List of student internships offered by new*cleo*

–academic year–
2023–2024

April 17, 2024

Preface

This document contains the internship offers supported by *new*cleo for students enrolled in the academic year 2023/2024. Each offer contains the specifications and modalities for applications and execution of the internship work. The content of this document is licensed and distributed according to Creative Commons CC-BY-NC-SA, Attribution Noncommercial Share Alike.

List of Internships

Modeling of once-through thermal channels with phase separation by centrifugal force

Daniele Tomatis*[1], Giuseppe Francesco Nallo[2], and Fabio Moretti[1]

[1] *new*cleo, *Via Galliano 27, 10129 Torino, Italy*
[2] *Politecnico di Torino, Dipartimento Energia, Corso Duca degli Abruzzi 24, 10127, Torino, Italy*

March 16, 2024

– Internship proposal –
(ID No. 1000073)

***Keywords* —** Bayonet tube, LFR, DHR, flow boiling
***Topics* —** Physical modelling, two-phase thermal-hydraulics, numerical mathematics

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Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

*new*cleo has planned an experimental campaign with external partners in order to optimize the design of components for lead-cooled fast reactors. In this framework, mathematical models of the components are needed to reproduce accurately their physical behavior, with the aim of supporting design studies. This internship is proposed to students attending the last year of the Master program in Nuclear Engineering with particular interest in thermal-hydraulics and heat transfer. This internship work could possibly continue with a PhD program.

Description

During this internship, the student will develop a mathematical model of a once-through heat exchanger of bayonet type presenting innovative features capable of preventing possible unstable operation. Such exchangers are made of coaxial tubes, as schematically shown in Figure 1. Subcooled water enters from the top of the inner tube and flows downwards. After, it enters the outer tube, where it flows upwards while being heated by the surrounding lead, eventually leaving the system as superheated steam. The flow boiling occurs in helicoidal parallel channels

*Contact person, daniele.tomatis@newcleo.com

within the outer tube, so that inertial phase separation is expected radially because of the centrifugal force. The outer tube constitutes an inert zone filled by helium to guarantee separation between water and lead. The physical model must describe the different flow boiling regimes encountered within the outer tube, accounting for the presence of inertial phase separation due to the centrifugal force. The full technical details will be provided during the internship, after acceptance of the candidate.

A complete literature review is requested to find the most appropriate physical correlations characterizing the flow and the heat transfer in the channels. The heat exchange between neighbouring channels can be neglected as first approximation (adiabatic assumption). The student will derive the conservation equations to describe the thermal-hydraulic model of the system, and check the validity of suitable closure relations and physical correlations used in the model. The development of a Python code solving the identified equations is requested, with the verification of the numerical solution on simplified case problems. Finally, preliminary investigations about the validation of the model are expected at the end of the internship, despite the complete validation against other computer codes is postponed for future work. At the end of the internship, the preparation of a technical report is expected to describe the work done by the student and to compile the analysis of the results.

This internship will be supervised by an engineer from *new*cleo and the academic staff at PoliTo. This study supports the preparation of an experimental facility whose construction is planned in 2024.

Work plan

1. Literature review and retrieval of the existing work
2. Discussion of the problem
3. Derivation of conservation equations in the channel (adiabatic conditions among channels)
4. Assessment of the physical correlations to characterize the flow and the heat transfer
5. Implementation and verification of the numerical solution
6. Analysis of results and proposal of validation plan
7. Model upgrade with intra-channel heat exchange (optional)
8. Preparation of a technical report

Applicant profile

Master or PhD student in Nuclear, Mechanical or Aeronautical Engineering.
Fundamentals in thermal-hydraulics and heat transfer, multiphase flow.
Required computer skills: Python programming, linux (optional).

References

[1] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

[2] N. E. Todreas, M. S. Kazimi, and M. Massoud. *Nuclear systems Volume II: Elements of thermal hydraulic design*. CRC press, 2021.

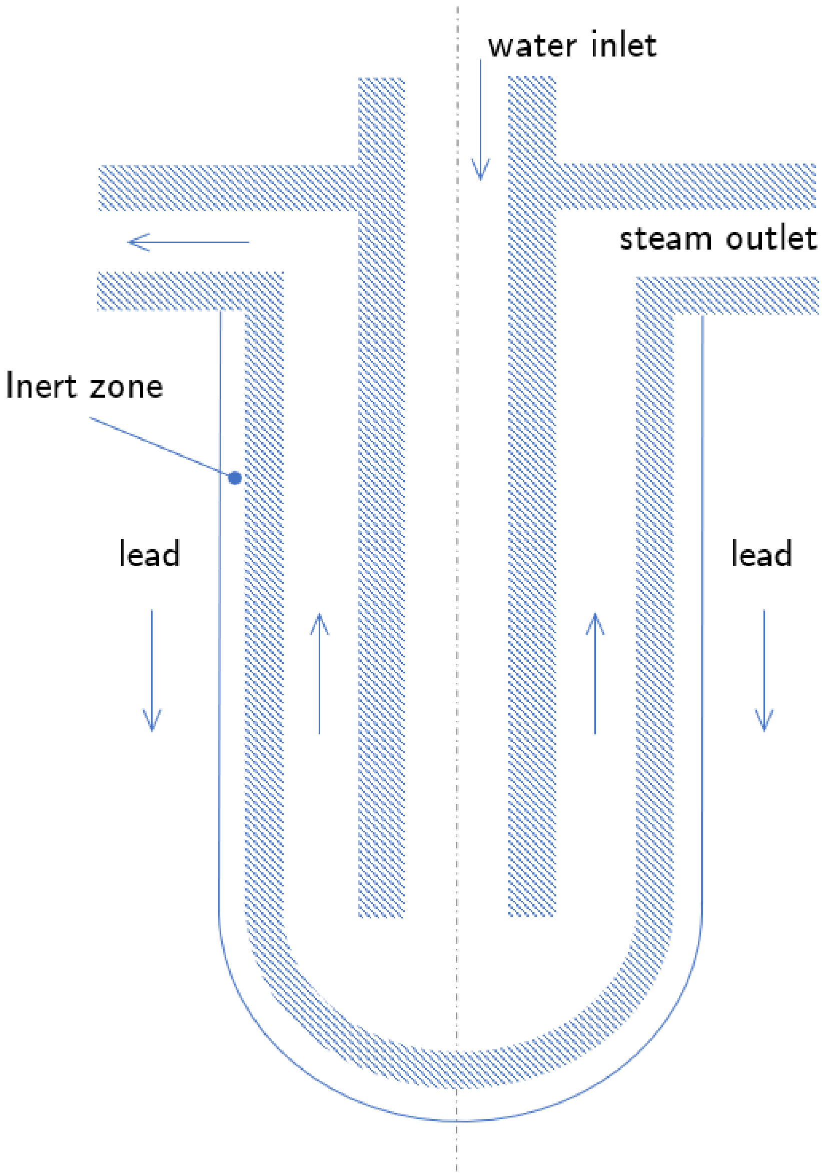

Figure 1: Schematic of a bayonet tube heat exchanger.

[3] A. Bersano, N. Falcone, C. Bertani, M. De Salve, and B. Panella. Conceptual design of a bayonet tube steam generator with heat transfer enhancement using a helical coiled downcomer. *Progress in Nuclear Energy*, 108:243–252, September 2018.

[4] D. Rozzia, A. Toti, M. Tarantino, L. Gramiccia, D. Vitale Di Maio, and F. Giannetti. Double-wall bayonet tube steam generator for LFR application – preliminary characterization. Technical Report NNFISS-LP3–032, ENEA Ricerca Sistema Elettrico, Italy, 2011.

Validation of ECCO calculations of LFR fuel assemblies by Monte Carlo calculations

Daniele Tomatis*[1], Matteo Falabino[1], and Roberto Spaggiari[1]

[1] new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– Internship proposal –

(ID No. 1000247)

***Keywords* —** LFR, V&V, ECCO, lattice calculations, cross section preparation
***Topics* —** Physical modeling, neutronics, fuel design

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

*new*cleo is designing new units of lead-cooled fast reactors (LFR) aiming to increase the utilization of plutonium produced by the many light water reactors that are currently operating worldwide. The fuel elements are exposed to a fast neutron spectrum favoring fission of heavier actinides. The reactor is cooled by molten lead that shows low neutron absorption and shields radiation protecting the core vessel.

The computer code ECCO (European Cell COde) from the ERANOS 2.3N code suite is used for all the activities of fuel design. ERANOS is a system of computer codes developed in the 1990s for the calculation of fast reactors. ECCO solves the neutron transport equation by the collision probability method using the subgroup method to shield the cross sections of the resonant nuclides. This internship focuses on the validation of the results obtained by ECCO on typical hexagonal fuel assemblies using the Monte Carlo computer code OpenMC.

*Contact person, daniele.tomatis@newcleo.com

Description

The fuel assemblies used in LFRs are built upon a hexagonal lattice with hollow fuel pellets inside the fuel rods. A typical fuel assembly for LFR is shown in Fig. 1. The fuel is made of mixed uranium and plutonium oxides. The rods can also contain poorly-enriched fuel along the axis that makes breeding zones for the optimization of the core cycle. A metallic wire is helically wrapped around the cladding of the fuel rods to avoid mechanical contact between neighboring rods. The assemblies are boxed and immersed in molten lead, which removes the heat released by nuclear reactions while flowing through the assemblies.

During this internship, the candidate will calculate a set of fuel assemblies by the Monte Carlo code OpenMC in order to compare pin-wise reaction rates and integral quantities like the neutron multiplication factor with the corresponding quantities obtained with the calculations performed by ECCO. Simplified calculation schemes are generally adopted with ECCO, thus introducing physical approximations in the problem to solve, but with the advantage of achieving fast calculations. Instead, Monte Carlo calculations introduce fewer approximations but at the cost of longer calculations. They are then used to validate the deterministic calculations in a representative set of cases, featuring different assembly types. Comparisons of reaction rates in the typical 33-group energy mesh of ERANOS are also requested to validate the self-shielding step done by ECCO. The validation will be performed with fresh fuel, and optionally after exposure at different burnup steps.

Finally, the student will study the anisotropy effects for this kind of assemblies, especially in presence of a central cooling tube. At the end of the internship, the preparation of a technical report is requested to describe the work done by the student and to compile the analysis of the results. This internship will be supervised by engineers from *new*cleo.

Work plan

1. Retrieval of the existing work about ECCO calculations
2. Setup and installation of OpenMC
3. Analysis of the test cases
4. Problem discussion
5. Calculation of the different cases by OpenMC
6. Analysis of results
7. Preparation of the technical report

Applicant profile

Master or PhD student in Nuclear Engineering, Theoretical or applied Physics.
Background: *fundamentals in reactor physics, neutronics and Monte Carlo methods*.
Required computer skills: Python programming (intermediate level), Linux, LaTeX scientific editing (optional).

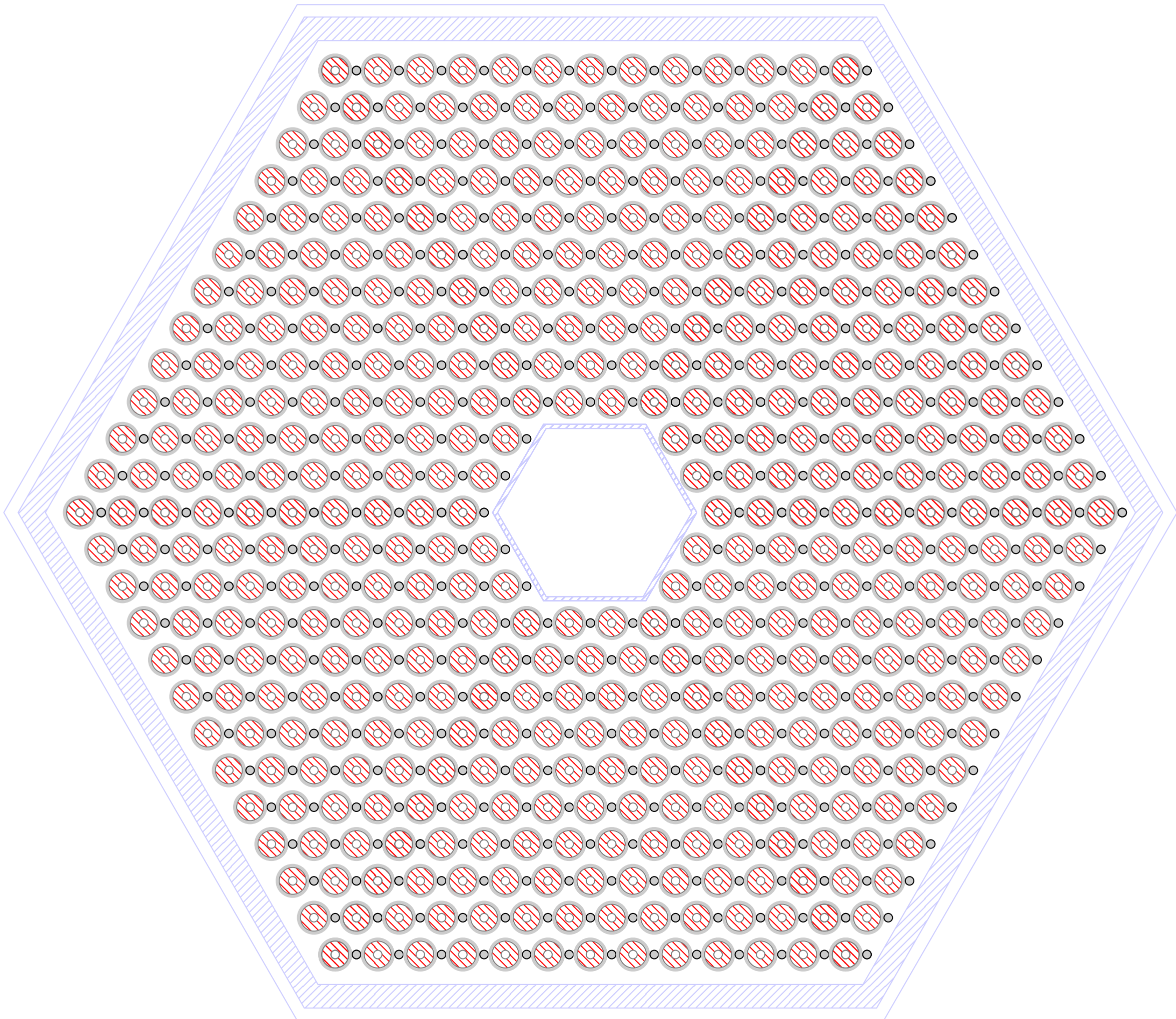

Figure 1: Section of a boxed fuel assembly with central tube.

