



Original Article

Xenon in molten salt reactors: The effects of solubility, circulating particulate, ionization, and the sensitivity of the circulating void fraction

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ABSTRACT

Xenon behaves differently in molten salt reactors (MSRs) compared to solid fuel reactors. This behavior needs exploring due to the large reactivity effect of the ^{135}Xe isotope, given the current interest in MSR power plant development for commercial deployment. This paper focuses on select topics in xenon transport, reviews relevant past works, and proposes specific research questions to advance the state of the art in each of the focus areas. Specifically, the paper discusses the issue of xenon solubility in MSRs, the behavior of particulates circulating in MSR fuel salt and its influence on the xenon transport, the possibility of ionization of xenon atoms which changes its effective size and thus affects its mass transport, and finally the issue of circulating void fraction and how it is measured. This work presents specific recommendations for MSR designers to research the limits of Henry's law validity, circulating particulate scrubbers, validity of mass transport coefficients in high radiation fields, and the effects of pump speed on circulating void fraction.

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1. Introduction

Molten salt reactors (MSRs) use a molten alkali-halide fuel salt as both a working fluid and a fuel matrix.¹ Actinium fluorides, dissolved in the fuel salt, circulate between a graphite moderating region and a heat exchanger. Whilst the fuel salt is in the moderating region, neutrons become sufficiently thermalized such that an ongoing nuclear chain reaction is sustained, generating heat. Upon leaving the moderating region, the fuel salt flows into the heat exchanger, where the heat is transferred to a secondary side. Finally, the fuel salt travels through a fuel pump which imparts inertia to the fuel salt and maintains salt circulation and a particular mass flow rate. A review of MSRs, including historical reactors and the involvement in Generation-IV, is given by Serp et al. [1].

The fission product, ^{135}Xe ($t_{1/2} = 9.10$ h),² is of considerable

interest to reactor physics considerations, given its microscopic thermal neutron absorption cross section, which is often stated as 2.6 Mb. ^{135}Xe is produced in fission, along with the ^{135}Xe progenitors, ^{135}Te ($t_{1/2} = 19$ s), and ^{135}I ($t_{1/2} = 6.57$ h), which successively decay, through β^- decay, into ^{135}Xe . Note, early ^{135}Xe models, such as that which is reported in ORNL-TM-1070 [3] (published in 1965), did not include ^{135}Te behavior. This may be because, as reported by Kathawa, Fry, and Thoennessen [4], the half-life of ^{135}Te was not “observed” until 1969, although, there were some estimates before then. Furthermore, we note that there is, in fact, a non-trivial yield of ^{135}Sb from fission, which transmutes, eventually, into ^{135}Xe , and this ^{135}Sb has, in prior analyses, been omitted.

There are phenomenological differences in ^{135}Xe behavior in a fluid fueled reactor, such as an MSR, compared to a solid fueled reactor, such as a pressurized water reactor. Whereas in a solid fueled reactor the solid fuel matrix acts to immobilize the ^{135}Xe , the ^{135}Xe is free to migrate in an MSR. There exists a porous gas space within the moderator, and there are also bubbles (also called circulating voids in the literature) circulating with the fuel salt, and ^{135}Xe is free to migrate to these gaseous spaces. The existing theory of MSR xenon behavior, as presented in the annex of ORNL-4541 [5], states that xenon behavior, in an MSR at steady state, will obey Equation (1).

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¹ This paper focuses on graphite moderated systems with fluorine as the halide, due to vast past experience and current popularity of this choice.

