6.28E+02	627.83	0.00E+00		5.69E+02	569.39	0.00E+00
	7.46E+02	745.97	0.00E+00		6.30E+02	630.07	0.00E+00		5.71E+02	570.52	0.00E+00
	7.51E+02	751.22	0.00E+00		6.33E+02	632.53	0.00E+00		5.72E+02	571.72	0.00E+00
	7.57E+02	756.52	0.00E+00		6.35E+02	635.02	0.00E+00		5.73E+02	572.96	0.00E+00
	7.62E+02	761.86	0.00E+00		6.38E+02	637.54	0.00E+00		5.74E+02	574.23	0.00E+00
	7.67E+02	767.23	0.00E+00		6.40E+02	640.09	0.00E+00		5.76E+02	575.52	0.00E+00
	7.73E+02	772.65	0.00E+00		6.43E+02	642.67	0.00E+00		5.77E+02	576.85	0.00E+00
	7.78E+02	778.09	0.00E+00		6.45E+02	645.27	0.00E+00		5.78E+02	578.21	0.00E+00
	7.84E+02	783.58	0.00E+00		6.48E+02	647.9	0.00E+00		5.80E+02	579.6	0.00E+00
	7.89E+02	788.54	0.00E+00		6.50E+02	650.35	0.00E+00		5.81E+02	580.97	0.00E+00

Figure F-6: Excel verification of the heat structure temperature values

Sub 3, Value 1				Sub 3, Value 2				Sub 3, Value 3				Sub 3, Value 4				Sub 3, Value 5			
Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff
	8.74E+02	674.01	0.00E+00		6.74E+02	674.04	0.00E+00		5.78E+02	577.99	0.00E+00		5.57E+02	557.19	0.00E+00		5.57E+02	557.19	0.00E+00
	8.83E+02	682.67	0.00E+00		6.78E+02	677.79	0.00E+00		5.80E+02	579.79	0.00E+00		5.59E+02	558.58	0.00E+00		5.59E+02	558.58	0.00E+00
	8.92E+02	692.44	0.00E+00		6.82E+02	681.9	0.00E+00		5.82E+02	581.69	0.00E+00		5.60E+02	559.99	0.00E+00		5.60E+02	559.99	0.00E+00
	9.02E+02	702.28	0.00E+00		6.86E+02	686.03	0.00E+00		5.84E+02	583.6	0.00E+00		5.61E+02	561.44	0.00E+00		5.61E+02	561.44	0.00E+00
	9.12E+02	712.16	0.00E+00		6.90E+02	690.16	0.00E+00		5.86E+02	585.51	0.00E+00		5.63E+02	562.88	0.00E+00		5.63E+02	562.88	0.00E+00
	9.22E+02	722.09	0.00E+00		6.94E+02	694.31	0.00E+00		5.87E+02	587.46	0.00E+00		5.64E+02	564.38	0.00E+00		5.64E+02	564.38	0.00E+00
	9.32E+02	732.08	0.00E+00		6.98E+02	698.48	0.00E+00		5.89E+02	589.42	0.00E+00		5.66E+02	565.85	0.00E+00		5.66E+02	565.85	0.00E+00
	9.42E+02	742.11	0.00E+00		7.03E+02	702.65	0.00E+00		5.91E+02	591.38	0.00E+00		5.67E+02	567.35	0.00E+00		5.67E+02	567.35	0.00E+00
	9.52E+02	752.2	0.00E+00		7.07E+02	706.83	0.00E+00		5.93E+02	593.37	0.00E+00		5.69E+02	568.87	0.00E+00		5.69E+02	568.87	0.00E+00
	9.61E+02	761.24	0.00E+00		7.11E+02	710.68	0.00E+00		5.95E+02	595.32	0.00E+00		5.70E+02	570.41	0.00E+00		5.70E+02	570.41	0.00E+00
Sub 4, Value 1				Sub 4, Value 2				Sub 4, Value 3				Sub 4, Value 4				Sub 4, Value 5			
	7.06E+02	705.6	0.00E+00		6.15E+02	614.66	0.00E+00		5.67E+02	566.88	0.00E+00		5.57E+02	556.68	0.00E+00		5.57E+02	556.68	0.00E+00
	7.09E+02	709.29	0.00E+00		6.16E+02	614.46	0.00E+00		5.68E+02	567.78	0.00E+00		5.58E+02	557.58	0.00E+00		5.58E+02	557.58	0.00E+00
	7.13E+02	713.44	0.00E+00		6.18E+02	618.43	0.00E+00		5.69E+02	568.73	0.00E+00		5.59E+02	558.52	0.00E+00		5.59E+02	558.52	0.00E+00
	7.18E+02	717.62	0.00E+00		6.20E+02	620.43	0.00E+00		5.70E+02	569.7	0.00E+00		5.59E+02	559.48	0.00E+00		5.59E+02	559.48	0.00E+00
	7.22E+02	721.82	0.00E+00		6.22E+02	622.45	0.00E+00		5.71E+02	570.7	0.00E+00		5.60E+02	560.49	0.00E+00		5.60E+02	560.49	0.00E+00
	7.28E+02	726.05	0.00E+00		6.24E+02	624.49	0.00E+00		5.72E+02	571.72	0.00E+00		5.62E+02	561.52	0.00E+00		5.62E+02	561.52	0.00E+00
	7.30E+02	730.31	0.00E+00		6.27E+02	626.55	0.00E+00		5.73E+02	572.77	0.00E+00		5.63E+02	562.57	0.00E+00		5.63E+02	562.57	0.00E+00
	7.35E+02	734.6	0.00E+00		6.29E+02	628.63	0.00E+00		5.74E+02	573.84	0.00E+00		5.64E+02	563.66	0.00E+00		5.64E+02	563.66	0.00E+00
	7.39E+02	738.91	0.00E+00		6.31E+02	630.72	0.00E+00		5.75E+02	574.92	0.00E+00		5.65E+02	564.78	0.00E+00		5.65E+02	564.78	0.00E+00
	7.43E+02	742.8	0.00E+00		6.33E+02	632.68	0.00E+00		5.76E+02	576.01	0.00E+00		5.66E+02	565.93	0.00E+00		5.66E+02	565.93	0.00E+00

Figure F-7: Excel verification of the heat structure temperature (continued)

