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DOCTORAL SCHOOL MATERIALS SCIENCE AND ENGINEERING

EXTENDED SUMMARY
OF THE DOCTORAL THESIS

ADSORPTION OF VOLATILE RADIOTOXIC ELEMENTS IN GENIV-LFR

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INTRODUCTION

The development of advanced nuclear systems within the Generation IV framework has intensified research efforts aimed at improving reactor safety, sustainability, and resource efficiency. Among the proposed concepts, lead-cooled fast reactors (LFRs) represent a particularly promising technology due to the favourable physical and chemical properties of the lead coolant, including its high boiling point, low vapour pressure, and chemical inertness. In this context, the ALFRED (Advanced Lead Fast Reactor European Demonstrator) project constitutes a key European initiative designed to demonstrate the technological feasibility of LFR systems and to support their future deployment [1].

A critical aspect of LFR operation concerns the behaviour of radioactive impurities generated during reactor operation. These include activation products arising from neutron interactions with the coolant and structural materials, as well as fission products released from the nuclear fuel under off-normal conditions. While the majority of these species remain dissolved or retained within the liquid metal, a subset of radionuclides exhibits significant volatility and may transfer to the cover gas [2,3]. This liquid–gas transfer represents a primary pathway contributing to the radiological source term and is therefore directly relevant to safety assessment, environmental impact, and reactor monitoring [4].

Despite its importance, the quantitative prediction of volatile radionuclide behaviour in heavy liquid metal systems remains subject to significant uncertainty. Existing approaches are largely based on equilibrium thermodynamics and often rely on incomplete or outdated datasets, particularly with regard to Henry's law volatility constants at reactor-relevant temperatures [5,6]. In addition, these approaches frequently neglect the influence of transport processes and system-specific operating conditions, leading to conservative but potentially unrealistic source-term estimations. As a result, current methodologies do not fully capture the coupled nature of impurity behaviour, where thermodynamic partitioning, chemical interactions, and transport mechanisms act simultaneously.

Further limitations arise from the scarcity of experimental data obtained under representative conditions. In particular, the validation of thermodynamic models is hindered by the lack of reliable analytical techniques capable of quantifying impurities at ultra-trace levels in lead matrices. Strong matrix effects, including signal suppression and spectral interferences, significantly complicate the application of conventional analytical methods. At the same time, the mechanisms governing the transport of volatile species from the liquid phase to the cover gas, such as bubble formation, interfacial mass transfer, and gas-phase mixing, remain insufficiently characterised.

These limitations highlight the need for an integrated research approach capable of addressing impurity behaviour in a physically consistent manner. In particular, accurate source-term assessment and reliable monitoring strategies require the combined consideration of three key aspects: (i) thermodynamic equilibrium governing liquid–gas partitioning; (ii) analytical capability enabling trace-level quantification of impurities; and (iii) transport processes controlling the migration and detection of species within the reactor system.

The present thesis addresses this need by developing and applying an integrated framework for the investigation of volatile radiotoxic elements in lead-cooled fast reactors, with particular reference to the ALFRED system. The central hypothesis is that a combined approach, integrating thermodynamic modelling, experimental investigation, and analytical method development, enables a quantitative and physically consistent characterisation of impurity behaviour under reactor-relevant conditions.

Based on this framework, the research is guided by the following key questions:

RQ1: How the ALFRED source term can be improved using updated thermodynamic data and extended impurity inventories?
RQ2: Which analytical methodologies enable reliable quantification of trace impurities in liquid lead?
RQ3: What mechanisms govern the transport of volatile species from the liquid phase to the cover gas?
RQ4: How do retention and adsorption processes influence radionuclide partitioning and their implications for monitoring and safety assessment?

To address these questions, the research is structured around three primary objectives:
(O1) re-evaluation of the ALFRED source term using updated thermodynamic and experimental data;
(O2) development of a robust analytical methodology for trace impurity determination in lead;
(O3) design and operation of an experimental facility for investigating noble gas transport under representative conditions.

The originality of the thesis lies in the integration of these complementary approaches into a unified methodology for the analysis of impurity behaviour. Rather than treating thermodynamic equilibrium, analytical measurement, and transport phenomena as separate aspects, the work demonstrates that they must be considered jointly in order to establish a consistent relationship between impurity inventories in the coolant and measurable concentrations in the cover gas.

Through this integrated approach, the work advances the understanding of impurity behaviour in heavy liquid metal systems and contributes to the development of reliable monitoring and safety assessment methodologies for Generation IV lead-cooled fast reactors.

From a scientific perspective, the thesis contributes to improving the understanding of liquid–gas partitioning in heavy liquid metal systems, particularly through the generation of new experimental data for key volatile elements. From a methodological perspective, it establishes an analytical capability for trace-level quantification in lead matrices and provides an experimental basis for investigating transport processes under controlled conditions. From an applied perspective, the results support the development of more realistic source-term assessments and more effective monitoring strategies for Generation IV LFR systems.

The research is inherently multidisciplinary, combining elements of nuclear engineering, thermodynamics, materials science, analytical chemistry, and radiochemistry. By addressing the coupled nature of impurity behaviour across these domains, the thesis contributes to bridging the gap between theoretical prediction, experimental validation, and practical implementation in reactor systems.

In this way, the work provides both fundamental insight into the behaviour of volatile radiotoxic elements in heavy liquid metals and a practical framework for their quantification and monitoring, thereby supporting the advancement of safe and reliable Generation IV lead-cooled fast reactor technologies.

1. Literature review on the behaviour of impurities in heavy liquid metals

This chapter establishes the theoretical and scientific foundation for assessing radioactive impurities in the ALFRED reactor. It provides a comprehensive analysis of the origin, behaviour, and potential release pathways of radionuclides generated during reactor operation, while evaluating the current state of knowledge regarding their thermodynamic properties and transport mechanisms in heavy liquid metal systems.

The source term represents a central concept in nuclear safety analysis, describing the inventory, composition, and potential release of radioactive materials under both normal operation and accident scenarios. It is defined not only by the magnitude of radionuclide inventories, but also by their physical and chemical forms, release mechanisms, and temporal evolution [4], all of which directly influence radiological risk assessments, safety-system design, and licensing procedures.

1.1. Radionuclide generation and transfer pathways

In the ALFRED reactor, radioactive impurities originate primarily from neutron activation of the lead coolant and structural materials, and from fission products generated within the nuclear fuel. Depending on their thermodynamic proprieties, these radionuclides may remain dissolved in the molten lead, accumulate at structural interfaces, or migrate towards the cover gas [7].

Potential release pathways include structural failures, cover-gas leakage, interaction between primary and secondary circuits, and containment breaches [8]. These scenarios define the boundary conditions for source-term evaluation and highlight the need for a comprehensive understanding of impurity transport across the reactor system.

Radionuclide migration is governed by coupled physico-chemical processes. At the liquid–gas interface, evaporation and condensation control phase exchange, while within the liquid phase, dissolution, precipitation, and chemical reactions determine impurity stability. At structural interfaces adsorption, adsorption and deposition processes influence long-term accumulation. These mechanisms collectively lead to a dynamic redistribution of radionuclides. However, current models remain largely equilibrium-based and do not adequately capture transport-controlled phenomena under reactor conditions.

1.2. Inventory of activation and fission products

Neutronic simulations preformed within the LEADER project, provide quantitative estimates of radionuclide inventories [9,10]. Activation products are present at extremely low concentrations, typically in the ppb to ppt range relative to the total mass of molten lead as illustrated in. Fig. 1. Despite their low mass fraction, their radiological significance may be considerable due to high activity. [11].

