List of student internships offered by new*cleo*

–academic year–

2024–2025

September 20, 2024

Preface

This document contains the internship offers supported by *new*cleo. 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 *new*cleo

Privately funded and headquartered in London, *new*cleo 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, *new*cleo 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, *new*cleo has business, scientific, operations and industrial manufacturing capabilities in a vertically integrated model designed to deliver its ambitious timeline for its plan-to-market.

*new*cleo'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, *new*cleo'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 *new*cleo's passive safety systems ensure very high levels of safety;

- **Cost**: *new*cleo'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.

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

*new*cleo 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.

List of Internships

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

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[2] *Politecnico di Torino, Dipartimento Energia, Corso Duca degli Abruzzi 24, 10127, Torino, Italy*

September 20, 2024

– Internship proposal –
(ID No. 1000073)

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

Location	*new*cleo S.p.A, 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

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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.

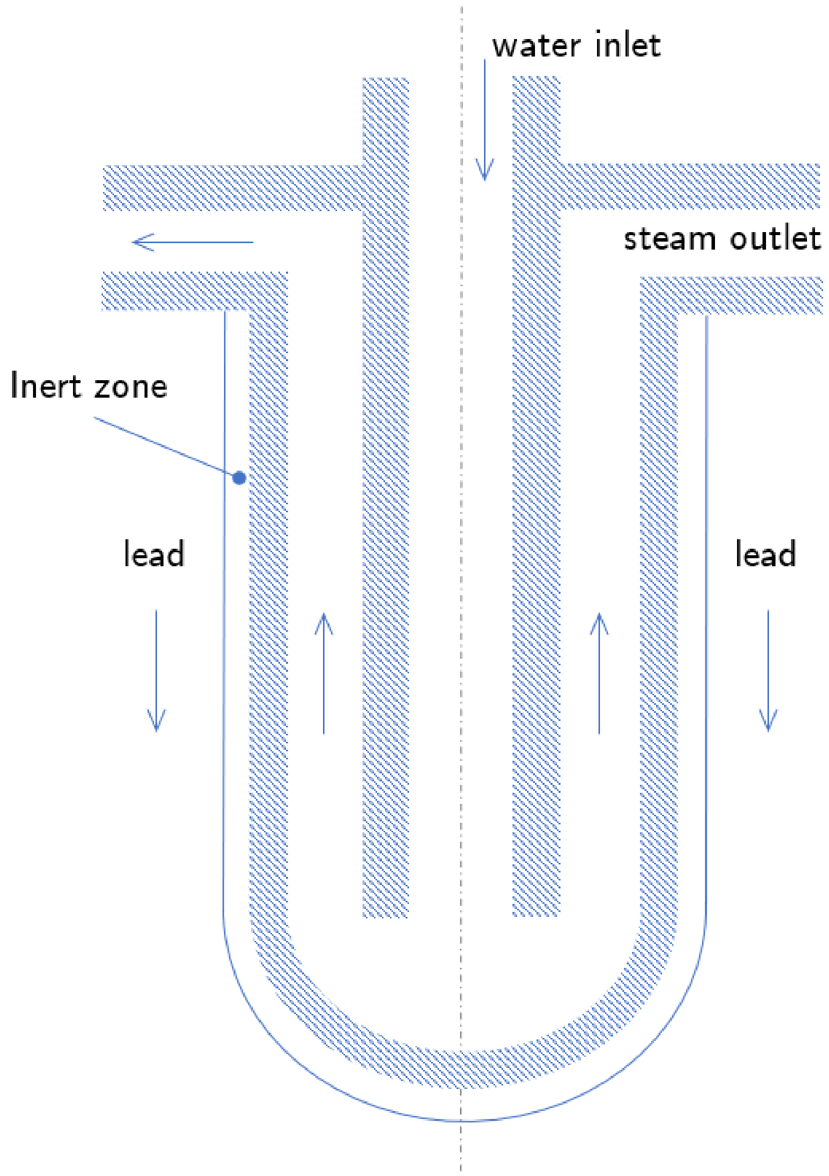

Figure 1: Schematic of a bayonet tube heat exchanger.