² Unless otherwise stated, half-life and cross-section data is obtained from the chart of nuclides prepared by Baum, Knox, and Miller [2].

$$\{\text{Generation Rate}\} = \{\text{Burnup Rate in Salt}\} + \{\text{Migration Rate to Graphite}\} + \{\text{Migration Rate to Bubbles}\}, \quad (1a)$$

$$\{\text{Graphite Migration}\} = \{\text{Decay Rate in Graphite}\} + \{\text{Burnup in Graphite}\}, \quad (1b)$$

$$\{\text{Bubble Migration}\} = \{\text{Decay Rate in Bubbles}\} + \{\text{Burnup in Bubbles}\} + \{\text{Stripping Rate in Bubbles}\}. \quad (1c)$$

The major numerical work in this field began with the 1961 report ORNL-CF-61-5-62 [6] by Miller, which investigated the effects of the mass diffusion coefficient and xenon stripper efficiency on the xenon poison fraction. Miller's model used a first order rate equation to model the xenon stripper and a slab diffusion equation to model the migration of ^{135}Xe from the fuel salt into the graphite. The next major model was the 1969 report ORNL-4069 [7] by Kedl and Houtzeel. In this model, diffusion into the graphite stringers was changed from a slab diffusion model to a cylindrical diffusion model. Furthermore, Kedl and Houtzeel's model was the first one to include migration into bubbles and subdivide the reactor into regions based on neutron flux. In 1971, a model reported in ORNL-TM-3464 [8] by Engel and Steffy was formulated by lumped volume methods and was the first model to investigate transient behavior. The thread of transient work was later continued by Shimazu [9], who presented a transient model that was substantially simpler than the ORNL-TM-3464 xenon model. Shimazu's 1977 work would be later expanded by Suzuki and Shimazu in 2004 to include a balance of plant model [10].

In regards to experimental investigations, the two major reports on this subject are ORNL-4069 [7] and ORNL-TM-3464 [8]. Both report on experimental and operational data obtained from the Molten Salt Reactor Experiment (MSRE). The data in ORNL-4069 highlight the *Krypton Experiment*, an experiment performed in the pre-operational phase of the MSRE operation that aimed to measure mass transfer coefficients through measurements of radioactive krypton off gas. Actual xenon transient and steady state xenon load data was reported in ORNL-TM-3464.

To the best of our knowledge, no models of MSR xenon behavior that can be reasonably said to be validated exist. Although, the prior major modeling efforts outlined in ORNL-4069 [7] and ORNL-TM-3464 [8] did have some limited success in fitting their model to particular scenarios, we believe it is reasonable to assert the general case is as of yet unresolved. Indeed, because of this lack of success, we believe it reasonable to consider there may be phenomenological blind spots in the current understanding of MSR xenon theory. Therefore, this paper attempts to investigate, review, and explore some of the phenomenology relevant to MSR xenon theory and plot a path forward for future research efforts.

This paper builds on our 2019 review article [11] and attempts to clarify and expand on some of the concepts we laid out in regards ^{135}Xe behavior in an MSR in the context of xenon solubility, circulating particulate, and the size and ionization of ^{135}Xe in an MSR. The paper discusses potential issues and outlines potentially fruitful research questions relevant for MSR design.

2. Solubility of xenon

Prior xenon analyses have assumed the xenon in the fuel salt is sufficiently dilute so that Henry's law,

$$H = \frac{C_i}{P_i}, \quad (2)$$

is applicable, and, as such, extensive use of this constant is made in

the mass transfer relations employed in MSR xenon analyses. Henry's law, however, assumes the solution acts as a *ideal dilute solution*, which technically is only true as the concentration of the xenon solute approaches zero. No experimental evidence was found that indicated any sort of upper bound for xenon concentration, past which Henry's law would not be applicable, nor were there any measurements of ^{135}Xe concentration in the fuel salt. Westh and Haynes [12], however, did experimentally investigate the extent of the Henry region in some non-molten salt substances and concluded there is a lower limit, in terms of mole-fraction, of Henry-like behavior on the order of 1×10^{-5} for a water solute and hexane solvent and 1×10^{-4} for hexane solutes and solvents.³ That being said, these values are likely far too high for ^{135}Xe in molten salts, considering the solubility of xenon in LiF-BeF₂ (64-36 mol%) is on the order of 4.2×10^{-8} to 3.0×10^{-7} mol% [13]. Furthermore, molten salts are different chemical systems than water/hexane systems, and, as such, are likely to be considerably different.