References

[1] Paul K Romano, Nicholas E Horelik, Bryan R Herman, Adam G Nelson, Benoit Forget, and Kord Smith. Openmc: A state-of-the-art monte carlo code for research and development. *Annals of Nuclear Energy*, 82:90–97, 2015.

[2] Gérald Rimpault, Danièle Plisson, Jean Tommasi, Robert Jacqmin, Jean-Marie Rieunier, Denis Verrier, and Didier Biron. The ERANOS code and data system for fast reactor neutronic analyses. In *Proc. Int. Conf. on the New Frontiers of Nuclear Technology PHYSOR2002: Reactor Physics, Safety and High-Performance Computing, Seoul, South Korea*, Oct 7-10 2002.

[3] E Garcia, P Sciora, T Kooyman, G Rimpault, H Guo, and B Faure. Flux distribution of the Superphénix start-up core for the validation of neutronic codes. *Annals of Nuclear Energy*, 133:889–899, 2019.

[4] Kenneth Allen, Travis Knight, and Samuel Bays. Benchmark of advanced burner test reactor model using mcnpx 2.6. 0 and eranos 2.1. *Progress in Nuclear Energy*, 53(6):633–644, 2011.

[5] Siyu Lyu, Daogang Lu, and Danting Sui. Neutronics benchmark analysis of the ebr-ii shrt-45r with sac-3d. *Nuclear Engineering and Design*, 364:110679, 2020.

Development of the thermal model of a once-through steam generator with spiral geometry and cross-flow

Daniele Tomatis*[1] and Giuseppe Francesco Nallo[2]

[1] *newcleo, Via Galliano 27, 10129 Torino, Italy*
[2] *NEMO group, Dipartimento Energia, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy*

March 16, 2024

– Internship proposal –
(ID No. 1000303)

***Keywords* —** LFR, cross-flow heat exchanger, spiral tube, flow boiling
***Topics* —** Physical modelling, two-phase thermal-hydraulics, numerical mathematics

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

*new*cleo has planned an experimental campaign in collaboration with external partners in order to optimize the design of the components for the next units of lead-cooled fast reactors. In this framework, mathematical models of the components are needed to reproduce accurately their physical behavior, with the aim of supporting the design studies.

Description

During this internship, the student will develop a mathematical model of a once-through heat exchanger that presents innovative features to achieve a compact design. The exchanger is made of many layers, each containing a single spiral-shaped tube, arranged in a staggered lattice along the axial direction. The tubes are all immersed in molten lead, which flows outwards from the center to the periphery of the exchanger. The exchanger can be described in cylindrical geometry with the spirals representing the tubes lying in parallel polar planes. Subcooled water enters the spirals at the periphery of the exchanger, flowing inwards inside the tubes, and

*Contact person, daniele.tomatis@newcleo.com

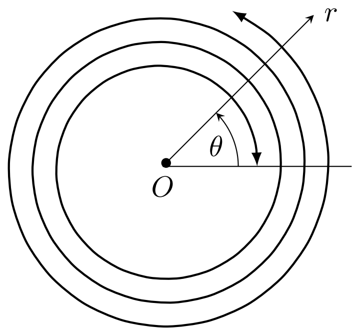

Figure 1: Archimedean spiral.

exits as superheated steam, see Figure 1. The Archimedean or arithmetic spirals are drawn according to the following equation:

$$r = a + b\theta, \tag{1}$$

where a is the centerpoint offset and b is the ratio of the pitch between two consecutive arms of the spiral (pitch) over 2π.

Molten lead flows radially outwards exchanging heat with the water that flows inside the tubes, and can be considered as uniformly distributed along the azimuthal coordinate θ when encountering the first spiral loop. Lead has a very low Prandtl number, so that thermal diffusion shall be taken into account, both radially and azimuthally. Flow-boiling occurs inside the spiral-shaped tubes, and phase separation is expected in the section of the tube because of the centrifugal force applied by the curvilinear motion. Different correlations for heat transfer between lead and water are expected at the two sides of the tube as a consequence of phase separation. Heat-transfer phenomena in presence of phase separation have been extensively studied for helical configurations in the past, but not for spiral configurations. The student will perform a review of the existing literature to find appropriate physical correlations for heat transfer between lead and water in the configuration at hand. New correlations for the distributed friction in cross-flow are expected to become available during the internship thanks to the first results of the experimental campaign.

The student will derive the conservation equations to describe the thermal-hydraulic model of the system, and check the validity of suitable closure relations and physical correlations used in the model. The development of a Python code solving the identified equations is requested, with the verification of the numerical solution in simplified case problems. Finally, preliminary investigations about the validation of the model are expected at the end of the internship, despite the complete validation against other computer codes is postponed for future work. At the end of the internship, the preparation of a technical report is expected to describe the work done by the student and to compile the analysis of the results.

This internship will be supervised by an engineer from *new*cleo and the academic staff at PoliTo. This study supports the preparation of an experimental facility whose construction is planned in 2024.

Work plan

1. Literature review and retrieval of the existing work
2. Problem discussion and definition

3. Derivation of the conservation equations in the spiral-like tube
4. Assessment of the physical correlations to characterize the flow and the heat transfer
5. Implementation and verification of the numerical solution
6. Analysis of results and proposal of validation plan
7. Preparation of a technical report

Applicant profile

Master or PhD student in Nuclear, Mechanical or Aeronautical Engineering. Students in theoretical Physics and applied Mathematics will also be considered for the position.
Background: *fundamentals in thermal-hydraulics and heat transfer, multiphase flow*.
Required computer skills: Python programming, linux, LaTeX scientific editing (optional).

References

[1] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

[2] N. E. Todreas, M. S. Kazimi, and M. Massoud. *Nuclear systems Volume II: Elements of thermal hydraulic design*. CRC press, 2021.

[3] Vincenzo Luci and Vittorio Vaiarelli. THEST: an in-house tool for spiral-tube steam generator design and verification. Technical report, *new*cleo SrL, Turin, Italy, 2021. LFR-000-NC-A-T-25-0002.

[4] Andrew Michael Fsadni and Justin P.M. Whitty. A review on the two-phase heat transfer characteristics in helically coiled tube heat exchangers. *International Journal of Heat and Mass Transfer*, 95:551–565, 2016.

[5] Paisarn Naphon and Somchai Wongwises. A review of flow and heat transfer characteristics in curved tubes. *Renewable and Sustainable Energy Reviews*, 10(5):463–490, 2006.

Assessment of neutronic data for the calculation of LFR fuel rods by TRANSURANUS

Daniele Tomatis*[1] and Erik Guizzardi[1]

[1] *new*cleo, *Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– Internship proposal –
(ID No. 1000360)

***Keywords* —** LFR, TRANSURANUS, Monte Carlo
***Topics* —** Physical modelling, neutronics, fuel performance and thermo-mechanical codes

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	3–4 months

Context

*new*cleo is designing new Lead-cooled Fast Reactor (LFR) units for small and modular reactors using MOx fuel. At *new*cleo, fuel performance analysis is performed by the thermo-mechanical computer code TRANSURANUS (TU) distributed by the Joint Research Center of the European Commission based in Karlsruhe, Germany. *new*cleo has started a careful review of the code in order to ensure its suitability and fitness for the applications with LFR fuel rod types that are currently under design. Such work is also meant producing an upgraded version of the code to extend its range of applications, and in particular, to provide reliable predictions when modelling LFR fuel rods. The goal of this internship is to produce new neutronic data by Monte Carlo calculations that is needed for the TU calculations of LFR fuel rods.

Description

During this internship, the student will perform Monte Carlo calculations of LFR fuel rods by the computer code OpenMC to prepare neutronic data needed by the simplified burnup models implemented in TU. The data represent microscopic one-group reaction rates for the nuclides

*Contact person, daniele.tomatis@newcleo.com

considered in the reduced decay chain of TU. The calculations are requested for both fresh and irradiated fuel, and at different exposure periods. The approach of data preparation will be validated against existing TU data used for LWR fuel types.

Among the target data, the student will have to find feasible and valid means to estimate the radial power distribution inside the hollow fuel pellets by fine tallies, still achieving narrow statistical uncertainty around the expected values in reasonable time. Approximation in the definition of the problem to match the expected critical conditions at operation will be necessary. The production of a technical report is expected at the end of the internship to describe the work done by the student and to compile the analysis of the results.

Work plan

1. Problem discussion and definition
2. Setup of calculations by OpenMC
3. Validation of the approach by comparisons with existing data
4. Analysis of results
5. Preparation of a technical report

Applicant profile

Master or PhD student in Nuclear Engineering. Students in theoretical Physics and applied Mathematics will also be considered for the position.
Background: *fundamentals in Monte Carlo methods for neutral particle transport*.
Required computer skills: Python programming, linux, FORTRAN and LaTeX scientific editing (optional).

References

[1] K Lassmann. TRANSURANUS: a fuel rod analysis code ready for use. *Journal of Nuclear Materials*, 188:295–302, 1992.

[2] K Lassmann and H Blank. Modelling of fuel rod behaviour and recent advances of the TRANSURANUS code. *Nuclear Engineering and design*, 106(3):291–313, 1988.

[3] Paul K Romano, Nicholas E Horelik, Bryan R Herman, Adam G Nelson, Benoit Forget, and Kord Smith. OpenMC: A state-of-the-art Monte Carlo code for research and development. *Annals of Nuclear Energy*, 82:90–97, 2015.

[4] Jerome Spanier and Ely M Gelbard. *Monte Carlo principles and neutron transport problems*. Dover Publications, Inc., Mineola, New York, 2008.

Development of a Python package with thermal-hydraulic correlations for LMFR – lmth23

Daniele Tomatis*and Daniele Panico

*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– *Internship proposal* –
(ID No. 1000378)

***Keywords* —** LMFR, physical correlations, heat exchange, friction factor, fuel bundles, Python
***Topics* —** Heat transfer, thermal-hydraulics, frictional pressure loss, python programming

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	First or second quarter of 2024
Duration	4–5 months

Context

*new*cleo is preparing a large experimental campaign of thermal-hydraulic experiments to support the design activities for new LFR units. A compilation of the available empirical correlations from literature in a single and comprehensive library is currently on-going to characterize heat transfer and thermal-hydraulic phenomena with liquid metals. This library will also collect the results from the future experiments. This internship position focuses on the literature review about the existing correlations and supports the development of this library.

Description

Several empirical correlations are available in literature to describe heat transfer, thermal-hydraulics and pressure drop phenomena occurring in presence of liquid metals, which are used as coolant for nuclear fast reactors. Every physical correlation comes with its validity range given in terms of dimensionless numbers, flow conditions, and for particular geometrical configurations. The use of a correlation outside the validity range does not guarantee accurate predictions of the quantity of interest. So a careful check about the correlation's appropriateness must be done before use.

*Contact person, daniele.tomatis@newcleo.com

Some correlations yield directly dimensionless numbers, expressing the importance of a given phenomenon with respect to other competing ones, like in the case of the Nusselt number that measures the ratio between heat transfer by convection and heat transfer by conduction alone. Indeed, heat transfer and pressure drop correlations (Darcy factor for instance) are fundamental for the design of heat exchangers, which constitutes a large part of the forthcoming experimental program planned by *new*cleo.

Unfortunately, it is difficult to find a comprehensive and compact tool to make such correlations readily available for engineers when designing LFR components. For this reason, *new*cleo is implementing a Python package as unique and standardized entry point for evaluating all the empirical correlations needed for general LMFR applications. Moreover, this package will be used to support the next experimental campaign, including possible implementation of the new correlations arising from it.

During this internship the student will participate to the development of the Python package $\mathrm{lmth23}$ (Liquid-Metal Thermal-Hydraulics).

In particular, the correlations for the friction factor and for the Nusselt number in LMFR fuel bundles and once-through heat exchangers with cross-flow will be considered. A wide list of correlations for the friction factor can be found in [1]. Instead, correlations for the Nusselt number are given in [2]. The first release of the package will provide the desired quantity given the characteristic geometric parameters and coolant velocity at input to calculate the Reynolds number appropriately. In addition to reviewing and implementing the physical correlations, the student will focus on implementation techniques and high quality standards for code development. This will make the package easier to maintain and extend in the future, serving both uses in industry and research. Therefore, the student will develop/consolidate skills in the following aspects of software engineering in Python:

- Object-Oriented programming based on SOLID principles;
- Python Dynamic programming;
- design patterns (template and factory patterns in particular);
- CI/CD pipelines (including regression tests);
- write well-documented code for scientific applications.

The internship will be supervised by an engineer from R&D team of *new*cleo.

Work plan

1) Literature review and identification of the main correlations to implement
2) Code architecture design
3) Code implementation
4) Definition and implementation of tests
5) Preparation of a technical report

Applicant profile

Master student in Nuclear, Mechanical or Aerospace Engineering; Applied Physics; Informatics and Computational Sciences.

Skills:

- Fundamentals in thermal-hydraulics and heat transfer
- Basic knowledge of software programming (previous experience in Python is very appreciated)
- Basic knowledge of Linux operative system

Nice to have: experience using git, basic knowledge on liquid metal-cooled fast reactors.

References

[1] S.K. Chen, N.E. Todreas, and N.T. Nguyen. Evaluation of existing correlations for the prediction of pressure drop in wire-wrapped hexagonal array pin bundles. *Nuclear Engineering and Design*, 267:109–131, 2014.

[2] Konstantin Mikityuk. Heat transfer to liquid metal: Review of data and correlations for tube bundles. *Nuclear Engineering and Design*, 239(4):680–687, 2009.

[3] Giridhar Chetan. *Learning Python Design Patterns*. Packt Publishing, Birmingham - Mumbai, 2 edition, 2016.

[4] Mariano Anaya. *Clean Code in Python: Refactor your legacy code base*. Packt Publishing, Birmingham, 2018.

[5] Lutz Mark. *Learning Python: Powerful Object-Oriented Programming*. O'Reilly Media, Sebatopol, USA, 5 edition, 2013.

