KYOTO FUSIONEERING: MATERIALS COMPATIBILITY TESTING FACILITIES

R.M. HOLMES[1], P.J. BARRON[1], J. MCGRADY[1], K. MUKAI[1,2], C. BAUS[1,2]

[1]Kyoto Fusioneering Ltd, Chiyoda-ku, Tokyo, Japan
[2]Institute of Advanced Energy, Kyoto University, Uji, Kyoto, Japan

Email contact of corresponding author: r.holmes@kyotofusioneering.com

ABSTRACT

Kyoto Fusioneering Ltd (KF), a privately-funded fusion engineering company that spun out of Kyoto University in 2019, is developing technologies to support the rapid expansion of the fusion industry [1]. Specifically, KF is, among other plant relevant components, pursuing advanced breeder blanket concepts that operate at high temperatures to increase the energy conversion efficiency of the power cycle. Such an approach necessitates the use of unique material-coolant combinations. For example, structural materials including SiC composites and liquid metal or molten salt coolants are employed together in self-cooled systems, which can bring safety, cost and efficiency benefits. These advantages were the motivation behind developing KF's SCYLLA© breeder blanket concept, which utilises SiC composites as a structural material with a LiPb coolant [2]. KF is also investigating FLiBe and pure Li coolant options, since they confer different benefits compared with LiPb, especially concerning tritium breeding performance. However, uncertainties remain regarding coolant compatibility with SiC composites, particularly in fusion environments involving extremes of temperature, neutron flux and coolant velocity.

With this in mind, KF is developing various testing facilities to advance the readiness of the aforementioned coolant options for commercial deployment. KF is commissioning a FLiBe test loop with an inventory of 1 kg, which can operate at temperatures up to 650 ºC. A pure Li test loop, which can operate at 600 °C with an inventory of 3.7 kg is also under construction, and is scheduled to enter operation in early 2024. Finally, KF's flagship facility, the UNique Integrated Testing facilitY (UNITY), which is currently under construction in Japan, will incorporate a LiPb loop with an inventory of approximately 300 L, which will reach a maximum temperature of ~1000 ºC [3]. While SiC composites are envisaged for the SCYLLA© breeder blanket concept, other materials such as Mo are being investigated for components not exposed to a high neutron flux.

This paper outlines future plans for materials testing in the test loops detailed above based on an in-house literature survey.

INTRODUCTION

As a fusion reactor material, SiC composites have a very long history, comparable to that of reduced-activation ferritic martensitic (RAFM) steels [4]. Due to their low emissivity and high temperature properties, the application of SiC composites in fusion blankets was anticipated from the earliest days when fusion power plants were originally conceived, and has been used in many power plant concept designs. Since the main part of the energy extraction for utilisation takes place from the blanket, the higher the temperature of the blanket design, and in particular the medium into which the heat is extracted, the higher the efficiency of electricity generation. Furthermore, higher temperatures in the region of 850 ºC would open up process heat and hydrogen production applications for fusion power plants, in turn increasing the commercialisation and decarbonisation potential of the technology. Ceramic materials such as SiC composites generally have higher heat resistance, lower activation, shorter half-lives and smaller neutron absorption cross-sections than metal materials, as well as characteristics such as recovery from irradiation damage and a low tritium permeability, thus illustrating their great potential as ideal fusion power plant materials. These advantages were the motivation behind developing KF's SCYLLA© breeder blanket concept, which utilises SiC composites as a structural material with a LiPb coolant that simultaneously acts as a breeder, coolant and neutron multiplier [2].

In reality, however, the development of practical SiC composites for fusion applications has been reasonably slow. Fusion materials research and development has not been able to reach the level of development of industrial technologies such as mass production, welding and fabrication, as well as standards and quality control, which are essential for practical materials. Another crucial issue to resolve is the compatibility of SiC composites with coolants [5]. While there has been extensive research in oxygen, steam, and combustion environments, the effects of irradiation on these environments still needs to be studied. Due to their potential use in current light water nuclear reactors, behaviour of SiC composites in hydrothermal environments, including irradiation has a more comprehensive body of work. However, environments that are more likely to be used in generation IV nuclear reactors, like liquid metals or molten salt, have very few compatibility studies, and almost no irradiation work.