Apart from xenon concentration itself, there is the potential for other gases dissolved in the fuel salt to influence the xenon behavior. In nucleation theory if a cluster of atoms, with a phase different than its parent phase, exceeds a *critical radius*,

$$r_c = \frac{2\gamma_{12}}{\Delta G_r}, \quad (3)$$

a discrete phase inclusion will form [14], p. 8–23] Presumably, this cluster of atoms need not necessarily be limited to one isotopic or chemical species, and, as such, a xenon atom will nucleate if it joins a cluster of existing gas atoms with equal to or greater than the critical radius. Note, the critical radius is a function of the Gibbs energy, ΔG_r , which is a function of temperature, pressure, and fuel salt composition. It therefore follows that the critical radius will change as a function of fuel salt composition, which changes as a function of burn-up.

This brings us into considerations of xenon solubility in the fuel salt. Although there have been several studies of xenon solubility in fuel salt (see Ref. [13] for example), the following research questions are, to the best of our knowledge, unanswered:

- How does the solubility limit, as measured in-lab, relate to the solubility limit, in-situ?
- What happens the ^{135}Xe produced after the fuel salt has reached its solubility limit? A priori, we expect it to form discrete gaseous phase inclusions, but no direct observational evidence of this was found.
- If discrete gaseous phase inclusions are formed, what are their fate? Do they join the existing circulating void phase? Are there mass transfer processes that apply specifically to these newly formed phase inclusions that do not affect the existing circulating void phase?

³ C and N hexane.

- If gaseous phase inclusions are formed, what are they comprised of? Is it only xenon, which has amalgamated, or a collection of other substances that is dependent on the fuel composition? For the purposes of modeling efforts, are these new phase inclusions functionally the same as the existing circulating void phase?
- Does the phenomenology of newly formed phase inclusions effectively reduce to the phenomenology of the circulating void fraction? Can xenon behavior, in a reactor operating past its solubility limit, be predicted by a validated bubble model alone or is a more in-depth modeling effort necessary?

Given that there exists a critical radius, we propose there also exists a corresponding *bubble-out concentration*, C_{BO} , of dissolved gas, beyond which all newly generated ^{135}Xe will form discrete phase inclusions. Thus, we propose, the concentration of dissolved gases can be delineated into three distinct regimes:

1. THE IDEAL DILUTE SOLUTION REGION where the behavior of ^{135}Xe is effectively predicted by Henry's law.
2. THE NON-HENRY-LIKE REGION, in which the behavior of ^{135}Xe deviates, by some predetermined magnitude, from Henry's law.
3. THE BUBBLE-OUT REGION Where all new ^{135}Xe produced in the reactor immediately forms discrete phase inclusions.

The precise concentrations of ^{135}Xe , and other gases, which delineate these regions, have yet to be established for any salt. Ideally, there would be a method to correlate a particular fuel salt's Henry's constant, burn-up, and solubility to the three aforementioned regions.

3. Circulating particulate

Prior work on MSR xenon modeling has neglected any effects of circulating particulate on ^{135}Xe behavior. That being said, there are some considerations that can be made here.

First, is the effects of a mobile solid phase on ^{135}Te behavior. ORNL-4865 [15], which is a report on fission product behavior in the MSRE, states, in the context of the MSRE, "*Nobel metal fission products [such as Te] do not form fluorides which are stable in salt at the redox potential of the fuel salt*" [ibid., p. 27]. Furthermore, "*recent observations ... suggest that a soluble, reactive form of [the] telluride ion can exist in molten salt at a presently undefined redox potential*" [ibid., p. 29], and "*it is plausible tellurium is largely associated by undissolved solids by chemisorption or reaction*" [ibid., p. 29]. Contrary to this, the ORNL-4069 [7] and ORNL-TM-3464 [8] xenon models both assume ^{135}Te remains in solution as an ion. Note, ORNL-4865 was published in 1975, after both ORNL-4069 and ORNL-TM-3464, which were published in 1969 and 1971 respectively, so the authors of ORNL-4069 and ORNL-TM-3464 would likely not have been aware of the observations from ORNL-4865. With this being said, it is foreseeable that, in terms of ^{135}Xe behavior, the behavior of ^{135}Te , and its interplay with particulate, may be negligible; however, no evidence was found that indicates this is the case.