[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.

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]

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September 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	*new*cleo S.p.A, 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

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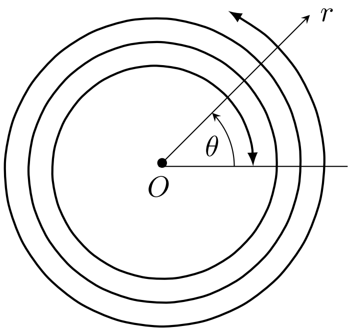

Figure 1: Archimedean spiral.

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

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September 20, 2024

– Internship proposal –

(ID No. 1000360)

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

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Location	*new*cleo S.p.A, 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

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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.

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

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September 20, 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 S.p.A, 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.

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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.

Study of coolant heating in LFR

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September 20, 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 S.p.A, 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

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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.

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

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September 20, 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 S.p.A, 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

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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 *

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September 20, 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

Location	*new*cleo S.p.A, 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

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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 *

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September 20, 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.

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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.

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

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September 20, 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

Location	*new*cleo S.p.A, 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.

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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.

[3] BERTHOUD GEORGES and JAYANTI SREENIVAS. Characterization of dryout in helical coils. Service des Transferts Therrniques, Centre d Etudes Nucleaires de Grenoble, 85X-38041 Grenoble, France, 1989.

[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.

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

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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

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[2]new*cleo S.p.A, Via Galliano 27, 10129 Torino, Italy*

September 20, 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.

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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.

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

Elena Travaglia and Daniele Tomatis*

new*cleo S.p.A, Via Galliano 27, 10129 Torino, Italy*

September 20, 2024

– Internship proposal –
(ID No. 1003986)

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

Location	*new*cleo S.p.A, 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.

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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 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.

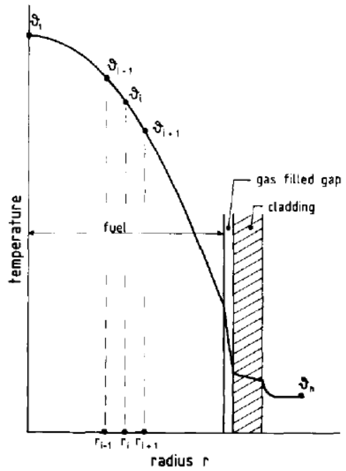

Figure 1: Schematic rappresentation of the stationary radial temperature profile in a slice of the fuel rod

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*

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September 20, 2024

– Internship proposal –
(ID No. 1003987)

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

Location	*new*cleo S.p.A, 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.

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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 *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.

Verification of fission gas release module for fast reactor applications

Andrea Salomone, Elena Travaglia, and Daniele Tomatis*

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

September 20, 2024

– Internship proposal –
(ID No. 1004126)

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

Location	*new*cleo S.p.A, 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.

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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.

Testing and characterization of structural materials for advanced nuclear systems – Part A

– Internship Proposal –

(ID No. 1005093)

Luca Silvioli[1] and Francisco Garcia Ferre[*2]

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July 19th, 2024

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

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Location *new*cleo S.p.A, C.R. ENEA Brasimone 40032 Camugnano (BO), Italia

Starting date October 15th, 2024

Duration 1-3 months

Context

Lead-cooled fast reactors (LFRs) are considered one of the most promising reactors among several 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 programme 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 support commissioning of experimental equipment and to carry out experimental tests, producing a report that analyses the generated experimental data.