Thermal power calculation of a closed channel of LFR

Daniele Tomatis*

newcleo SrL, Via Galliano 27, 10129 Torino, Italy

March 16, 2024

– *Internship proposal* –
(ID No. 1000393)

***Keywords* —** LFR, simplified closed channel model, multi-physics coupling
***Topics* —** Physical modelling, coupled neutronics and thermal-hydraulics, nonlinear eigenvalue problem

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Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

*new*cleo is designing new LFR units for which many calculations coupling neutronics and thermal-hydraulics are needed to verify the expected performances and safety requirements. This internship work is about applying a new solution method for the coupled problem that reproduces the physical behavior of a representative sub-channel in the fuel assembly. The main goal of this new method is providing fast estimates to support preliminary studies, or providing better initialization for more advanced computer codes in order to reduce the total computational runtime when looking for high-definition numerical solutions.

Description

This internship studies the multi-physics coupling between neutronics, heat transfer and thermal-hydraulics occurring inside the fundamental element of a nuclear reactor designed on a lattice of fuel pins. This element is also called sub-channel. The coupling must reproduce the thermal feedback on the neutron reactivity of the system due to changes in the fuel temperature, in the thermo-dynamical properties of the coolant and/or in possible changes of the lattice geometry. In particular, neutrons interacting with the nuclear fuel release the thermal energy, which is computed by a neutron model derived from the Boltzmann equation. The energy transferred

*Contact person, daniele.tomatis@newcleo.com

to the coolant is accounted in the conservation equations of the fluid, which is assumed as incompressible as first approximation; this approximation is often valid when liquid metals are used to cool the reactor. This work is limited to steady state conditions at normal operation and to operation under self-sustained chain reaction with fast neutron spectrum.

In general, the coupled problem is solved numerically through successive calls to different computer codes, which are solving separately the physics under coupling (Picard iterations). Specifically, the partial solution from a given solver is used to linearize the other problems solved by the other codes, and the convergence on all output quantities is sought iteratively. Other techniques using the gradient-like methods have been proposed in literature to achieve the solution with fewer calls to the separate codes. However, the existing methods can incur into the problem of false convergence, and they demand remarkable computational resources. Recently, a new method suggested to reformulate the problem by combining the coupled equations in a new form, in order to cope with these disadvantages [1]. This method was applied in the simple case of PWR sub-channel under the assumption of incompressible fluid. The goal of the current internship is to apply this technique to the typical sub-channel of a lead-cooled fast reactor, where the fluid incompressibility is a valid assumption.

During this internship, the student will be introduced to the reactor physics fundamentals, contributing actively to research with mathematical methods' development, scientific programming and technical editing of documents.

Work plan

1. Literature review and retrieval of the existing work
2. Problem discussion and definition
3. Generation of nuclear data at different physical conditions by OpenMC
4. Implementation and verification of the numerical solution
5. Analysis of results
6. Preparation of the final report

Applicant profile

Master or PhD student in Nuclear, Mechanical or Aeronautical Engineering. Students in theoretical Physics and applied Mathematics will also be considered for the position.
Background: *fundamentals in thermal-hydraulics and heat transfer, reactor physics*.
Required computer skills: Python programming, linux, LaTeX scientific editing.

References

[1] Daniele Tomatis. Reformulation of the coupled problem for the simplified closed channel. *Annals of Nuclear Energy*, 130:377–387, 2019.

[2] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

[3] N. E. Todreas, M. S. Kazimi, and M. Massoud. *Nuclear systems Volume II: Elements of thermal hydraulic design*. CRC press, 2021.

[4] Alain Hébert. *Applied reactor physics*. Presses inter Polytechnique, 2009.

Study of coolant heating in LFR

Daniele Tomatis*

new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– Internship proposal –
(ID No. 1000484)

***Keywords* —** LFR, coolant heating, neutron-photon transport, data correlation
***Topics* —** Physical modelling, Monte Carlo calculations, statistical inference

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	4–5 months

Context

Coupled neutronics and thermal-hydraulic calculations are needed for the design and safety studies of a nuclear reactor. These calculations need proper laws and correlations for thermo-physical properties and other data at input. A new physical correlation for coolant heating is necessary for the next LFR units designed by *new*cleo. This internship work is about performing coupled neutron-photon calculations by the computer code OpenMC of several representative physical configurations of LFR fuel assemblies, in order to obtain a set of data for the derivation of a valid correlation predicting coolant heating in molten lead.

Description

This internship focuses on energy deposition in molten lead that constitutes the coolant of LFR units (pool-type reactors) [1]. A portion of the energy released from fission is not deposited in the fuel because of the transport of neutral particles, namely neutrons and photons, leaking out of the pellet where they originated by fission [2]. These particles can collide with the surrounding media (cladding, structure and coolant) transferring energy at every collision. Actually, the amount of energy deposited in the coolant is only a small fraction, but it is required for the setup

*Contact person, daniele.tomatis@newcleo.com

of realistic thermal-hydraulics calculations of the sub-channels in the fuel assemblies. For instance, such fraction is about 3% in PWR (thermal reactors) [3]. For LFR, coolant heating must still be studied, with lead showing a different behavior under radiation than water.

Coupled neutron-photon calculations performed by Monte Carlo computer codes can provide reliable estimates of the coolant heating by radiation, with the possibility to use corrections accounting also for the contribution of delayed emissions from fission. In addition, heating shall consider also alpha and beta decays of radioactive nuclides arising at exposure. After studying first fresh fuel at different physical conditions, a methodology to investigate burnup effects along exposure will be addressed. The results will be analyzed to find a statistical correlation capable to provide reliable predictions of the energy deposited in the molten lead.

During this internship, the student will be introduced to LFR reactor physics and engineering, with particular attention to Monte Carlo methods and neutronics. The student will develop advanced skills as user of the Monte Carlo computer code OpenMC. The preparation of a technical report with a complete analysis of the results is requested at the end of the internship.

Work plan

1. Literature review and study of the main physical phenomena
2. Problem discussion and definition
3. Setup of OpenMC calculations
4. Validation of the approach by comparisons on existing LWR and FR problems
5. Analysis of results to obtain a physical correlation for the coolant heating
6. Preparation of the final report

Applicant profile

Master or PhD student in Nuclear Engineering. Students in theoretical Physics and applied Mathematics will also be considered for the position.
Background: *fundamentals in reactor physics and Monte Carlo methods*.
Required computer skills: Python programming, linux, LaTeX editing.

References

[1] Pierdomenico Lorusso, Serena Bassini, Alessandro Del Nevo, Ivan Di Piazza, Fabio Giannetti, Mariano Tarantino, and Marco Utili. GEN-IV LFR development: status & perspectives. *Progress in Nuclear Energy*, 105:318–331, 2018.

[2] Dan Gabriel Cacuci. *Handbook of Nuclear Engineering*. Springer Science & Business Media, 2010.

[3] Shai Kinast and Daniele Tomatis. Energy deposition in coolant of PWR under normal operation and accident conditions. *Nuclear Engineering and Design*, 384:111479, 2021.

Modelling of the DHR heat exchanger using the computer code AC^2-ATHLET

Antonino Lombardo and Daniele Tomatis*

new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– Internship proposal –

(ID No. 1001150)

***Keywords* —** Bayonet tube, LFR, DHR, flow boiling, ATHLET
***Topics* —** Physical modelling, two-phase thermal-hydraulics, system code modeling

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

*new*cleo has planned an experimental campaign with external partners in order to optimize the design of components for lead-cooled fast reactors. In this framework, the use of thermal-hydraulic system codes is very important to reproduce the physical behavior during transients, and so to make decisions in design studies. New heat exchangers of the bayonet-shell type for the Decay Heat Removal system [3] are currently under development as passive components to remove the residual heat and to cool down the molten lead after shutdown. These heat exchangers will be installed in the reactor pool, being fed with water as secondary fluid that falls by gravity from a tank placed on top of the pool.

An experimental program is starting in the second half of 2023 at the thermal-hydraulic laboratory of the Energy Department of the Politecnico di Torino, Italy, with the goal of testing the mechanical and thermal-hydraulic performances of the prototypes for DHR heat exchangers. The current internship is proposed to students attending the last year of the Master program in Nuclear Engineering with particular interest in thermal-hydraulics. This internship work is in support of the experimental activities, and could possibly continue with a PhD program.

*Contact person, daniele.tomatis@newcleo.com

Description

The components under study are heat exchangers made up of coaxial tubes immersed in the liquid lead pool [1]. During transients, subcooled water enters the inner tube and flows downwards. Then, it enters the outer tube where it is heated up by the surrounding lead, eventually leaving the system as superheated steam. The liquid lead is not in direct contact with the outer tube because they are separated by a helium-filled gap flowing in a surrounding gap between the component walls. The full technical details will be provided during the internship, after acceptance of the candidate.

The internship work will focus on the transient simulations of the two-phases boiling heat transfer occurring inside the component, by using the code AC^2-ATHLET 3.3 [2]. A complete literature review is required to find the most appropriate physical correlations to characterize the flow and heat transfer in the channels. These correlations will be compared with those available in the code, and if appropriate, used for the simulations by ATHLET using plugin functions. The setup of the calculations will make use of specific ATHLET's tools for processing input and output data. The student is expected to write a technical report at the end of the internship to describe the work done and to compile the analysis of the numerical results.

Work plan

During this internship, the student will be introduced to the system code AC_2-ATHLET for the modeling and design of thermal-hydraulics components and loops in steady state and transient conditions.

The student will develop the knowledge required for the description of hydraulic systems by means of control volumes and ATHLET's own specific fluid and solid objects. The acquired skills will be used to characterize and study an element of the Decay Heat Removal system.

The expected working plan is detailed in the following:

a) Literature review of the phenomena occurring in the bayonet-tube DHR
b) Discussion of the problem
c) ATHLET introduction and training
d) DHR modeling
e) Setup of the calculations
f) Analysis of results by taking advantage of ATHLET tools
g) Preparation of a technical report

Applicant profile

Master student in Nuclear, Mechanical or Aeronautical Engineering; Applied Mathematics and Physics.
Background: *Fundamentals in thermal-hydraulics and heat transfer, multiphase flow*.
Computer skills: Linux, bash, LaTeX, Python.

References

[1] D. Rozzia, A. Toti, M. Tarantino, L. Gramiccia, D. Vitale Di Maio, and F. Giannetti. Doublewall bayonet tube steam generator for LFR application - preliminary characterization. *Technical Report NNFISS-LP3-032*, ENEA Ricerca Sistema Elettrico, 2011.

[2] A. Schaffrath, M. Sonnenkalb, and A. Wielenberg. Grs code system AC2. *Kerntechnik*, 84(5):356-356, 2019.

[3] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

Primary loop LFR modeling setup in support to safety analyses with system codes

Barbara Calgaro *

new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– *Internship proposal* –
(ID No. 1001772)

***Keywords* —** LFR, primary system, core inlet and outlet boundary conditions, system thermal-hydraulic codes
***Topics* —** thermal-hydraulics/ multiphysics/ multiscale modelling, safety assessment

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

Primary system thermal-hydraulic (hereinafter, TH) calculations, [1] and [2], are needed for the design and the safety analysis of a nuclear reactor, and in particular of a small LFR. Suitable modelling strategies are to be chosen according to the available calculation platforms [3], selecting appropriate models and closure laws. For LFR reactors, discussions are still ongoing to define what may be the state-of-the-art approach [4] for pool and components TH analyses. In this context, primary system modeling with TH system codes are to be developed, verified and validated by defining best practices in terms of numerics improvements or phenomenological representation, especially if supported by international discussions and the interest from industrial stakeholders.

Description

This internship aims to make a step forward to define an initial best-practice proposal for the primary system TH modeling of small lead fast reactors to support safety assessments [5], [6].

*Contact person, barbara.calgaro@newcleo.com

The model shall include robust sub-models of the primary pool, the down-comer, the bottom vessel with dedicated radial core power and axial distribution, with the aim of optimising the modeling of the primary coolant heat transfer from the core to the heat exchangers.

Within this activity, a simplified model of a lead-cooled fast reactor, capable of addressing the above-mentioned requirements, shall be proposed, with the purpose of assessing a comparison between the maturity level of the most indutrial TH system codes and those under development in terms of their applicability to new reactor concepts.

During this internship, the student will be introduced to small modular reactors and in particular to fast reactors (mainly LFR), considering TH system codes in order to address the required modelling activity. At the end of the internship, the preparation of a technical report with a complete analysis of the results is required.

Work plan

1. Literature review and study of the main physical phenomena
2. Problem discussion and definition
3. Setup of TH system code calculations
4. Verification of the approach through the preparation of a generic LFR test case
5. Analysis of results and proposition of an automation approach for pre- and post-processing oriented to parametric analysis
6. Preparation of the final report

Applicant profile

Master's or PhD student in Nuclear Engineering. Students of theoretical Physics and applied Mathematics will also be considered for the position.
Background: *fundamentals in reactor physics and TH (better if multiphysics) approaches, but also computational TH*.
Required computer skills: Python programming, Linux, LaTeX editing.

References

[1] N. E. Todreas, M. S. Kazimi, and M. Massoud. *Nuclear systems Volume II: Elements of thermal hydraulic design*. CRC press, 2021.

[2] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

[3] The RELAP5-3D© Code Development Team INL. *Code Manual Volume IV: Models and Correlations*. INL, Nuclear Safety Analysis Division, USA, 2015.

[4] A. Alemberti and et al. Lead-cooled Fast Reactor, LFR, Risk and Safety Assessment White Paper. *GEN IV international Forum*, 2014.

[5] Barbara Vezzoni and Fabrizio Gabrielli. Optimization of Safety Parameter for an Innovative Fast Reactor Concept. *Special Issue on Sustainability Journal Sustainability*, 4:1274–1291, 2012.

[6] B. Calgaro, B. Vezzoni, G. Forasassi, and N. Cerullo. Spent Nuclear Fuel Radiotoxicity Evaluation in the context of Minor Actinides Management with ADS Systems. *Proceedings International Conference On Nuclear Engineering ICONE16 Orlando FL*, 0:0, 2008.

LFR modeling setup of primary system components in support to safety analyses

Barbara Calgaro *

newcleo SrL, Via Galliano 27, 10129 Torino, Italy

March 16, 2024

– Internship proposal –
(ID No. 1001773)

Keywords **—** LFR, primary system, core inlet and outlet boundary conditions, system thermal-hydraulics codes, primary system components
Topics **—** thermal-hydraulics/ multiphysics/ multiscale modelling, safety assessment

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Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

Primary system thermal-hydraulic (hereinafter, TH) calculations, [1] and [2], are needed for the design and safety analyses of a nuclear reactor, and in particular of a small LFR. Suitable modelling strategies are to be chosen according to available calculation platforms [3], selecting models and closure laws. For LFR reactors, discussions are still ongoing to define what may be the state-of-the-art approach [4] for pool and components TH analyses. In this context, advanced modeling with TH system codes are to be developed, verified and validated by defining the best practices in the field of numerics or phenomenological representation improvements, especially if supported by international discussions and the interest from industrial stakeholders.

