

List of student internships offered by newcleo

–academic year–
2024–2025

May 9, 2025

Preface

This document contains the internship offers supported by *newcleo*. Each offer contains the specifications and modalities for the application and execution of the internship work.

Please submit your CV and motivation letter to the contact person indicated in the internship offer.

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About newcleo

Privately funded and headquartered in London, *newcleo* was launched in 2021 – and since raised a total of EUR 400m – to be an innovator in the field of nuclear energy. Its mission is to generate safe, clean, economic and practically inexhaustible energy for the world, through a radically innovative combination of existing, accessible technologies.

With visionary co-founders, *newcleo* capitalises on thirty years of R&D activity in metal-cooled fast reactors and liquid-lead cooling systems, and its senior management and advisory team can boast hundreds of years in cumulative hands-on experience.

Counting on around 800 highly skilled employees across Europe, *newcleo* has business, scientific, operations and industrial manufacturing capabilities in a vertically integrated model designed to deliver its ambitious timeline for its plan-to-market.

newcleo's technology, mostly comprising a novel approach to already qualified solutions, addresses equally well the three challenges affecting the nuclear industry to date:

- **Waste:** fast reactors are capable of efficient “burning” (i.e., fission) of depleted uranium, plutonium and minor actinides. When operated with mixed-oxide (MOX) fuel generated from reprocessed nuclear waste, *newcleo*'s reactors not only ensure sustainability by closing the fuel cycle, but can also boost energy independence;
- **Safety:** lead-cooled reactors operate at atmospheric pressure. The properties of lead (thermal capacity and conductivity, boiling point, chemically inert, low neutron activation, shielding properties) together with *newcleo*'s passive safety systems ensure very high levels of safety;
- **Cost:** *newcleo*'s reactor design has been optimised over the last 20 years leading to the concept of an ultra-compact and transportable 200MWe module with improvements in energy density compared to other technologies. Costs are kept low by means of simplicity, compactness, modularity, atmospheric pressure operation and elevated output temperature.

newcleo is also working to significantly invest in MOX fuel manufacturing in developed countries, extracting energy from the current nuclear industry by-products.

newcleo is ready to develop a new, sustainable, and completely safe way of generating nuclear energy that will help humanity reach zero emissions and mitigate global warming.

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

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December 20, 2024

– *Internship proposal* –
(ID No. 1000073)

Keywords — Bayonet tube, LFR, DHR, flow boiling

Topics — Physical modelling, two-phase thermal-hydraulics, numerical mathematics

Location newcleo S.p.A., Via Galliano 27, 10129 Torino, Italy

Starting date To be defined

Duration 5–6 months

Context

newcleo 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

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leaving the system as superheated steam. The flow boiling occurs in helicoidal parallel channels 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 newcleo 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.