While SiC composites are considered as stable, inert materials for most applications, many environments present in various nuclear systems can be considered aggressive/incompatible with SiC composites. In oxygen environments, the formation of a protective SiO_2 layer is the main driving force behind SiC composites' resistance to high temperature conditions [5]. Therefore, reactions that either disrupt or remove the oxide render SiC composites vulnerable. When a silica layer cannot form, then the compatibility depends on the ability of the base SiC composites' atomic bonding and microstructure of the SiC composites to resist attack. For example, neutron irradiation can break the Si–C bonds on the surface and possibly engender dissolution of SiC composites, which could lead to it becoming unstable in coolant environments that would usually be considered benign. The grade of SiC composites also has a strong influence on their behaviour. As such, KF is developing two types of SiC composite that can be used in the SCYLLA© breeder blanket concept and heat exchanger components, since different areas of the power generation cycle require different material properties. For example, the heat exchanger SiC composites should be highly hermetic with favourable thermal conductivity, while the blanket SiC composites exposed to fusion neutrons will require a high level of radiation tolerance [1]. How they interact with the various coolant options however remains to be determined.

With the many uncertainties around SiC composite behaviour in mind, KF is developing multiple materials-coolant compatibility testing loops, focused on LiPb, FLiBe and pure Li coolants, since they allow higher temperature operation and thus can be utilised in the more efficient Brayton cycle. To support the experimental programme design for these facilities, literature surveys were carried out on key material-coolant combinations, which are outlined in the next section of this paper.

MATERIALS AND COOLANT COMPATIBILITY

There have been several studies on compatibility of SiC composites with LiPb for fusion related research, which are summarised in Table 1. Various types of SiC composites have been used across the studies, including CVD, CVI, PiP and NITE variants, all of which have been shown to react differently in the LiPb environment. CVD, CVI, PiP and NITE variants differ according to their processing method, and thus lead to SiC composites with various structures and properties, such as density, crystallinity, hermeticity, thermal conductivity, and chemical stability. Regarding the LiPb conditions reported, the temperature ranges from 400 to 1200 °C, and time from 100 to 5000 hours. Most studies have focused on static LiPb environments, while a few have investigated compatibility of SiC composites in flowing LiPb, with flow velocities up to ~0.5 ms^{-1}.

TABLE 1. KEY LITERATURE ON SiC-LiPb COMPATIBILITY

Reference Study	SiC Composite Material	Static/Flowing LiPb	Time	Temperature
Barbier (2002) [6]	CVI SiC: as-received and scratched surfaces	Static	3000 h	800 °C
Pint (2007) [7]	Monolithic CVD β-SiC	Static	5000 h	800 °C
			2000 h	1100 °C
			1000 h	1200 °C
Zhu (2009) [8]	PiP SiC with CVD SiC coating	Static	500 h	700 °C
Zhao (2010) [9]	PiP SiC with and without CVD β-SiC coating	Static (Fe, Cr and Ni impurities)	500 h	700 °C
Ling (2011) [10]	PiP SiC with and without CVD β-SiC coating	Static	200 h	800 °C
			1000 h	800 °C
Park (2011) [11]	NITE SiC with fibre coated with C	Flowing (0.1-0.37 ms^{-1})	1000 h	900 °C
Tosti (2013) [12]	CVI SiC	Static	100 h	400 °C
Pint (2013) [13]	CVD SiC	Static	1000 h	500 °C
			1000 h	600 °C
			1000 h	700 °C
Park (2018) [14]	CVD SiC and CVI SiC	Flowing (~0.1-0.5 ms^{-1})	1800 h	900 °C
			3000 h	700 °C
		Static	1000 h	900 °C
Pint (2021) [15]	CVD SiC	Flowing (~0.95 cms^{-1})	1000 h	600-700 °C
Romedenne (2023) [16]	CVD SiC	Flowing (~0.07 cms^{-1})	1000 h	550-650 °C