Sub 5, Value 1				Sub 5, Value 2				Sub 5, Value 3				Sub 5, Value 4				Sub 5, Value 5			
Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff
	7.25E+02	724.7	0.00E+00		6.22E+02	621.71	0.00E+00		5.68E+02	568.18	0.00E+00		5.57E+02	556.5	0.00E+00		5.57E+02	556.5	0.00E+00
	7.29E+02	728.79	0.00E+00		6.24E+02	623.68	0.00E+00		5.69E+02	569.17	0.00E+00		5.57E+02	557.21	0.00E+00		5.57E+02	557.21	0.00E+00
	7.33E+02	733.4	0.00E+00		6.26E+02	625.84	0.00E+00		5.70E+02	570.2	0.00E+00		5.58E+02	557.94	0.00E+00		5.58E+02	557.94	0.00E+00
	7.38E+02	738.01	0.00E+00		6.28E+02	628.01	0.00E+00		5.71E+02	571.25	0.00E+00		5.59E+02	558.69	0.00E+00		5.59E+02	558.69	0.00E+00
	7.43E+02	742.64	0.00E+00		6.30E+02	630.19	0.00E+00		5.72E+02	572.31	0.00E+00		5.59E+02	559.47	0.00E+00		5.59E+02	559.47	0.00E+00
	7.47E+02	747.28	0.00E+00		6.32E+02	632.38	0.00E+00		5.73E+02	573.4	0.00E+00		5.60E+02	560.27	0.00E+00		5.60E+02	560.27	0.00E+00
	7.52E+02	751.94	0.00E+00		6.35E+02	634.58	0.00E+00		5.74E+02	574.48	0.00E+00		5.61E+02	561.11	0.00E+00		5.61E+02	561.11	0.00E+00
	7.57E+02	756.61	0.00E+00		6.37E+02	636.78	0.00E+00		5.76E+02	575.58	0.00E+00		5.62E+02	561.95	0.00E+00		5.62E+02	561.95	0.00E+00
	7.61E+02	761.29	0.00E+00		6.39E+02	638.99	0.00E+00		5.77E+02	576.69	0.00E+00		5.63E+02	562.82	0.00E+00		5.63E+02	562.82	0.00E+00
	7.66E+02	765.51	0.00E+00		6.41E+02	641.05	0.00E+00		5.78E+02	577.78	0.00E+00		5.64E+02	563.71	0.00E+00		5.64E+02	563.71	0.00E+00
Sub 6, Value 1				Sub 6, Value 2				Sub 6, Value 3				Sub 6, Value 4				Sub 6, Value 5			
	5.57E+02	556.74	0.00E+00		5.57E+02	556.74	0.00E+00		7.60E+02	759.72	0.00E+00		6.34E+02	634.43	0.00E+00		5.71E+02	570.55	0.00E+00
	5.58E+02	557.6	0.00E+00		5.58E+02	557.6	0.00E+00		7.64E+02	764.46	0.00E+00		6.37E+02	636.6	0.00E+00		5.72E+02	571.57	0.00E+00
	5.59E+02	558.44	0.00E+00		5.58E+02	558.44	0.00E+00		7.70E+02	769.79	0.00E+00		6.39E+02	638.98	0.00E+00		5.73E+02	572.65	0.00E+00
	5.59E+02	559.28	0.00E+00		5.59E+02	559.28	0.00E+00		7.75E+02	775.11	0.00E+00		6.41E+02	641.37	0.00E+00		5.74E+02	573.74	0.00E+00
	5.60E+02	560.12	0.00E+00		5.60E+02	560.12	0.00E+00		7.80E+02	780.44	0.00E+00		6.44E+02	643.76	0.00E+00		5.75E+02	574.85	0.00E+00
	5.61E+02	560.98	0.00E+00		5.61E+02	560.98	0.00E+00		7.86E+02	785.78	0.00E+00		6.46E+02	646.16	0.00E+00		5.76E+02	575.97	0.00E+00
	5.62E+02	561.83	0.00E+00		5.62E+02	561.83	0.00E+00		7.91E+02	791.12	0.00E+00		6.49E+02	648.57	0.00E+00		5.77E+02	577.1	0.00E+00
	5.63E+02	562.7	0.00E+00		5.63E+02	562.7	0.00E+00		7.96E+02	796.49	0.00E+00		6.51E+02	650.97	0.00E+00		5.78E+02	578.23	0.00E+00
	5.64E+02	563.58	0.00E+00		5.64E+02	563.58	0.00E+00		8.02E+02	801.66	0.00E+00		6.53E+02	653.39	0.00E+00		5.79E+02	579.37	0.00E+00
	5.64E+02	564.47	0.00E+00		5.64E+02	564.47	0.00E+00		8.07E+02	806.7	0.00E+00		6.56E+02	655.62	0.00E+00		5.81E+02	580.5	0.00E+00

Figure F-8: Excel verification of the heat structure temperature (continued)

Sub 7, Value 1				Sub 7, Value 2				Sub 7, Value 3				Sub 7, Value 4				Sub 7, Value 5			
Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff
	7.57E+02	756.97	0.00E+00		6.33E+02	633.46	0.00E+00		5.70E+02	570.39	0.00E+00		5.57E+02	556.58	0.00E+00		5.57E+02	556.58	0.00E+00
	7.62E+02	761.51	0.00E+00		6.36E+02	635.57	0.00E+00		5.71E+02	571.41	0.00E+00		5.57E+02	557.38	0.00E+00		5.57E+02	557.38	0.00E+00
	7.67E+02	766.6	0.00E+00		6.38E+02	637.87	0.00E+00		5.72E+02	572.49	0.00E+00		5.58E+02	558.19	0.00E+00		5.58E+02	558.19	0.00E+00
	7.72E+02	771.67	0.00E+00		6.40E+02	640.18	0.00E+00		5.74E+02	573.57	0.00E+00		5.59E+02	559.01	0.00E+00		5.59E+02	559.01	0.00E+00
	7.77E+02	776.75	0.00E+00		6.42E+02	642.49	0.00E+00		5.75E+02	574.66	0.00E+00		5.60E+02	559.85	0.00E+00		5.60E+02	559.85	0.00E+00
	7.82E+02	781.84	0.00E+00		6.45E+02	644.81	0.00E+00		5.76E+02	575.76	0.00E+00		5.61E+02	560.7	0.00E+00		5.61E+02	560.7	0.00E+00
	7.87E+02	786.93	0.00E+00		6.47E+02	647.13	0.00E+00		5.77E+02	576.88	0.00E+00		5.62E+02	561.56	0.00E+00		5.62E+02	561.56	0.00E+00
	7.92E+02	792.04	0.00E+00		6.49E+02	649.45	0.00E+00		5.78E+02	578	0.00E+00		5.62E+02	562.42	0.00E+00		5.62E+02	562.42	0.00E+00
	7.97E+02	797.16	0.00E+00		6.52E+02	651.78	0.00E+00		5.79E+02	579.12	0.00E+00		5.63E+02	563.3	0.00E+00		5.63E+02	563.3	0.00E+00
	8.02E+02	801.77	0.00E+00		6.54E+02	653.94	0.00E+00		5.80E+02	580.24	0.00E+00		5.64E+02	564.19	0.00E+00		5.64E+02	564.19	0.00E+00
Sub 8, Value 1				Sub 8, Value 2				Sub 8, Value 3				Sub 8, Value 4				Sub 8, Value 5			
Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff	Iter	Conv	I216	Diff
	5.57E+02	556.57	0.00E+00		5.57E+02	556.57	0.00E+00		8.13E+02	813.1	0.00E+00		6.53E+02	653.01	0.00E+00		5.74E+02	573.67	0.00E+00
	5.57E+02	557.34	0.00E+00		5.57E+02	557.34	0.00E+00		8.19E+02	819.27	0.00E+00		6.56E+02	655.68	0.00E+00		5.75E+02	574.88	0.00E+00
	5.58E+02	558.13	0.00E+00		5.58E+02	558.13	0.00E+00		8.26E+02	826.17	0.00E+00		6.59E+02	658.58	0.00E+00		5.76E+02	576.1	0.00E+00
	5.59E+02	558.95	0.00E+00		5.59E+02	558.95	0.00E+00		8.33E+02	833.03	0.00E+00		6.61E+02	661.45	0.00E+00		5.77E+02	577.3	0.00E+00
	5.60E+02	559.77	0.00E+00		5.60E+02	559.77	0.00E+00		8.40E+02	839.98	0.00E+00		6.64E+02	664.3	0.00E+00		5.78E+02	578.49	0.00E+00
	5.61E+02	560.62	0.00E+00		5.61E+02	560.62	0.00E+00		8.47E+02	846.75	0.00E+00		6.67E+02	667.16	0.00E+00		5.80E+02	578.69	0.00E+00
	5.61E+02	561.47	0.00E+00		5.61E+02	561.47	0.00E+00		8.54E+02	853.88	0.00E+00		6.70E+02	670.01	0.00E+00		5.81E+02	580.89	0.00E+00
	5.62E+02	562.32	0.00E+00		5.62E+02	562.32	0.00E+00		8.61E+02	860.54	0.00E+00		6.73E+02	672.86	0.00E+00		5.82E+02	582.1	0.00E+00
	5.63E+02	563.19	0.00E+00		5.63E+02	563.19	0.00E+00		8.67E+02	867.46	0.00E+00		6.76E+02	675.72	0.00E+00		5.83E+02	583.32	0.00E+00
	5.64E+02	564.08	0.00E+00		5.64E+02	564.08	0.00E+00		8.74E+02	873.68	0.00E+00		6.78E+02	678.37	0.00E+00		5.85E+02	584.54	0.00E+00

