List of student internships offered by new*cleo*

–academic year–
2024–2025

December 11, 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.

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

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

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November 12, 2024

– Internship proposal –
(ID No. 1000073)

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

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Location	*new*cleo SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
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.

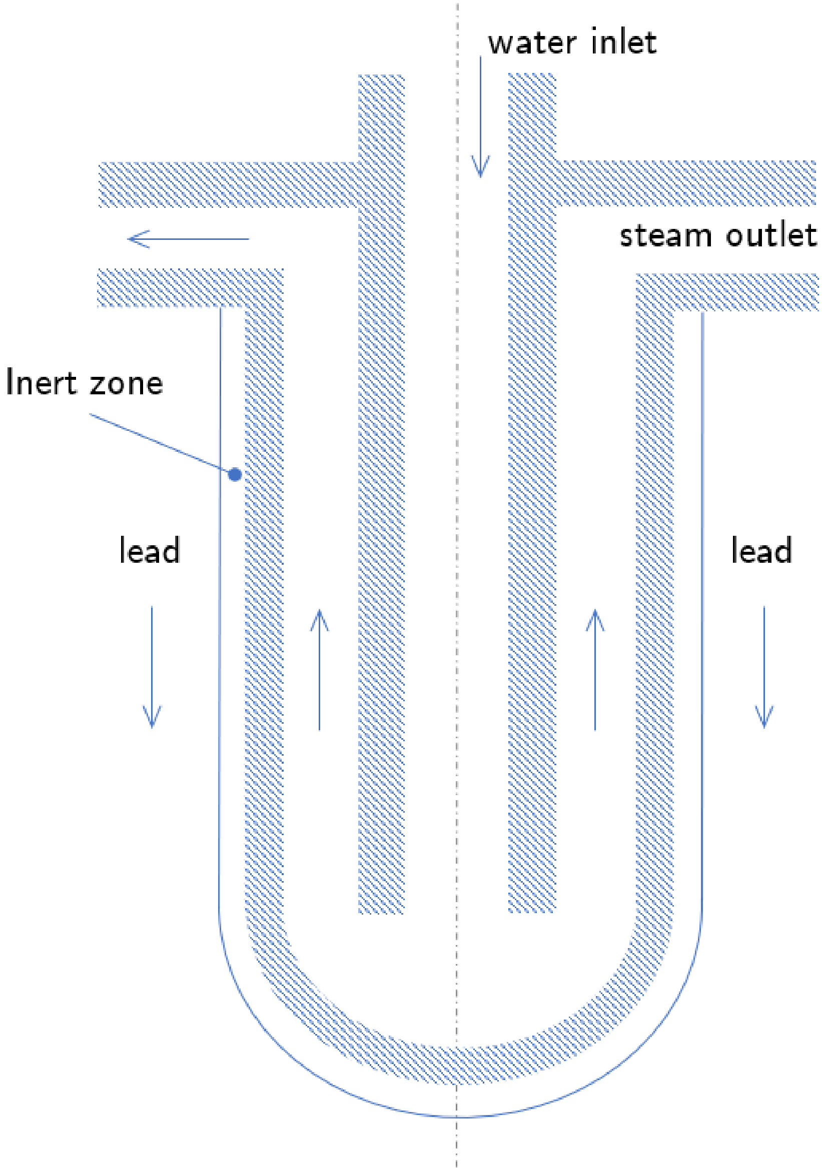

Figure 1: Schematic of a bayonet tube heat exchanger.

[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.

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

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November 12, 2024

– Internship proposal –

(ID No. 1000247)

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

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

Context

*new*cleo is designing new units of lead-cooled fast reactors (LFR) aiming to increase the utilization of plutonium produced by the many light water reactors that are currently operating worldwide. The fuel elements are exposed to a fast neutron spectrum favoring fission of heavier actinides.