Additionally, there is the potential for the poison isotopes to interact with circulating corrosion product particulate. ORNL-TM-3464 reported "*Holdup in corrosion-product scale was shown to be significant in an aqueous system due to iodine adsorption.*" [8, p. 5] Prior modeling efforts had ignored any sort of behavior related to holdup of poison isotopes onto corrosion products. ORNL-4865

reported 20–90% of tellurium was associated with metal in the MSRE. [15, p.139] The xenon model [16] for the HRT⁴ included phenomenology related to ^{135}I diffusion onto corroded wall surfaces; however, no information was found that indicated that any MSR xenon model had included ^{135}I adsorption phenomenology.

There also exists the potential for surface active particles (surfactants) to affect circulating void behavior, which*, would, in turn, effect ^{135}Xe behavior, since ^{135}Xe migrates to the circulating voids. In the classical two-film theory, the phase boundary resistance is assumed to be negligible [17]. However, we propose, when surfactants are present they tend to accumulate on the phase boundaries. This will in turn create an added resistance that must be taken into account when developing the mass transport across the surface. In ORNL-TM-3884 [18, p. 27], floating scums, which are likely formed, in-part, by the coagulation and de-entrainment of circulating particulate, were hypothesized to possess many properties of a surfactant. ORNL-TM-4122 [19], p. 12] reported a correlation by Hinze, which is a function of surface tension, that predicts the maximum bubble diameter in turbulent flow,

$$d_{max} = K_1 \left(\frac{\gamma_{12g}}{\rho_c} \right)^{3/5} \left(\frac{\rho_c}{\epsilon_{sp}g} \right)^{2/5} \quad (4)$$

Given that surfactants lower the surface tension of a substance, and the maximal bubble size, in turbulent flow, is determined by the surface tension, it follows that the addition of circulating particulate, which is hypothesized to act as a surfactant, to the fuel-salt, would affect the maximal bubble size, and hence, the ^{135}Xe behavior. Presumably, the addition of a surfactant would lead to a lower surface tension, which would lead to a lower maximal bubble diameter, which would lead to more bubbles required to encompass the same void fraction, which would lead to more surface area for mass transfer, which would lead to more hold-up of ^{135}Xe in the circulating voids. Additionally, since the rate of mass transfer induced by bubble stripping is, likely, not the same as the rate of mass transfer induced by fuel salt stripping, it follows that the steady-state xenon poison fraction in the reactor core will likewise change with the addition of surfactants. There is observational evidence for this in MSRE venturi jet tests, where smaller bubbles were generated when a surface active material was present. [18], p. 27] Furthermore, Vazirzadeh, Bouchard, and Chen reported fine particles affected both the interactions of bubbles as well as bubble weight and volume in a flotation column [20].

Variation in surface tension, induced by the addition of particulate, which acts as a surfactant, we claim, will also affect the bubble pressure. The Laplace pressure [21], p. 61],

$$p_b = p_l + \frac{2\gamma_{12}}{r_b}, \quad (5)$$

which describes pressure inside a bubble, is a function of surface tension. Therefore, as surface tension is decreased, by the addition of particulate which acts as a surfactant, the pressure inside the bubble is likewise decreased, and, correspondingly, the quantity of ^{135}Xe potentially stored within a single bubble will likewise decrease. This becomes increasingly important with bubbles with small bubble radii, r_b , such as those, which presumably, would be generated by the amalgamation of gaseous fission products, such as ^{135}Xe .