Appendix G: Plots of all eight sensitivity study calculations

Inlet Enthalpy + 10%

Table 42: Plots for inlet enthalpy + 10%

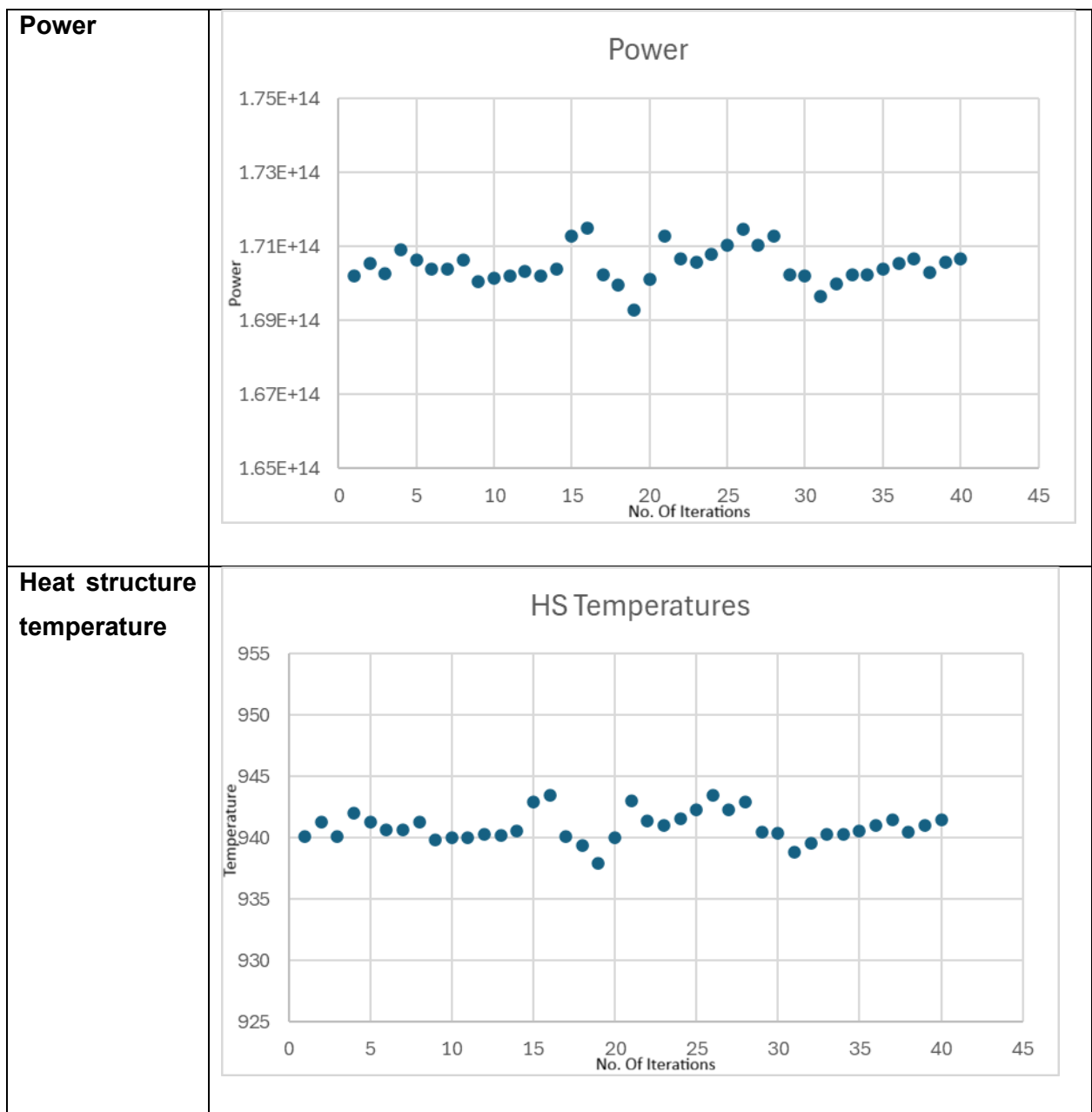
<u>Value</u>	<u>Plot</u>
Power	Power Power No. Of Iterations
Heat structure temperature	HS Temperatures Temperature No. Of Iterations

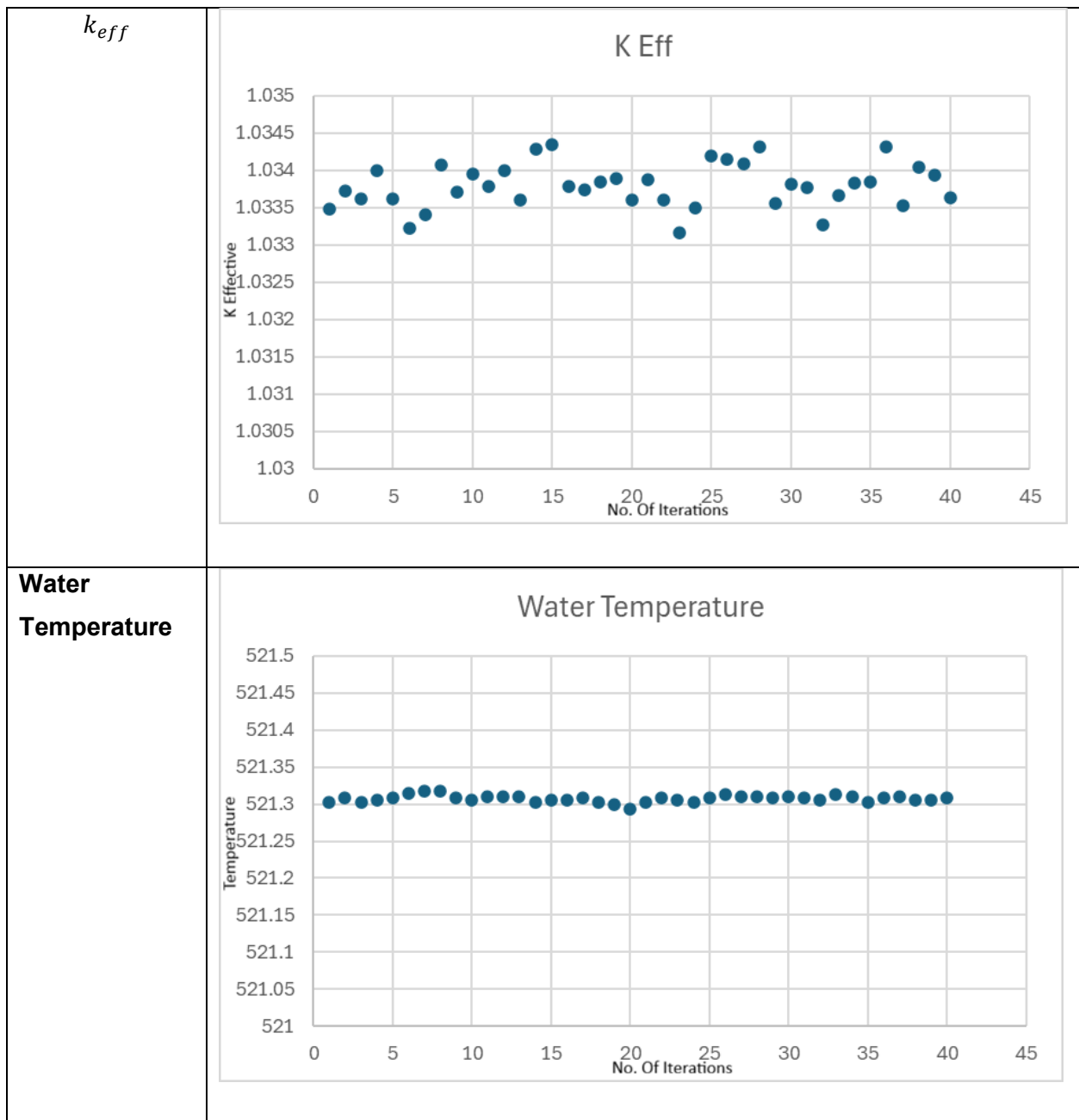
k_{eff}	K Eff No. Of Iterations
Water Temperature	Water Temperatures No. Of Iterations