The computer code ECCO (European Cell COde) from the ERANOS 2.3N [1] code suite is used for all the activities of fuel design. ERANOS is a system of computer codes developed in the 1990s for the calculation of fast reactors. ECCO solves the neutron transport equation by the collision probability method using the subgroup method to shield the cross sections of the resonant nuclides. This internship focuses on the validation of the results obtained by ECCO on typical hexagonal fuel assemblies using the Monte Carlo computer code OpenMC [2].

Description

During this internship, the candidate will calculate a set of fuel assemblies by the Monte Carlo code OpenMC in order to compare pin-wise reaction rates and integral quantities like the neutron multiplication factor with the corresponding quantities obtained with the calculations performed by ECCO. Simplified calculation schemes are generally adopted with ECCO, thus introducing physical approximations in the problem to solve, but with the advantage of achieving fast

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calculations. Instead, Monte Carlo calculations introduce fewer approximations but at the cost of longer calculations. They are then used to validate the deterministic calculations in a representative set of cases, featuring different assembly types. Comparisons of reaction rates in the typical 33-group energy mesh of ERANOS are also requested to validate the self-shielding step done by ECCO. The validation will be performed with fresh fuel, and optionally after exposure at different burnup steps.

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

Work plan

1. Study of the main approximeation involved in ECCO calculations.
2. Literature review of the existing work about ECCO V&V
3. Analysis of the test cases
4. Problem discussion
5. Calculation of the different cases
6. Analysis of results
7. Preparation of the technical report

Applicant profile

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

References

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

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

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

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

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

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November 12, 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 SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
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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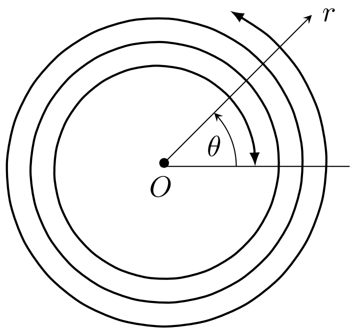

Figure 1: Archimedean spiral.

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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November 12, 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 SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
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.

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

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November 12, 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 SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
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 *

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

November 12, 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 SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
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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November 12, 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	To be defined
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.

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

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December 4, 2024

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

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

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

Context

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

Description

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

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

`https://newcleo-dev-team.github.io/lbh15/index.html` and
`https://github.com/newcleo-dev-team/lbh15`, respectively.

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

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

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

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

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

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

Work plan

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

Applicant profile

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

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

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

References

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

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

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

Implementation of a scientific software providing the thermodynamic properties of gases

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

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

November 25, 2024

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

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

Location	*new*cleo SA, 9 Rue des Cuirassiers, 69003 Lyon 3e, France
Starting date	To be defined
Duration	5 – 6 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 analysis.

This internship consists of creating a Python module that gives the thermophysical properties of gases. Among the options available, one is to wrap the existing implementation (`AGA8`) in Python according to the results of pre-design studies. This will require the use of interface 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. However, better options may be found: the candidate will be asked to investigate which is the most suitable one and to implement it!

The goal is to implement a complete software package, consisting of base code, test suite and the automated documentation.

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) Relevant test suite.
5) 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 object-oriented 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*

newcleo SpA, Via Galliano 27, 10129 Torino, Italy

November 12, 2024

– Internship proposal –
(ID No. 1003986)

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

Location	*new*cleo SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
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.

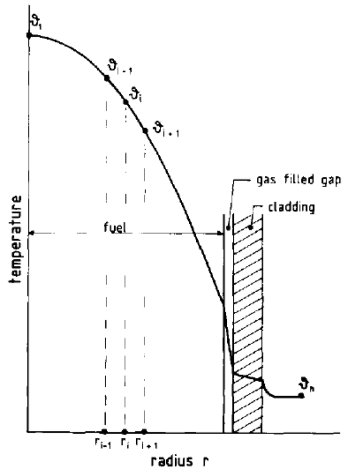

Figure 1: Schematic rappresentation of the stationary radial temperature profile in a slice of the fuel rod

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

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November 12, 2024

– Internship proposal –
(ID No. 1003987)

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

Location	*new*cleo SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
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.