[*] Contact person: francisco.garcia.ferre@newcleo.com

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 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 review the scientific literature and internal documentation to select suitable materials for testing. The intern will work in Brasimone laboratories to commission experimental equipment and prepare materials specimens to characterize through one or more of the following techniques:

- Optical microscopy
- Scanning Electron Microscopy equipped with EDX and EBSD
- X-ray diffraction
- Tensile tests
- Slow strain rate tests
- Creep tests
- Fatigue and creep-fatigue tests
- Other tests in collaboration with *new*cleo's branch in Turin

The intern will also work in collaboration with the *new*cleo's branches in Turin (where other equipment will be available, such as (high temperature) nanoindentation) and Lyon (where engineering studies are carried out).

Work plan

a) Literature review & materials selection
b) Experimental campaign planning
c) Materials testing with custom equipment
d) Data analysis
e) Preparation of reports and final presentation

Applicant profile

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

Skills:

- Knowledge of material manufacturing processes, testing and characterization techniques.

- Required computer skills: knowledge of Excel and data analysis software. Experience with programming languages (Matlab, Python) is a plus.
- 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)

Advancements in the thermal-hydraulic modelling of a lead cooled modular fast reactor (LFR) and related experimental facilities with CFD/TH system codes

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September 20, 2024

– *Internship proposal* –
(ID No. 1005141)

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

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Location	Dipartimento di Ingegneria Civile Industriale - DICI - Università di Pisa
Starting date	09 September 2024
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, *new*cleo is involved in the design and construction of Advanced Modular Reactors (AMR) based on lead technology.

Thermal-hydraulic (hereinafter, TH) scientific codes are used for the design and safety analyses of LFR. Suitable modelling strategies are yet to be chosen according to the available calculation platforms, including the selection of the most appropriate models and closure laws. For LFR reactors, discussions are still ongoing to define what may be the approach to use as reference for multi-scale analyses [1].

Both advanced 3D CFD codes and 1D system TH codes may play an important role in the definition of the best practices to follow for improving the modelling of physical phenomena, such as head losses and heat exchanges. In this context, special focus should be provided to open-source codes, thanks to their potential in supporting a wider community and facilitating education and training activities.

*Contact person, barbara.calgaro@newcleo.com

Description

In the framework of the collaboration between DICI UNIPI and *new*cleo, and in continuity with and support of a PhD programme already activated, the present internship programme is proposed focusing on how to approach multi-scale 3D/1D problems and the potential benefit of coupling TH system codes and CFD codes.

The proposed internship will contribute to identify improvements in the modelling of head loss and heat exchange phenomena in liquid metals that are used as coolant of core hexagonal fuel pin bundle or primary system components of a pool-type nuclear fast reactor. The purpose is to capture the main 3D phenomena by detailing accurately their features and by looking for their most appropriate representation, mainly focusing on CFD and TH system codes requirements. This internship will provide the criteria for selecting the most appropriate modelling approach between 3D and 1D according to the specific application and will propose an approach for making them interact.

The target is to meet the R&D needs of *new*cleo C&M department by providing preliminary methodologies associated to the identified use case to be applied lately for safety analysis. Such methodologies will be tested and deployed against open literature mock-ups and available measurements or new experimental campaigns ongoing or foreseen by *new*cleo.

Work plan

The workplan is structured according to the following items:

1. Open literature short review of 1D/3D modelling and simulation of liquid metal flows by both alone and coupled 1D and 3D codes.
2. Selection of a representative geometry and phenomena to be reproduced with CFD codes and/or TH system codes.
3. Automation of pre- and post-processing to perform parametric and sensitivity analysis with respect to different closure laws.
4. Presentation of the work done in terms of adopted mesh, modelling approaches, tools and physical results.
5. Formalisation with 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 TH*.

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.

Testing and characterization of structural materials for advanced nuclear systems – Part B

– Internship Proposal –

(ID No. 1005221)

Luca Silvioli[1] and Francisco Garcia Ferre[*2]

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July 19th, 2024

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

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Location *new*cleo S.p.A C.R. ENEA Brasimone 40032 Camugnano (BO), Italia

Starting date November 18th, 2024

Duration 3 months

Context

Lead-cooled fast reactors (LFRs) are considered one of the most promising reactors among several 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 programme 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 support commissioning of experimental equipment and to carry out experimental tests, producing a report that analyses the generated experimental data.