Inlet Enthalpy -10%

Table 43: Plots for inlet enthalpy - 10%

<u>Value</u>	<u>Plot</u>
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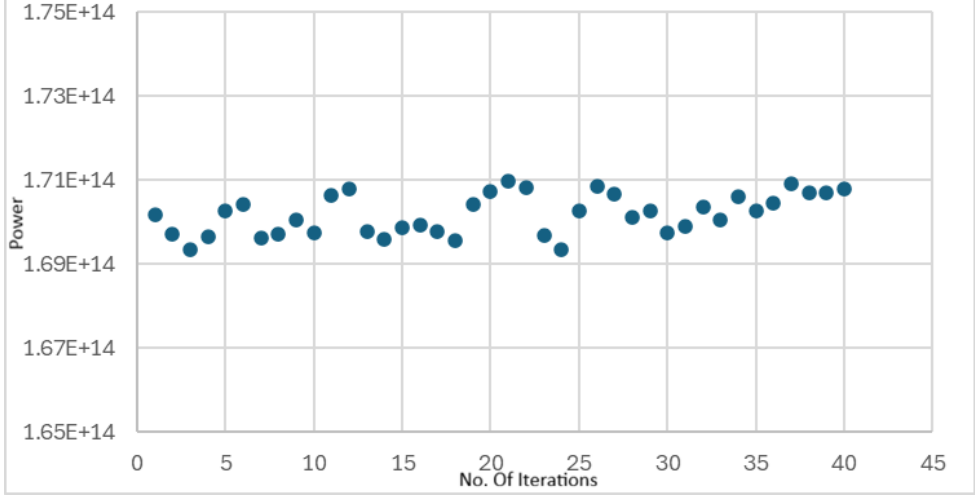
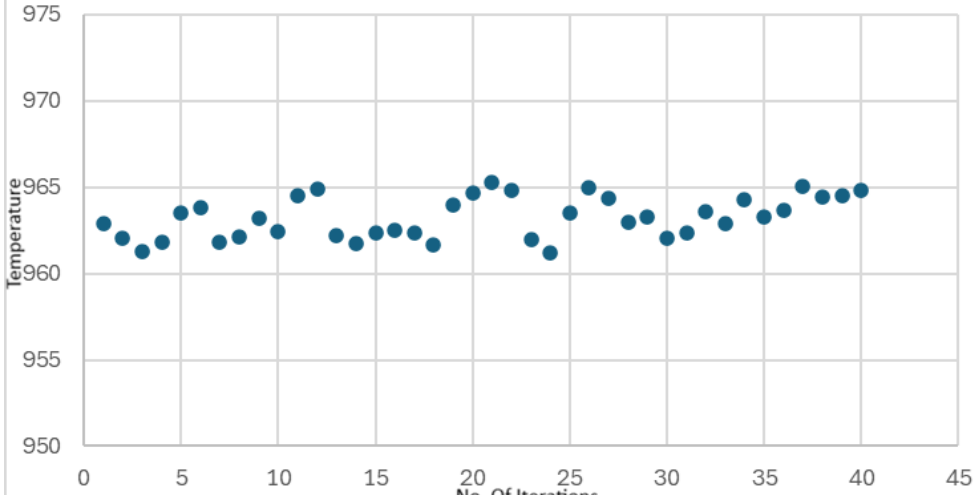




Mass Flow rate +10%

Table 44: Plots for mass flow rate + 10%

<u>Value</u>	<u>Plot</u>
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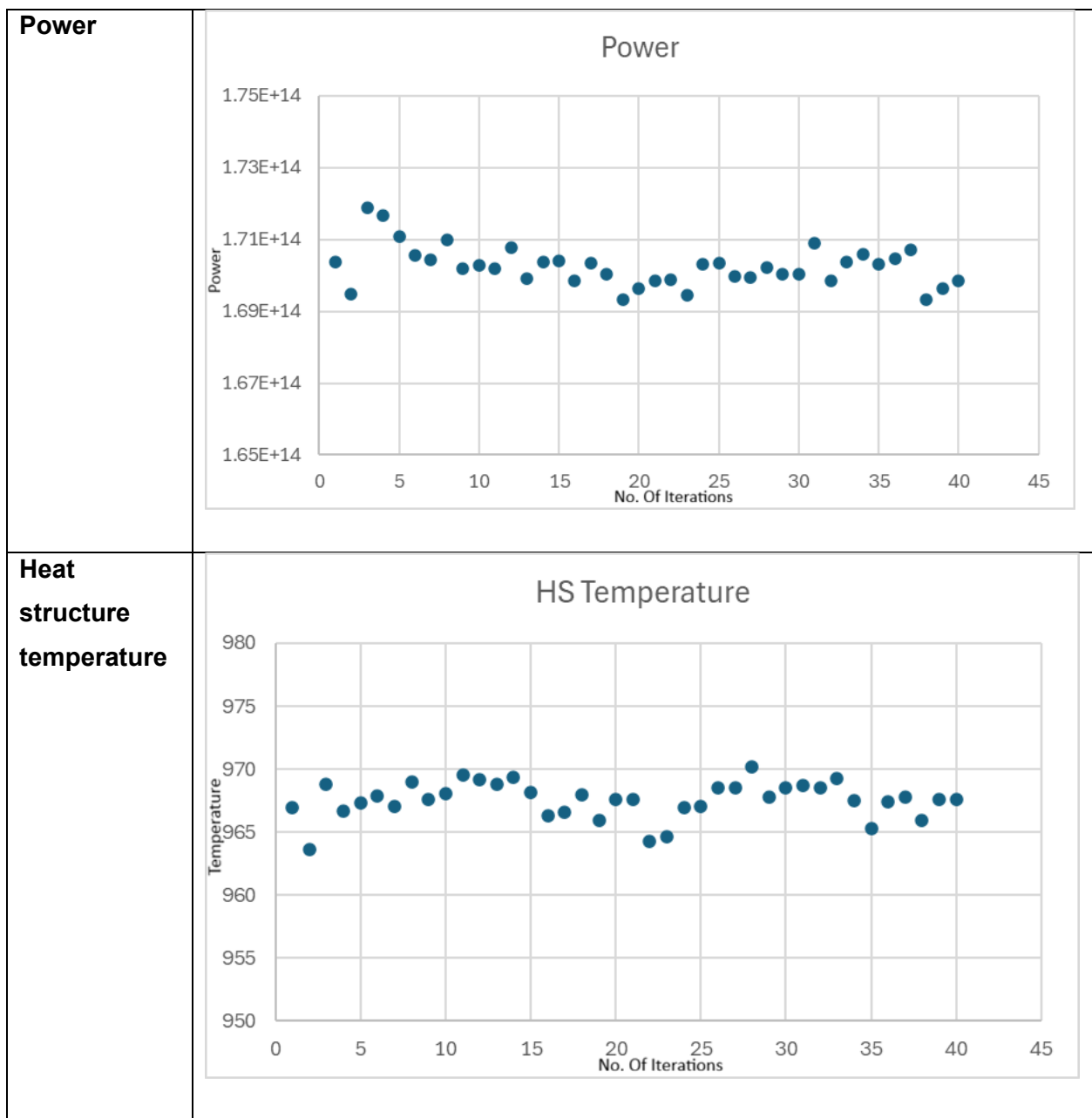
Power	Power  Power No. Of Iterations
Heat structure temperature	HS Temperatures  Temperature No. Of Iterations