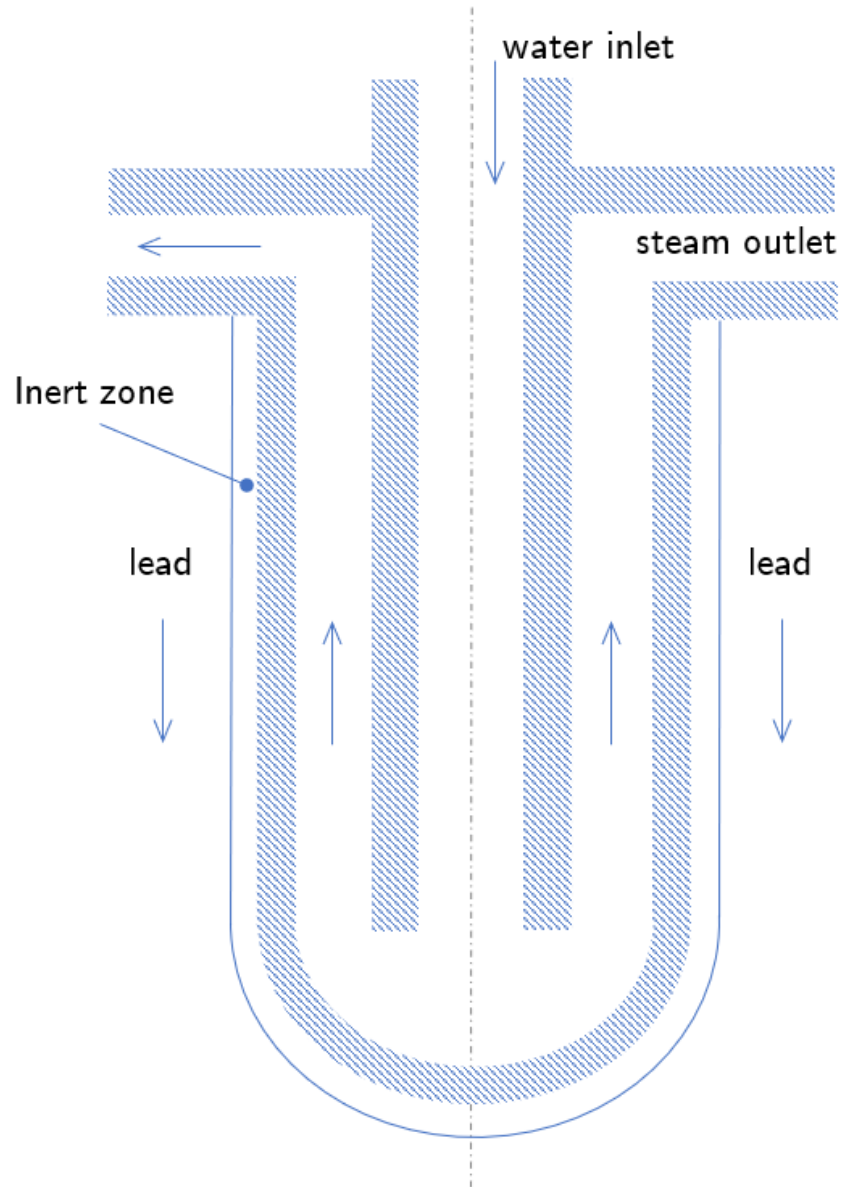


Figure 1: Schematic of a bayonet tube heat exchanger.

- [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 down-comer. *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.

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

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December 20, 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 *newcleo S.p.A., Via Galliano 27, 10129 Torino, Italy*

Starting date To be defined

Duration 5–6 months

Context

newcleo 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 exits

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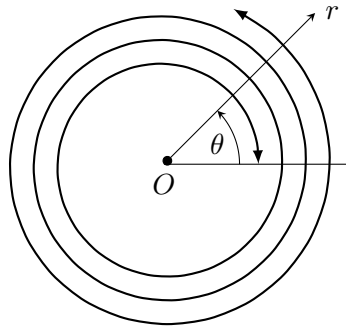


Figure 1: Archimedean spiral.

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

$$r = a + b\theta, \quad (1)$$

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 newcleo 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, newcleo 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

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December 20, 2024

– *Internship proposal* –
(ID No. 1000360)

Keywords — LFR, TRANSURANUS, Monte Carlo

Topics — Physical modelling, neutronics, fuel performance and thermo-mechanical codes

Location newcleo S.p.A., Via Galliano 27, 10129 Torino, Italy

Starting date To be defined

Duration 3–4 months

Context

newcleo is designing new Lead-cooled Fast Reactor (LFR) units for small and modular reactors using MOx fuel. At newcleo, 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. newcleo 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

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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.

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

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December 20, 2024

– *Internship proposal* –
(ID No. 1001776)

Keywords — LMFR, irradiated liquid-metal properties, Python

Topics — Radioactive nuclides volatility, confinement and interaction with liquid metals

Location newcleo S.p.A., 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, newcleo'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 (**Lead Bismuth Handbook 2015**) is a Python package developed by newcleo 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

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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 newcleo 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, Sebastopol, USA, 5 edition, 2013.

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

Elena Travaglia and Daniele Tomatis*

newcleo S.p.A., Via Galliano 27, 10129 Torino, Italy

December 20, 2024

– *Internship proposal* –
(ID No. 1003986)

Keywords — TRANSURANUS, numerical acceleration, non-linear iterations

Topics — fuel performance, numerical mathematics, computational modelling

Location *newcleo S.p.A., Via Galliano 27, 10129 Torino, Italy*

Starting date To be defined

Duration 4–6 months

Context

newcleo 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.