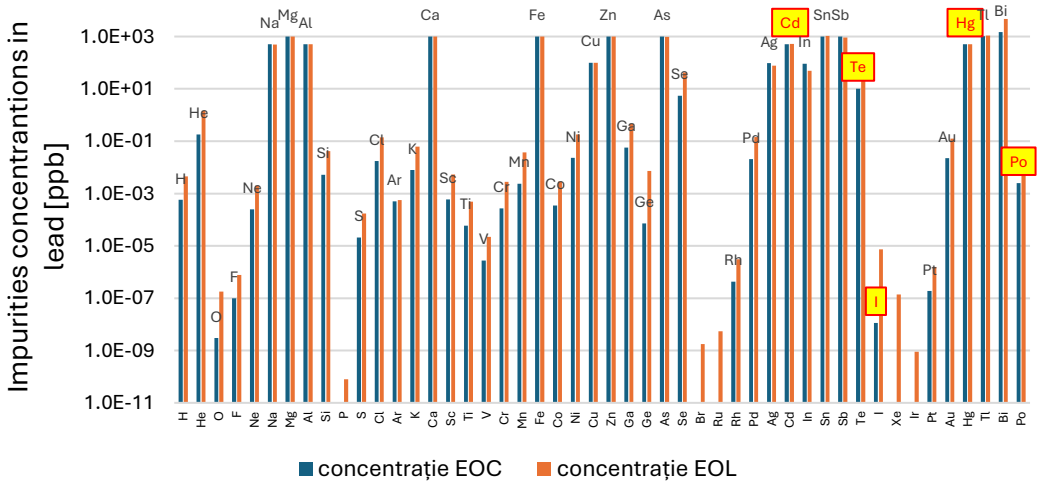


Fig. 1 Activation products concentration in molten lead after 5 years of irradiation (EOC) and at end of life (EOL)

Under normal operation, fission products remain confined within the fuel matrix or in the gas plenum of the fuel-element. However, in the event of fuel-cladding failure, a fraction may be released into the coolant. Among these, volatile radionuclides such as iodine, caesium, tellurium, and noble gases represent the most relevant contributors to the gaseous source term. As shown in Fig. 2 The activity of the volatile FPs in the ALFRED core at EOC - data from [12], short-lived isotopes dominate the overall activity,

while long-lived species contribute only a minor fraction, although their impact may remain significant depending on their toxicity, volatility, and transport behaviour.

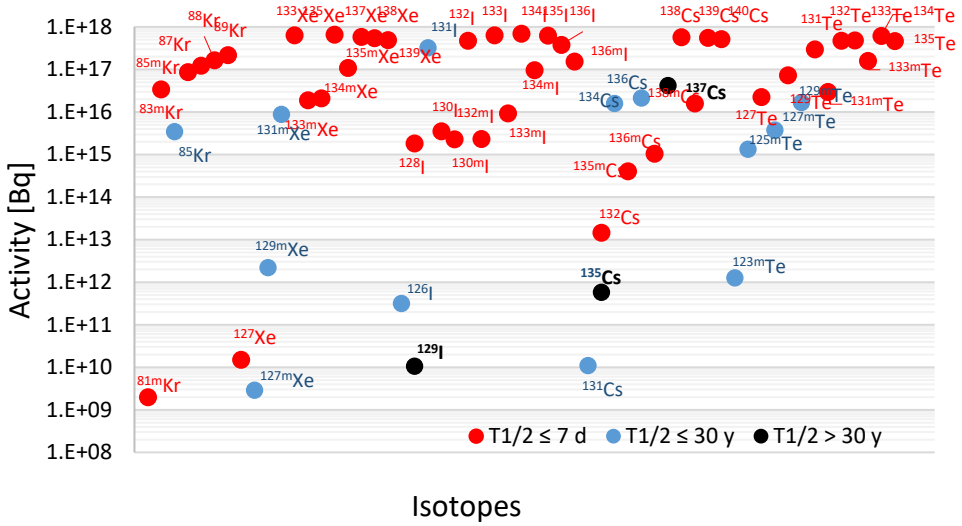


Fig. 2 The activity of the volatile FPs in the ALFRED core at EOC - data from [12]

1.3. Thermodynamic framework for impurity behaviour

The behaviour of impurities in molten lead is fundamentally governed by thermodynamic equilibrium. The distribution between the liquid and gas phases is controlled by chemical potential, which depends on temperature, concentration, and interactions with the solvent [6].

Under conditions relevant to LFR operation, impurities are present at very low concentrations, allowing the assumption of ideal dilute solutions. This enables the application of Henry's law to relate dissolved concentration to equilibrium partial pressure:

$$P_A = K_{H,A} \cdot X_A \tag{1}$$

where K_H is Henry's law volatility constant, a temperature-dependent parameter incorporating both vapour pressure and activity coefficient. This constant represents a key parameter for evaluating the volatility of radionuclides and their potential transfer to the cover gas.

By combining this relation with the ideal gas law, this method allows estimation of gaseous inventories. However, such approach represents a first-order approximation. In real systems, impurity behaviour is strongly influenced by chemical interactions with lead, dissolved oxygen, and other species. The formation of oxides typically reduces volatility, while the formation of gaseous compounds may enhance it. The composition of the cover gas, including oxygen, hydrogen, and water vapour, therefore plays a critical role.

Furthermore, interfacial phenomena such as adsorption, surface enrichment, and kinetic limitations may lead to deviations from equilibrium predictions, highlighting the need for experimental validation.

1.4. Synthesis of knowledge gaps

The analysis identifies several key limitations in the current understanding of impurity behaviour in heavy liquid metal systems.

A first major gap concerns the reliability of source-term assessment. Existing evaluations often rely on incomplete or outdated thermodynamic datasets and do not consistently account for all relevant volatile species, leading to significant uncertainties.

A second limitation relates to analytical capability. The quantification of trace impurities in molten lead is hindered by strong matrix effects, which limit detection sensitivity and accuracy at ppb and ppt levels. This restricts the ability to validate models experimentally and to implement reliable monitoring strategies in operating systems.

A third gap concerns transport processes. While equilibrium models describe potential release, the kinetics of impurity migration, particularly the roles of convection, diffusion, and interfacial mass transfer, remain insufficiently characterised.

Finally, the scarcity of experimental data obtained under reactor-relevant conditions constrains model validation, as many studies rely on simplified systems or non-representative concentrations.

1.5. Research objectives

In response to these gaps, the thesis defines a structured research programme aimed at improving the understanding and quantification of volatile radionuclide behaviour in LFRs.

The first objective focuses on the **re-evaluation of the ALFRED source term through updated thermodynamic data and new experimental results**, including the extension of impurity inventory and the experimental determination of key parameters, notably the Henry's law volatility constant for tellurium.

The second objective addresses the **development of an analytical methodology for trace impurities quantification in lead**, based on matrix separation and high-sensitivity techniques.

The third objective involves the **experimental investigation of noble gas transport, through the design and operation of a dedicated facility**, enabling the study of transport mechanisms and detection behaviour under representative conditions.

Conclusions of the chapter

This chapter demonstrates that impurity behaviour in LFRs is governed by a complex interplay of thermodynamic, chemical, and transport phenomena. While molten lead effectively retains most radionuclides, a subset of volatile species may contribute to the gaseous source term and must be considered in safety assessments.

The analysis highlights the limitations of current knowledge and establishes the need for integrated approaches combining modelling, experimentation, and advanced analytical techniques. By defining the scientific context and identifying the key research gaps, this chapter provides the conceptual foundation for the subsequent work presented in the thesis.

2. Experimental research on volatile impurities

2.1. Source-Term Re-evaluation for the ALFRED Reactor

Chapter 3 is dedicated to the re-evaluation of the radiological source term associated with volatile impurities in the ALFRED. The analysis addresses a central safety issue in HLM systems, namely the partitioning of activation and fission products between the molten lead coolant and the cover gas. Although most radionuclides remain strongly retained in the liquid phase, a limited number of species exhibit sufficient volatility to accumulate in the gaseous region. Even at very low concentrations, these species are relevant for radiological protection, reactor monitoring, and accident assessment.

The chapter combines thermodynamic modelling with new experimental results to provide a more realistic estimate of the gaseous radiological inventory. Compared with earlier evaluations [13], the analysis incorporates updated Henry's law volatility constants, extends the range of investigated elements, and includes new experimental data for tellurium obtained within the present thesis. This approach contributes directly to the refinement of source-term prediction.