k_{eff}	K Eff Water Temperature
Water Temperature	

Mass Flow rate -10%

Table 45: Plots for mass flow rate - 10%

<u>Value</u>	<u>Plot</u>
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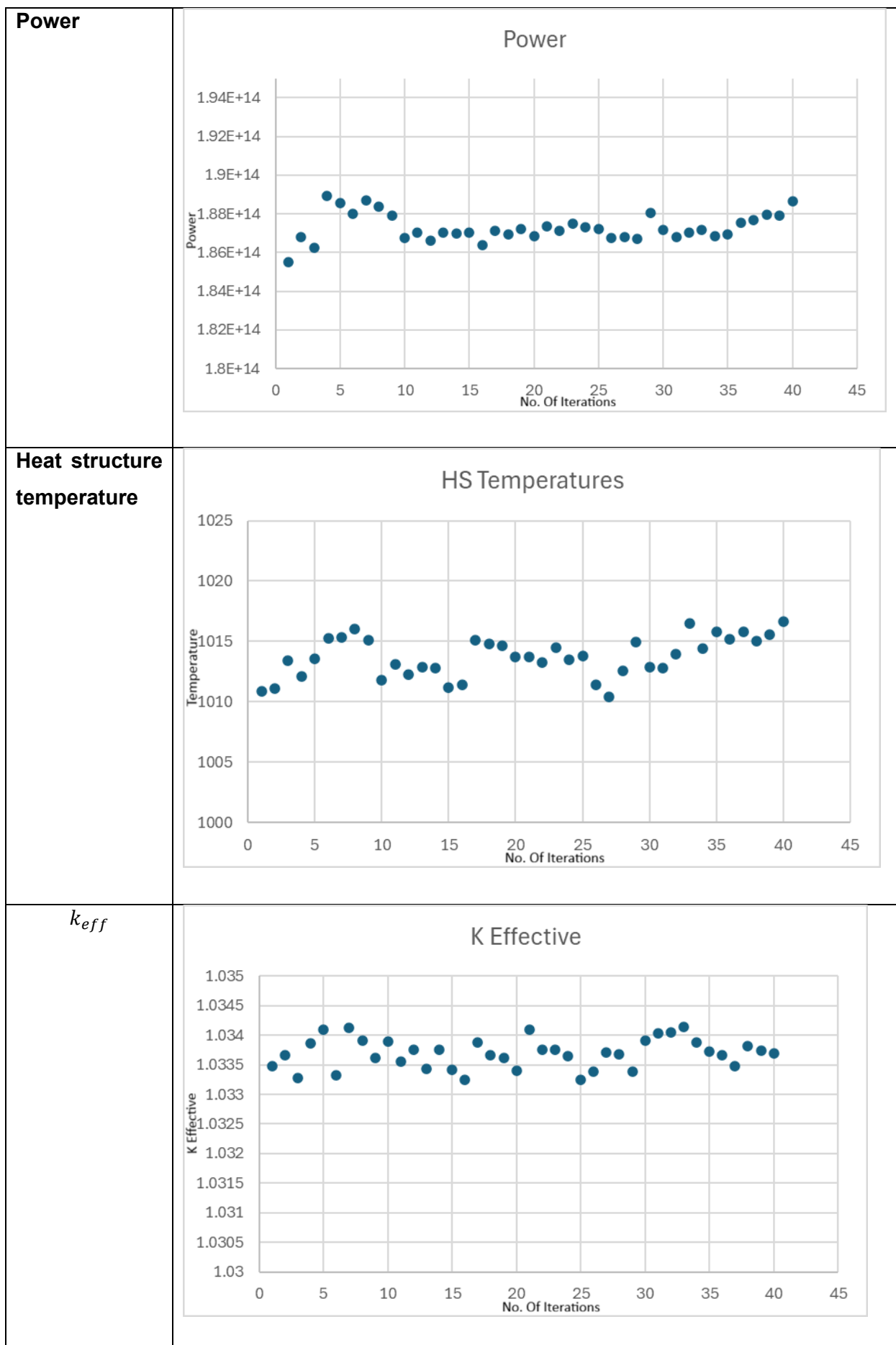


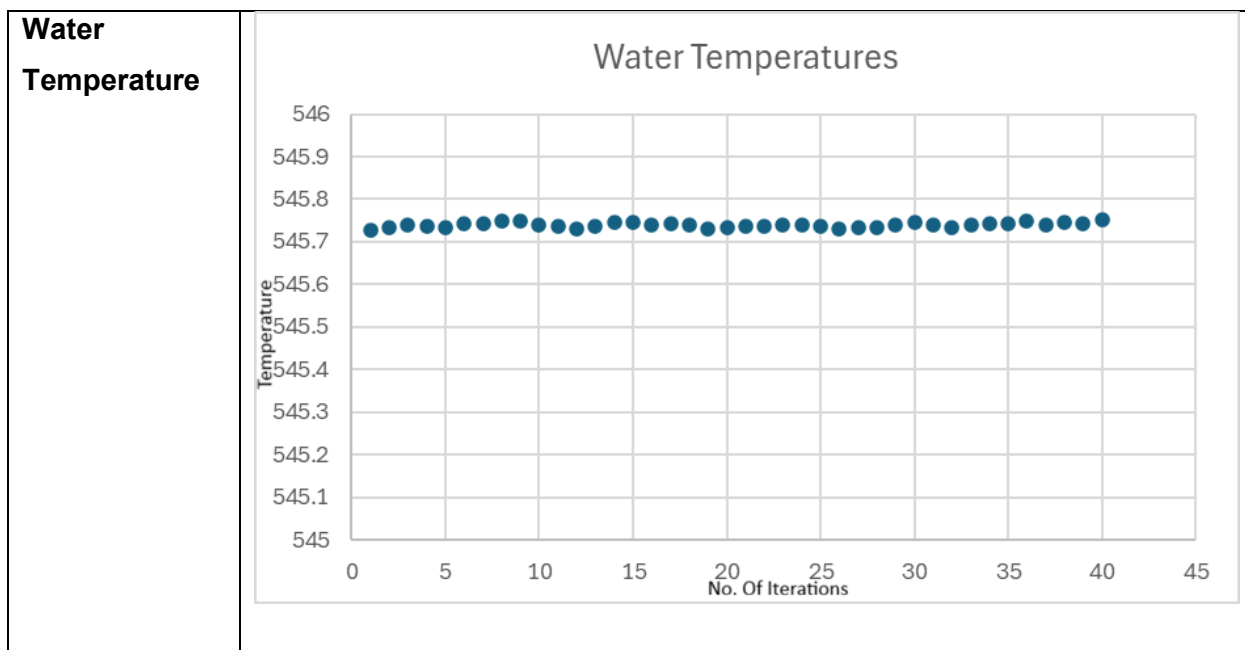
k_{eff}	K Eff No. Of Iterations
Water Temperature	Water Temperature No. Of Iterations