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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 technique to accelerate the convergence of such numerical method. Some of this technique 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 newcleo, 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.

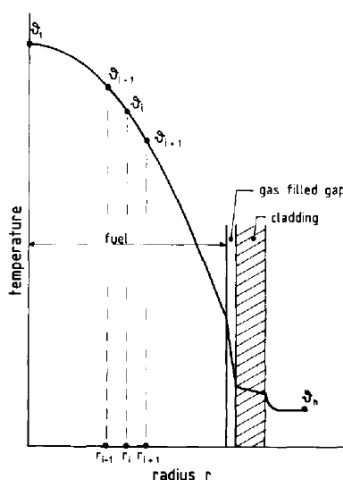


Figure 1: Schematic representation of the stationary radial temperature profile in a slice of the fuel rod

Work plan

- Literature review and retrieval of the existing work
- Discussion of the problem
- 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 S.p.A., Via Galliano 27, 10129 Torino, Italy

December 20, 2024

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

Keywords — TRANSURANUS, Burnup model, LFR

Topics — nuclear fuel design, fuel performance and thermomechanics, computational modeling

Location newcleo S.p.A., Via Galliano 27, 10129 Torino, Italy

Starting date To be defined

Duration 5–6 months

Context

Currently, *newcleo* 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, *newcleo* 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]. *newcleo* 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.

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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 newcleo 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.

Validation of lead-water heat exchangers modelling in ATHLET through benchmarking with simplified tools

Matteo Rostagno ^{*1}

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January 17, 2025

– *Internship proposal* –

(ID No. 1005558)

Keywords — LFR, Heat Transfer, separate effect test, system TH codes

Topics — multiphysics/multiscale modelling, safety assessment, scientific codes

Location newcleo SpA, Via Galliano 27, 10129 Torino, Italy

Starting date To be defined

Duration 5–6 months

Context

Lead technology is one of the most promising alternatives for the development of advanced nuclear reactors and sustainable energy scenarios. In this context, *newcleo* is involved in the design and construction of Advanced Modular Reactors (AMR) lead-cooled.

For Lead Fast Reactor (LFR), a major role for compactness is played by the efficiency of the in pool heat exchangers (Steam Generator, Decay Heat Removal) and the optimization of their working point is under discussion. Thermal-hydraulic system codes (hereinafter, STH) are used for the design and safety analyses of LFRs [1]. Suitable modelling strategies are yet to be chosen according to the available calculation environment, including the selection of the most appropriate models and closure laws.

The development of tools and models able to support the design phase is of major importance, as well as the justification of the assumptions of adopted tools.

The code validation against the available experimental measurements for the specific purpose of the LFR is done through the choice of the most suitable closure laws, having a direct influence on the results provided by the code itself.

It may also support the validation of the ATHLET code, thus improving the selection of the most suitable closure laws.

The validation effort will be part of a wider activity dedicated to the STH codes Validation and Verification (V&V) to attain a reasonable level of robustness for the adopted tools.

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Description

This internship will support the identification and modelling of heat exchange phenomena occurring between lead coolant, reactor internals and secondary water loop in different scenarios (steady state, transient and accidental).

The focus will be the assessment of the most appropriate closure laws for irradiation, conduction and convection justifying this choice and highlighting the differences. This task will be carried out by means of the analysis of heat exchanges regimes and flow pattern maps.

In the hypothesis of a geometry representative of a LFR pool, this internship will provide the criteria for selecting the most appropriate closure laws among the ones available in the ATHLET code and/or asking for the implementation of new ones and the justification behind this choice.

For these purposes, simplified Python tool will be associated to the STH code in order to facilitate the assessment of selected closure laws and heat transfer mechanisms providing a first comparison against ATHLET.

Parametric and sensitivity analysis will be performed in order to understand the differences among assessed closure laws, their validity domain and the possible extrapolation to reactor operating conditions. As optional work, dimensional analysis may be used to justify the semi-empirical form of the correlations and to propose possible improvements.