Description

This internship aims to make a step forward to define LFR primary system TH modeling mainly oeriented to its major components to support safety assessments [5], [6]. The model shall

*Contact person, barbara.calgaro@newcleo.com

include robust sub-models of the primary pool, the down-comer, the bottom vessel with dedicated core power radial and axial distribution with the objective of optimising the modeling of the primary system components. The stage may focuses on one of the following components: steam-generator two-phase flows, decay heat removal system, core TH heat removal function, etc.

Within this activity, a simplified model of a lead-cooled fast reactor, capable of addressing the above-mentioned requirements, shall be proposed, with the purpose of assessing a comparison between the maturity level of the most indutrial TH system codes or those under development in terms of their applicability to new reactor concepts.

During this internship, the student will be introduced to small modular reactors and in particular to fast reactors (mainly LFR), considering TH system codes in order to address the required modelling activity. At the end of the internship, the preparation of a technical report with a complete analysis of the results is required.

Work plan

1. Literature review and study of the main physical phenomena
2. Problem discussion and definition
3. Setup of TH system code calculations
4. Verification of the approach through the preparation of a generic LFR test case
5. Analysis of results and proposition of an automation approach for pre- and post-processing oriented to parametric analysis
6. Preparation of the final report

Applicant profile

Master's or PhD student in Nuclear Engineering. Students of theoretical Physics and applied Mathematics will also be considered for the position.
Background: *fundamentals in reactor physics and TH (better if multiphysics) approaches, but also computational TH*.
Required computer skills: Python programming, Linux, LaTeX editing.

References

[1] N. E. Todreas, M. S. Kazimi, and M. Massoud. *Nuclear systems Volume II: Elements of thermal hydraulic design*. CRC press, 2021.

[2] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

[3] The RELAP5-3D© Code Development Team INL. *Code Manual Volume IV: Models and Correlations*. INL, Nuclear Safety Analysis Division, USA, 2015.

[4] A. Alemberti and et al. Lead-cooled Fast Reactor, LFR, Risk and Safety Assessment White Paper. *GEN IV international Forum*, 2014.

[5] Barbara Vezzoni and Fabrizio Gabrielli. Optimization of Safety Parameter for an Innovative Fast Reactor Concept. *Special Issue on Sustainability Journal Sustainability*, 4:1274–1291, 2012.

[6] Barbara Calgaro and Barbara Vezzoni. Advanced Couplings and Multiphysics Sensitivity Analysis Supporting the Operation and the Design of Existing and Innovative Reactors. *Energies*, 15:3341, 2022.

Advanced LFR modeling setup in support to safety analyses

Barbara Calgaro [*]

*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy

March 16, 2024

– *Internship proposal* –
(ID No. 1001774)

***Keywords* —** LFR, primary system, core inlet and outlet boundary conditions, opensource advanced codes
***Topics* —** multiphysics/multiscale modelling, safety assessment, open source codes

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Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

Coupled neutronics and thermal-hydraulic (hereinafter, TH) calculations, [1] and [2], are needed for the design and safety analyses of a nuclear reactor, and in particular of a small LFR. Suitable modelling strategies are to be chosen according to available calculation platforms, selecting models and closure laws. For LFR reactor, discussions are still ongoing to define what may be the state-of-the-art approach for multiphysics analyses. In this context, advanced open source codes with multiphysics/multiscale capabilities may play an important role in the definition of the best practices and shared innovations in the field of numerics improvements or phenomenological representation, especially if supported by international discussions and interest from industrial stakeholders.

Description

This internship aims to define an initial best-practice proposal for the multiphysics modelling of small modular reactors in support of safety assessments, with a focus on fast reactors and

[*]Contact person, barbara.calgaro@newcleo.com

in particular to LFRs [3]. Open source tools such as Gen-Foam shall be considered [4]. The model must include robust sub-models of the radial and axial distribution of the core power and of the primary coolant system, and be able to simulate different operating conditions in relatively short timescales. Indeed, the core neutronic feedbacks following any variation in Nuclear Steam Supply System (NSSS) operating conditions, together with the knowledge of the energy deposition in the coolant [5], are part of the key information from the components to the primary system.

Within this activity, a simplified model of a generic lead-cooled fast reactor, capable of addressing the above-mentioned requirements, shall be proposed, with the purpose of assessing the maturity of open source codes in terms of applicability to new reactor concepts. This simplified model will allow to have a first quantification of representative indicators of the safety behaviour of the innovative systems. [4].

During this internship, the student will be introduced to small modular reactors and in particular to fast reactors (mainly LFR), considering multiphysics, multiscale opensource codes to address the required modelling activity. At the end of the internship, the preparation of a technical report with a complete analysis of the results is required.

Work plan

1. Literature review and study of the main physical phenomena
2. Problem discussion and definition
3. Setup of GenFoam calculations
4. Verification of the approach through the preparation of a generic LFR test case
5. Analysis of results and proposition of an automation approach for pre- and post-processing oriented to parametric analysis
6. Preparation of the final report

Applicant profile

Master's or PhD student in Nuclear Engineering. Students of theoretical Physics and applied Mathematics will also be considered for the position.
Background: *fundamentals of reactor physics and multiphysics approaches, but also computational TH*.
Required computer skills: Python programming, Linux, LaTeX editing.

References

[1] N. E. Todreas, M. S. Kazimi, and M. Massoud. *Nuclear systems Volume II: Elements of thermal hydraulic design*. CRC press, 2021.

[2] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

[3] Barbara Calgaro and Barbara Vezzoni. Advanced Couplings and Multiphysics Sensitivity Analysis Supporting the Operation and the Design of Existing and Innovative Reactors. *Energies*, 15:3341, 2022.

[4] Carlo Fiorina. GenFOam. *Nuclear Engineering and Design*, 294:24–37, 2015.

[5] Barbara Vezzoni and Fabrizio Gabrielli. Optimization of Safety Parameter for an Innovative Fast Reactor Concept. *Special Issue on Sustainability Journal Sustainability*, 4:1274–1291, 2012.

Improvement in LFR modeling with system codes approach in support to safety analyses

Barbara Calgaro *

new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– *Internship proposal* –
(ID No. 1001775)

***Keywords* —** LFR, primary system, core inlet and outlet boundary conditions, system thermal-hydraulic codes
***Topics* —** multiphysics/multiscale modelling, safety assessment, system thermal-hydraulic codes

Location	Pisa
Starting date	As soon as possible
Duration	5–6 months

Context

Thermal-hydraulic (hereinafter, TH) calculations [1] are needed for the design and safety analyses of a nuclear reactor, and in particular of a small LFR. Suitable modelling strategies are to be chosen according to the available calculation platforms, selecting models and closure laws. For LFR reactors, discussions are still ongoing to define what may be the state of the art approach for TH system analyses dedicated to safety studies. In this context, TH system codes play an important role by allowing the modeling of the entire primary system with a reasonable level of detail. Due to the presence of multi-physics phenomena, the capability of such codes to model the primary system and relevant components, such as the primary pump, the downcomer, the steam-generator, the core, the decay heat removal (DHR), etc. under normal and accidental conditions is of great importance. The state-of-the-art analysis of already proposed approaches and the proposition of a appropriate generic nodalisation for selected steady-state and transient test cases are at the core of this activity for the definition of best practices and shared innovations in the field of numerical improvements or phenomenological representation, especially if supported by international discussions and the interest of industrial stakeholders.

*Contact person, barbara.calgaro@newcleo.com

Description

This internship aims to define an initial best-practice proposal for the system codes application to small modular reactors in support of safety assessments, with specific focus on fast reactors and in particular to LFRs [2]. System code models shall include robust meshing of primary system for LFR composed mainly by a pool and primary components such as the steam generators, primary pumps, the core lower and the upper plena, the decay heat removual, while being capable of simulating different operating conditions in a relatively short time. The core neutronic feedbacks following any variation in Nuclear Steam Supply System (NSSS) operating conditions are modeled with point kinetics in first approximation. Neutronic power, together with the energy deposited in coolant, is part of the major information to be modeled and exchanged among components and primary system [3].

Within this activity, a model of a generic lead-cooled fast reactor, capable of addressing the above-mentioned requirements, shall be proposed, with the purpose of assessing the maturity of TH system codes in terms of applicability to LFRn. This model will provide an initial nodalisation suggested to address parametric analyses on a list of selected steady-state and accidental transient cases (Design Basis or DECs. [4]).

During this internship, the student will be introduced to small modular reactors and in particular to fast reactors (mainly LFR), considering mainly multiphysics, system codes to address the required modelling activity. At the end of the internship, the preparation of a technical report with a complete analysis of the results is required.

Work plan

1. Literature review and study of the main physical phenomena
2. Problem discussion and definition
3. Setup of system codes calculations
4. Verification of the approach through the preparation of a generic LFR test case
5. Analysis of results and proposition of an automation approach for pre- and post-processing oriented to parametric analysis
6. Preparation of the final report

Applicant profile

Master's or PhD student in Nuclear Engineering. Students of theoretical Physics and applied Mathematics will also be considered for the position.
Background: *fundamentals of reactor physics, TH and multiphysics approaches, but also computational TH*.
Required computer skills: Python programming, Linux, LaTeX editing.

References

[1] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

[2] M. Angelucci, D. Martelli, G. Barone, I. Di Piazza, and N. Forgione. STH-CFD Codes Coupled Calculations Applied to HLM Loop and Pool Systems. *Science and Technology of Nuclear Installations*, 2017:13, 2017.

[3] Dominique Bestion. 11 - The structure of system thermal-hydraulic (SYS-TH) code for nuclear energy applications. *Thermal-hydraulics of water cooled nuclear reactor*, 4:639–727, 2017.

[4] Barbara Calgaro and Barbara Vezzoni. Advanced Couplings and Multiphysics Sensitivity Analysis Supporting the Operation and the Design of Existing and Innovative Reactors. *Energies*, 15:3341, 2022.

Upgrade of the Python package lbh15 with properties of irradiated heavy liquid metals used in nuclear fast reactors

Daniele Panico*[1] and Gabriele Ottino[1]

[1]newcleo SrL, Via Galliano 27, 10129 Torino, Italy

March 16, 2024

– Internship proposal –
(ID No. 1001776)

***Keywords* —** LMFR, irradiated liquid-metal properties, Python
***Topics* —** Radioactive nuclides volatility, confinement and interaction with liquid metals

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	First or second quarter of 2024
Duration	4–5 months

Context

Chemical control of the primary coolant in liquid-metal nuclear reactors is of crucial importance during plant operation, preventing alteration or degradation of materials such as steel and other structural alloys by corrosion. In addition, the control system considers the purification of the coolant from hazardous radioactive nuclides, originated by nuclear reactions, to prevent excessive dose release in case of leaks. Therefore, *new*cleo's activities on lead chemical control are the objects of intensive studies, both in terms of experiments and theoretical modeling. In order to support both types of activities, the Python package lbh15 is under active development within the Codes and Methods team to offer an unique and standardized entry point for the use of empirical correlations of physical properties.

Description

lbh15 (**L**ead **B**ismuth **H**andbook 20**15**) is a Python package developed by *new*cleo based on the reference handbook edited by OECD-NEA [1], as contribution to the expert group on heavy liquid metal technologies. The metal properties are implemented as analytical functions from

*Contact person, daniele.panico@newcleo.com

empirical correlations. The package is also equipped with services for function characterization that use the standard Python packages for scientific computation, namely NumPy and SciPy. The release of the second version of lbh15 is scheduled by the end of 2023: it will implement both thermophysical and thermochemical properties of molten lead (Pb), of bismuth (Bi) and of their eutectic alloy (LBE). The package repository and the related documentation can be found at
`https://newcleo-dev-team.github.io/lbh15/index.html` and
`https://github.com/newcleo-dev-team/lbh15`, respectively.

During the internship, the student will develop new features in lbh15 by implementing the topics covered in chapter 5 of the above-mentioned handbook. Specifically, the student will work on the integration of the following subjects:

a) volatilisation of hazardous nuclides (Polonium, Caesium, Iodine, etc.) from liquid metals;
b) estimation of equilibrium vapour pressure;
c) gas phase purification.

For check and illustration purposes, the student will be involved in the development of one or more simple Python applications/tests focused on the exploitation of the properties just implemented.

lbh15 adopts high quality standards for code development. Hence, the student will develop/consolidate skills about the following aspects of the Python-based software engineering ([2], [3]):

- Object-Oriented programming based on SOLID principles;
- Python Dynamic programming;
- Design patterns (template and factory patterns in particular);
- CI/CD pipelines (including regression tests);
- Well-documented code writing for scientific applications.

The student will be followed by the Codes and Methods group members of *new*cleo that are developing lbh15.

Work plan

1) Handbook [1] review and identification of the main correlations to implement
2) Code architecture design
3) Code implementation
4) Test application definition and implementation
5) Preparation of a technical report

Applicant profile

Master student in Industrial Engineering, Chemistry, Applied Physics or Computer Science.
Skills and background:

- Fundamentals in thermodynamics and chemistry
- Basic knowledge of software programming (previous experience in Python appreciated, but not fundamental)
- Basic knowledge of Linux operative system

Nice to have: experience using git, basic knowledge on liquid metal-cooled fast reactors.

References

[1] C. Fazio et Al. Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies. Technical Report No. 7268, OECD/Nuclear Energy Agency (NEA), Paris, France, 2015.

[2] Giridhar Chetan. *Learning Python Design Patterns*. Packt Publishing, Birmingham - Mumbai, 2 edition, 2016.

[3] Lutz Mark. *Learning Python: Powerful Object-Oriented Programming*. O'Reilly Media, Sebatopol, USA, 5 edition, 2013.

Modeling the thermal-hydraulic of a pool-type reactor using the AC^2-ATHLET computer code

Daniele Tomatis*[1] and Cristiano Ciurluini †[2]

[1]new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*
[2]*Sapienza Università di Roma, Piazzale Aldo Moro 5, 00185 Roma, Italy*

March 16, 2024

– Internship proposal –
(ID No. 1001912)

***Keywords* —** Pool, LFR, ATHLET code
***Topics* —** Physical modelling, thermal-hydraulics, system code modeling

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	Last quarter of 2023
Duration	3–4 months

Context

*new*cleo has planned an experimental campaign with external partners in order to optimize the design of components for lead-cooled fast reactors. In this framework, the use of thermal-hydraulic system codes is very important to reproduce the physical behavior during transients, and so to make decisions in design studies.