2.1.1. Methodological framework and input data

The source-term assessment is based on the assumption of thermodynamic equilibrium between impurities dissolved in molten lead and their corresponding gaseous species. For dilute solutions, the equilibrium partitioning is described by Henry's law, using temperature-dependent volatility constants derived from experimental correlations. By combining these constants with the molar fractions of radionuclides in the lead coolant, the equilibrium partial pressure and corresponding activity in the cover gas can be determined.

The analysis considers representative ALFRED operating conditions (430-520 °C) [14] and a transient ULOF scenario with temperatures up to 750 °C [15]. In Table 1 are summarised the volatile elements considered in this study, together with their inventories, activities, and molar fractions in molten lead assuming complete dissolution. A conservative assumption neglects gas purification and circulation systems, thereby providing an upper-bound estimate of gaseous inventories.

The results are interpreted in terms of both mass concentrations and radioactive activities, allowing direct comparison with occupational exposure criteria and providing a more meaningful assessment of radiological significance [16].

Table 1 Volatile elements inventory and corresponding molar fractions at 100% dissolution in lead.

Elements	APs Mass [g]	APs Activity [GBq]	APs Molar Fraction	FPs Mass [g]	FPs Activity [GBq]	APs + FPs Molar Fraction
Po	8.59E-3	1.43E3	2.50E-12	-	-	-
Hg	1.70E3	4.90E3	5.17E-7	-	-	-
Cd	1.71E3	3.29E3	9.28E-7	4.53	2.71E4	9.30E-7
Te	3.43E1	5.30E-4	1.64E-8	2.71E1	3.21E6	2.93E-8
I	3.83E-8	-	1.84E-17	1.26E1	9.34E6	6.06E-9
Cs	-	-	-	2.42E2	4.66E5	1.11E-7
Kr	-	-	-	1.68E1	3.72E6	1.20E-8
Xe	-	-	-	2.69E2	1.81E7	1.23E-7

2.1.2. Behaviour of key volatile activation products

The analysis identifies Po, Hg and Cd as the principal activation products contributing to the volatile source term.

Polonium exhibits extremely low volatility, with more than 99.999 % of the inventory retained in molten lead over the investigated temperature range [17]. Despite this strong retention, its radiological relevance remains high due to its alpha-emitting nature and extreme toxicity [18,19].

Mercury is found to be the most volatile activation product. exhibits the highest volatility. Its equilibrium partial pressures are several orders of magnitude higher than those of other metallic impurities [20], making it the dominant contributor to the gaseous inventory under normal operating conditions.

Although most mercury remains dissolved, the fraction transferred to the gas phase may approach or exceed reference exposure limits if considered in isolation, emphasising the need for effective monitoring and retention systems.

Cadmium represents the second most volatile metallic impurity and is particularly relevant because it originates from both activation and fission processes. In assessing its volatility no experimental data on the evaporation of Cd from HLM has been found and thus the vapor pressure of pure Cd has been used. [21]. The results show that cadmium contributes significantly to the gaseous inventory even under normal operation, while its importance increases further under fuel-failure conditions. Its behaviour is therefore critical for both routine monitoring and accident scenarios.

2.1.3. Tellurium: new experimental determination of Henry's law volatility constant

This work provides the first experimentally validated determination of the Henry's law volatility constant for tellurium in the temperature range relevant to LFR operation. This impurity is of particular interest because it is produced both as an activation product and as a fission product, and because its thermodynamic behaviour is closely related to that of polonium.

To address the limited availability of data, a dedicated experimental campaign was conducted using the transpiration method [22,23]. Experiments were performed with neutron-activated tellurium dissolved in lead–bismuth eutectic over a temperature range of 220–600 °C. The method enables the determination of vapour pressure at very low concentrations by transporting evaporated species with a carrier gas and quantifying the deposited activity.

A schematic representation of the experimental arrangement is provided in Fig. 3. The main component of the set-up is a fused-silica transpiration tube with a length of 650 mm and an inner diameter of 14 mm, positioned inside a tubular furnace mounted on a movable support [24]. The mobility of the furnace made it possible to place the hot zone directly over the sample only during the exposure period. All operations were performed in an inert-atmosphere glovebox (UNIlab, M. Braun) under purified argon, with O_2 and H_2O concentrations maintained below 1 ppm, in order to minimise oxidation effects.

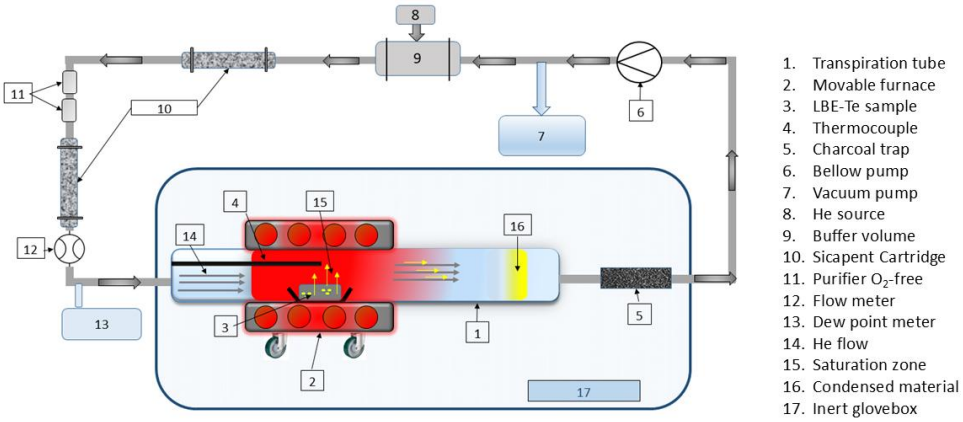


Fig. 3 Schematic representation of the transpiration set-up

The results, illustrated in Fig. 4, confirm that tellurium is strongly retained in the liquid metal, with volatility significantly lower than that of the pure element. In the temperature range 350–600 °C, the experimental data show good agreement with available literature values and yield a consistent temperature correlation:

$$log\ H_v^{px} = 9.76(32) - \frac{8204(280)}{T} \quad (1)$$

This correlation provides, for the first time, experimentally validated data in the temperature range relevant to LFR operation. The agreement across a wide concentration range indicates that tellurium behaves as an ideal dilute solute under these conditions.

At lower temperatures, deviations from linear behaviour are observed, suggesting possible effects related to surface phenomena, oxide formation, or changes in speciation. These findings highlight the need for further investigation of low-temperature behaviour under controlled redox conditions.

The comparison with polonium data shows similar temperature dependence [24], supporting the use of tellurium as a surrogate for studying polonium behaviour in heavy liquid metal systems.

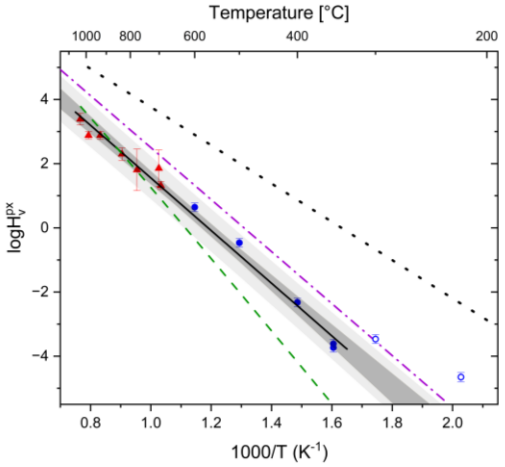


Fig. 4 Henry's law volatility constant of Te evaporated from LBE. Blue circles: data measured in this work; red triangles:- data from [23]; black dotted line - vapour pressure of pure Te [25]; dashed green line – vapour pressure of pure PbTe [26]; black solid line: apparent linear fit of all data with T ≥ 350 °C; the dark and light grey shaded areas represent the 95 % confidence and prediction bands of the apparent linear fit; dashed-dotted violet line: temperature function of Henry's law volatility constant of Po in LBE derived in [24]

2.1.4. Behaviour of iodine and caesium

Iodine and caesium are primarily relevant under fuel-failure conditions. Their inventories in the coolant are negligible during normal operation but may increase significantly following cladding failure.