The target is to meet the *newcleo* Codes & Methods (C&M) department needs in term of codes V&V. Such methodology will be tested and deployed against open literature mock-ups with available measurements and lay the groundwork for new experimental campaigns ongoing or foreseen by *newcleo*.

Work plan

The work plan is structured according to the following items:

1. Review of the state-of-the-art literature with focus on available experimental measurements and mock-ups but and on heat exchange phenomena and modelling between liquid metal flows and water.
2. Adaptation of available simplified python tools to the selected mock-ups test section geometries.
3. Automation of pre- and post-processing to analyse experimental measurements and closure laws.
4. Proposition of a benchmark against ATHLET and the simplified tool in a geometry representative of an heat exchanger for LFR applications.
5. Presentation of the work done in terms of adopted theory, modelling approaches, tools and physical results.
6. Drafting of a final report.

Applicant profile

Master's 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 Thermal-hydraulics.*

References

- [1] Ferry Roelofs. *Thermal hydraulics aspects of liquid metal cooled nuclear reactors*. Woodhead Publishing, 2018.
- [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] 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.

Validation of liquid lead flow patterns modelling in ATHLET through benchmarking activities

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January 17, 2025

– *Internship proposal* –
(ID No. 1005559)

Keywords — LFR, Heat Transfer, separate effect test, system TH codes

Topics — multiphysics/multiscale modelling, safety assessment, scientific codes

Location newcleo SpA, Via Galliano 27, 10129 Torino, Italy

Starting date To be defined

Duration 5–6 months

Context

Lead technology is one of the most promising alternatives for the development of advanced nuclear reactors and sustainable energy scenarios. In this context, *newcleo* is involved in the design and construction of Advanced Modular Reactors (AMR) lead-cooled.

Thermal-hydraulic system codes (hereinafter, STH) are used for the design and safety analyses of Lead Fast Reactors (LFR) [1]. Suitable modelling strategies are yet to be chosen according to the available calculation environment.

The development of tools and models able to support the design phase is of major importance, as well as the justification of the assumptions of adopted tools.

Closure laws directly influence the results provided by a STH code.

Their assessment done by means of experimental measurements or by comparison with other codes is crucial to have reliable results from the STH code. The focus of this activity is the assessment of the flow pattern regimes and head losses correlation with the support of specialized tools, as OpenModelica, frequently used to optimize the hydraulic network and to perform balance of plant analyses.

The activity will support the validation of the ATHLET code, improving the selection of the most suitable closure laws.

The validation effort will be part of a wider activity dedicated to the STH codes Validation and Verification (V&V) to attain a reasonable level of robustness for the adopted tools.

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Description

The proposed internship will deal with the simulation representative of the primary circuit of a simplified model of an LFR in different operating conditions. ATHLET will be the STH code that will profit the work realized by this study but, initially, to easily compare experienced flow pattern regimes and head losses correlation (concentrated and distributed) other simplified tools will be associated.

After a review of the available literature focusing on the characterization of the typical flow pattern in lead cooled primary system by means of similar approaches, a feasibility analysis will be carried out with the aim of investigating the OpenModelica support to STH V&V practices.

The proposed internship will contribute to identify experimental measurement campaigns or test cases available in literature for Liquid Metal Fast Reactors (LMFR), or to valorize those already identified, and to prepare the appropriate pre- and post-processing data for calculations and associated results for OpenModelica.

Those comparisons will be used firstly to assess closure laws and flow pattern regimes. Parametric and sensitivity analysis is performed in order to understand the differences among assessed closure laws, their validity domain and the possible extrapolation to reactor operating conditions. As optional work, dimensional analysis may be used to justify the correlation semi-empirical forms and to propose possible improvements.

The target is to meet the *newcleo* Codes & Methods (C&M) department needs in term of codes V&V. Such methodology will be tested and deployed against open literature mock-ups with available measurements and lay the groundwork for new experimental campaigns ongoing or foreseen by *newcleo*.