[*] Contact person: francisco.garcia.ferre@newcleo.com

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 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 review the scientific literature and internal documentation to select suitable materials for testing. The intern will work in Brasimone laboratories to commission experimental equipment and prepare materials specimens to characterize through one or more of the following techniques:

- Optical microscopy
- Scanning Electron Microscopy equipped with EDX and EBSD
- X-ray diffraction
- Tensile tests
- Slow strain rate tests
- Creep tests
- Fatigue and creep-fatigue tests
- Other tests in collaboration with *new*cleo's branch in Turin

The intern will also work in collaboration with the *new*cleo's branches in Turin (where other equipment will be available, such as (high temperature) nanoindentation) and Lyon (where engineering studies are carried out).

Work plan

a) Literature review & materials selection
b) Experimental campaign planning
c) Materials testing with custom equipment
d) Data analysis
e) Preparation of reports and final presentation

Applicant profile

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

Skills:

- Knowledge of material manufacturing processes, testing and characterization techniques.

- Required computer skills: knowledge of Excel and data analysis software. Experience with programming languages (Matlab, Python) is a plus.
- 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)

Numerical modelling and analysis of high-pressure water leakage in liquid lead pool

Gabriele Ottino * [1] and Domenic D'Ambrosio † [2]

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September 20, 2024

– *Internship proposal* –
(ID No. 1005388)

Keywords — Steam generator tube rupture, LFR, liquid lead pool, CFD
Topics — Fluid dynamics, numerical modelling, multiphase, safety analysis

Location	*new*cleo S.p.A, Via Galliano 27, 10129 Torino, Italy
Starting date	September 2024
Duration	6 months

Context

*new*cleo is involved in the design of lead-cooled fast reactors (LFR). Experimental campaigns and numerical simulations are the main tools used to support all the necessary design phases. In this context, safety analyses are also important, as they provide a clear overview of the possible incidental scenario, thus allowing the most appropriate measures to be defined. Among the others, there is an incidental case where a well-defined modelling approach is still lacking, and experimental activities have yet to be defined. This is the case when a tube in the spiral water-steam generator suddenly ruptures, creating a high-pressure wave that propagates through the liquid lead. The aim of this internship is to get a clear view of the state of the art in numerical modeling of this phenomenon and to try to estimate the source term following the tube rupture: such source term will represent the initial condition to be applied in future work to estimate the consequences of the tube rupture in the liquid lead vessel.

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Description

The physics related to the phenomenon of steam generator tube rupture is very complex and must be studied in depth and accurately in each of its aspects [1]. The first objective of this work is to perform a thorough literature review to acquire knowledge of the state-of-the-art models and numerical methods used to investigate this or similar problems. The literature review will consider all the elements related to the rupture:

1. the phase of the water fluid within the pipes at the moment of the rupture and its relation with the pipe shape and how it may be predicted with reduced-order models or CFD;
2. the effect of the geometric form and type of the rupture on the water jet entering the liquid lead bath;
3. the interaction of the water jet with the liquid lead;
4. the propagation of waves within the liquid lead;
5. the potential risks associated with points 3 and 4.

It is expected that this review will be conducted and reported, aiming to be useful in defining the main steps of future related research activities.

The second part of the thesis will focus on the estimation of the source term to be used as the initial condition of numerical models to reproduce the effect of such a rupture in the liquid lead vessel. As the water/steam flow is at a pressure a few orders of magnitude higher than the pressure of the liquid lead, it is expected that a chocking condition will occur across the rupture section. The investigation of the phenomena in the tube can then be separated from those relating to the propagation of the water/steam in the liquid lead.