For iodine, the analysis assumes formation of PbI_2, which limits its volatility. Even under conservative assumptions, the predicted gaseous concentrations remain below reference exposure limits [6]. However, its radiological importance requires improved analytical capabilities for accurate detection.

For caesium, the available thermodynamic data are more uncertain. The behaviour was estimated using corrected vapour-pressure correlations [27], indicating that caesium may accumulate in the cover gas under accident conditions. The large uncertainties associated with its speciation highlight the need for further experimental investigation.

2.1.5. Integrated source-term assessment

The integration of all analysed species, presented in Fig. 5, provides a comprehensive evaluation of the ALFRED source term. The results show that mercury dominates the gaseous inventory under normal conditions, followed by cadmium and tellurium, while polonium remains strongly retained. Under accident

scenarios, the contribution of fission products increases significantly, with noble gases becoming dominant in the gas phase.

Although the estimated concentrations in the cover gas are generally low (ppm to ppb range or lower), their radiological impact remains significant due to the high specific activity of certain radionuclides. The results confirm that more than 99.995% of radionuclides remain retained in the liquid phase, demonstrating the strong retention capability of molten lead.

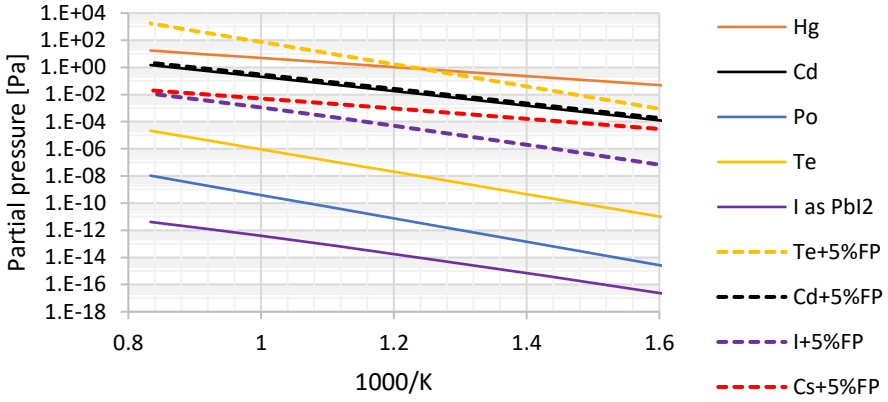


Fig. 5 Partial pressure variation with temperature for volatile impurities in normal condition (continuous lines) and a postulated accident scenario of 5% of FPs released in ALFRED (dashed lines)

Conclusions and contribution of Chapter 3

Chapter 3 demonstrates that the volatile radionuclides behaviour in ALFRED is governed by thermodynamic partitioning between the liquid and gas phases, with strong retention in the liquid metal for most species. A limited group of volatile elements, particularly mercury and cadmium, contributes to the gaseous inventory under normal conditions, while fission products become dominant under accident scenarios.

The chapter makes several original contributions. It delivers an updated source-term assessment based on improved thermodynamic data, extends the analysis to additional volatile elements, and introduces new experimental results for tellurium. The determination of the Henry's law volatility constant for tellurium represents a key contribution, reducing uncertainties in source-term prediction and enabling more accurate modelling of chalcogen behaviour.

2.2. Analytical methodology for trace impurities

This analytical capability is essential for validating thermodynamic predictions and for enabling reliable monitoring of impurity behaviour under reactor conditions.

Chapter 4 presents the development of an analytical methodology for the determination of trace impurities in lead matrices under conditions relevant to lead-cooled fast reactor (LFR) technology [28]. This work addresses a critical challenge identified in the thesis: the quantification of ultra-trace impurities in molten lead in the presence of an overwhelming matrix excess. This capability is essential for the ALFRED reactor, where safe operation depends not only on thermal and neutronic performance but also on accurate monitoring of coolant chemistry.

The analytical difficulty arises from the extreme disparity between the lead matrix and the analytes of interest. Lead dominates the sample composition, while impurities are present at ultra-trace levels. In ICP-MS, this leads to severe matrix effects, including signal suppression, spectral interferences, and

instability of ion transmission due to space-charge effects. High lead concentrations may also damage instrumental components. Consequently, direct ICP-MS analysis is unsuitable without prior matrix removal [29,30].

Alternative analytical techniques were evaluated but found inadequate for this application. Atomic absorption spectrometry lacks multi-element capability, ICP-OES does not provide sufficient sensitivity, X-ray fluorescence suffers from matrix effects, and neutron activation analysis is limited by operational complexity. ICP-MS remains the most suitable technique, provided that matrix effects are effectively mitigated.

The analytical strategy developed in this chapter therefore combines ICP-MS with a selective matrix separation step. The methodology focuses on cadmium and tellurium as representative analytes relevant to source-term assessment. Cadmium is characterised by relatively high volatility, while tellurium is important both as a fission product and as a surrogate for polonium behaviour.

Matrix removal was achieved using extraction chromatography with Sr-resin, based on crown-ether chemistry. Under controlled nitric acid conditions (0.2–1 M HNO_3), Pb^{2+} ions are selectively retained, while Cd and Te remain in solution. This selective separation forms the basis of the developed analytical procedure.

2.2.1. Experimental methodology

The analytical protocol consists of three main stages: dissolution of lead samples, chromatographic separation, and ICP-MS analysis. Lead samples (~1 g) were dissolved in 2 M nitric acid at 80 °C and diluted to obtain concentrations of approximately 20 mg mL^{-1}. Solutions were spiked with Cd and Te in the range 5–125 ppb to simulate reactor-relevant impurity levels.

Matrix separation was performed, according to the protocol presented in Fig. 6, by loading aliquots onto preconditioned Sr-resin columns. Lead was retained, while analytes were collected in two eluate fractions using 1 M and 0.2 M nitric acid. Quantification was carried out by ICP-MS (ELAN DRC II), with calibration curves showing excellent linearity ($R^2 > 0.995$) and measurements performed in triplicate.

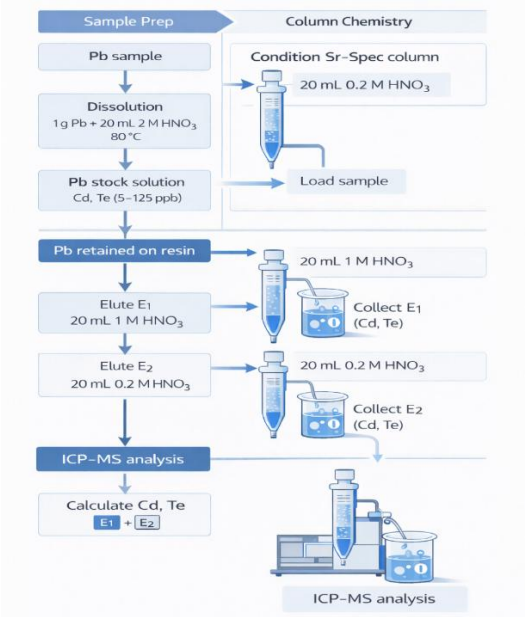


Fig. 6 Schematic protocol for Pb matrix removal and determination of trace Cd and Te impurities using Sr-Spec extraction chromatography followed by ICP-MS analysis

2.2.2. Results and interpretation

The results, summarized in Table 2, demonstrate that nearly all analyte mass is recovered in the first eluate, confirming effective separation of trace elements from the lead matrix. Analytical precision was high, with relative standard deviations below 2%.

Initial recoveries exceeding 100% revealed the presence of intrinsic Cd and Te impurities in the starting lead material. After correcting for this background contribution, recoveries fell within acceptable ranges (approximately 95–115%), consistent with quantitative analyte transfer and literature data.

Application of the method to real lead samples confirmed the presence of trace Cd and Te, as well as significant bismuth concentrations in some materials. This finding is particularly relevant for LFR systems, as bismuth can contribute to Po-210 formation through neutron activation.

Lead retention efficiency on the Sr-resin reached approximately 99.88%, demonstrating effective matrix removal. Additional experiments confirmed that matrix effects are strong: signal suppression exceeded 86% for Cd and 92% for Te in the presence of lead. This result clearly establishes that matrix separation is essential for accurate analysis.