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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November 12, 2024

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

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

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Location	*new*cleo SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
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

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

Barbara Calgaro *[1]

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November 12, 2024

– *Internship proposal* –

(ID No. 1005558)

***Keywords* —** LFR, Heat Transfer, separate effect test, system TH codes
***Topics* —** multiphysics/multiscale modelling, safety assessment, scientific codes

Location	*new*cleo SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
Duration	5–6 months

Context

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

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

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

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

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

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

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Description

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

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

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

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

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

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

Work plan

The work plan is structured according to the following items:

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

Applicant profile

Master's student in Nuclear Engineering. Students of theoretical Physics and applied Mathematics will also be considered for the position.
Background: *fundamentals of reactor physics and multiphysics approaches, but also computational Thermal-hydraulics*.

References

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

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

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

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

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

Barbara Calgaro *[1] and Matteo Rostagno[1]

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November 12, 2024

– Internship proposal –
(ID No. 1005559)

***Keywords* —** LFR, Heat Transfer, separate effect test, system TH codes
***Topics* —** multiphysics/multiscale modelling, safety assessment, scientific codes

Location	*new*cleo SpA, Via Galliano 27, 10129 Torino, Italy
Starting date	To be defined
Duration	5–6 months

Context

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

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

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

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

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

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

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

*Contact person, barbara.calgaro@newcleo.com

Description

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

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

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

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

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

Work plan

The work plan is structured according to the following items:

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

Applicant profile

Master's student in Nuclear Engineering. Students of theoretical Physics and applied Mathematics will also be considered for the position.

Background: *fundamentals of reactor physics and multiphysics approaches, but also computational thermal-hydraulic*.

References

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

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

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

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

Création d'un outil de prédimensionnement mécanique et thermomécanique selon les critères du RCC-MRx

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1er Octobre, 2024

– Offre de stage –

(ID No. 1005678)

Mots-clés — Mécanique, calcul, Ansys, RCC-MRx, codes de calculs scientifiques, calcul par éléments finis, Python
Sujets — Ingénierie mécanique, mode de ruine, RCC-MRx, calcul, critère, développement d'outil

Lieu	*new*cleo SA – Tour Silex[2], 9 rue des Cuirassiers - 69003 Lyon, France
Date de début	mars 2025
Durée	5–6 mois

Contexte

Le réacteur à neutrons rapides refroidi au plomb (Lead Fast Reactor) développé par *new*cleo doit respecter les normes en vigueur et être validé par l'Autorité de Sûreté nucléaire (ASN). Suivre les recommandations du code RCC-MRx est l'un des aspects qui nous permettra d'atteindre cet objectif.

Le code RCC-MRx propose notamment des critères qui doivent être vérifiés afin de prévenir différents modes de ruine dans les structures. Cette validation est effectuée par le service calcul qui remonte les informations au service de conception. Ainsi tout au long du développement du réacteur, une bonne communication entre les différents services est primordiale pour réduire le nombre d'itérations du design et prévenir les risques le plus en amont possible.

Description

Le but de ce stage est de créer un outil simplifié pour estimer les marges par rapport aux critères du code RCC-MRx afin d'aider l'équipe de conception à réduire le nombre

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d'itérations lors des phases de design. Une première phase de prise en main du sujet vous conduira à établir un cahier des charges et à prendre connaissance du code RCC-MRx.
Le cœur du sujet sera la création d'un outil de calcul simple d'utilisation et utilisant des formules analytiques pour estimer des contraintes et les différentes grandeurs physiques entrant en compte dans le calcul des critères (comme par exemple : les contraintes dans l'épaisseur d'une plaque soumise à un gradient de température, celles dans une cuve sous pression etc…). Cet outil pourra prendre la forme d'un code python, VBA ou bien encore de feuilles d'abaque consultables.