Work plan

The work plan is structured according to the following items:

1. Review of the state-of-the-art in the usage of system thermal-hydraulic codes for LFRs modelling or process tools.
2. Getting started with the simulation of the simplified loop representative of LFR's primary system model with ATHLET.
3. Reproduction of the same simplified model with OpenModelica.
4. Comprehension, assessment and comparison of the behavior of above-mentioned codes on such simplified configuration.
5. Improvement of the full scale primary system input deck with correlations and models assessed in the previous activities trying to retrieve from the OpenModelica model as much information as possible for improving the corresponding ATHLET model.
6. Identification of the layout of some possible tool chains to exploit at best the thermal-hydraulic software used in this work.
7. Drafting of a final report.

Applicant profile

Master's 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 thermal-hydraulic.*

References

- [1] Ferry Roelofs. *Thermal hydraulics aspects of liquid metal cooled nuclear reactors*. Woodhead Publishing, 2018.
- [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] 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.

Calculation of neutron activation under cyclic exposure in LFR

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December 20, 2024

– *Internship proposal* –
(ID No. 1006013)

Keywords — LFR, neutron activation, depletion and transmutation, cyclic exposure

Topics — Reactor physics and analysis, radiation dose, reactor analysis, physical modeling

Location C.so Stati Uniti 38, Torino (TO), Italy

Starting date As soon as possible

Duration 5–6 months

Context

newcleo is developing innovative small modular reactors that use lead as a coolant. The molten lead flows through the reactor core to cool it, and is then recirculated in an outer loop. This system periodically exposes the lead coolant to high neutron fluxes. Lead may contain impurities from the manufacturing process or because of chemical corrosion occurring within the components of the reactor during its lifetime. Activation studies are required to quantify the harmfulness of the irradiated lead coolant and to assess the maximum amount of impurities that can be tolerated at the reactor startup. The internship focuses on developing a methodology to calculate the lead activation under periodic, or cyclic, neutron flux exposure in *newcleo* LFRs. The mathematical framework of the methodology could also be applied to other problems showing activation of radioactive material during reactor operation.

Description

In nuclear reactors, the coolant is exposed to high neutron flux during normal reactor operation. This exposure leads to the formation of activation products. Therefore, activation studies must

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be performed to estimate the exposure and dose rates of the coolant after being irradiated in the reactor. These dose rate data are used by the engineering teams to design radiation shielding components and to estimate potential radiation damage to steel structures.

The lead-cooled SMR designed by newcleo is the subject of this study. In a pool reactor, lead flows through the reactor core where it is exposed to a high neutron flux. It is then recirculated in an outer loop with a lower neutron flux.

The evolution of a material under neutron irradiation by transmutation and radioactive decay is described by the Bateman equation:

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

where $\mathbf{n}(t)$ is the vector of nuclide concentrations at time t , and $\mathbf{A}(\mathbf{n}(t), t)$ is a matrix containing the decay constants and microscopic reaction rates, also known as depletion matrix. Indeed, the build-up and depletion of harmful isotopes in the reactor coolant is strongly correlated with the reaction rates, which vary with the intensity and spectrum of the neutron flux, and must be known as an input to the problem [1]. Computer codes that solve the neutron transport problem are used to calculate the rates in advance in realistic core configurations. The OpenMC Monte Carlo transport code [2] will be used for the simulation of the neutron transport and the calculation of the reaction rates in the zones of interest.

Although mass inventory calculations under the influence of decay and transmutation are generally quite fast, their successive execution reproducing cyclic exposure can bring to unacceptable runtime because of a very high number of loop passages. The solution of 1 for the irradiation of a material with constant neutron flux for a time interval h is given by:

$$\mathbf{n}(t_0 + h) = \mathbf{n}(t_0) \exp[\mathbf{A}(\mathbf{n}(t_0), t_0)h] \quad (2)$$

While the solution of 2 requires the solution of a single matrix exponential, an inventory analysis in circulating conditions requires the solution of many, especially after partitioning the reactor in zones characterized by different magnitude of the same reaction rates. The simplification of the depletion chains, in this context, is necessary to reduce the dimension of \mathbf{A} and to avoid possible ill-conditioning due to a large amount of nuclides varying with very different time scales. Simplified chains also allow a deeper understanding of the physics involved in the problem. Solutions obtained with the FISPACT II code [3] are used as a reference to assess the reliability of the results.