Despite its effectiveness, the methodology has certain limitations. The procedure is multi-step and requires careful control to avoid contamination and ensure reproducibility. In addition, intrinsic impurities in the lead matrix must be characterised prior to analysis. The current validation focuses on Cd and Te, and further work is needed to extend the method to other relevant elements.

Table 2 Recoveries corrected for the contribution of the lead powder

Element	**Experiment/ Elution**	**Mass from spike [µg]**	**Mass of elution [g]**	**Corrected initial concentration [ppb]**	**Corrected recovery [%]**	**Average recovery from LBE samples** [31] **[%]**
Cd	Exp.1 / E1	0.083	23.769	6.28	101.8	
	Exp.2 / E1	0.132	23.819	8.27	95.0	
	Exp.3 / E1	0.004	21.798	3.23	113.6	
	Exp.4 / E1	0.008	21.782	3.40	115.9	
			The average recovery of Cd		**106.6 ± 8.6**	**107.5 ± 5.2**
Te	Exp.1 / E1	0.083	23.769	3.98	90.8	
	Exp.2 / E1	0.131	23.819	5.98	86.8	
	Exp.3 / E1	0.004	21.798	0.75	123.7	
	Exp.4 / E1	0.008	21.782	0.91	121.4	
			The average recovery of Te		**105.7±17.0**	**96.0 ± 4.8**

Conclusions and contribution of Chapter 4

Chapter 4 demonstrates that the second objective of the thesis has been achieved through the development of a validated methodology for the determination of trace impurities in lead. The study confirms that direct ICP-MS analysis is unsuitable for ultra-trace measurements due to strong matrix effects, and that extraction chromatography using Sr-resin provides an effective solution.

The proposed procedure enables efficient retention of the lead matrix, quantitative recovery of cadmium and tellurium, and reliable measurement of these elements at trace levels. The methodology was also successfully applied to real lead materials, providing relevant information on intrinsic impurity levels, particularly for bismuth.

From the perspective of original contribution, the chapter provides a validated analytical route for trace impurity determination in lead, quantifies the extent of matrix-induced signal suppression, and demonstrates the effectiveness of Sr-resin under optimised conditions. The developed approach provides a practical basis for coolant chemistry monitoring.

2.3. Noble Gas Transport Investigations

Chapter 5 addresses a key aspect of safety and monitoring in LFR namely the transport behaviour of noble gases released following fuel-cladding failure. The chapter combines a conceptual analysis of noble gas migration under reactor conditions with the experimental investigation performed using the NOGATILL facility. It contributes directly to Objective O3 of the thesis, which concerns the design, implementation, and use of a dedicated experimental installation for studying xenon and krypton transport under controlled conditions relevant to LFR systems.

The motivation for this research lies in the need for reliable early detection of fuel-cladding degradation. In LFRs, fission products are normally confined within the fuel matrix by the cladding. However, irradiation damage, corrosion, or mechanical degradation may lead to cladding breach and release fission gases into the coolant. Among these, xenon and krypton are of particular importance because of their chemical inertness, low solubility in liquid lead, and high volatility. These properties favour rapid migration towards the cover gas and make them suitable indicators for gas-based monitoring systems [32].

Gas-tagging techniques, in which specific isotopic compositions of noble gases are introduced into fuel pins, enable the identification of failed fuel assemblies through isotopic analysis of the cover gas [33–37]. However, the effectiveness of such systems depends not only on analytical sensitivity but also on the physical processes governing gas migration from the release point to the detection system. These include bubble formation and rise in the liquid metal, gas release at the liquid–gas interface, and subsequent transport in the cover gas. The limited availability of experimental data on these processes in heavy liquid metals represents an important knowledge gap addressed in this chapter.

A preliminary assessment for the ALFRED reactor indicates that expected concentrations of tagging gases in the cover gas are extremely low, typically in the range of tens to hundreds of ppb [38]. This requires high-sensitivity detection systems capable of distinguishing tagging gases from background fission products. The isotopic composition measured in the cover gas therefore reflects a complex mixture of intrinsic fission gases, tagging gases, and residual background species, further emphasising the importance of understanding transport phenomena alongside analytical capabilities.

2.3.1.NOGATILL experimental facility

To investigate these processes experimentally, a dedicated installation was designed with the capability to operate with molten lead at reactor-relevant temperatures, inject noble gases under controlled conditions, maintain an inert cover gas atmosphere, and monitor gas composition in real time. The system also had to allow control of gas circulation and variation of key operational parameters such as temperature, flow rate, and injection mode. These requirements led to the development of the **NOGATILL** (*NOble GAses Transport In Liquid Lead*) experimental facility at RATEN-ICN.

The NOGATILL facility consists of three main subsystems: a melting vessel for preparing molten lead, a storage vessel for conditioning and oxygen control, and a test vessel where noble gas transport

experiments are conducted (Fig. 7). The melting vessel enables controlled preparation of molten lead under inert atmosphere, while the storage vessel ensures proper oxygen concentration through hydrogen-based reduction processes, maintaining conditions relevant to LFR operation. The test vessel represents the core experimental section, where noble gases are injected into a vertical column and their migration toward the cover gas is analysed.

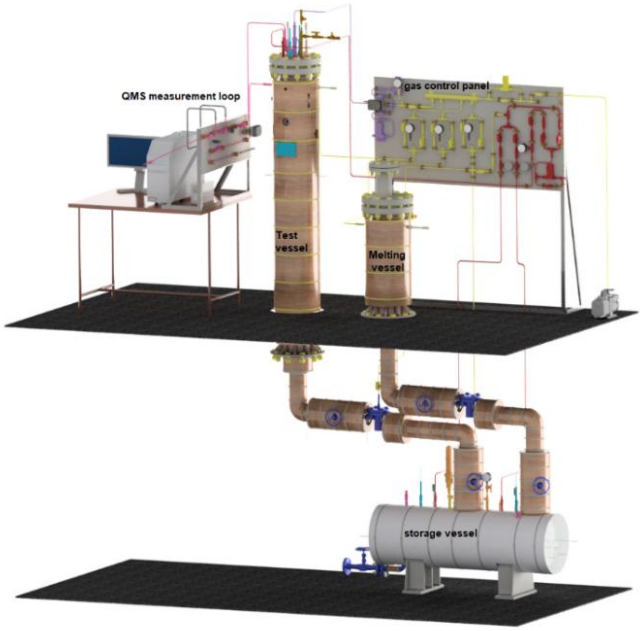


Fig. 7 General layout of the NOGATILL experimental facility for investigating noble-gas transport in molten lead

A key feature of the facility is the integration of a gas handling and monitoring system, which includes precise mass flow controllers for xenon and krypton injection, a mixing chamber for preparing gas mixtures, and a recirculation loop connected to a quadrupole mass spectrometer (QMS). This configuration enables continuous monitoring of noble gas concentrations in the cover gas and allows determination of detection delays following gas release.

2.3.2. Experimental Methodology and Gas Analysis

The experimental matrix involved controlled noble gases injections under different operating conditions, designed to simulate various fuel failure scenarios. Two main injection modes were considered: impulse injection, representing sudden cladding rupture, and continuous injection, representing gradual leakage through small defects.

Gas detection was performed using quadrupole mass spectrometry, which enables real-time analysis of gas composition based on mass-to-charge ratio. The technique provides high sensitivity and allows unambiguous identification of noble gases through their characteristic isotopic signatures. Ionisation is achieved by electron impact, after which the generated ions are separated in the quadrupole mass filter. The resulting spectra allow precise determination of detection times and time-dependent concentration changes.

2.3.3. Experimental results and transport behaviour

The axial temperature distribution inside the test vessel was monitored using three Type K thermocouples installed at different vertical positions (Fig. 8). Thermocouple TC18 was located in the upper region of the vessel (0.20 m below the top flange), TC19 in the middle region (0.65 m), and TC20 near the bottom of the vessel (1.70 m). These measurement points allow the characterization of the vertical temperature profile along a monitored height of approximately 1.50 m, corresponding to the region relevant for gas transport between the injection point and the cover gas sampling zone.