During the thesis, the student will try to identify all the possible scenarios that could arise depending on the location of the rupture in the steam generator tube. The flow in the tube undergoes several regime transitions that change its physical properties: the liquid single phase is mainly close to the entrance, the vapour single phase is close to the outlet, and in between there are intermediate conditions that require appropriate modelling treatment depending, for example, on the location of the rupture along the tube cross section. Apart from the analytical models available in the literature, the student will assess which models and numerical methods are implemented in available CFD tools, and will begin analyses on simple configurations to familiarize herself/himself with the code. In this context, she/he will compare results, computational time, and resources associated with each method. Finally, she/he will consider scenarios close to the actual ones, selecting the methodology that appears most appropriate in terms of accuracy and cost trade-off.

Work plan

The expected work plan is detailed below:

1. A literature review that will include all the physical aspects arising from the rupture of a steam generator tube adjacent to a liquid lead bath.
2. Definition of a plan of action with the final aim of studying the phenomenon as a whole.

3. Identification of scenarios to be investigated for estimating the conditions at the rupture of a steam generator tube.
4. Analysis of physical models and numerical methods implemented in at least one CFD tool to estimate such conditions.
5. Selection of the most appropriate models and methods and application to the previously identified scenarios.
6. Preparation of the thesis report.

Applicant profile

Master's student in Aerospace or Nuclear Engineering, preferably with a specialization in Aerogasdynamics (not mandatory).

Required computer skills: Aerospace Engineering Master's level knowledge of Computational Fluid Dynamics, some experience with commercial CFD codes (attendance of university-level CFD courses, or courses where CFD was used, is sufficient).

Knowledge of LaTeX editing is appreciated, but not mandatory.

References

[1] Nicolò. Garelli and Michel Gaetan. Steam generator tube rupture: state-of-the-art review. Internal report, newcleo SpA, June 2023.

[2] Xi Huang, Peng Chen, Yuan Yin, Bo Pang, Yongchun Li, Xing Gong, and Yangbin Deng. Numerical investigation on lbe-water interaction for heavy liquid metal cooled fast reactors. *Nuclear Engineering and Design*, 361:110567, 2020.

[3] Sergey E Yakush, Nikita S Sivakov, Oleg I Melikhov, and Vladimir I Melikhov. Numerical modeling of water jet plunging in molten heavy metal pool. *Mathematics*, 12(1):12, 2023.

[4] Junjie Yuan, Li Liu, Ruiqi Bao, Da Li, Xiaoyan Tian, Haotian Luo, Zheng Jia, Maolong Liu, and Hanyang Gu. Numerical simulation of jet boiling characteristics of high-pressure water injected into high-temperature liquid lead–bismuth in a confined space. *Applied Thermal Engineering*, page 123432, 2024.

This internship is in collaboration with:

POLITECNICO DI TORINO

Cross-section preparation for LFR by DRAGON5

Gianluca Cirillo*[1], Sigtryggur Hauksson[1], and Daniele Tomatis[2]

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September 20, 2024

– Internship proposal –

(ID No. 1005407)

***Keywords* —** LFR, lattice calculation, cross-section preparation, DRAGON
***Topics* —** Physical modelling, neutron transport

Location	EDF Lab Paris-Saclay, Bd Gaspard Monge, 91120 Palaiseau
Starting date	End of 2024 or beginning of 2025
Duration	5–6 months

Context

*new*cleo is designing new Lead-cooled Fast Reactor (LFR) units for small modular reactors. These reactors have a fast neutron spectrum allowing for fission of heavier actinides, such as plutonium that is a by-product of light water reactors. Cooling is done by molten lead which shields photon radiation and has low neutron absorption.