The pool-type configuration of the lead-cooled reactors provides advantages in terms of safety, but at the same time it brings new challenges with regard to the simulation of the pool. The onset of natural recirculation and the 3D characterisation of the flow field, due to the open configuration and position of the components inside the pool, imply the need for special studies and models in order to properly account for the flow behaviour using system codes. The fast simulation of main flow temperatures and exchanged power to the secondary side and safety components plays a key role for the study of normal and off normal conditions. Among them, new heat exchangers of the bayonet type for the Decay Heat Removal system [1] are currently under development as passive components to remove the residual heat and to cool down the molten lead after shutdown. These last heat exchangers will be installed in the reactor pool

*Contact person, daniele.tomatis@newcleo.com
†Contact person, cristiano.ciurluini@uniroma1.it

and will be fed with water as secondary fluid, which will fall by gravity from a tank placed on top of the pool.

The current internship is proposed to students attending the last year of the Master program in Nuclear Engineering with particular interest in thermal-hydraulics. This internship work is in support of the experimental activities, and could possibly continue with a PhD program.

Description

One of the most relevant safety aspects related to the LFR operations is the thermal stratification occurring within a quasi-stagnant Heavy Liquid Metal (HLM) pool. It consists in the separation between the hot and the cold liquid layers inside the pool. The phenomenon has been already studied in the past, related to LWRs, where the thermal stratification can occur in the piping system, in the pressurizer, or in the passive safety systems where a large tank at low pressure operates as heat sink. In HLM pool-type systems the thermal stratification is due to the heat losses from the internal component and towards the external environment. The hot fluid, heated by the internals, moves upward staying in the upper volume of the pool, while the cold liquid metal is confined, forming layers at different temperature inside the pool. The thermal stratification is an important aspect for the safety of the nuclear power plants as it affects the structural integrity of the reactor, causing fatigue in nuclear components. Another important aspect is the free level motion within the pool, considering the possible variations during the transients.

The proposal work will be focused on transient simulations the entire pool, by using AC_2-ATHLET[2] code. A complete literature review is required to find the most appropriate modelling approach to characterize the flow and the heat transfer within the components that characterize the primary side. In addition, special attention will be given to the free surface and the nodalization in the nearby axial domain. At the end of the internship, the preparation of a technical report is expected, using ATHLET's given tools for the post-processing of inputs and outputs, to describe the work done by the student and to compile the analysis of the results.

This internship will be supervised by an engineer from *new*cleo.

Work plan

During this internship, the student will be introduced to the system code AC_2-ATHLET for the modeling and design of thermal-hydraulics components and loops in steady state and transient conditions.

The student will develop the knowledge required for the description of hydraulic systems by means of control volumes and ATHLET's own specific fluid and solid objects. The acquired skills will be used to characterize and study the pool configuration under study.

The expected working plan is detailed in the following:

a) Literature review of the phenomena occurring in the pool
b) Discussion of the problem
c) ATHLET introduction and training
d) DHR and safety systems modeling
e) Reactor pool modeling
f) Setup of the calculations

g) Analysis of results by taking advantage of ATHLET tools
h) Preparation of a technical report

Applicant profile

Master student in Nuclear, Mechanical or Aeronautical Engineering; Applied Mathematics and Physics.
Background: *Fundamentals in thermal-hydraulics and heat transfer, multiphase flow.*
Computer skills: Linux, bash, LaTeX, Python.

References

[1] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

[2] A. Schaffrath, M. Sonnenkalb, and A. Wielenberg. Grs code system AC2. *Kerntechnik*, 84(5):356-356, 2019.

[3] D. Rozzia, A. Toti, M. Tarantino, L. Gramiccia, D. Vitale Di Maio, and F. Giannetti. Doublewall bayonet tube steam generator for LFR application - preliminary characterization. *Technical Report NNFISS-LP3-032*, ENEA Ricerca Sistema Elettrico, 2011.

This internship is in collaboration with:

SAPIENZA
UNIVERSITÀ DI ROMA

Calculations of kinetic parameters of LFR with the OpenMC Monte Carlo code

Daniele Tomatis *[1] and Nicolò Abrate[2]

[2] *Politecnico di Torino, Dipartimento Energia, NEMO Group, Corso Duca degli Abruzzi 24, 10129, Torino, Italy*
[1] new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– Internship proposal –
(ID No. 1003338)

***Keywords* —** Lead Fast Reactors, neutron transport, Monte Carlo methods, kinetic parameters
***Topics* —** Reactor physics and analysis, radiation transport, physical modeling

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Location	Turin, Italy (*new*cleo and Politecnico di Torino)
Starting date	As soon as possible
Duration	5–6 months

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*new*cleo is developing new Lead-cooled Fast Reactor (LFR) units for small and modular reactors using fuel that contains plutonium, which is produced by light water reactors currently operating worldwide. The presence of minor actinides and of a fast neutron spectrum in LFRs makes the dynamics of these reactors faster than traditional water (thermal) reactors, thus demanding more accurate estimates of the integral kinetic parameters characterizing the system. The calculation of the kinetic parameters is fundamental for many engineering applications involving system-level analysis and safety studies. This internship focuses on the implementation, verification and validation of different methods for estimating the kinetic parameters with the Monte Carlo computer code OpenMC [1], which is becoming a reference tool for high-fidelity simulation of neutron transport. A recent work proposed some methods for the calculations of the kinetic parameters in OpenMC [2], but that version of the code is not publicly available. This work is intended continuing this research with the latest version of the computer code.

Description

During the internship, the candidate will firstly conduct a literature review of the methods [3, 4, 2] commonly used in Monte Carlo neutron transport for the estimation of the kinetic parameters [5], e.g., the effective neutron lifetime Λ and the effective delayed neutron fraction β_{eff}.

*Contact person, daniele.tomatis@newcleo.com

Afterwards, the candidate will get familiar with the open-source Monte Carlo transport code OpenMC by performing an approximated estimation of the kinetic parameters for some LFR models of interest, without any adjoint flux weighting. Thanks to the outcomes of the literature review, the candidate will implement and compare then different methods for the estimation of adjoint-weighted parameters in OpenMC.

A validation of the methods will be carried out by both exploiting the computational and experimental results available in the literature (e.g., the Flattop system), and possibly comparing the OpenMC results with the kinetic parameters estimated by the Monte Carlo computer code Serpent 2 [6]. Of course, the kinetic parameters of the LFR design will be compared with the ones obtained without adjoint flux weighting, in order to evaluate the discrepancies between the two approaches, which are expected to be relevant [7].

During the internship, the candidate will gain a better insight into the Monte Carlo methods for particle transport, developing specific skills related to the calculation of adjoint-weighted parameters. The candidate will become a proficient user and developer of OpenMC, acquiring competences in Python programming as well. At the end of the internship period, the candidate is supposed to prepare a technical report describing the work performed and the results obtained. This internship will be supervised by the members of the Codes and Methods group in *new*cleo and the academic staff at Politecnico di Torino.

Work plan

a) Literature review of methods to estimate kinetic parameters in Monte Carlo codes
b) OpenMC introduction and training
c) Calculation of non-adjoint-weighted kinetic parameters of LFR
d) Selection and implementation of methods for adjoint-weighted kinetic parameters
e) Validation of the methods and analysis of the results
f) Preparation of a technical report

Applicant profile

Master or PhD student in Nuclear Engineering.
Background: fundamentals in reactor physics and Monte Carlo methods.
Required computer skills: A good knowledge of Python and Linux operating systems (or willingness to learn). Knowledge of the C++ programming language is appreciated, but not required.

References

[1] P. K. Romano, N. E. Horelik, B. R. Herman, A. G. Nelson, B. Forget, and K. Smith. Openmc: A state-of-the-art monte carlo code for research and development. *Annals of Nuclear Energy*, 82:90–97, 2015.

[2] X. Peng, J. Liang, B. Forget, and K. Smith. Calculation of adjoint-weighted reactor kinetics parameters in openmc. *Annals of Nuclear Energy*, 128:231–235, 2019.

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[4] V. Vitali, F. Chevallier, A. Jinaphanh, P. Blaise, and A. Zoia. Spectral analysis by direct and adjoint monte carlo methods. *Annals of Nuclear Energy*, 137:107033, 2020.

[5] A. F. Henry. The application of reactor kinetics to the analysis of experiments. *Nuclear Science and Engineering*, 3(1):52–70, 1958.

[6] J. Leppänen, M. Aufiero, E. Fridman, R. Rachamin, and S. van der Marck. Calculation of effective point kinetics parameters in the serpent 2 monte carlo code. *Annals of Nuclear Energy*, 65:272–279, 2014.

[7] B. Verboomen, W. Haeck, and P. Baeten. Monte carlo calculation of the effective neutron generation time. *Annals of nuclear energy*, 33(10):911–916, 2006.

This internship is in collaboration with:

1859

Politecnico di Torino

Calculation of the numerical benchmark ALFRED with the Monte Carlo computer code OpenMC

Daniele Tomatis *[1]

[1] new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– Internship proposal –
(ID No. 1003353)

***Keywords* —** Lead Fast Reactors, ALFRED, Monte Carlo, OpenMC
***Topics* —** Reactor physics and analysis, neutron transport, physical modeling

Location	Turin, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

*new*cleo is developing new Lead-cooled Fast Reactor (LFR) units for small and modular reactors exploiting the physical peculiarities associated to a fast spectrum nuclear system [3]. The absence of operating experience with LFR demands deeper investigation of these nuclear devices. The Advanced LFR European Demonstrator (ALFRED), proposed by the Nuclear Energy Agency (NEA), is a useful numerical benchmark to study LFR physics. This internship focuses on the neutron physics of LFR. The student will make practice with neutronics calculations using the Monte Carlo computer code OpenMC [2], which is a reference tool for high-fidelity neutron transport simulation. The numerical benchmark shows different calculation models, starting from pin-cell problems and assembly/supercell problems up to whole core simulations. This benchmark is used at *new*cleo to validate existing calculation schemes and elaborate new ones for high-fidelity calculations of different LFR designs.

Description

During the internship, the candidate will first conduct a literature review on ALFRED, including the benchmark specifications [1], in order to analyse the materials' definition and the geometric

*Contact person, daniele.tomatis@newcleo.com
[1] *https://www.oecd-nea.org/jcms/pl_66836/lead-cooled-fast-reactor-benchmark-lfr.*

data describing the core. Afterwards, the candidate will get familiar with the open-source Monte Carlo transport code OpenMC by modelling the different phases characterizing the benchmark. These stages are associated to different scales of the problem under study: pin-cell, assembly, super-assembly, whole core, see Figure 1.

Several quantities must be calculated for each configuration: the fundamental eigenvalue, reactivity worths, criticality factors, the neutron flux distribution, neutron spectra, cross sections and reaction rates [1]. The student will become an advanced user of the code by using properly targeted tallies and filters, also being introduced to statistical error propagation in the post-processing phase. The results thus obtained will be interpreted from both physical and numerical points of view. The candidate will develop skills in Python programming thanks to the user interface of OpenMC. Finally, this internship aims training the candidate to develop a research-driven approach towards the challenging physics characterizing LFR systems. At the end of the internship period, the candidate will prepare a technical report describing the work performed and the results obtained. This internship will be supervised by the members of the Codes and Methods group in *new*cleo.

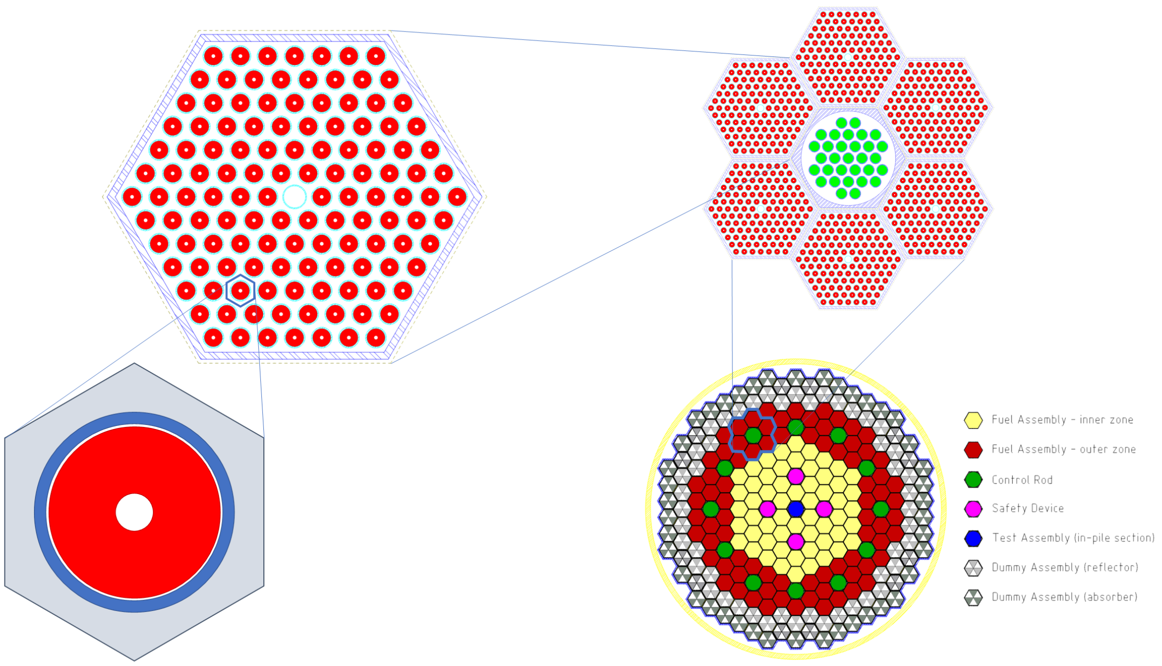

Figure 1: Design of the Advanced LFR European Demonstrator (ALFRED)

Work plan

a) Literature review about full-core Monte Carlo calculations and ALFRED
b) OpenMC introduction and training
c) Preparation of the input files and of the numerical model
d) Calculation of the results as requested by the benchmark specifications
e) Post-processing and physical interpretation of the results
f) Preparation of a technical report

Applicant profile

Master or PhD student in Nuclear Engineering.
Background: fundamentals in reactor physics and Monte Carlo methods.
Required computer skills: A good knowledge of Python and Linux operating systems (or willingness to learn). Knowledge of C++ programming language is a plus (optional).