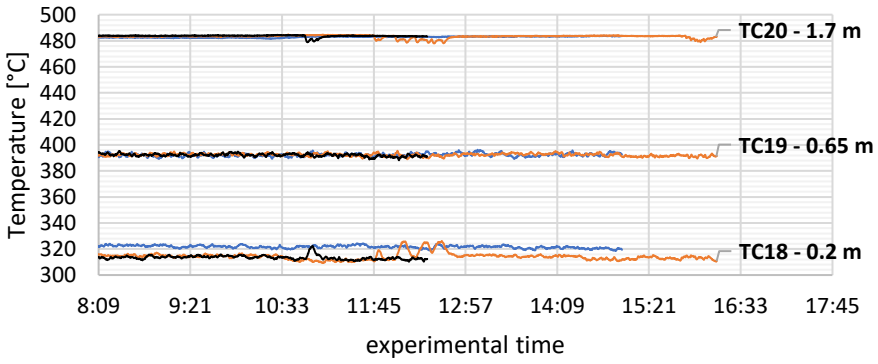


Fig. 8 Temperature distribution during all experimental tests. Blue line – Test 1; orange line – Tests 2&3; black line – Test 4.

A stable thermal stratification was established inside the test vessel, characterised by a strong axial temperature gradient of approximately 111 °C m^{-1}. This gradient resulted in a corresponding density stratification, with colder and denser gas in the upper region and hotter, less dense gas near the bottom. Such conditions significantly influence gas transport by promoting buoyancy-driven flow and affecting mixing behaviour.

The QMS spectra recorded at plateau conditions for all four tests (Fig. 9) exhibit a stable and well-resolved cover-gas composition, confirming the attainment of steady-state mixing following noble gas injection. The dominant peak at m/z = 40 amu corresponds to argon (^{40}Ar), which defines the baseline composition of the system. Minor peaks associated with residual gases, including H_2, N_2, and doubly ionised argon ($^{40}Ar^{2+}$), aper at low intensities, indicating a controlled and stable experimental environment with negligible contamination. In the magnified view, distinct isotopic clusters of krypton and xenon are clearly identified. The krypton isotopes appear in the range m/z = 82–86 amu, while xenon isotopes are observed in the range m/z = 129–136 amu, together with doubly ionised xenon species at approximately half the nominal mass values. Although the absolute signal intensity varies, being highest in Test 1 due to the larger injected volume, the relative isotopic distributions remain consistent. This confirms complete mixing of the injected gases within the cover gas and demonstrates the robustness of the QMS system for resolving trace noble gas concentrations under all investigated conditions.

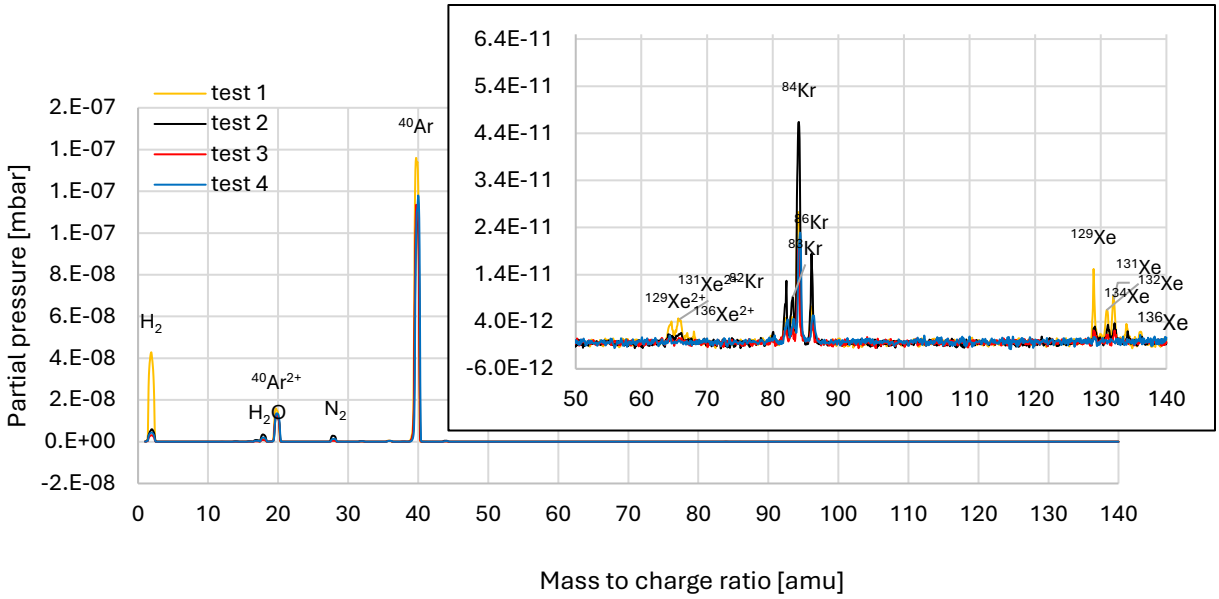


Fig. 9 QMS spectra recorder at plateau for all 4 tests

The main results obtained from the four noble gas injection tests are summarised in Table 3, which compares the injection conditions, detection delays, and the time required to reach steady-state plateau concentrations.

These results show that detection behaviour is strongly influenced by both injection mode and carrier gas flow. The observed detection times are far shorter than those expected for molecular diffusion over comparable distances, which would require several hours. This clearly indicates that noble gas migration in the gas phase is dominated by convective transport. The calculated Péclet numbers confirm that convection is the governing mechanism, driven by a combination of injection-induced momentum, buoyancy effects associated with thermal stratification, and forced circulation in the recirculation loop.

Table 3 Summary of noble gas injection conditions, detection times, and measurement durations for Tests 1–4

Test	Injection type	Gas injected	First detection (Kr)	First detection (Xe)	Time to plateau
Test 1	Impulse (sequential)	10 mL Kr + 70 mL Xe	49 min	1 h 46 min	~2h 7 min
Test 2	Impulse (binary mixture)	5 mL Kr + 5 mL Xe	12 min	14 min	~34 min
Test 3	Impulse + Ar flow	5 mL Kr + 5 mL Xe	3.5 min	12 min	~37 min
Test 4	Continuous injection	10 mL Kr	7 min	—	~63 min

A quantitative interpretation of the results was performed using characteristic transport time scales. Apparent transport velocities were derived from experimental detection delays, showing values on the order of 10^{-3} to 10^{-2} m s^{-1}. These values increase substantially under forced flow conditions, highlighting the role of gas circulation in accelerating transport processes.

The implications for reactor conditions were analysed by considering the full transport pathway of noble gases in LFR systems. Because of their extremely low solubility in liquid lead [39], noble gases released from failed fuel are expected to form bubbles rapidly and rise towards the free surface under buoyancy forces. Estimated bubble rise times are on the order of seconds, which is significantly shorter

than the transport times observed in the cover gas. This establishes a clear hierarchy of transport processes: rapid bubble transport in the liquid metal, slower redistribution in the cover gas, and negligible contribution from molecular diffusion.

Consequently, the overall detection delay in reactor monitoring systems is primarily governed by processes occurring in the cover gas region rather than in the liquid metal. Thermal stratification, gas mixing, and recirculation dynamics therefore play a decisive role in determining detection times. This finding has direct implications for the design and optimisation of monitoring systems, indicating that improvements headspace circulation and sampling strategies may significantly enhance detection performance.

The experimental work presented in this chapter provides valuable data on noble gas transport under controlled conditions representative of LFR environments. The NOGATILL facility enables systematic investigation of gas migration mechanisms and offers a flexible platform for future studies involving molten lead. The results contribute to a more comprehensive understanding of noble gas behaviour and support the development of reliable fuel-failure detection systems based on cover gas monitoring.