The methodology developed for lead activation could be applied in the future to the evolution of any circulating fluid in the reactor, such as secondary water in the steam generators.

During the internship, the student will be introduced to the physics and engineering of the LFR reactors, acquiring notions and developing skills in mathematical modeling, particle transport and evolution problems. The student will learn how to use OpenMC and FISPACT II, learning Python programming too. At the end of the internship, the student will write a technical report on the analysis of the results from the numerical simulations.

The student will be followed by the Codes and Methods group members of newcleo.

Work plan

During the internship, the student will be introduced to the open source Monte Carlo transport code OpenMC for calculating neutron and photon fluxes in specific zones of interest. The student will also set up input decks for the lead activation study. The internship will investigate and

model a complex problem exploring theoretical aspects of neutron transport and transmutation. Fundamental aspects of Monte Carlo modeling and simulation of nuclear reactors, as well as important topics related to radiation protection, will also be covered during the internship. Finally, the goal is to enhance the student's Python programming skills and confidence in the modeling and analysis of complex phenomena.

The expected working plan is detailed in the following:

- a) Literature review of activation problems
- b) Analysis of similar study cases and discussion of the problem
- c) OpenMC and FISPACT II introduction and training
- d) Calculation of neutron flux and reaction rates in specific areas using an existing OpenMC full reactor model
- e) Setup of the activation calculation
- 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] Fredrik Dehlin and Janne Wallenius. Activation analysis of the lead coolant in SUNRISE-LFR. *Nuclear Engineering and Design*, 414:112503, 2023.
- [2] 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.
- [3] FISPACT-II: An Advanced Simulation System for Activation, Transmutation and Material Modelling. *Nuclear Data Sheets*, 139:77–137, 2017. Special Issue on Nuclear Reaction Data.

Conception mécanique du circuit primaire H/F

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2 octobre 2024

– Proposition de stage –

(ID No. 1006030)

Mots Clefs – Circuit primaire, structure de supportage

Sujets – Conception mécanique structure de supportage

Lieu newcleo SA – Tour Silex², 9 rue des Cuirassiers - 69003 Lyon, France

Date de début premier trimestre 2025

Durée 5–6 mois

Contexte

Le réacteur à neutrons rapides refroidi au plomb (Lead Fast Reactor) développé par newcleo est un concept intégré. Cela induit un inventaire en plomb important au sein de la cuve primaire, avec un point d'attention important concernant les structures de supportage et en particulier la justification sismique de celle-ci.

Description

Au sein du service de conception du circuit primaire du réacteur, vous serez amené à vous familiariser avec les pratiques en vigueur dans le nucléaire, (sûreté, code de construction, requis sismiques).

Puis accompagné de l'équipe conception de Newcleo vous pourrez mettre en pratique ces notions afin de participer à la proposition d'un système de supportage du réacteur. Vous serez également amené utiliser vos acquis scolaires afin de justifier sommairement ce système de supportage vis-à-vis de contraintes spécifiques liées au réacteurs (requis sismiques et de températures, requis d'extrapolation au LFR 200).

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Feuille de route

- Conception et prédimensionnement de pièces mécaniques selon le code de construction applicable [1].
- Bibliographie, conception et calcul du système de supportage du réacteur.
- Préparation d'un rapport technique.

Profil du candidat

- 3ième année de formation école ingénieur.
- Conception mécanique.
- Maîtrise des outils de CAO, Solidworks est un plus.
- Transfert thermique.
- Calculs éléments finis.
- Profil curieux, autonome et avec une appétence pour la conception mécanique.
- Maîtrise de l'anglais, l'italien est un plus.

Références:

- [1] RCC MRx - Règles de conception et de construction des matériels mécaniques des installations nucléaires hautes températures, expérimentales et de fusion. ed. 2022.