Dans un second temps, viendra la phase de qualification de l'outil en comparant ces résultats à ceux obtenus sur des cas simples en utilisant le logiciel Ansys (ANSYS APDL 2023 R2) ainsi que le post processeur *new*cleo, qui est un programme python.

Cet outil pourra évoluer pour prendre en comptes plus de situations et différents modes de ruines et sera utilisé par les équipes de *new*cleo lors des prochains choix de design.

Feuille de route

- Lecture de documents techniques internes pour comprendre le projet.
- Prise en main du code RCC-MRx.
- Echanges avec l'équipe de conception, établissement d'un cahier des charges.
- Création d'un outil de calcul (Python ou VBA et/ou abaques).
- Qualification de l'outil à travers des cas test, utilisation d'ANSYS et du post-processeur *new*cleo.
- Préparation d'un rapport technique.

Profil du candidat

- Formation en école d'ingénieur avec spécialisation en génie nucléaire ou mécanique.
- Connaissance de l'environnement informatique pour des calculs scientifiques (Calcul par élément finis, environnement linux, langage informatique par ex. Python ou VBA, la maitrise de GIT est un plus).
- Maîtrise de l'anglais, l'italien est un plus.
- Vous aimez la technique et les sciences en général.
- Vous êtes une personne confiante et vous vous efforcez chaque jour à être digne de la confiance de vos collègues.
- Vous cherchez activement à être une personne curieuse, raisonnable, attentionnée et engagée.

Références

[1] RCC-MRx Design and Construction Rules for Mechanical Components of Nuclear Installations: High Temperature, Research and Fusion Reactors; 2022 edition
[2] https://ansyshelp.ansys.com/public/account/secured?returnurl=/Views/Secured/prod_page.html?pn=Mechanical%20APDL&pid=MechanicalAPDL&lang=en&prodver=24.2

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Conception d'un échangeur de chaleur pour l'évacuation de la puissance résiduelle

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2 septembre 2024

– *Proposition de stage* –

(N° ID : 1005978)

Mots-clés — Conception, SolidWorks, échangeur
Sujets — Conception mécanique, échangeur de chaleur, prédimensionnement thermique et mécanique

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Lieu	*new*cleo SA – Tour Silex[2], 9 rue des Cuirassiers - 69003 Lyon, France
Date de début	premier trimestre 2025
Durée	4–6 mois

Contexte

L'évacuation de la puissance résiduelle constitue l'une des trois fonctions fondamentales de sûreté pour un réacteur nucléaire. Elle permet de maintenir le réacteur à des niveaux de température acceptables dans les conditions de fonctionnement normales et/ou accidentelles.
Plusieurs systèmes sont mis en place pour assurer cette fonction. Afin de garantir un haut niveau d'indépendance entre ces systèmes, *new*cleo a fait le choix d'implémenter un système permettant le refroidissement par l'extérieur de la cuve principale du réacteur.

L'échangeur principale de ce système présente une conception complexe qui doit répondre à de nombreuses exigences, du fait de sa position et de l'importance de la fonction à laquelle il contribue.

Description

Le stage consistera à concevoir l'échangeur d'évacuation de la puissance résiduelle par l'extérieur de la cuve principales des réacteurs LFR de *new*cleo.
Les activités à réaliser comprendront :

- De la conception mécanique assistée par ordinateur (CAO – Solidworks)

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- Proposition de principes de conception répondant à l'ensemble des exigences
  - Agencement des tubes,
  - Principes de supportage,
  - …
- Création de maquette 3D

- Des calculs de prédimensionnement thermiques (évaluation préliminaire des performances thermiques de l'échangeur) à l'aide d'outil analytiques internes (Excel VBA)
- Des calculs de prédimensionnement mécaniques : Statiques et dynamiques (SolidWorks)

Feuille de route

a) Analyse fonctionnelle
b) Proposition de principes de conception
c) Création de maquette 3D
d) Calculs thermiques
e) Calculs mécaniques
f) Préparation d'un rapport technique.