Finally, we note the possibility for circulating particulate to deposit and coat the surface of graphite stringers, and thereby, change the amount of surface area available for mass transfer to the graphite stringers. Migration of noble fission products to the graphite stringers was studied in ORNL-TM-3884 [18]; however, no information was found related to how the accessibility of the

⁴ The Homogeneous Reactor Test, a 5.0 MW_{th} aqueous homogeneous reactor operated at Oak Ridge National Laboratory 1957–1961.

graphite pore-space would be affected, or the change in effective mass transfer area due to particulate deposition. Post-irradiation examination of MSRE graphite was reported in ORNL-TM-4174 [22], however, no information was found on the surface evolution of MSRE graphite stringers. We therefore propose the following research questions:

- Can significant quantities of particulate collect on the surface of MSR graphite?
- If so, what effect does this have on ^{135}Xe mass transfer into the graphite?
- What steps can be taken to mitigate the accumulation of particulate on graphite stringer surfaces such that the ^{135}Xe remains constant over the lifetime of the reactor?
- If a surface layer of particulate has formed, are there any active solutions to remove the collected particulate on graphite stringer surfaces?

4. Size of ^{135}Xe and ionization

The sum of all xenon's ionization energies is ≈ 0.2 MeV [23]. Fission products are *born* with a kinetic energy, split between the products, in excess of 160 MeV [24]. Additionally, each fission generates 6 MeV of prompt γ -radiation energy [25]. Since the energy generated in fission is much greater than the ionization energy of xenon, we therefore propose that much of the ^{135}Xe found in an MSR, with a sufficient radiation field, will exist in an ionized state. Furthermore, if we accept an ^{135}Xe atom is *born* ionized, due to the kinetic energy of the fission process, we also propose that, so long as there is a sufficient radiation field, such as the γ -radiation from fission, the ^{135}Xe will remain ionized.

We set up our discussion on the effect of ionization with the following consideration: the atomic radius of ^{135}Xe is related to its mass transfer behavior through the mass diffusion coefficient. Since xenon behavior is predicted, in existing models, by the mass transfer coefficient, k_m , which is given through the Sherwood Number, Sh , and the Sherwood number is a function of the mass diffusion coefficient, D , and the mass diffusion coefficient can be predicted through the Einstein-Stokes equation [26], p. 126],

$$D = \frac{k_b T}{6\pi\mu r_{Xe}}, \quad (6)$$

and the Einstein-Stokes relationship is a function of the atomic radius of xenon, it follows that the xenon behavior is dependent on the size of the xenon atom. With that being said, given that the Einstein-Stokes equation assumes in its derivation that the diffusing particle is in a continuous medium, and the constituent molecules of molten salts have a comparable radius to xenon, it is questionable if the Einstein-Stokes equation is applicable to ions diffusing in molten salts. This, however, was investigated by Brockis and Reddy who investigated a number of tracers in molten salts, and compared experimental data for mass diffusion coefficients with mass diffusion coefficients produced by the Einstein-Stokes equation with crystal radii used for the atomic radius parameter. [27], p. 655,] Brockis and Reddy state,

"The essential applicability of this phenomenological equation is clearly shown by using the numerical comparison of $D\mu/T = k_b/6\pi$. The right-hand side is 0.7×10^9 for $r = 300$ pm, and the mean of the experimental values is 0.6×10^9 , which is not bad!"

The question What is the size of the xenon atom? is a question in itself; i.e. what is meant by the size of the xenon atom? This

Table 1
Atomic radii of xenon.

Type	Radius [Å]	Source
Covalent Radius	1.36	[30], p. 9–58]
van der Waal's Radius	2.16	[ibid.]
Lennard-Jones Collision Radius	2.02	[31], p. 24]
Grimes, Blander, Watson	2.18	[29]
Kinetic Theory	1.75	[32], p. 249]

sentiment is reflected in Pau, Berg, and McMillan's 1990 paper [28] on the application of Stoke's law to ions in aqueous solutions,

"One of the most difficult questions involved in the transition from a continuum medium to the case of real solvent molecules of size comparable to the atomic dimensions of the mobile ion is unit is the meaning to be attached to the particle radius".

Some atomic radii for xenon are listed in Table 1. It is unclear to us which would be most appropriate to use for the calculation of the mass diffusion coefficient. Blander, Grimes, Smith, and Watson report the radii of rare gas atoms in a solid would be a "lower limit" of a hole created by a gas atom in a molten salt [29].