Development of additively manufactured sensors for LFR environment

Enrico Virgillito ^{*1}, Daniele De Caro¹ and Francisco Garcia Ferrè¹

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November 11, 2024

– *Internship proposal* –
(ID No. 1006289)

Keywords — Additive Manufacturing, sensors, LFR, alloy development

Topics — New alloy development, Sensors development

Location newcleo S.p.A. – Via Galliano 27, 10129 Torino, Italy

Starting date First quarter of 2025

Duration 6 months

Context

Lead-Cooled Fast Neutron Reactors (LFRs) operate under extreme conditions, requiring robust monitoring and control technologies. The "DAO - Diagnostica in Ambienti Ostili" project led by *newcleo* aims at developing advanced diagnostic systems to monitor components in hostile environments like lead-cooled reactors. Current sensors cannot withstand these conditions, prompting research into new materials and packaging to enhance fiber resistance. Additive Manufacturing (AM) technology will produce sensor prototypes, integrated with IoT platforms and digital twins for advanced data analysis using AI. These sensors will monitor critical components such as reactor steam generators and steel plant equipment, enduring high temperatures and stresses. A key innovation is embedding sensors into components via AM (Laser Powder Bed Fusion technology), optimizing sensitivity and operational integration. This novel approach also scales sensor deployment to larger structures. The project will deliver hardware, software, and demonstrators, advancing diagnostics in hostile environments.

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Description

The internship will focus on activities in Work Packages (WPs) 1.2 and 2.4 of the DAO project. WP 1.2 aims to define use cases, feasibility, requirements, and Key Performance Indexes (KPIs) for the diagnostic platform in hostile environments, considering parameters like operating temperatures, pressures, radiation, and corrosion. This will guide decisions on fiber types, coatings, and packaging materials, using both traditional and AM methods. Two AM technologies, Laser Powder Bed Fusion (LPBF) and Wire-Arc Additive Manufacturing (WAAM), will be studied, with AISI 316L as a substrate material due to its industrial relevance.

WAAM will be explored in WP 2.4 to design and produce fiber-integrated sensor prototypes within structures created through AM, replicating reactor vessel scales. This integration during the manufacturing process allows sensor placement in normally inaccessible locations, preserving material properties and eliminating post-manufacturing inspections. WAAM capability to create complex geometries enables enhanced system monitoring, reducing production and maintenance costs compared to traditional methods.

The project also aims to develop scalable sensor-equipped vessel prototypes, leveraging WAAM to optimize processes and demonstrate practical applications, supported by external expertise to advance WAAM technological maturity.

The internship will be divided into a literature review phase, a visit to partner phase, a laboratory activities phase, a data analyses phase, and a reporting phase.

Work Plan

The internship candidate will be led by *newcleo* internal resources from Materials and Chemistry Areas. During the internship, some visit to partner companies and research institutes will be possibly carried out. The internship will be concluded with the production of the following documentation by the candidate:

- A literary review of use cases of sensors in LFR conditions with identification of the minimum functional requirements that will serve as the basis for sensor design (Word file).
- Definition of the necessary functional requirements and the indices that quantify performance (KPIs). The parameters to be defined will be used to evaluate the feasibility of obtaining useful information for diagnosing structures in hostile environments (Word file).
- Microstructural and mechanical performance analyses of WAAM samples produced. Samples will be provided by external partner(s). The laboratory tests will be conducted in a university or external partner. A subsequent data analyses phase will be performed (Word file).
- A final report in which machine settings for WAAM printing, provided through process files, are explained; in the report, the effects of the process parameters on the produced material characteristics will be indicated (Word file).

Applicant profile

Master or PhD student in Nuclear, Chemistry, Material science, Mechanical or Aeronautical Engineering; Applied Mathematics and Physics.

Required computer skills: work entirely in a terminal without the desktop environment.