Power +10 %

Table 46: Plots for power + 10%

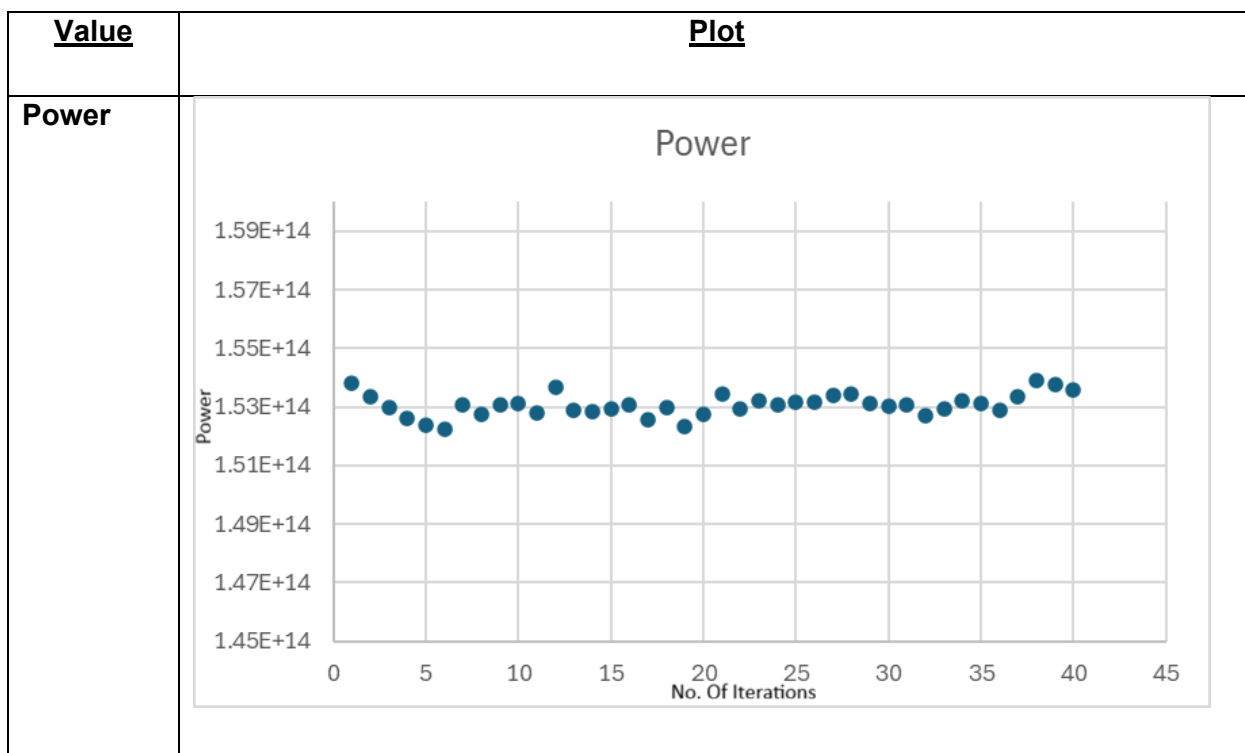
<u>Value</u>	<u>Plot</u>
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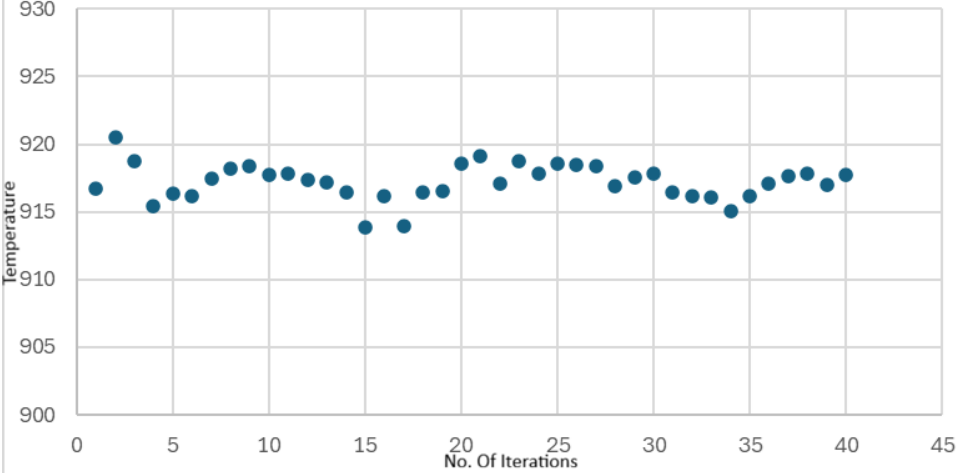
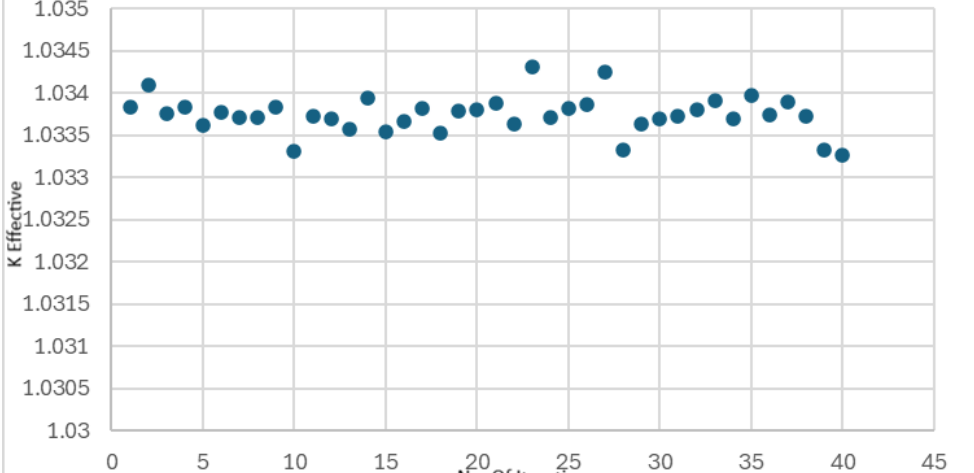