Designing reactor units requires accurate calculations of neutron transport in the core of the reactor. These calculations are usually performed by deterministic neutron transport codes which require special treatment of resonance self-shielding. This energy self-shielding accounts for depression in neutron flux due to resonances of the cross sections. In this internship, the candidate will perform detailed validation of transport calculations of LFR fuel elements with DRAGON5 focusing on the self-shielding models and optimizing the calculation scheme. The candidate will study different elements of the core like fuel, reflector and shield assemblies composed of multiple unit cells.

Description

The candidate will use the lattice transport computer code DRAGON, developed at Polytechnique de Montréal, Québec, Canada, which solves the Boltzmann transport equation deterministically[1]. DRAGON has extended self-shielding capabilities employing different methods.

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[1] `https://www.polymtl.ca/phys/en/dragon-download`

The student will work closely with his/her tutors on the validation of DRAGON5 calculations of LFR, analyzing the results produced with the different calculation options and comparing them against the results obtained with the Monte Carlo computer code OpenMC.[2] This comparison will require the calculation of key quantities such as the neutron reactivity and multi-group reaction rates by the two codes. The goal is for DRAGON to give accurate results for all unit cells found in the core of *new*cleo's LFR design. The validation will require the candidate to choose appropriate computational methods for cross-section self-shielding, nuclear data libraries and calculation meshing.

After studying single fuel pin cell problems to get numerical evidence of the known theory background, the candidate will carry out validation of calculations representing patterns of unit cells arranged in hexagonal grids. Such patterns are made of fuel assemblies, reflector or shield blocks and control elements, depending on the specific configuration under study. Validation will only concern two-dimensional calculations performed by DRAGON. Heterogenous configurations will be handled in this work by a new graphical user interface that is currently under development to create unstructured geometries for DRAGON5 calculations. As an optional goal at the end of the internship, the student will try to obtain simplified calculation schemes with DRAGON by adding more approximations to reduce the total computational time. Finally, the candidate will produce a technical report at the end of the internship to compile the results.

Work plan

a) Literature review and study of the main physical phenomena.
b) Training and practice with DRAGON.
c) Problem discussion and set-up of calculations.
d) Calculation and analysis of self-shielding for a unit cell.
e) Calculation and analysis of neutron transport in fuel elements and patterns of assemblies.
f) Preparation of the final report.

Applicant profile

Master student in Nuclear Engineering or student in Applied Mathematics and Physics.
Background: fundamentals in reactor physics, neutronics and applied mathematics.
Required computer skills: Linux, computer programming in a standard language (intermediate), 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.

[3] Alain Hébert. An investigation of distributed self-shielding effects with the Tone's method. In *Proc. Int. Conf. on the Physics of Reactors*. PHYSOR 2018, 2018.

[2] `https://openmc.org/`

[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.

Modelling the transport of alpha particles with Monte Carlo computer codes

Sigtryggur Hauksson *[1], Nunzio Burgio[2], and Daniele Tomatis[3]

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[2] *ENEA, Via Anguillarese, 301 – 00123 S. Maria di Galeria, Rome, Italy*
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September 20, 2024

– *Internship proposal* –
(ID No. 1005542)

***Keywords* —** Inherent neutron sources, (α,n) reactions, stopping power
***Topics* —** Particle physics, physical modelling, nuclear data

Location	EDF Lab Paris-Saclay, Bd Gaspard Monge, 91120 Palaiseau
Starting date	Fall 2024
Duration	5–6 months

Context

Neutrons can be spontaneously produced in matter through different processes. One important process is alpha-induced reactions, so-called (α,n) reactions, where alpha particles hit light elements in the target such as beryllium, oxygen, nitrogen and lithum, causing non-negligible neutron production. These alpha particles are produced in the decay of heavier nuclei like unstable actinides and are slowed down in matter before hitting the target elements.

Many applications in nuclear engineering, aerospace engineering, and particle physics require a precise understanding of these (α,n) reactions and other inherent neutrons sources in matter, such as delayed neutron emission and spontaneous fission. *new*cleo, which is designing new Lead-cooled Fast Reactor (LFR) units for small modular reactors, needs to calculate inherent neutron sources for safety and radioprotection studies of mixed oxide (MOX) fuel.