References

[1] J. R. Lamarsh and A. J. Baratta. *Introduction to Nuclear Engineering. 2nd Edition*. Addison-Wesley, Reading, 1983.

[2] P. K. Romano, N. E. Horelik, B. R. Herman, A. G. Nelson, B. Forget, and K. Smith. Openmc: A state-of-the-art monte carlo code for research and development. *Annals of Nuclear Energy*, 82:90–97, 2015.

[3] A. E. Waltar, D. R. Todd, and P. V. Tsvetkovo. *Fast Spectrum Reactors*. Springer, 2012.

Modelling the thermohydraulics of a spiral-type once-through steam generator by advanced models using the AC^2-ATHLET computer code

Antonino Lombardo *and Daniele Tomatis

new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– *Internship proposal* –

(ID No. 1003528)

***Keywords* —** LFR, cross-flow heat exchanger, spiral tube, flow boiling, ATHLET code
***Topics* —** Physical modelling, two-phase thermal-hydraulics, system code modeling

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Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	3–4 months

Context

*new*cleo has planned an experimental campaign with external partners in order to optimize the design of components for lead-cooled fast reactors. In this framework, the use of thermal-hydraulic system codes is very important to reproduce the physical behaviour during transients, and so to make decisions in design studies. Among these new components, newcleo is currently investigating a newly designed steam generator. It is essential to assess the correct thermal behaviour of the primary and secondary sides of this component. Several experimental campaigns are starting this year to support the design program. Meanwhile, the study of the most appropriate physical models to be adopted in numerical simulations is crucial for the preliminary identification of the component performances and the design of the same experimental test facilities.

The current internship is proposed to students attending the last year of the Master program in Nuclear Engineering with particular interest in thermal-hydraulics.

*Contact person, antonino.lombardo.2@newcleo.com

Description

During this internship, the student will perform numerical simulations of the once-through spiral-type heat exchanger by the computer code AC_2-ATHLET developed by GRS [1]. This steam generator consists of many layers, each containing a single spiral tube following an Archimedean or arithmetic spiral. The resulting bundle is arranged in a staggered lattice with equal vertical and radial spacing. The tubes are all immersed in molten lead, which flows outwards from the center to the periphery of the exchanger. Subcooled water enters the spirals at the periphery of the exchanger, flowing inwards inside the tubes, and exits as superheated steam. Flow-boiling occurs inside the tubes, with possible phase separation in the section during certain flow regimes due to the centrifugal force caused by the tube curvature. Different correlations for heat transfer between lead and water are therefore needed along the tube.

The student will carry out a review of the existing literature to find the most appropriate physical correlations for heat transfer in the configuration at hand. In the past, several studies have been carried out for modeling helically-coiled heat exchangers [2] and heat transfer phenomena in presence of phase separation. Unfortunately, nothing seems available in literature yet for spiral geometries at the chosen operating conditions. ATHLET mainly offers heat transfer correlations for straight tubes, as normally done by system codes. Since the fluid conditions are different from those in straight pipes, it is necessary to consider other correlations too. For example, it is known from previous studies in helicoidal bundles that the onset of the thermal crisis is remarkably delayed due to the phase displacement inside the tube and the rewetting of the walls by the liquid droplets [3].

Although helical coils have a different characterizing geometry, both spirals and helicals may show similar presence of secondary flows inside the tubes. These are created by the centrifugal force acting on the fluid, which results in two counter-rotating vortices. They are expected to improve heat transfer and to create a stronger interaction between the two phases during water boiling. Due to the development of secondary flows, the Nusselt number in spirals is found to be directly proportional to the curvature ratio of the spiral and inversely proportional to the pitch to diameter ratio [4]. Some studies shown that most helical correlations could be eventually used for spirals if the average radius of curvature of the spiral coils is used in the correlations [5]. Therefore, a better estimate of the component thermal performance may be obtained using different heat transfer correlations.

Recent versions of ATHLET allow the use of external user-defined correlations for the calculation of heat transfer modes. These are implemented through dynamic libraries interfaced with the executable. This internship focuses on the development of appropriate external models that will be selected, tested and used for the characterization of the tube bundle performance. At the end of the internship, the preparation of a technical report is requested to describe the work done by the student and to compile the analysis of the results.

This internship will be supervised by an engineer from *new*cleo.

Work plan

During this internship, the student will be introduced to the system code AC_2-ATHLET for the modeling and design of thermal-hydraulics components and loops in steady state and transient conditions.

The student will develop the knowledge required for the description of the hydraulic systems by means of control volumes and ATHLET's own specific fluid and solid objects. The acquired skills will be used to characterize one representative spiral layer of the steam generator under study. The final goal of this work will be the comparison of the results obtained with the correlations that are already available in the code and with the new user-defined correlations.

The preliminary work-plan is detailed below:

a) Literature review of the phenomena occurring in the spiral tubes
b) Discussion of the problem
c) ATHLET introduction and training
d) Setup of the model for the spiral SG
e) Development of dynamic libraries for the selected correlations
f) Test of the libraries in simplified case studies
g) Analysis of results
h) Preparation of a technical report

Applicant profile

Master student in Nuclear Engineering.
Background: *Fundamentals in thermal-hydraulics and heat transfer, multiphase flow*.
Computer skills: Linux, bash, LaTeX, Python.

References

[1] A. Schaffrath, M. Sonnenkalb, and A. Wielenberg. Grs code system AC2. *Kerntechnik*, 84(5):356-356, 2019.

[2] Paisarn Naphon and Somchai Wongwises. A review of flow and heat transfer characteristics in curved tubes. *Renewable and Sustainable Energy Reviews*, 10(5):463–490, 2006.

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[4] Patil Rahul Harishchandra. Fluid flow and heat transfer analogy for laminar and turbulent flow inside spiral tubes. International Journal of Thermal Sciences 139:362–375, 2019.

[5] Shah R. K. and Joshil S. D. Convective heat transfer in curved ducts. handbook of single phase convective heat transfers. 1987.

[6] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

Calculation of LFR fuel elements by the lattice transport computer code DRAGON

Daniele Tomatis *[1]

[1]new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– Internship proposal –

(ID No. 1003558)

***Keywords* —** LFR, V&V, DRAGON, lattice calculations, cross section preparation
***Topics* —** Physical modeling, neutronics, fuel design

Location	Saclay ou Saint-Quentin-en-Yvelines
Starting date	As soon as possible
Duration	5–6 months

Context

*new*cleo is designing new units of lead-cooled fast reactors (LFR) aiming to increase the utilization of plutonium produced by the many light water reactors that are currently operating worldwide. The fuel elements are exposed to a fast neutron spectrum favouring fission of heavier actinides. The reactor is cooled by molten lead that shows low neutron absorption and shields photon radiation.

*new*cleo is considering the lattice transport computer code DRAGON [1], developed at the Polytechnique de Montréal, Canada, for the calculations of its fuel elements and for general cross section preparation. DRAGON offers advanced methods for self-shielding of cross sections of resonant nuclei and different solvers for the Boltzmann transport equation, including the method of characteristics in unstructured geometries. DRAGON is a reference computer code for the calculations of light water thermal reactors. This computer code is currently under upgrade to also calculate fast reactors showing typical hexagonal fuel assemblies. This internship supports the validation of the lattice calculations performed by DRAGON with the comparison of the results obtained by the Monte Carlo computer code OpenMC.

*Contact person, daniele.tomatis@newcleo.com
[1] https://www.polymtl.ca/phys/en/dragon-download

Description

The fuel assemblies used in LFRs are built upon a hexagonal lattice with hollow fuel pellets inside the fuel rods. The assemblies are boxed showing a central channel that can host the instrumentation or enhance cooling. The fuel is made of mixed uranium and plutonium oxides. The rods can also contain depleted uranium fuel that makes breeding blanket zones for the optimization of the core cycle. The fuel rods are spaced by a metallic wire that is helically wrapped around the cladding to avoid mechanical contact between neighbouring rods. Other spacing solutions based on grids can be adopted. The assemblies are boxed and immersed in molten lead, which removes the heat released by nuclear reactions while flowing through the assemblies.

During this internship, the candidate will calculate a set of fuel assemblies by the deterministic code DRAGON and by the Monte Carlo code OpenMC to compare pin-wise reaction rates and integral quantities like the neutron multiplication factor. Different techniques for cross section preparation will be tested with DRAGON, using unstructured geometries and the method of characteristics to calculate the neutron transport. Monte Carlo calculations introduce fewer approximations but at the cost of longer calculations. They are then used to validate the deterministic calculations in a representative set of cases, featuring different assembly types. Comparisons of reaction rates in the typical 33-group energy mesh of ERANOS (another deterministic computer code) are requested to validate the self-shielding step done by DRAGON. The validation will be performed with fresh fuel and after exposure at different burnup steps.

At the end of the internship, the preparation of a technical report is requested to describe the work done by the student and to compile the analysis of the results. This internship will be supervised by engineers from *new*cleo.

Work plan

a) Literature review and problem definition
b) Training and practice of DRAGON
c) Setup of OpenMC calculations
d) Problem discussion
e) Calculation and analysis of results
f) Preparation of the technical report

Applicant profile

Master or PhD student in Nuclear Engineering, Theoretical or applied Physics.
Background: *fundamentals in reactor physics, neutronics and Monte Carlo methods*.
Required computer skills: Python programming (intermediate level), Linux, LaTeX scientific editing (optional).

References

[1] Alain Hébert. A review of legacy and advanced self-shielding models for lattice calculations. *Nuclear science and engineering*, 155(2):310–320, 2007.

[2] Alain Hébert. *Applied reactor physics*. Presses inter Polytechnique, 2009.

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[4] Paul K Romano, Nicholas E Horelik, Bryan R Herman, Adam G Nelson, Benoit Forget, and Kord Smith. Openmc: A state-of-the-art monte carlo code for research and development. *Annals of Nuclear Energy*, 82:90–97, 2015.

Burnup calculation of LFR fuel assemblies by the Monte Carlo computer code OpenMC

Matteo Zammataro*and Daniele Tomatis

new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 15, 2024

– *Internship proposal* –
(ID No. 1003578)

***Keywords* —** LFR, burnup calculation, depletion and transmutation, Monte Carlo
***Topics* —** Reactor physics and analysis, numerical simulation, fuel design

Location	Turin, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

*new*cleo is developing innovative small modular reactors that use lead as a coolant. Burnup calculations are a critical step in the neutronic analysis of such a reactor system, predicting the performance of the fuel elements in terms of neutron reactivity. Deterministic and Monte Carlo codes are typically used for this analysis, where a solver of the Boltzmann transport equation is coupled to a depletion solver. To solve the equations governing transmutation and decay, several numerical methods are available. In order to improve the efficiency of our burnup calculations, this internship focuses on the comparison of the numerical methods available in the depletion solver that is implemented in the Monte Carlo computer code OpenMC [1].

Description

The small modular LFRs designed by *new*cleo operates using solid MOX as nuclear fuel. When nuclear fuel is irradiated over a period of time, the nuclides in the fuel undergo transmutation as a result of nuclear reactions and radioactive decay. This time-dependent process of transmutation of nuclides in the presence of a neutron flux is known as depletion. The neutron-induced

*Contact person, matteo.zammataro@newcleo.com

transmutations are strictly correlated with the neutron flux, which in turn depends on the composition of the fuel. Therefore, for the analysis of nuclear systems, it is necessary to couple a neutron transport solver with a transmutation/decay solver. The equation for the decay and transmutation of nuclides in the presence of a neutron flux can be written as

$$\frac{d\mathbf{n}}{dt} = \mathbf{A}(\mathbf{n}, t)\mathbf{n}, \qquad \mathbf{n}(t=0) = \mathbf{n}_0, \tag{1}$$

where $\mathbf{n} \in R^n$ is the nuclide density vector, $\mathbf{A}(\mathbf{n}, t) \in R^{n\times n}$ is the burnup matrix containing the decay and transmutation coefficients, and $\mathbf{n}_0$ is the initial density vector. A variety of numerical methods exist to solve such an equation. The depletion module of the open source Monte Carlo code OpenMC [2] provides 8 of these methods, ranging from the simple **predictor integrator** to more complex ones. The predictor integrator uses an explicit time scheme to solve the depletion equation. Over a time step $t \in [t_i, t_i + h]$, the solution of the equation 1 using the predictor integrator can be written as

$$\mathbf{A}_i = A(\mathbf{n}_i, t_i), \tag{2}$$

$$\mathbf{n}_{i+1} = \exp\left[\mathbf{A}_i \cdot h\right] \mathbf{n}_i. \tag{3}$$

Since the predictor integrator method is extremely simple, it is not expensive in terms of computational cost, but it may require very small h values to get acceptable numerical accuracy. More complex methods, such as the commutator-free Lie [3] and the predictor-corrector methods [4], can treat the non-linearity of the problem by limiting the associated computational effort for the numerical solution. During the internship, the student will compare the performances of these methods using an OpenMC model of a LFR core. This internship will result in a better understanding of the neutronic analysis of a reactor core. The student will become proficient in using OpenMC and will also learn how to program in Python. At the end of the internship, the student will write a technical report on the analysis of the results of the numerical simulations. The student will be supervised by the members of the Codes and Methods group of *new*cleo.

Work plan

During the internship, the student will be introduced to the OpenMC open source Monte Carlo transport code for the simulation of stationary neutron problems featuring fuel elements in eigenvalue calculation mode. The student will also set up input decks for burnup calculations. Different numerical methods will be used to solve the burnup equation. The internship will explore different numerical methods and allow the student to develop an optimized methodology for a coupled problem, increasing the accuracy in the numerical simulation.

The expected working plan is detailed in the following:

a) Literature review of solving methods for depletion solvers
b) Analysis of similar study cases and discussion of the problem
c) OpenMC introduction and training
d) Burnup analysis on a LFR fuel element using different numerical methods to solve the depletion equation
e) Burnup analysis on a LFR core model using different numerical methods to solve the depletion equation
f) Analysis of the results
g) Preparation of a technical report

Applicant profile

Master or PhD student in Nuclear Engineering, Applied Mathematics and Physics.
Background: fundamentals in reactor physics.
Required computer skills: A good knowledge of Python and Linux operating systems (or willingness to learn). Knowledge of LaTeX editing is appreciated, but not required.