Now, in consideration of the effect of the ionization, mentioned at the start of this section, the ionization of ^{135}Xe , Born states, in his book on atomic physics [32, p. 249],

"We see⁵ that the negative ions, which have an inert gas configuration with a smaller nuclear charge than the corresponding inert gas, are larger than the latter, the reason being of course that the electrons in these ions are more loosely bound so that their orbits have greater radii. A corresponding, mutatis mutandis, hold for positive ions also."

Given that ionization effects the atomic radius of an atom, and, as previously argued, ^{135}Xe produced in the reactor is in an ionized state, it follows that the radius of ^{135}Xe in an active nuclear reactor will be different than the ^{135}Xe in a non-radioactive experiment. Specifically, since

$$Sh \propto^{-1} D, \quad (7)$$

and,

$$D \propto^{-1} r_{Xe}, \quad (8)$$

and r_{Xe} is smaller in a radioactive environment than a non-radioactive environment, it follows that

$$Sh \propto r_{Xe} \Rightarrow k_m \propto r_{Xe}, \quad (9)$$

and k_m in a non-nuclear mock-up will be greater than that of a operating nuclear system.

5. Circulating void fractions

Given that, according to the analysis in ORNL-4069 [7], it is possible the majority of the ^{135}Xe to be found in the circulating voids, it follows that consistent ^{135}Xe behavior will likely depend on a consistent quantity of gas circulating with the fuel salt. Modeling and prediction is complicated by two factors: determining what the circulating void fraction is and keeping the circulating void fraction

⁵ In an attached tabulation of ionic radii.

consistent.

ORNL-TM-2318 [33] reports an attempt was made to determine the void fraction in the MSRE using pressure perturbations. These pressure perturbation experiments produced a “large spread” of results between 0.023% and 0.045%. Additionally, ORNL-TM-2315 [34] reports using neutron noise analysis to determine the void fraction in the MSRE. The neutron noise experiments concluded that the void fraction in the MSRE is “more nearly zero than the previously accepted value of 0.1%”. According to the ORNL-4069 xenon model, the xenon poison fraction contributed by the bubble ^{135}Xe content would vary by a factor of ≈ 5 between the minimum investigated value of $\approx 0.05\%$ and 0.1%.

Furthermore, as reported in ORNL-TM-3464 [8], the void fraction is not only dependent on the type of cover-gas used, but also on the rotational speed of the fuel pump. Indeed, a 100 RPM variation in fuel pump speed, in one case, lead to an increase in circulating void fraction in excess of 6.5 fold.

6. Conclusions

This paper has examined some aspects of MSR xenon behavior related to solubility, circulating particulate, the size and ionization of ^{135}Xe , and the circulating void fraction. A brief review of MSR xenon theory has been given. The interplay between solubility and xenon concentration has been discussed, and three regimes of xenon concentration have been proposed along with several research questions related to the solubility of xenon in the fuel salt. Furthermore, the potential effects of circulating particulate on xenon behavior have been described along with several related research questions. Additionally, the size of ^{135}Xe and the potential for ionization of ^{135}Xe to affect that size and diffusion properties has been explored. Finally, this paper has looked at the circulating void fraction and examined some potential barriers to proper modeling of it. There are certainly many uncertainties related to ^{135}Xe in MSRs, and this paper has attempted to examine some of them.

7. Recommended future work

The following recommendations are made to guide future work:

1. Efforts should be made to delineate the precise concentration of ^{135}Xe , and other gases, in molten salts which Henry's law is valid for. If reactors are not expected to operate within the Henry region, efforts should be made to formulate mass transfer laws which do not depend on Henry's constant.
2. If we accept that it is reasonable to presume that circulating particulate will affect ^{135}Xe behavior, efforts should be made to mitigate the quantity of circulating particulate in the fuel salt and control its evolution with respect to time. Then, ^{135}Xe behavior can be maintained at a constant, and the ^{135}Xe behavior at the beginning of the fuel cycle life will, more likely, be the same as the ^{135}Xe behavior at the end of the core life.
3. Experimentation should be performed to test the hypothesis that xenon mass transfer coefficients, in a sufficiently strong radiation field, will be less than mass transfer coefficients outside of a radiation field. If this hypothesis is found to be true, then mass transfer coefficients measured in a non-nuclear mock-up should be considered an upper limit to the actual mass transfer coefficients.
4. If there is indeed an operating region where minor variations in pump speed will lead to major variations in circulating void fractions, efforts should be made to avoid this operating region and carefully control pump speed such that the circulating void fraction remains constant.