References

- [1] Morana A, Girard S, Marin E, Marcandella C, Paillet P, Périsset J, Macé JR, Boukenter A, Cannas M, Ouerdane Y. "Radiation tolerant fiber Bragg gratings for high temperature monitoring at MGy dose levels" Opt Lett. 2014 Sep 15;39(18):5313-6. doi: 10.1364/OL.39.005313. PMID: 26466259
- [2] Quentin Pouille et Al. "Additive Manufacturing and Optical Sensors, Towards a New Way for Nuclear Material Monitoring", WM2023 Conference, February 26 – March 2, 2023, Phoenix, Arizona, USA
- [3] J.Popławski et Al "Metal-coated optical fiber embedment in WAAM aluminium parts for distributed temperature sensing". <https://indi.to/RP9Ty>

Cross section preparation for LFR by Monte Carlo computer codes

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May 9, 2025

– *Internship proposal* –
(ID No. 1008549)

Keywords — LFR, OpenMC, cross section preparation

Topics — Physical modelling, neutron transport, reactor physics

Location newcleo S.p.A., Via Galliano 27, 10129 Torino, Italy

Starting date To be defined

Duration 5 months

Context

newcleo is designing small lead fast reactors (LFR) operating in a pool that contains all the primary system components. Cooling is done by molten lead which shields photon radiation and has low neutron absorption.

The core can show high heterogeneity to meet the criteria of compactness, target neutron leakage and power shape, breeding or burning features. The core is made of a main active zone, possibly surrounded by a shielding or breeding blanket.

Although computer simulation by Monte Carlo codes like OpenMC [1] allows today to carefully represent many details of the reactor, simplified calculation schemes relying on homogenization theory and equivalence theory must still be adopted to perform faster core calculations [2, 3], thus easing the whole design process. During this internship, the student will prepare homogenized cross sections by OpenMC and use them after to perform calculations with the deterministic full-core codes VARIANT [4] and DONJON [5].

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Description

Deterministic computer codes allow fast neutron calculations and are largely employed in reactor physics and analysis. They rely on assumptions and approximations that must be carefully verified and validated. For instance, using lattice calculations of fuel elements in fundamental mode neglects the environment effects and the local core conditions, introducing sometimes an inconvenient limitation in the calculation scheme. Provided that the material inventory of all fuel elements is known, the Monte Carlo simulation can be used to overcome this limitation, yet paying a higher computational cost.

A new feature in the code OpenMC to prepare homogenized cross sections on hexagonal grids is currently under development and it will be tested during this internship, together with a reduced nuclide chain suitable to lead fast reactors. After, a suitable interface will be developed to load the set of homogenized data into VARIANT and DONJON, which use different solution methods to obtain the neutron flux distribution over the full core. These codes use low-order transport methods, with a lower computational effort. Besides, the core configurations calculated by OpenMC and used for detailed cross section preparation will allow to assess the performance of low-order transport solutions. The setup of the calculation input files and the interfaces will be performed on git version control. Finally, the candidate will produce a technical report at the end of the internship to compile the results, by quantifying the gain in runtime obtained while using the deterministic codes and by assessing the performance in physical accuracy and numerical precision.

Work plan

- a) Literature review and study of homogenization and equivalence theory.
- b) Training and practice with the computer codes.
- c) Setup of the core model by OpenMC.
- d) Preparation of the cross section model.
- e) Setup of the core calculations.
- f) Analysis of results and preparation of the final report.

Applicant profile

Master student in Nuclear Engineering or student in Applied Mathematics and Physics.

Background: fundamentals in applied mathematics and the physics of nuclear reactors.

Required computer skills: Linux, Python (intermediate), \LaTeX scientific editing (optional).

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] George I Bell and Samuel Glasstone. *Nuclear reactor theory*. US Atomic Energy Commission, Washington, DC (United States), 1970.
- [3] J. R. Lamarsh and A. J. Baratta. *Introduction to Nuclear Engineering. 2nd Edition*. Addison-Wesley, Reading, 1983.
- [4] 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 *PHYSOR 2002-International Conference on the New Frontiers of Nuclear Technology: Reactor Physics, Safety and High-Performance Computing*, 2002.
- [5] A Hébert. DRAGON and DONJON: a legacy open-source reactor physics project at Polytechnique Montréal. In *Proceedings of the IAEA Technical Meeting on the Development and Application of Open-Source Modelling and Simulation Tools for Nuclear Reactors, Milano, Italy, June, 2022*.