References

[1] Paul K. Romano, Nicholas E. Horelik, Bryan R. Herman, Adam G. Nelson, Benoit Forget, and Kord Smith. OpenMC: A state-of-the-art Monte Carlo code for research and development. *Annals of Nuclear Energy*, 82:90–97, 2015. Joint International Conference on Supercomputing in Nuclear Applications and Monte Carlo 2013, SNA + MC 2013. Pluri- and Trans-disciplinarity, Towards New Modeling and Numerical Simulation Paradigms.

[2] Paul K. Romano, Colin J. Josey, Andrew E. Johnson, and Jingang Liang. Depletion capabilities in the OpenMC Monte Carlo particle transport code. *Annals of Nuclear Energy*, 152:107989, 2021.

[3] Elena Celledoni, Arne Marthinsen, and Brynjulf Owren. Commutator-free Lie group methods. *Future Generation Computer Systems*, 19(3):341–352, 2003. Special Issue on Geometric Numerical Algorithms.

[4] Aarno Isotalo. Comparison of Neutronics-Depletion Coupling Schemes for Burnup Calculations–Continued Study. *Nuclear Science and Engineering*, 180(3):286–300, 2015.

Development of advanced materials for LFR reactors

– Internship Proposal –

(ID No. 1003849)

Marialuisa Gentile[*1] and Francisco Garcia Ferrè[1]

[1]*new*cleo *SrL, Via Galliano 27, 10129 Torino, Italia*

March 06, 2024

***Keywords* —** LFR materials, corrosion, metals, ceramic materials, coatings
***Topics* —** stainless steel, optical microscopy, mechanical tests, secondary electron microscopy, x-ray diffraction, surface treatments, wetting

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Location *new*cleo SrL, Via Galliano 27, 10129 Torino, Italy

Starting date Between September 2024 and March 2025

Duration 3 – 6 months

Context

Lead-cooled fast reactors (LFRs) are considered one of the most promising technologies to meet the requirements introduced for advanced nuclear systems. The operation of small modular reactors with a fast neutron spectrum poses several material challenges to scientists and engineers due to the extreme environmental conditions inside the reactor [1]. Therefore, the development of advanced materials is fundamental to successfully deploy new power reactors [2]. *new*cleo is committed to a large R&D program to assess the feasibility of metallic materials and coatings for nuclear applications. In this framework, the aim of the internship is to study the current state of the art of nuclear structural materials, to carry out experimental tests in the laboratory, and to apply artificial intelligence (AI) to accelerate material discovery.

Description

Corrosion protection of materials used in LFRs is one of the main issues that hinders the development of this class of nuclear reactors. The integrity of structural materials is strongly affected by neutron doses, burnup level and operating parameters such as temperature and

[*] Contact person: marialuisa.gentile@newcleo.com

oxygen concentration. Understanding the mechanism behind the failure of materials in LFR plays a vital role in improving the safety criteria of nuclear reactors and promoting research on advanced materials.

The successful candidate will analyze data presented in scientific literature to identify gaps in the current state of the art and apply AI to material manufacturing. The intern will work in laboratories to prepare specimens and characterize them through the following techniques:

- Optical microscopy
- Secondary Electron Microscopy
- X-ray diffraction
- Mechanical tests
- Nanoindentation
- Wettability measurements
- Thermal analysis tests
- Heat treatments

The intern will work in collaboration with the *new*cleo's branches in Brasimone and Lion.

Work plan

a) Literature review
b) Materials manufacturing
c) Materials testing
d) Data analysis
e) Preparation of a final report and presentation

Applicant profile

Master student in Nuclear Engineering, Mechanical Engineering, Materials Science, Chemistry, Physics, Chemical Engineering.

Skills:

- Knowledge of material manufacturing processes and characterization techniques.
- Required computer skills: knowledge of Excel and data analysis software. Experience with programming languages (Matlab, Python) is desirable.
- Languages: English (at least B2 level). French is a plus.

References

[1] Malerba, L. et al., Materials for Sustainable Nuclear Energy: A European Strategic Research and Innovation Agenda for All Reactor Generations. *Energies,* **15**, 1845 (2022)

[2] Fulger, M., Khumsa-Ang, K., Šípová, M., Ducu, C. M. & Sáez-Maderuelo, A. Special Issue: Behavior of Materials (Alloys, Coatings) in Conditions Specific to Gen IV Nuclear Reactors., *Coatings.* **13**, 58 (2022)

Implementation of a scientific software providing the thermodynamic properties of gases

Pierre-Alexandre Pantel*[1], Gabriele Ottino[2], and Daniele Tomatis[2]

[1]new*cleo SA, 9 Rue des Cuirassiers, 69003 Lyon 3e, France*
[2]new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– *Internship proposal* –
(ID No. 1003858)

***Keywords* —** GERG, gas, computing, Python
***Topics* —** Thermodynamic properties, applied mathematics, programming, optimization

Location	*new*cleo SA, 9 Rue des Cuirassiers, 69003 Lyon 3e, France
Starting date	June – July, 2024
Duration	2 months

Context

Chemical control of the primary system in liquid-metal nuclear reactors is of crucial importance during plant operation, preventing alteration or degradation of materials such as steel and other structural alloys by corrosion. In addition, the control system handles the purification of the coolant and other involved elements, such as inert atmosphere system controllers, from hazardous radioactive nuclides, originated by nuclear reactions, to prevent excessive dose release in case of leaks.

*new*cleo's activities on chemical control systems are the objects of intensive studies, both in terms of experiments and numerical modeling. To support both types of activities, *new*cleo needs a new Python package to offer a unique and standardized entry point for the use of empirical correlations for the thermodynamic properties of common gases. *Codes & Methods* team is in charge of this activity.

*Contact person, pierre-alexandre.pantel@newcleo.com

Description

The computation of the thermodynamic properties (such as density, enthalpy, etc.) of gases is a crucial subject for many industries, particularly in the energy sector, whether carbon-free or not. To provide a scientific support to these stakeholders, an European research group known as "GERG" (*Groupe Européen de Recherches Gazières*) is compiling all the knowledge available on this subject. In particular, this group has published two documents of interest to us [1, 2] that provide wide-range equations of state for 21 natural gases and their mixtures.

Our final goal is to implement a Python module to compute the thermodynamic properties of gases. In this context, the candidate will actively contribute to the first release of this new tool, based on the results provided by an internal pre-design analysis.

This internship consists in wrapping the existing implementation (`AGA8`) in Python, according to the pre-design study results. This will require the use of interfacing modules such as `ctypes` or `swig`, as well as the adaptation of the existing code whenever the structure of the final tool could be simplified.

The candidate will be supported by the *Codes & Methods* team members of *new*cleo. The team adopts high quality standards for code development, thus allowing the candidate to develop/consolidate her/his skills about the following aspects of the software engineering [3, 4]:

- Object-Oriented programming based on SOLID principles;
- Well-documented code writing for maintainability purposes.

Work plan

1) GERG [1, 2] articles review.
2) Existing tool review (`AGA8`).
3) Wrapping code to a Python environment.
4) Preparation of a technical report.

Applicant profile

Master student in Industrial Engineering, Chemistry, Applied Physics, Informatics or Computer Science.
Skills and background:

- Fundamentals in thermodynamics.
- Basic knowledge of software programming (previous experience in Python appreciated, but not fundamental).
- Basic knowledge of Linux operative system.

Nice to have: experience using `git`, basic knowledge on liquid metal-cooled fast reactors.

References

[1] O. Kunz, R. Klimeck, W. Wagner, and M. Jaeschke. The GERG-2004 Wide-Range Equation of State for Natural Gases and Other Mixtures. Technical report, 2007.

[2] O. Kunz and W. Wagner. The GERG-2008 Wide-Range Equation of State for Natural Gases and Other Mixtures: An Expansion of GERG-2004. *Journal of Chemical & Engineering Data*, 57(11):3032–3091, 2012.

[3] Chetan Giridhar. *Learning Python Design Patterns*. Packt Publishing, Birmingham - Mumbai, 2 edition, 2016.

[4] Mark Lutz. *Learning Python: Powerful Object-Oriented Programming*. O'Reilly Media, Sebastopol, USA, 5 edition, 2013.

Investigation of variance reduction methods based on weight-windows for radiation transport simulations in deep penetration problems arising in LFR reactors

Matteo Zammataro*[1], Matteo Falabino[1], and Nicolò Abrate[2]

[2] *Politecnico di Torino, Dipartimento Energia, NEMO Group, Corso Duca degli Abruzzi 24, 10129, Torino, Italy*
[1] new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

March 16, 2024

– Internship proposal –
(ID No. 1003888)

***Keywords* —** Variance reduction methods, Monte Carlo, OpenMC, LFR, Weight Windows
***Topics* —** Radiation shielding calculations, Monte Carlo calculations

Location	Turin, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

As lead fast reactors (LFR) gain prominence in the future nuclear energy landscape, it becomes imperative to thoroughly investigate and optimise various aspects of their operation, including radiation protection calculations. In particular, the estimation of the dose rate on the vessel roof is of paramount importance for verifying the feasibility of *in-situ* interventions during reactor operation and maintenance. *new*cleo as one of the most important players in the Gen-IV nuclear industry, is interested in ensuring that all these safety requirement are respected. The stage consists in the investigation of variance reduction methods allowing to perform Monte Carlo radiation shielding calculations with reduced computations times.

*Contact person, matteo.zammataro@newcleo.com

Description

The design calculations for the development of the LFR concept at *new*cleo include a set of high-fidelity radiation transport simulations, such as the calculation of the dose rate at the top of the reactor pool or in spent fuel pools. These engineering calculations require the calculation of photon and neutron fluxes that are several orders of magnitude smaller than those close to the particle source. Hence, the well-known issues of classical deep-penetration problems in the Monte Carlo (MC) framework arise. In addition to the slow convergence rate of the MC method, which scales as $1/\sqrt{N}$, where N indicates the number of particle histories, the major challenge is the very small number of particles reaching the tallying volumes far from the source. Hence, a standard simulation would take a very long computational time, and, in some cases, it may not even be possible.

These problems are usually overcome by using Variance Reduction (VR) techniques, i.e. methods capable of artificially increasing the probability of rare events, while maintaining the same expected value. Among these, Global Variance Reduction (GVR) methods aim at equally populating each region of the model, thus allowing physical observables to be estimated with an acceptable accuracy across the entire model [1]. By providing global information, and highlighting possible preferential propagation channels for radiation, this class of variance reduction methods is of considerable interest in the preliminary design stages of nuclear power plants.

The Weight Window (WW) is a popular VR method that allows control of the particle population by selectively splitting or subjecting particles to Russian roulette, depending on their likelihood of contributing to a given score [1]. Weight windows are defined on a spatial and energy mesh of the entire phase space. For each of these phase space regions, a weight window consists of a range of statistical weights within which the particle is allowed to remain. If it has a weight greater than the WW upper bound, it is split, whereas if the weight is less than the lower bound, it plays Russian roulette. The Method of Automatic Generation of Importances by Calculation (MAGIC) [2] allows to get an efficient calculation of the WW maps for the calculation of the neutron and photon fluxes throughout the model. The use of the MAGIC together with the OpenMC Monte Carlo code [3] is currently under investigation in *new*cleo.

During the internship, the student is demanded to contribute in this study, In particular, the student will compare the results of OpenMC and WW with the reference ones generated with standard OpenMC calculations (without WW). The candidate will also perform several investigations aimed at finding the proper setup of MAGIC WW maximising the calculation performances. This internship will result in a better understanding of the Monte Carlo and Variance Reduction method. The student will become proficient in using OpenMC. At the end of the internship, the student will write a technical report on the analysis of the results of the numerical simulations. The student will be supervised by the members of the Codes and Methods group of *new*cleo, and by Dr. N.Abrate from Politecnico di Torino.

Work plan

The student will be introduced to the use of OpenMC Monte Carlo code for radiation shielding calculations. The student will learn how to properly setup MC calculations and how to post-process results. The internship will explore different setup of the weight window maps for both neutrons and neutron-photons coupled problems.

The expected working plan is detailed in the following:

a) Literature review on the application of VR methods to shielding problems.
b) OpenMC introduction and training.
c) Investigation of several options for the MAGIC method.
d) Analysis of the results
e) Preparation of a technical report
f) (optional) Contributions to the development of the OpenMC code
g) (optional) Preparation of a scientific publication.

Applicant profile

Master student in Nuclear Engineering.
Background: fundamentals in reactor physics, fundamentals in Monte Carlo mothods.
Required computer skills: Basic knowledge of Python and Linux operating systems. Knowledge of LaTeX editing is appreciated, but not required.

References

[1] Madicken Munk and Rachel N. Slaybaugh. Review of hybrid methods for deep-penetration neutron transport. *Nuclear Science and Engineering*, 193(10):1055–1089, 2019.

[2] Andrew Davis and Andrew Turner. Application of novel global variance reduction methods to fusion radiation transport problems. In *International conference on mathematics and computational methods applied to nuclear science and engineering*, Rio de Janeiro, RJ (Brazil), May 2011.

[3] Paul K. Romano, Nicholas E. Horelik, Bryan R. Herman, Adam G. Nelson, Benoit Forget, and Kord Smith. OpenMC: A state-of-the-art Monte Carlo code for research and development. *Annals of Nuclear Energy*, 82:90–97, 2015. Joint International Conference on Supercomputing in Nuclear Applications and Monte Carlo 2013, SNA + MC 2013. Pluri- and Trans-disciplinarity, Towards New Modeling and Numerical Simulation Paradigms.

This internship is in collaboration with:

Comparison of numerical acceleration methods for nonlinear iterations used in the computer code TRANSURANUS

Elena Travaglia and Daniele Tomatis*

newcleo SrL, Via Galliano 27, 10129 Torino, Italy

March 29, 2024

– Internship proposal –

(ID No. 1003986)

***Keywords* —** TRANSURANUS, numerical acceleration, non-linear iterations
***Topics* —** fuel performance, numerical mathematics, computational modelling

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	4–6 months

Context

*new*cleo is currently in the process of developing advanced Lead-cooled Fast Reactor (LFR) units tailored for small and modular reactors. These units incorporate innovative features aimed at addressing the unique challenges associated with LFR technology. Simultaneously, the company is committed to meeting sustainability, economic, and safety objectives, aligning with the criteria set for the fourth generation of nuclear reactors.