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Nomenclature

ΔG_r	Change in Gibb's energy by the formation of a bubble
ε_{sp}	Specific energy dissipation
γ_{12}	Surface tension between phases 1 and 2, in this paper, the fuel-salt and a gaseous phase, such as the contents of a bubble
μ	Dynamic viscosity
ρ_c	Density of the continuous phase (the fuel salt); as opposed to the dispersed phase(s) (the circulating voids)
C_i	Concentration of a species
D	Mass diffusion coefficient
d_{max}	Maximum bubble diameter
g	Acceleration due to gravity
H	Henry's Constant
K_1	An experimentally determined constant
k_b	Boltzman's constant
k_m	Mass transfer coefficient
p_b	Bubble pressure
P_i	Partial pressure of a species
p_l	Liquid pressure
r_b	Bubble radius
r_c	Critical radius
r_{xe}	Radius of a xenon atom
Sh	Sherwood number
T	Temperature
$t_{1/2}$	Half-life

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.net.2019.11.026>.

References

- [1] J. Serp, M. Allibert, O. Beneš, S. Delpech, O. Feynberg, V. Ghetta, D. Heuer, D. Holcomb, V. Ignatiev, J. Kloosterman, L. Luzzi, E. Merle-Lucotte, J. Uhlir, R. Yoshioka, D. Zhimin, The molten salt reactor (MSR) in generation IV: overview and perspectives, *Prog. Nucl. Energy* 77 (2014) 308–319.
- [2] E. Baum, H. Knox, T. Miller, *Nuclides and Isotopes: Chart of the Nuclides*, 16 edition, Lockheed Martin, 2010.
- [3] S. Ball, T. Kerlin, ORNL-TM-1070: Stability Analysis of the Molten-Salt Reactor Experiment, Oak Ridge National Laboratory, 1965. Technical report.
- [4] J. Kathawa, C. Fry, M. Thoennessen, Discovery of palladium, antimony, tellurium, iodine, and xenon isotopes, *Atomic Data Nucl. Data Tables* 99 (1) (2013) 22–52. ISSN 0092-640X.
- [5] R. Robertson, ORNL-TM-4541: Conceptual Design Study of a Single-Fluid Molten-Salt Breeder Reactor, Oak Ridge National Laboratory, 1971. Technical report.
- [6] J. Miller, ORNL-CF-61-5-62: Xenon Poisoning in Molten Salt Reactors, Oak Ridge National Laboratory, 1961. Technical report.
- [7] R. Kedi, A. Houtzeel, ORNL-4069: Development of a Model for Computing Xe-135 Migration in the MSRE. Technical Report, Oak Ridge National Laboratory, 1967.
- [8] J. Engel, R. Steffy, ORNL-TM-3464: Xenon Behavior in the Molten Salt Reactor Experiment, Oak Ridge National Laboratory, 1971. Technical report.
- [9] Y. Shimazu, Transient xenon analysis in a molten salt breeder reactor, *J. Nucl. Sci. Technol.* 14 (11) (1977) 805–810.
- [10] K. Suzuki, Y. Shimazu, Transient xenon effect on plant control in MSRs-validation of simulation model, in: *Proceedings of ICAPP '04*, Pittsburgh, PA, USA, 2004.