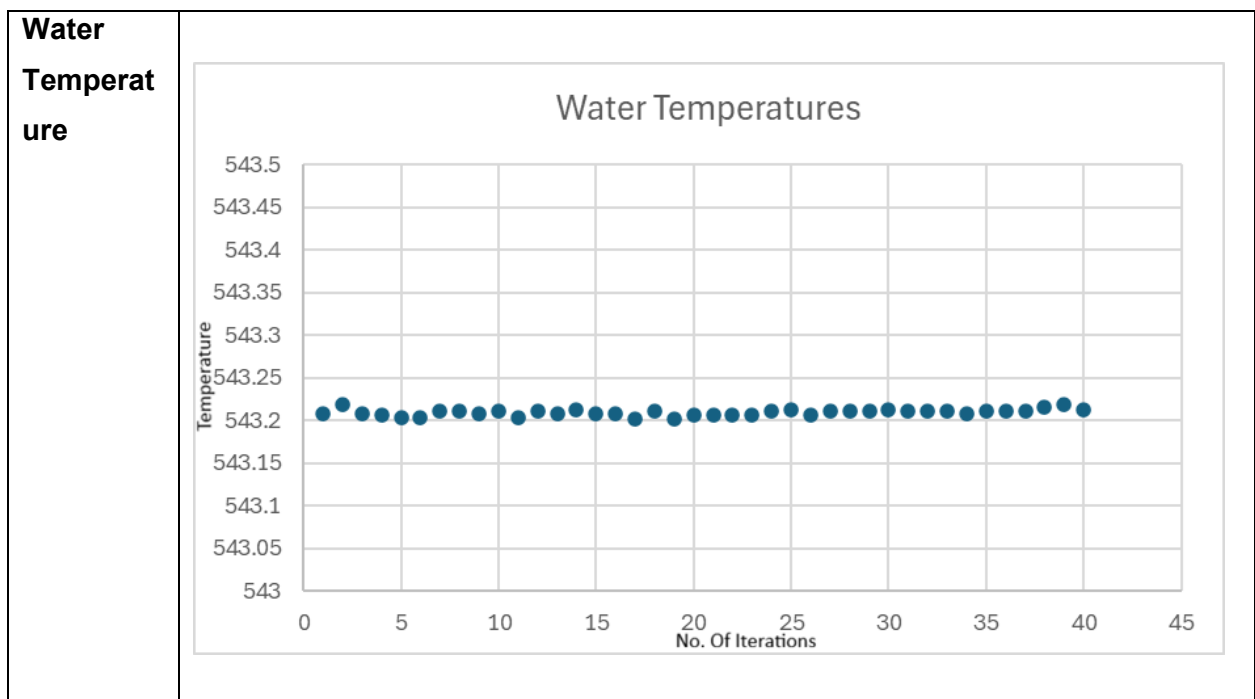


Power -10%

Table 47: Plots for power - 10%

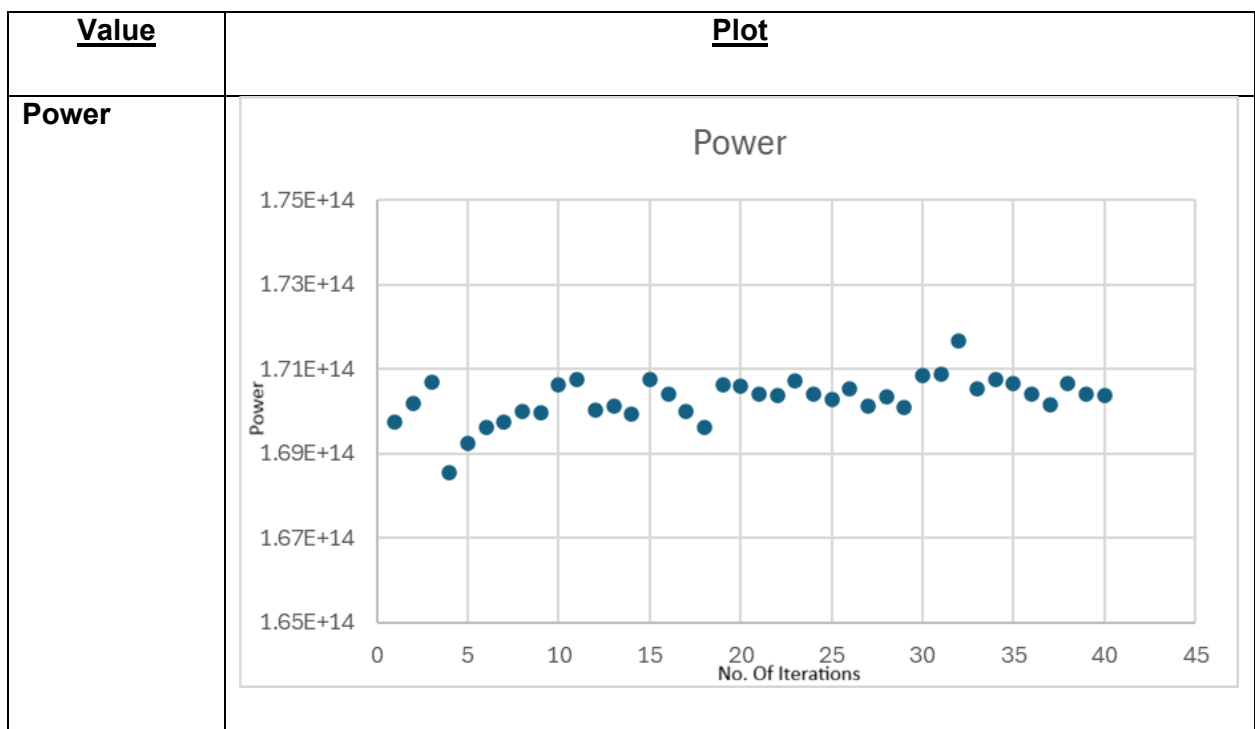


Heat structure temperature	HS Temperatures  <table border="1"> <caption>Approximate data for HS Temperatures</caption> <thead> <tr> <th>No. Of Iterations</th> <th>Temperature</th> </tr> </thead> <tbody> <tr><td>1</td><td>917</td></tr> <tr><td>2</td><td>920</td></tr> <tr><td>3</td><td>919</td></tr> <tr><td>4</td><td>915</td></tr> <tr><td>5</td><td>916</td></tr> <tr><td>6</td><td>916</td></tr> <tr><td>7</td><td>917</td></tr> <tr><td>8</td><td>918</td></tr> <tr><td>9</td><td>918</td></tr> <tr><td>10</td><td>918</td></tr> <tr><td>11</td><td>917</td></tr> <tr><td>12</td><td>917</td></tr> <tr><td>13</td><td>917</td></tr> <tr><td>14</td><td>916</td></tr> <tr><td>15</td><td>914</td></tr> <tr><td>16</td><td>916</td></tr> <tr><td>17</td><td>914</td></tr> <tr><td>18</td><td>916</td></tr> <tr><td>19</td><td>916</td></tr> <tr><td>20</td><td>919</td></tr> <tr><td>21</td><td>918</td></tr> <tr><td>22</td><td>917</td></tr> <tr><td>23</td><td>918</td></tr> <tr><td>24</td><td>918</td></tr> <tr><td>25</td><td>918</td></tr> <tr><td>26</td><td>918</td></tr> <tr><td>27</td><td>918</td></tr> <tr><td>28</td><td>917</td></tr> <tr><td>29</td><td>917</td></tr> <tr><td>30</td><td>917</td></tr> <tr><td>31</td><td>916</td></tr> <tr><td>32</td><td>916</td></tr> <tr><td>33</td><td>916</td></tr> <tr><td>34</td><td>915</td></tr> <tr><td>35</td><td>916</td></tr> <tr><td>36</td><td>917</td></tr> <tr><td>37</td><td>917</td></tr> <tr><td>38</td><td>917</td></tr> <tr><td>39</td><td>917</td></tr> <tr><td>40</td><td>917</td></tr> </tbody> </table>	No. Of Iterations	Temperature	1	917	2	920	3	919	4	915	5	916	6	916	7	917	8	918	9	918	10	918	11	917	12	917	13	917	14	916	15	914	16	916	17	914	18	916	19	916	20	919	21	918	22	917	23	918	24	918	25	918	26	918	27	918	28	917	29	917	30	917	31	916	32	916	33	916	34	915	35	916	36	917	37	917	38	917	39	917	40	917
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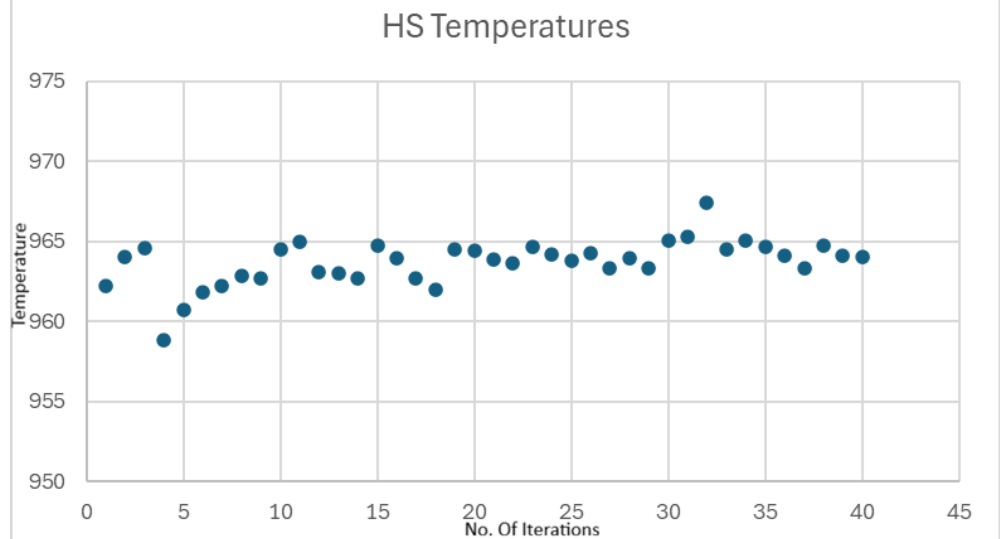