Profil du candidat

Etudiant en master d'ingénierie mécanique.
Compétences :

- Conception mécanique.
- Maitrise de logiciel CAO.
- Calcul mécanique.
- Autonomie.
- Force de proposition.

Références

[1] D. Lisowski, Q. Lv, B. Alexandreanu, Y. Chen, R. Hu, T. Sofu., *An Overview of Non-LWR Vessel Cooling Systems for Passive Decay Heat Removal (Technical Letter Final report)*, 2021.
[2] M. Tarantino, *ALFRED overview and safety features*. 2021.

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Calculation of neutron activation under cyclic exposure in LFR

Daniele Tomatis *and Matteo Zammataro

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November 12, 2024

– Internship proposal –

(ID No. 1006013)

***Keywords* —** LFR, neutron activation, depletion and transmutation, cyclic exposure
***Topics* —** Reactor physics and analysis, radiation dose, reactor analysis, physical modeling

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Location	C.so Stati Uniti 38, Torino (TO), Italy
Starting date	As soon as possible
Duration	5–6 months

Context

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

Description

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

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be performed to estimate the exposure and dose rates of the coolant after being irradiated in the reactor. These dose rate data are used by the engineering teams to design radiation shielding components and to estimate potential radiation damage to steel structures.
The lead-cooled SMR designed by newcleo is the subject of this study. In a pool reactor, lead flows through the reactor core where it is exposed to a high neutron flux. It is then recirculated in an outer loop with a lower neutron flux.
The evolution of a material under neutron irradiation by transmutation and radioactive decay is described by the Bateman equation:

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

where $\mathbf{n}(t)$ is the vector of nuclide concentrations at time t, and $\mathbf{A}(\mathbf{n}(t), t)$ is a matrix containing the decay constants and microscopic reaction rates, also known as depletion matrix. Indeed, the build-up and depletion of harmful isotopes in the reactor coolant is strongly correlated with the reaction rates, which vary with the intensity and spectrum of the neutron flux, and must be known as an input to the problem [1]. Computer codes that solve the neutron transport problem are used to calculate the rates in advance in realistic core configurations. The OpenMC Monte Carlo transport code [2] will be used for the simulation of the neutron transport and the calculation of the reaction rates in the zones of interest.
Although mass inventory calculations under the influence of decay and transmutation are generally quite fast, their successive execution reproducing cyclic exposure can bring to unacceptable runtime because of a very high number of loop passages. The solution of 1 for the irradiation of a material with constant neutron flux for a time interval h is given by:

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

While the solution of 2 requires the solution of a single matrix exponential, an inventory analysis in circulating conditions requires the solution of many, especially after partitioning the reactor in zones characterized by different magnitude of the same reaction rates. The simplification of the depletion chains, in this context, is necessary to reduce the dimension of **A** and to avoid possible ill-conditioning due to a large amount of nuclides varying with very different time scales. Simplified chains also allow a deeper understanding of the physics involved in the problem. Solutions obtained with the FISPACT II code [3] are used as a reference to assess the reliability of the results.
The methodology developed for lead activation could be applied in the future to the evolution of any circulating fluid in the reactor, such as secondary water in the steam generators.
During the internship, the student will be introduced to the physics and engineering of the LFR reactors, acquiring notions and developing skills in mathematical modeling, particle transport and evolution problems. The student will learn how to use OpenMC and FISPACT II, learning Python programming too. At the end of the internship, the student will write a technical report on the analysis of the results from the numerical simulations.
The student will be followed by the Codes and Methods group members of *new*cleo.

Work plan

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

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

a) Literature review of activation problems
b) Analysis of similar study cases and discussion of the problem
c) OpenMC and FISPACT II introduction and training
d) Calculation of neutron flux and reaction rates in specific areas using an existing OpenMC full reactor model
e) Setup of the activation calculation
f) Analysis of the results
g) Preparation of a technical report

Applicant profile

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

References

[1] Fredrik Dehlin and Janne Wallenius. Activation analysis of the lead coolant in SUNRISE-LFR. *Nuclear Engineering and Design*, 414:112503, 2023.