Conclusions and contribution of Chapter 5

From the perspective of the thesis objectives, the work presented in this chapter directly fulfils objective O3, namely the design, construction, and operation of an experimental facility for investigating noble gas transport under conditions representative of lead-cooled fast reactors. This objective has been achieved through the development of the NOGATILL installation, which enabled controlled injection, transport, and detection of xenon and krypton in a thermally stratified environment. Beyond the realisation of the facility itself, the experimental campaign provided quantitative insights into transport mechanisms, detection delays, and the influence of operational parameters such as carrier gas flow and injection mode. The results validate the capability of the facility to reproduce relevant physical processes and establish a robust basis for the interpretation of cover gas monitoring signals. In this way, Chapter 5 contributes both methodologically, through the creation of dedicated experimental infrastructure, and scientifically, through the elucidation of transport phenomena governing noble gas behaviour in LFR systems.

General Conclusions

This thesis has provided a systematic and integrated investigation of the behaviour, quantification, and transport of volatile radiotoxic elements in heavy liquid metal systems, with particular focus on Generation IV lead-cooled fast reactors and the ALFRED concept. The research was motivated by the need to improve both the physical understanding and the practical capability to monitor impurities under representative reactor conditions, where non-isothermal regimes and the coupling between thermodynamic equilibrium and transport processes govern radionuclide distribution.

A central outcome of the thesis is the demonstration that impurity behaviour in lead-cooled systems is primarily controlled by the partitioning between the molten lead coolant and the cover gas, governed by thermodynamic equilibrium, retention mechanisms within the liquid phase, and transport-driven release processes. Under typical operating conditions relevant to LFRs, most volatile radiotoxic elements remain strongly retained in the liquid metal, with only a limited fraction transferred to the gas phase. This finding has direct implications for source-term assessment, indicating that the effective release of radionuclides is significantly lower than would be expected in systems where volatility dominates.

The research further demonstrates that reliable prediction of radionuclide behaviour cannot be achieved through thermodynamic modelling alone. Instead, accurate source-term assessment requires an integrated framework combining: (i) validated thermodynamic data governing phase partitioning; (ii) analytical capability for trace-level quantification in complex lead matrices; and (iii) an understanding of transport processes controlling the migration of species from the liquid phase to the cover gas. The thesis establishes this integrated approach as a necessary condition for physically consistent interpretation of impurity behaviour in LFR systems.

Within this framework, the experimental determination of the temperature dependence of the Henry's law volatility constant for tellurium represents a major original contribution. The results provide, for the first time, experimentally validated data over a temperature range relevant to LFR operation, thereby reducing uncertainties associated with liquid–gas partitioning. The observed behaviour confirms that tellurium is strongly retained in lead-based systems and exhibits characteristics consistent with ideal dilute solution behaviour at higher temperatures. Given its chemical analogy with polonium, these findings also contribute to improving the representation of one of the most radiologically significant elements in heavy liquid metal systems.

The re-evaluation of the ALFRED source term, incorporating updated thermodynamic data and an extended set of volatile elements, has resulted in a more comprehensive and physically consistent description of impurity behaviour. The analysis identifies mercury and cadmium as the dominant contributors to the gaseous inventory under normal operating conditions, while fission products, particularly noble gases, become dominant under accident scenarios. At the same time, the results confirm the strong retention capability of molten lead, with more than 99.995% of radionuclides remaining in the liquid phase. This refined assessment highlights the sensitivity of source-term predictions to both thermodynamic parameters and operational conditions, reinforcing the need for validated input data.

Complementing the thermodynamic analysis, the thesis establishes a robust analytical methodology for the determination of trace impurities in lead. The developed approach, based on selective matrix separation using Sr-Spec extraction chromatography coupled with ICP-MS, effectively overcomes the limitations associated with strong matrix effects. The work demonstrates that direct ICP-MS analysis of lead-rich samples is unsuitable for ultra-trace determination due to severe signal suppression and spectral interferences, while the implemented matrix removal procedure enables accurate and reproducible quantification of cadmium and tellurium at trace levels. The methodology therefore provides a practical and validated basis for coolant chemistry monitoring.

A further key contribution of the thesis is the investigation of noble gas transport under conditions representative of LFR cover gas environments. The design, construction, and operation of the NOGATILL experimental facility enabled controlled studies of xenon and krypton migration in a thermally stratified system. The experimental results demonstrate that gas transport is governed predominantly by convective mechanisms, strongly influenced by thermal stratification and carrier gas flow, while molecular diffusion plays a negligible role. A significant outcome is the identification of the processes controlling detection delays in cover gas monitoring systems, which are shown to depend primarily on gas-phase hydrodynamics rather than on transport in the liquid metal. This finding has direct implications for the optimisation of monitoring system design and response time.

Taken together, the results demonstrate that impurity behaviour in lead-cooled fast reactors is governed by a coupled interplay of thermodynamic equilibrium, chemical interactions, and transport phenomena. The thesis shows that accurate interpretation of cover gas measurements and reliable source-term prediction require the integration of these processes into a unified framework. In this respect, the work

moves beyond isolated analyses of volatility or transport and establishes a coherent methodology linking equilibrium partitioning, measurable concentrations, and system-specific dynamics.

From the perspective of original contributions, the thesis can be summarised as follows:

- experimental determination of the Henry's law volatility constant for tellurium in lead-based systems over a reactor-relevant temperature range;
- re-evaluation of the ALFRED source term using updated thermodynamic data and an extended inventory of volatile radionuclides;
- development and validation of an analytical methodology for trace impurity quantification in lead using extraction chromatography coupled with ICP-MS;
- design, construction, and experimental validation of the NOGATILL facility for investigating noble gas transport in heavy liquid metal systems;
- identification and quantification of transport-controlled detection delays in cover gas monitoring systems, demonstrating the dominant role of convective processes.

The original contributions of this thesis are directly reflected in the scientific publications associated with each research objective, demonstrating both the coherence of the research programme and its dissemination within the scientific community. The re-evaluation of the ALFRED source term and the thermodynamic analysis of volatile radionuclides (Objective O1) are presented in the work

- **Ivan, A**., Tarantino, M., Abrudeanu, M., Diaconu, D., Gugiu, D. (2025). *Assessment of volatile radionuclide release in the ALFRED lead-cooled fast reactor.* **Journal of Nuclear Engineering**, 6(3), 36. **https://doi.org/10.3390/jne6030036**

Complementing this, the experimental investigation of tellurium volatilisation and the determination of its thermodynamic behaviour in liquid lead–bismuth eutectic constitute a major original contribution of the thesis and are reported in:

- **Ivan, A**., Zobnin, V., Eichler, R., Vögele, A., Herrmann, D., Dressler, R., Neuhausen, J. *Evaporation of tellurium from liquid lead–bismuth eutectic studied by the transpiration method – accepted for publication in Journal of Radioanalytical and Nuclear Chemistry on march 2026*

The development and validation of the analytical methodology for trace impurity quantification in lead (Objective O2), based on matrix separation coupled with ICP-MS, are detailed in Ivan et al. (2025), where the methodological challenges and solutions associated with ultra-trace analysis in heavy liquid metal systems are systematically addressed:

- **Ivan, A**., Abrudeanu, M., Tarantino, M., Gugiu, D., Diaconu, D., Mirita, D. (2025). *Trace-level impurity quantification in lead-cooled fast reactors using ICP-MS: methodology and challenges.* **Reviews in Analytical Chemistry,** 44(1), 20250088. **https://doi.org/10.1515/revac-2025-0088**

The third objective (O3), concerning the investigation of noble gas transport, is supported by the design and experimental application of the NOGATILL facility, as documented in a paper that describes the experimental infrastructure and its capabilities for studying gas transport in liquid lead systems:

- **Ivan, A**., Hororoi, M., Arva, M., Mincu, M., Corbescu, B., Gugiu, D., Vîlcu, A. (2025). Experimental facility for noble gas transport in liquid lead. *U.P.B. Scientific Bulletin, Series B, Chemistry and Materials Science*, *87*(1), 121–133. Available online: https://www.scientificbulletin.upb.ro/static/pdfs/fullf57_999284.pdf

In addition, the experimental results on noble gas transport in argon cover gas conditions have been submitted for publication and accepted for publication in the *Romanian Journal of Physics*.