In the context of fuel performance analysis, newcleo relies on the TRANSURANUS (TU) thermo-mechanical computer code, which is distributed by the Joint Research Center of the European Commission in Karlsruhe, Germany, under a collaboration research agreement [1, 2]. Newcleo has initiated a meticulous examination of the code to ensure its suitability and adaptability for applications involving LFR technology. The goal is to employ precise physical models that guarantee reliable results in numerical simulations. This ongoing effort also includes improving the code to broaden its scope and enhancing its performances.

*Contact person, daniele.tomatis@newcleo.com

Description

The thermal analysis of an integral fuel rod can be treated by superposing one-dimensional radial and axial solutions. Given the multitude of non-linearities inherent in these processes, only numerical solution techniques prove feasible. These techniques are of critical importance as they determine numerical stability and, to a considerable extent, the overall computational cost.

TU solves heat transfer by the Fourier equation in the radial coordinate of the fuel rod, whose discretized form brings to a tridiagonal system. The nonlinearity of the coefficients in the second order differential equation is handled by successive substitutions. The resulting non-linear iterations are accelerated by minimizing the residuals through a numerical scheme based on Regula Falsi, initially implemented by Lassmann [3].
This procedure was adopted because calculating the temperature of a fuel rod, which is schematically shown in Fig. 1, is a computationally intensive task. Therefore, it is important to focus on obtaining convergence and minimizing the total numerical effort required.

In the current internship the student will perform a complete literature review of the existing models to solve heat conduction equation and techique to accelerate the convergence of such numerical method. Some of this techinque will be implemented and their performance will be compared.

The student will be introduced to the use of TU and will join the team of TU developers at *new*cleo, learning the best practices for collaborative work and quality-assured code development. The production of a technical report is expected at the end of the internship to describe the work done by the student and to compile the analysis of the results.

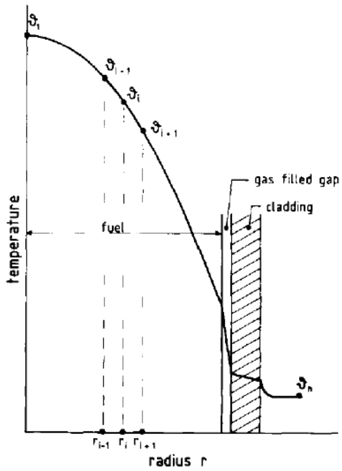

Figure 1: Schematic rappresentation of the stationary radial temperature profile in a slice of the fuel rod

Work plan

a) Litterature review and retrieval of the existing work
b) Discussion of the problem
c) Implementation and verification of the numerical solution

d) Analysis of the numerical results
e) Preparation of a technical report

Applicant profile

Master or PhD student in Nuclear, industrial or Software Engineering; Applied Physics; Mathematics.
Required computer skills: Basic knowledge of Linux operative system and software programming (previous experience in FORTRAN is appreciated, but not fundamental).
Knowledge of LaTeX editing is appreciated, but not required.

References

[1] K Lassmann. Transuranus: a fuel rod analysis code ready for use. *Journal of Nuclear Materials*, 188:295–302, 1992.

[2] K Lassmann and H Blank. Modelling of fuel rod behaviour and recent advances of the transuranus code. *Nuclear Engineering and design*, 106(3):291–313, 1988.

[3] K. Lassmann. A fast and simple iteration scheme for the temperature calculation in a fuel rod. *Nuclear Engineering and Design*, 103(2):211–214, 1987.

Analysis and verification of the burnup model implemented in the computer code TRANSURANUS

Elena Travaglia and Daniele Tomatis*

newcleo SrL, Via Galliano 27, 10129 Torino, Italy

March 29, 2024

– *Internship proposal* –
(ID No. 1003987)

***Keywords* —** TRANSURANUS, Burnup model, LFR
***Topics* —** nuclear fuel design, fuel performance and thermomechanics, computational modeling

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Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	5–6 months

Context

Currently, *new*cleo is designing advanced Lead-cooled nuclear Fast Reactors (LFR). These units incorporate innovative features aimed to address the unique challenges associated with the decarbonization of the energy market and reprocessing of spent nuclear fuel. Concurrently, the company is dedicated to fulfilling sustainability, economic, and safety goals, in line with the criteria established for the fourth generation of nuclear reactors.

In the domain of fuel performance analysis, *new*cleo relies on the TRANSURANUS (TU) thermo-mechanical computer code, which is provided by the Joint Research Center of the European Commission in Karlsruhe, Germany, under a collaboration agreement [1, 2]. *new*cleo is performing a thorough examination of the code to check that it can reliably reproduce the physical behavior of LFR fuel rods.

This ongoing endeavour also includes improving the code to broaden its range of applications, with a specific focus on providing trustworthy predictions for modeling LFR fuel rods. The final goal of this initiative is to develop an improved version of the code.

*Contact person, daniele.tomatis@newcleo.com

Description

The performance of a fuel rod is greatly influenced by several physical phenomena. The exposure of the fuel rod to neutron irradiation determines the time evolution of the isotopic concentrations, and of the power density distribution within the fuel. The power density is the main driving force of the local temperature profile. The temperature heavily affects material properties and many physical phenomena, such as fuel restructuring, actinide redistribution, fission gas release, creep of fuel and cladding [1, 2]. A thorough description of the time evolution of the isotopic concentration of heavy metals in the fuel is thus crucial. Accordingly, one of the first stages in describing fuel rod behaviour is to compute at each radial position in the fuel: the local burnup, the build-up of heavy metal nuclides and the formation of fission products. The equations used to describe these phenomena constitute the so-called burnup models.

A model called TUBRNP, developed by Lassmann in 1994 [3], is implemented in TU. This model predicts the radial power density distribution based on burnup together with the radial profiles of actinide concentrations.

During the internship, the student will study and verify the implementation of the simplified burnup model. In particular, it will be requested to revise the implementation of the calculation of the radial neutron flux distribution in the fuel slices that is currently preventing the use of user-input distributions.

In addition, to assess the physical consistency of the isotopic composition evolution in case of anomalous behavior, a parallel inventory analysis of LFR fuel rods will be performed using the depletion module of the OpenMC Monte Carlo code.

The student will be introduced to the use of TU for the calculation of fuel rods used in nuclear reactors. He/she will join the team of TU developers at *new*cleo where he will learn effective collaborative practices and methods for developing code with ensured quality. At the conclusion of the internship, the student is expected to produce a technical report detailing his/her contributions and experiences during the internship period.

Work plan

a) Literature review and retrieval of the existing work relating to TUBRNP
b) Code implementation
c) Analysis of the results
d) Preparation of a technical report

Applicant profile

Master or PhD student in Nuclear, Industrial or Software Engineering; Applied Physics
Computer skills: FORTRAN, Linux.
Knowledge of LaTeX editing is appreciated, but not required.

References

[1] K Lassmann. Transuranus: a fuel rod analysis code ready for use. *Journal of Nuclear Materials*, 188:295–302, 1992.

[2] K Lassmann and H Blank. Modelling of fuel rod behaviour and recent advances of the transuranus code. *Nuclear Engineering and design*, 106(3):291–313, 1988.

[3] K. Lassmann, C. O'Carroll, J. van de Laar, and C.T. Walker. The radial distribution of plutonium in high burnup uo2 fuels. *Journal of Nuclear Materials*, 208(3):223–231, 1994.

Development of a simplified Python-based tool for the design of a heat exchanger

Barbara Calgaro and Gabriele Ottino*

new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

April 12, 2024

– Internship proposal –
(ID No. 1004103)

***Keywords* —** Bayonet tube, LFR, DHR, flow boiling, Python
***Topics* —** Physical modelling, two-phase thermal-hydraulics, programming

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Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	4 months

Context

*new*cleo has planned an experimental campaign in order to optimize the design of components for lead-cooled fast reactors. The use of thermal-hydraulic system codes [3] is very important to reproduce the physical behavior during transients, and so to make decisions in design studies and to support safety analyses. New heat exchangers of the bayonet-shell type for the Decay Heat Removal system [4] are currently under development as components to remove the residual heat and to cool down the liquid lead after shutdown. These heat exchangers will be installed in the reactor pool, being fed with water as secondary fluid that comes from a tank placed on top of the pool.

In preparation to the future experimental program, with the goal of testing the mechanical and thermal-hydraulic performances of the prototypes for DHR heat exchangers, the current internship is proposed to students with particular interest in thermal-hydraulics. The aim is to develop a code that enhances the suite of design tools already available to engineers at *new*cleo it shall be faster and more agile than them, allowing engineers to focus only on the key quantities of interest, thus reducing setup and post-processing efforts.

*Contact person, barbara.calgaro@newcleo.com

Description

The components under study are heat exchangers made up of coaxial tubes immersed in the liquid lead pool [2]. During transients, subcooled water enters the inner tube and flows downwards. Then, it enters the outer tube where it is heated up by the surrounding lead, eventually leaving the system as superheated steam. The liquid lead is not in direct contact with the outer tube because they are separated by a helium-filled gap flowing in a surrounding gap between the component walls. The full technical details will be provided during the internship, after acceptance of the candidate.

The internship work will focus on the transient modelling of the two-phases boiling heat transfer occurring inside the component, by implementing a dedicated Python-based code. A complete literature review is required to find the most appropriate physical correlations to characterize the flow and heat transfer in the channels. Other in-house codes will also have to be taken as reference for the architecture definition. A preliminary comparison will be performed between the results of the implemented code and the ones provided by other tools already available internally. The student is expected to write a technical report at the end of the internship to describe the work done and the results. All the activities will be driven and supervised by the Codes and Methods group members of *new*cleo that are in charge of the development of methods and codes to be used by the engineering.

Work plan

The expected working plan is detailed in the following:

a) Study of the literature and of the already implemented in-house solutions (focused on similar problems)
b) Definition of the code architecture
c) Implementation of the code
d) Testing against third-party scientific system codes available internally
e) Preparation of a technical report

Applicant profile

Master student in Nuclear, Mechanical or Aeronautical Engineering; Applied Mathematics and Physics.
Skills and background:

- Fundamentals in thermal-hydraulics, heat transfer and multiphase flow;
- Basic knowledge of software programming (previous experience in Python appreciated, but not fundamental);
- Basic knowledge of Linux operative system.

Nice to have: experience using git, basic knowledge on liquid metal-cooled fast reactors.

References

[1] Paisarn Naphon and Somchai Wongwises. A review of flow and heat transfer characteristics in curved tubes. *Renewable and Sustainable Energy Reviews*, 10(5):463–490, 2006.

[2] D. Rozzia, A. Toti, M. Tarantino, L. Gramiccia, D. Vitale Di Maio, and F. Giannetti. Doublewall bayonet tube steam generator for LFR application - preliminary characterization. *Technical Report NNFISS-LP3-032*, ENEA Ricerca Sistema Elettrico, 2011.

[3] N. E. Todreas and M. S. Kazimi. *Nuclear systems Volume I: Thermal hydraulic fundamentals*. CRC press, 2021.

[4] N. E. Todreas, M. S. Kazimi, and M. Massoud. *Nuclear systems Volume II: Elements of thermal hydraulic design*. CRC press, 2021.

Verification of fission gas release module for fast reactor applications

Andrea Salomone, Elena Travaglia, and Daniele Tomatis*

new*cleo SrL, Via Galliano 27, 10129 Torino, Italy*

April 17, 2024

– Internship proposal –
(ID No. 1004126)

***Keywords* —** Transuranus, LFR
***Topics* —** Fission gas model, Physical modelling, fuel performance and thermo-mechanical codes

Location	*new*cleo SrL, Via Galliano 27, 10129 Torino, Italy
Starting date	As soon as possible
Duration	4-6 months

Context

*new*cleo is designing Lead-cooled Fast Reactors (LFR) with innovative features to address the challenges of LFR technology while meeting the sustainability, economic and safety goals required for the fourth generation of nuclear reactors. The design of the fuel elements deserves a special attention because LFRs use new materials and operate at higher temperatures and linear power levels compared to Light Water Reactors (LWR). *new*cleo is currently carrying out thermo-mechanical analysis of the fuel rods using the computer code TRANSURANUS [1], [2]. TRANSURANUS is a fuel performance computational tool developed by the Joint Research Center in Karlsruhe (JRC-Germany) and *new*cleo under a collaboration agreement. One of the key steps towards correctly modeling pin behavior is to adopt models and correlations whose range of validity encompasses the operating conditions and materials under consideration. TRANSURANUS has been extensively validated for LWRs, while it is still under development for what concerns Fast Reactor (FR) applications. It is therefore necessary to verify that the current implemented models in the code are suitable to correctly predict fuel behavior in FRs. This last effort is the main objective of the proposed internship.

*Contact person, daniele.tomatis@newcleo.com

Description

Fission gas behavior is one of the most relevant mechanisms in the context of fuel performance. Atomic gas diffusion, bubble formation and coalescence, and gas release are some of the processes to be modeled. Correlation-based and physics-based modules that account for the aforementioned phenomena can be adopted. TRANSURANUS includes both categories, with a physics-based model being still under development for FR applications. One of the needed efforts requires the verification of a proper implementation of such physics-based fission gas behavior module, which is the focus of the proposed internship. The intern will be asked to study TRANSURANUS fission gas behavior module and identify the most relevant variables and correlations involved. They will also be tasked with verifying the correct implementation of theoretical formulations to ensure the phenomena treated by the physics-based fission gas behavior module are correctly represented. The preparation of a technical report detailing the implementation and the analysis of the results is expected at the end of the internship.

Work plan

a) Problem statement
b) Review of current TRANSURANUS fission gas behavior module from a theoretical standpoint
c) Review of current TRANSURANUS fission gas behavior module from a computational standpoint
d) Verification of fission gas behavior module implementation
e) Analysis of numerical results
f) Preparation of a technical report

Applicant profile

a) Master in Nuclear Engineering
b) Academic knowledge of the thermo-mechanical phenomena of nuclear fuel
c) General computer and codes skill (Python, FORTRAN, Linux, LaTeX git ...)
d) Previous knowledge of fuel performance calculation codes and the physical phenomena of fission gas production and release

References

[1] A. Schubert, P. Van Uffelen, J. van de Laar, C.T. Walker, and W. Haeck. Extension of the transuranus burn-up model. *Journal of Nuclear Materials*, 376(1):1–10, 2008.

[2] P. Van Uffelen, C. Győri, A. Schubert, J. van de Laar, Z. Hózer, and G. Spykman. Extending the application range of a fuel performance code from normal operating to design basis accident conditions. *Journal of Nuclear Materials*, 383(1):137–143, 2008. Advances in Nuclear Materials: Processing, Performance and Phenomena.