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

[3] FISPACT-II: An Advanced Simulation System for Activation, Transmutation and Material Modelling. *Nuclear Data Sheets*, 139:77–137, 2017. Special Issue on Nuclear Reaction Data.

Conception mécanique du circuit primaire H/F

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2 octobre 2024

– *Proposition de stage* –

(ID No. 1006030)

***Mots Clefs* –** Circuit primaire, structure de supportage
***Sujets* –** Conception mécanique structure de supportage

Lieu	*new*cleo SA – Tour Silex[2], 9 rue des Cuirassiers - 69003 Lyon, France
Date de début	premier trimestre 2025
Durée	5–6 mois

Contexte

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

Description

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

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

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Feuille de route

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

Profil du candidat

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

Références:

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

LFR Steam Generators mechanical design: structural analyses and manufacturing aspects

Alexandre Villedieu[1] and Andrea Allio[*2]

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October 21, 2024

– *Internship proposal* –

(ID No. 1006125)

***Keywords* —** lead fast reactor, steam generator, finite-element analysis, structural mechanics, manufacturing engineering
***Topics* —** structural analysis of steam generators, manufacturing strategies and prototypes development

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Location *new*cleo S.p.A. – Corso Stati Uniti 38, 10128 Torino, Italy

Starting date First Quarter of 2025

Duration 5–6 months

Context

*new*cleo is designing small modular Lead-cooled Fast Reactor (LFR) using Mixed Oxide (MOx) fuel. The development of innovative technologies for lead-cooled fast reactors is a key point in *new*cleo's strategy. Several mechanical engineering aspects play a crucial role in the licensing of reactors. Among these, the structural verification of the components that compose the reactor and the validation of the manufacturing processes are the focus of this proposal.

Description

*new*cleo reactors employ spiral-tube shell-and-tube steam generators. Their aim is to transfer energy from the liquid lead, heated by the reactor core, to the water flowing inside the tubes, producing steam. The highly energized steam is directed to a steam turbine,

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which produces the mechanical power needed to generate electricity. The spiral-tube steam generators are conceived especially for their compactness and integrability within the reactor.
From a structural point of view, *new*cleo steam generators are very challenging, as they are characterized by large temperature differences and high pressure inside the tubes. Therefore, proper finite-element modelling (FEM) of the component, and its sub-parts, is crucial. One of the internship activities focuses on developing a FEM model and using it to perform analyses to investigate the structural integrity of the component under transient conditions. An example is the condition of increasing temperature of the hot liquid lead feeding the steam generator. The candidate will be supported by mechanical analysts and will acquire skills in the numerical modelling and simulation of structures.

Another central theme is the manufacturing of the steam generators. The most challenging aspects of the assembly sequence of these components are related to the tube bundle. The tube bundle consists of many spiral tubes stacked one above the other. The large number of tubes and the need for compactness, which is a main feature of *new*cleo reactors, require the development of procedures and the realization of mock-ups to test them in prototype conditions. A second activity of the internship is the study and proposal of a strategy to bend the tubes constituting the tube bundle at the top of the steam generators. In addition, it is required to design a mock-up of the tube bundle to test the strategy in a workshop. The candidate will be supervised by a manufacturing engineer and will acquire skills in manufacturing and prototyping of components.

Work Plan

The internship activity is scheduled according to the following plan:

a) Review of the existing work done on topics similar to described ones.
b) Development of a finite-element model of the case study with the support of *new*cleo structural analysts.
c) Simulation and presentation of the results of the structural analysis.
d) Proposal of a manufacturing strategy with the support of *new*cleo manufacturing engineers.
e) Development of a mock-up for manufacturing testing.
f) Preparation of a technical report.