Pressure +10%

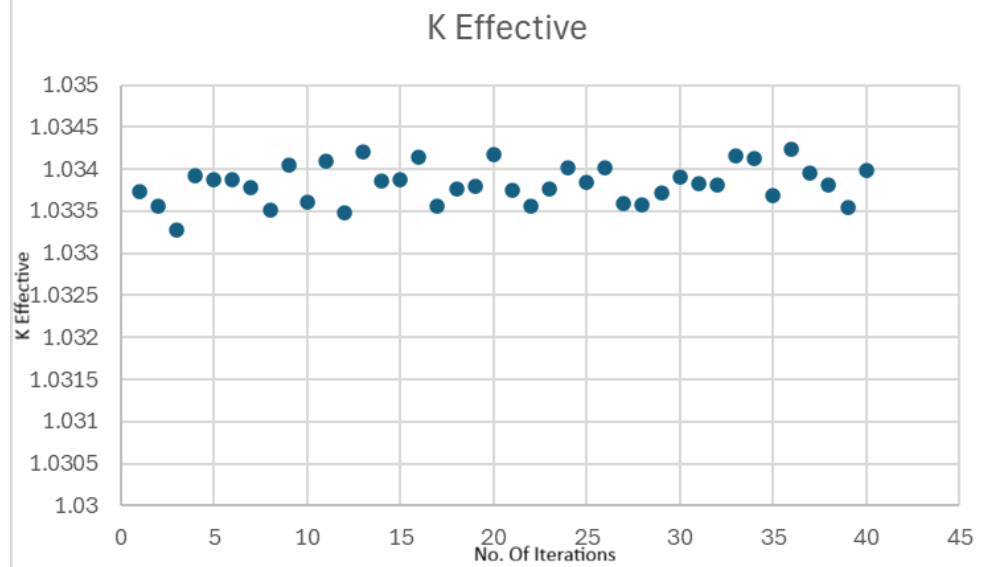
Table 48: Plots for pressure + 10%

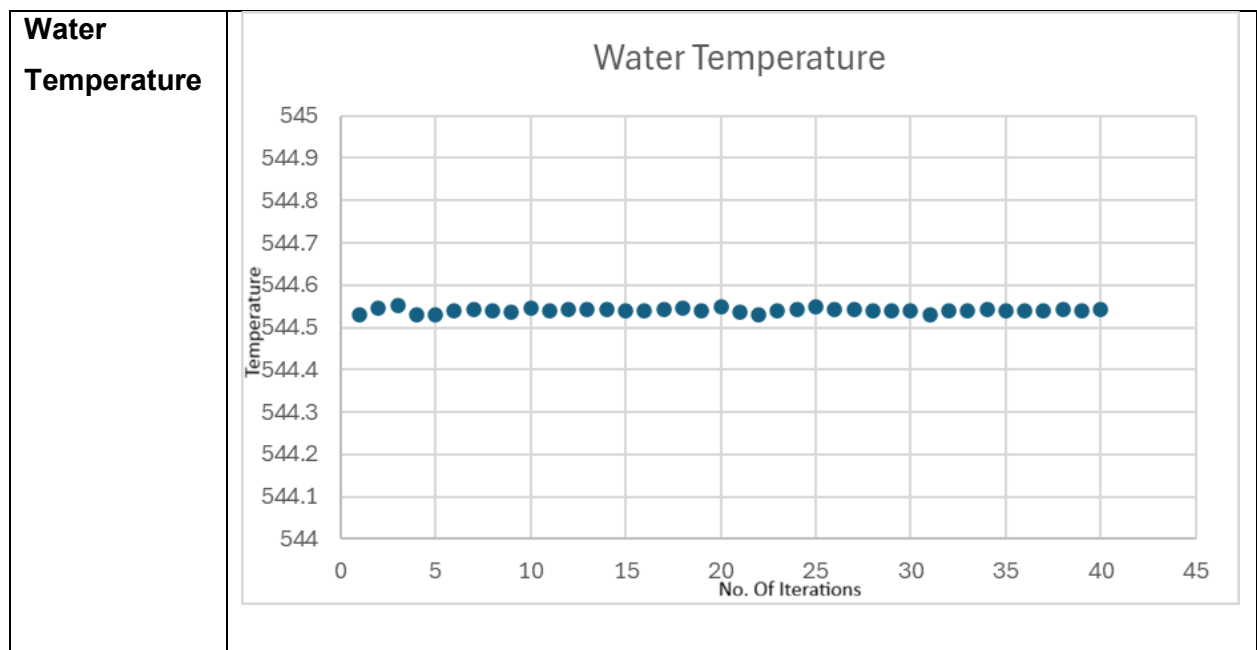


Heat
structure
temperature



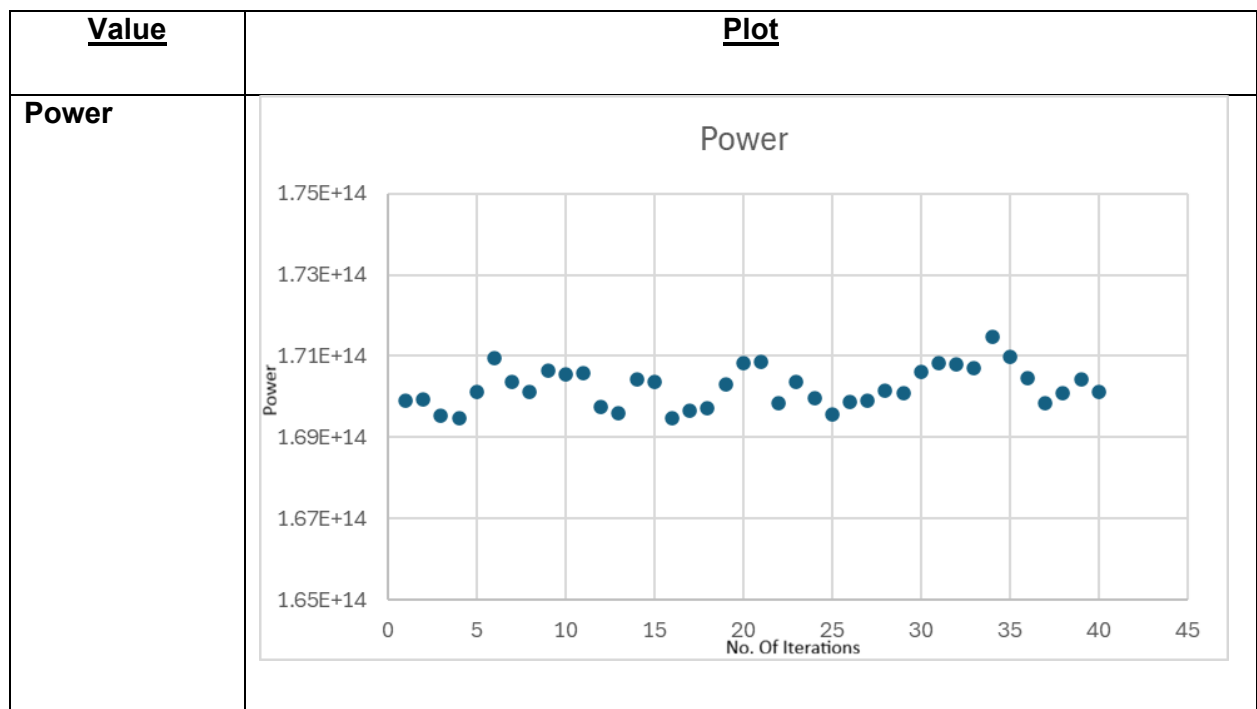
k_{eff}



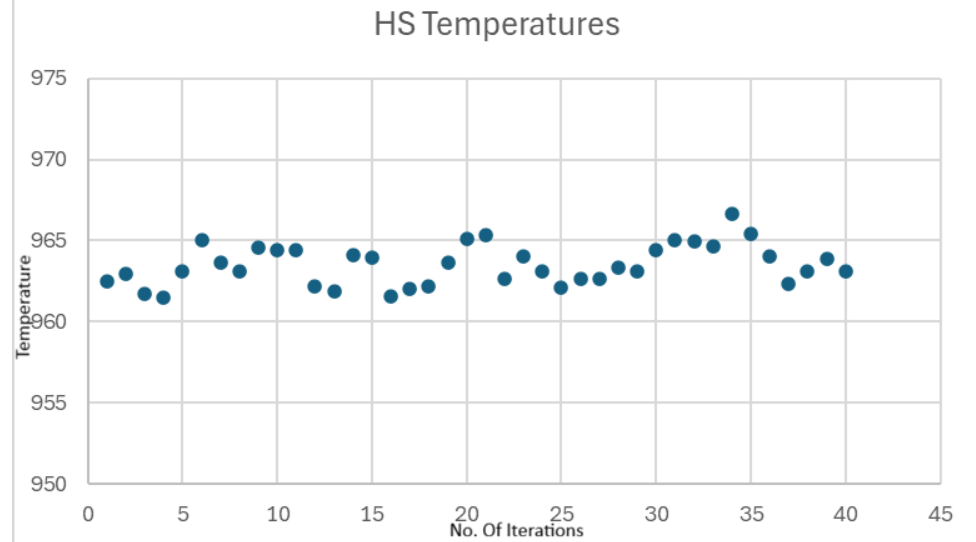


Pressure -10%

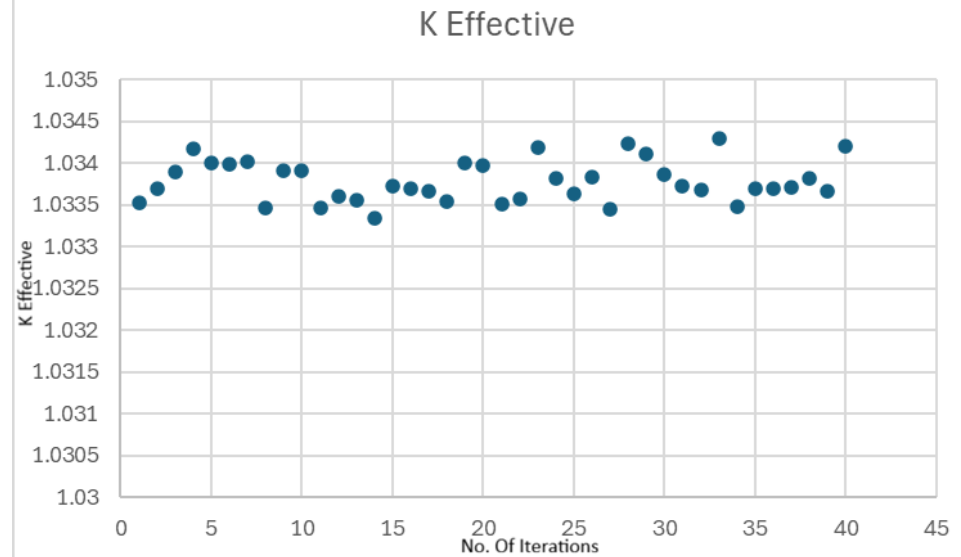
Table 49: Plots for pressure - 10%



**Heat structure
temperature**



k_{eff}



**Water
Temperature**