A key ingredient for neutron source calculations is to model accurately how alpha particles are slowed down and absorbed over a short range in matter, limiting how far they travel before triggering (α,n) reactions. The most complete description of the slowing down of alpha particles is given by Monte Carlo computer codes, like GEANT4[1] and PHITS[2], which simulate the

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[1]`https://geant4.web.cern.ch/`
[2]`https://phits.jaea.go.jp/`

trajectory of individual alpha particles as they scatter off atoms in electromagnetic and nuclear interactions. An alternative description, which is easier to use in neutron source calculations, characterizes the average energy loss of alpha particles per unit distance by a function know as the stopping power. In this internship, the student will validate the stopping power model for alpha particle transport by performing detailed Monte Carlo simulations in different geometric setups. The student will furthermore extract the stopping power for the range of nuclides needed in calculations of neutron sources.

Description

The student will use two Monte Carlo computer codes, GEANT4 and PHITS, to simulate the slowing down of alpha particles in matter. After studying the microscopic physics underlying these codes, the student will verify that stopping powers accurately reproduce energy loss in realistic Monte Carlo calculations. This will be done by showing that the distribution in energy loss in different events is small compared with the average energy loss, once statistical fluctuations have been minimized. This student will furthermore verify that the energy loss in material mixtures is the sum of the energy loss due to the different nuclides. The tests will be performed on homogeneous and heterogeneous problems in simplified 1-D geometries, with a beam of alpha particles entering at the boundary. The student will choose among the different microscopic models provided by the Monte Carlo codes, in particular among the options for electromagnetic interactions proposed by GEANT4.

In the latter half of the internship, the student will calculate stopping powers for alpha particles in the range of materials needed in applications. He/she will compare the values obtained from GEANT4 and PHITS with stopping power compilations such as SRIM[3], as well as the values used in libraries of SOURCES-4C[4], a compter code for neutron sources. The goal will be to decide on values for stopping powers for all the isotopes needed in neutron source calculations, and to create libraries with these stopping powers. At the end of the internship, the candidate will produce a technical report to compile the results.

Work plan

a) Literature review and study of the main physical phenomena.
b) Training with GEANT4 and PHITS.
c) Validation of the stopping power model.
d) Exploration of different parameters in the Monte Carlo codes.
e) Extraction of stopping powers in libraries.
f) Preparation of the final report.

Applicant profile

Master student in Nuclear Engineering or student in Applied Mathematics and Physics.
Background: fundamentals in neutronics and applied mathematics.
Required computer skills: Linux, Python (intermediate), LaTeX scientific editing (optional).

[3] http://www.srim.org/
[4] https://www.oecd-nea.org/tools/abstract/detail/ccc-0661/

References

[1] S. Agostinelli et al. Geant4—a simulation toolkit. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 506(3):250–303, 2003.

[2] Tatsuhiko Sato et al. Recent improvements of the particle and heavy ion transport code system – PHITS version 3.33. *Journal of Nuclear Science and Technology*, 61(1):127–135, 2024.

[3] Rui-Min Ji, Cheng-Gang Yu, Ming-Hai Li, Rui Yan, Yang Zou, and Gui-Min Liu. Study on inherent neutron sources in MSR. *Nuclear Science and Techniques*, 29:47, 2018.

[4] W.B. Wilson, R.T. Perry, W.S. Charlton, and T.A. Parish. Sources: A code for calculating (alpha, n), spontaneous fission, and delayed neutron sources and spectra. *Progress in Nuclear Energy*, 51(4):608–613, 2009.

[5] James F. Ziegler, M.D. Ziegler, and J.P. Biersack. SRIM – the stopping and range of ions in matter. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 268(11):1818–1823, 2010. 19th International Conference on Ion Beam Analysis.