Applicant profile

Master or PhD student in Nuclear, Mechanical or Aeronautical Engineering.
Fundamentals in common sense and goodwill.
Required computer skills: CAD software, preferably SOLIDWORKS, and Finite-Element tools, preferably ANSYS.

References

[1] https://ansyshelp.ansys.com/public/account/secured?returnurl=/Views/Secured/prod_page.html?pn=Mechanical%20APDL&pid=MechanicalAPDL&lang=en&prodver=24.2

[2] IAEA, Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: Steam Generators, https://www-pub.iaea.org/MTCD/Publications/PDF/TE_1668_web.pdf

Development of additively manufactured sensors for LFR environment

Enrico Virgillito *[1], Daniele De Caro[1] and Francisco Garcia Ferrè[1]

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November 11, 2024

– Internship proposal –

(ID No. 1006289)

***Keywords* —** Additive Manufacturing, sensors, LFR, alloy development
***Topics* —** New alloy development, Sensors development

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

Starting date First quarter of 2025

Duration 6 months

Context

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

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Description

The internship will focus on activities in Work Packages (WPs) 1.2 and 2.4 of the DAO project. WP 1.2 aims to define use cases, feasibility, requirements, and Key Performance Indexes (KPIs) for the diagnostic platform in hostile environments, considering parameters like operating temperatures, pressures, radiation, and corrosion. This will guide decisions on fiber types, coatings, and packaging materials, using both traditional and AM methods. Two AM technologies, Laser Powder Bed Fusion (LPBF) and Wire-Arc Additive Manufacturing (WAAM), will be studied, with AISI 316L as a substrate material due to its industrial relevance.
WAAM will be explored in WP 2.4 to design and produce fiber-integrated sensor prototypes within structures created through AM, replicating reactor vessel scales. This integration during the manufacturing process allows sensor placement in normally inaccessible locations, preserving material properties and eliminating post-manufacturing inspections. WAAM capability to create complex geometries enables enhanced system monitoring, reducing production and maintenance costs compared to traditional methods.
The project also aims to develop scalable sensor-equipped vessel prototypes, leveraging WAAM to optimize processes and demonstrate practical applications, supported by external expertise to advance WAAM technological maturity.
The internship will be divided into a literature review phase, a visit to partner phase, a laboratory activities phase, a data analyses phase, and a reporting phase.

Work Plan

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

- A literary review of use cases of sensors in LFR conditions with identification of the minimum functional requirements that will serve as the basis for sensor design (Word file).

- Definition of the necessary functional requirements and the indices that quantify performance (KPIs). The parameters to be defined will be used to evaluate the feasibility of obtaining useful information for diagnosing structures in hostile environments (Word file).

- Microstructural and mechanical performance analyses of WAAM samples produced. Samples will be provided by external partner(s). The laboratory tests will be conducted in a university or external partner. A subsequent data analyses phase will be performed (Word file).

- A final report in which machine settings for WAAM printing, provided through process files, are explained; in the report, the effects of the process parameters on the produced material characteristics will be indicated (Word file).

Applicant profile

Master or PhD student in Nuclear, Chemistry, Material science, Mechanical or Aeronautical Engineering; Applied Mathematics and Physics.
Required computer skills: work entirely in a terminal without the desktop environment.

References

[1] Morana A, Girard S, Marin E, Marcandella C, Paillet P, Périsse J, Macé JR, Boukenter A, Cannas M, Ouerdane Y. “Radiation tolerant fiber Bragg gratings for high temperature monitoring at MGy dose levels” Opt Lett. 2014 Sep 15;39(18):5313-6. doi: 10.1364/OL.39.005313. PMID: 26466259

[2] Quentin Pouille et Al. “Additive Manufacturing and Optical Sensors, Towards a New Way for Nuclear Material Monitoring”, WM2023 Conference, February 26 – March 2, 2023, Phoenix, Arizona, USA

[3] J.Popławski et Al “Metal-coated optical fiber embedment in WAAM aluminium parts for distributed temperature sensing”. https://indi.to/RP9Ty