- [11] T. Price, O. Chvala, R. Taylor, Molten salt reactor xenon analysis: review and decomposition, *J. Nucl. Eng. Radiat. Sci.* (2019). Accepted, awaiting publication.
- [12] P. Westh, C. Haynes, Y. Koga, How dilute is the Henry's law region? II, *J. Phys. Chem. B* 102 (25) (1998) 4982–4987.
- [13] G. Watson, R. Evans III, W. Grimes, N. Smith, Solubility of noble gases in molten fluorides. In *LiF-BeF₂*, *J. Chem. Eng. Data* 7 (2) (1962) 285–287.
- [14] J. Groza, J. Shackelford, *Materials Processing Handbook*, CRC Press, 2007.
- [15] E. Compere, S. Kirslis, E. Bohlmann, F. Blankenship, W. Grimes, ORNL-4865: Fission Product Behavior in the Molten Salt Reactor Experiment, Oak Ridge National Laboratory, 1975. Technical report.
- [16] W. Burch, ORNL-TM-228: Measurement of Xenon Poisoning in the HRT. Technical Report, Oak Ridge National Laboratory, 1962.
- [17] James R. Welty, Charles E. Wicks, Robert E. Wilson, *Fundamentals of Momentum, Heat and Mass Transfer*, John Wiley and Sons, Inc., New York, 1969.
- [18] R. Kedl, ORNL-TM-3884: the Migration of a Class of Fission Products (Noble Metals) in the Molten-Salt Reactor Experiment, Oak Ridge National Laboratory, 1972. Technical report.
- [19] C. Gabbard, ORNL-TM-4122: Development of a Venturi Type Bubble Generator for Use in the Molten Salt Reactor Xenon Removal System, Oak Ridge National Laboratory, 1972. Technical report.
- [20] A. Vazirizadeh, J. Bouchard, Y. Chen, Effect of particles on bubble size distribution and gas hold-up in column flotation, *Int. J. Miner. Process.* 157 (2016) 163–173.
- [21] L. Schramm, *Emulsions, Foams, and Suspensions: Fundamentals and Applications*, Wiley, 2006.
- [22] H. McCoy, B. McNabb, ORNL-TM-4174: Postirradiation Examination of Materials from the MSRE, Oak Ridge National Laboratory, 1972. Technical report.
- [23] A. Kramida, Yu Ralchenko, J. Reader, NIST ASD Team, NIST Atomic Spectra Database (ver. 5.6.1), [Online]. Available: National Institute of Standards and Technology, Gaithersburg, MD, 2018 [2018, November 13], <https://physics.nist.gov/asd>.
- [24] M. James, Energy released in fission, *J. Nucl. Energy* 23 (1969) 517–536.
- [25] S. Oberstedt, R. Billnert, A. Gatera, W. Geerts, P. Halipr, Prompt fission γ -ray spectra characteristics - a first summary, *Phys. Procedia* 64 (2015) 83–90.
- [26] E. Cussler, *Diffusion: Mass Transfer in Fluid Systems*, third ed., Cambridge University Press, 2007.
- [27] J. Bockris, A. Reddy, *Modern Electrochemistry*, vol. 1, Ionics. Kluwer Academic Publishers, 1998.
- [28] P. Pau, J. Berg, W. McMillan, Application of Stokes' law to ions in aqueous solution, *J. Phys. Chem.* 94 (6) (1990) 2671–2679.
- [29] M. Blander, W. Grimes, N. Smith, G. Watson, Solubility of noble gases in molten fluorides. II. In the *LiF-NaF-LF* Eutectic mixtures, *J. Phys. Chem.* 63 (7) (1959) 1164–1167.
- [30] W. Haynes (Ed.), *CRC Handbook of Chemistry and Physics*, 97th Edition, CRC Press, 2016.
- [31] R. Svehla, R-132: Estimated Viscosities and Thermal Conductivities of Gases at High Temperatures, NASA, 1962. Technical report.
- [32] M. Born, *Atomic Physics*, eighth ed., Dover Publications, 2013.
- [33] D. Robinson, J. Fry, ORNL-TM-2318: Determination of the Void Fraction in the MSRE Using Small Induced Pressure Perturbations, Oak Ridge National Laboratory, 1969. Technical report.
- [34] D. Fry, R. Kryter, R. Robinson, ORNL-TM-2315: Measurement of Helium Void Fraction in the MSRE Fuel Salt Using Neutron-Noise Analysis, Oak Ridge National Laboratory, 1968. Technical report.