- **Ivan, A**., Abrudeanu, M, Arva, M., Enache D., Călin S., Mincu, M., Hororoi, M. (2026) *Noble gas transport in argon cover gas conditions for ALFRED lead cooled fast reactor* – accepted for publication in **Romanian Journal of Physics**

Collectively, these publications substantiate the originality of the research, illustrate the direct correspondence between the thesis objectives and the obtained results, and confirm the scientific contribution of the work to the field of impurity behaviour and monitoring in lead-cooled fast reactor systems.

In conclusion, this thesis advances both the fundamental understanding and the practical capability to assess and monitor impurity behaviour in Generation IV lead-cooled fast reactors. By establishing an integrated approach combining thermodynamics, analytical chemistry, and transport phenomena, the work contributes to the development of more realistic safety assessments and supports the technological maturity of LFR systems.

Published papers

Web Of Science indexed papers

[1] **Ivan, A.**, Abrudeanu, M, Arva, M., Enache D., Călin S., Mincu, M., Hororoi, M., *Noble gas transport in argon cover gas conditions for ALFRED lead cooled fast reactor*, accepted for publication in Romanian Journal of Physics, **Q2, IF=1.9, 2026** **https://rjp.nipne.ro/accpaps/7684185F848FBC39E9757F5D795CE865B995FE51.pdf**

[2] **Ivan, A.**, Zobnin, V., Eichler, R., Vögele, A., Herrmann, D., Dressler, R., Neuhausen, J. (2026). *Evaporation of tellurium from liquid lead–bismuth eutectic studied by the transpiration method*, Springer – Journal of Radioanalytical and Nuclear Chemistry, **Q3, IF: 1.6, 2026**, **https://doi.org/10.1007/s10967-026-10858-4**

[3] **Ivan, A**., Tarantino, M., Abrudeanu, M., Diaconu, D., Gugiu, D. (2025). *Assessment of volatile radionuclide release in the ALFRED lead-cooled fast reactor.* **Journal of Nuclear Engineering**, 6(3), 36. **https://doi.org/10.3390/jne6030036 Q3 – JIF: 1.2, 2025**

[4] **Ivan, A**., Abrudeanu, M., Tarantino, M., Gugiu, D., Diaconu, D., Mirita, D. (2025). *Trace-level impurity quantification in lead-cooled fast reactors using ICP-MS: methodology and challenges.* **Reviews in Analytical Chemistry,** 44(1), 20250088. **https://doi.org/10.1515/revac-2025-0088 Q2 – JIF: 3.8, 2025**

[5] **Ivan, A**., Hororoi, M., Arva, M., Mincu, M., Corbescu, B., Gugiu, D., Vîlcu, A. (2025). Experimental facility for noble gas transport in liquid lead. *U.P.B. Scientific Bulletin, Series B, Chemistry and Materials Science*, *87*(1), 121–133. Available online: https://www.scientificbulletin.upb.ro/static/pdfs/fullf57_999284.pdf **Q4 – JIF: 0.3, 2025**

[6] Zobnin, V, **Ivan, A.**, Eichler, R., Vögele, A., Herrmann, D., Talip, Z., Neuhausen, J., *"Speciation of Tellurium During Volatilization from Lead–Bismuth Eutectic and Its Chemical Transport Properties,"* The Journal of Physical Chemistry C, **Q3, IF: 3.4. 2026 https://doi.org/10.1021/acs.jpcc.6c04168.**

[7] Zivadinovic, I., Neuhausen, J., **Ivan, A**., Dressler, R., Steinegger, P. (2024). *The influence of impurities on the evaporation behaviour of polonium from liquid Pb–Bi eutectic at high temperatures.* **Journal of**

Radioanalytical and Nuclear Chemistry. https://doi.org/10.1007/s10967-024-09823-w Q3 – JIF: 1.6, 2024

Conference contributions

[1] **Ivan, A**., Gugiu, D., Hororoi, M., Mincu, M., Corbescu, B., Vîlcu, A. (2023). Review of experimental studies on the behaviour of volatile elements from lead and LBE. Proceedings of the 14th Biennial International Conference on Sustainable Development through Nuclear Research and Education, Mioveni, Romania.

[2] **Ivan, A.,** Abrudeanu, M., Gugiu, D., Diaconu, D., Tarantino, M., Grasso, G. (2022). LFR technology – pillar for sustainable energy. Proceedings of the International Conference Zilele ASTR, Petroșani, Romania.

[3] **Ivan, A**., Gugiu, D. (2021). Polonium evaporation in LFR and an experimental device for testing absorbent materials. Proceedings of the 13th International Conference on Sustainable Development through Nuclear Research and Education, Mioveni, Romania.

[4] M. Nitoi, D. Gugiu, **A. Ivan**, M. Apostol, M. Constantin - RATEN ICN Contributions to ANSELMUS Project - The 15th Biennial International Conference on Sustainable Development through Nuclear Research and Education, Book of abstracts, 29-31 May, 2024, Mioveni, Romania

Other scientific contributions (reports and institutional publications)

[1] **Ivan, A**., Neuhausen, J., Zobnin, V., Vögele, A. (2022). Annual Report of the Laboratory of Radiochemistry / Evaporation of Tellurium from liquid Lead-Bismuth Eutectic using the transpiration method (LRC Annual Report, pp. 56–57). Paul Scherrer Institute. **https://www.psi.ch/en/lrc/annual-reports**

[2] Zobnin, V., **Ivan, A**. M., Neuhausen, J., Vögele, A., Eichler, R. (2022). **Annual Report of the Laboratory of Radiochemistry**/Evaporation of tellurium from liquid lead-bismuth eutectic studied using the thermosublimatography method (pp. 50–51). Paul Scherrer Institute. **https://www.psi.ch/en/lrc/annual-reports**

[3] M. Witschi, J. Neuhausen, I. Zivadinovic, **A. Ivan**, A. Vogele, V. Zobnin, R. Eichler, "A thermosublimatography study for volatilization and deposition of refractory metals and their compounds", **Annual Report 2022, Laboratory of Radiochemistry**, pag. 52-54, PSI Villigen, Switzerland **https://www.psi.ch/en/lrc/annual-reports**

[4] Liu, L., Zivadinovic, I., Herrmann, D. P., Vögele, **A., Ivan**, A., Neuhausen, J. (2023). Annual Report of the Laboratory of Radiochemistry / Evaporation behavior of cesium and iodine from lead-bismuth eutectic revealed by thermosublimatography (pp. 54–55). **https://www.psi.ch/en/lrc/annual-reports**

Scientific activity and research involvement

Participation in national and international research projects

[1] Euratom Research and Training Programme (EURATOM) Project: *ANSELMUS* – Grant Agreement No. 101061185 *Https://www.anselmus.eu/en*. European Union. Advanced Nuclear Safety and Engineering Modelling for Licensing Support. Retrieved 17 February 2026, from https://www.anselmus.eu/en

- Work Package WP3: Validation of safety systems
- Main objective (Task 3.2): Detection of fuel cladding defects
- Sub-task 3.2.2: Investigation of noble gas transport through a molten lead column.

[2] 4ALFRED Project *Research activities and experimental infrastructure for demonstration of lead-cooled fast reactor technology* Funded by PoCIDIF Programme (2021–2027): https://mfe.gov.ro/proiecte-strategice-de-180-de-milioane-de-euro-pentru-cercetare-in-energie-nucleara-avansata-si-inteligenta-artificiala/

Responsible for the development and implementation of the Meltin'Pot experimental facilities, dedicated to the study of severe accident scenarios in lead-cooled fast reactors.

[3] HORIZON EURATOM Project PASCAL - Proof of Augmented Safety Conditions in Advanced Liquid-metal-cooled systems (1 sept 2022 – 28 februarie 2023)

International training and fellowships

[4] International Atomic Energy Agency (IAEA) Fellowship Training program in nuclear power reactors (FSROM9038, 2105664) - 1 September 2022 – 28 February 2023
- Research internship at Paul Scherrer Institute (PSI), Villigen, Switzerland
- Focus: release behaviour of radioactive elements from molten heavy metals

[5] PATRICIA Heavy Metal Summer School, organized by SCK CEN Academy for Nuclear Science and Technology, Mol, Belgium, 4 – 8 Octobre 2021