Generally, below 1000 °C the CVD-type SiC composites have demonstrated to be the most stable, while at 1100 and 1200 °C an increase in the Si concentration in the LiPb was measured, which indicates some corrosion occurred [7]. The corrosion mechanism has been identified as the reaction between SiC and oxide impurities in LiPb, such as Li_2O, which results in the formation of an oxide layer [14]. Additionally, SiC composites can contain sintering additives such as alumina and yttria in amounts over 5%, which further complicates the situation. The specific composition of the reaction layer however depends on the impurities that are present within LiPb, for example reaction with Ni can lead to formation of Ni_xSi_y [9], reaction with Fe, Cr and Ni mixtures can result in formation of M_3C_2, M_3Si, M_5Si_3 and M_8SiC compounds (M = Fe, Cr and Ni) [15][16], and oxide layers have also been found to contain some Al and C [11]. Furthermore, reaction with impurities will typically release C into the LiPb, which can then transfer to non-SiC surfaces such as steels, resulting in the formation of carbides on the steel surface [13]. Thus, the purity of the LiPb has been highlighted as a key issue to resolve, given the various interactions impurities can have with SiC composites. Interestingly, some studies have shown that the thickness of the reaction layer, and thus corrosion rate, reduced with increasing temperature [15][16]. Increasing the LiPb flow velocity has been shown to increase the rate of reaction layer formation on the SiC surface, though despite the rate increase the ultimate reaction layer thickness approached a constant value regardless of flow velocity (in the range ~0.1-0.5 ms^{-1}) [14]. Compared with static conditions however, the reaction layer formed under flowing conditions was much thicker, which suggests a flow-induced corrosion mechanism is present. Finally, the presence of defects and pores on the SiC surface resulted in LiPb penetration into SiC composites and acted as sites for enhanced degradation, suggesting surface preparation is an important factor to be controlled [6][9].

Regarding the experimental equipment used for LiPb compatibility testing, static tests are typically carried out in capsules, whereby SiC composite samples and LiPb are sealed within an inert chamber often constructed of Mo (e.g. [6][7][8]). Rotating disk equipment has been utilised to examine the effects of LiPb flow velocity, where SiC composite samples are secured to a disk that can rotate within LiPb at different speeds, resulting in LiPb flow over the sample surface [11][14]. Thermal convection loops have been used more recently to examine the effect of flowing LiPb on corrosion of SiC composites in both hot and cold leg sections [15][16].

In addition to the studies on compatibility of SiC composites with LiPb, there are many LiPb loop facilities used around the world that can operate in the lower temperature range, up to ~550 °C, including: PICOLO [17][18], ELLI (Experimental Loop for Liquid breeder) [19], IELLLO (Integrated European Lead Lithium Loop) [20], MaPLE (Magnetohydrodynamic PbLi Experiment) [21], LIFUS II (Lithium for Fusion) [22], DRAGON-V [23], TEX (Tritium Extraction eXperiment) [24], and CLIPPER (Ciemat Lithium-lead loop for Permeation exPERiments) [25]. While such facilities may not focus on SiC composites or even corrosion experiments, they nonetheless demonstrate the extensive global experience, both past and present, of designing and operating LiPb loops.

Despite the existing body of work on compatibility of SiC composites with LiPb, and the various LiPb loop facilities around the world, there remain a number of gaps in our understanding about SiC composite behaviour in LiPb, particularly under the high temperature, irradiation conditions to be expected in KF's SCYLLA© breeder blanket concept [2]. Building on previous experience operating high temperature (900 °C) LiPb loops at Kyoto University (Fig. 1) [26], KF is currently constructing the UNique Integrated Testing facilitY (UNITY) in Japan, which will incorporate a LiPb loop with an inventory of approximately 300 L, and plans to operate at a maximum temperature of ~1000 °C [3]. The LiPb loop is part of UNITY's simulated power core, which aims to test materials and component compatibility, as well as measure hydrogen isotope permeation at operational temperatures using deuterium as a substitute for tritium [3].

FIG.1. Existing LiPb test loop at Kyoto University.

While there are no plans for in-situ irradiation testing in UNITY, the high temperature LiPb loop will allow testing of new grades of SiC composites currently under development in a so-called ‘multi-purpose testing section’, which incorporates corrosion testing units. KF is also considering the possibility of testing irradiated materials in this section. Issues such as the impact of LiPb impurities on behaviour of SiC composites and the influence of thermal gradients can be understood and resolved through extensive experimental programmes. Adjusting the Li:Pb ratio can also be used to control the tritium breeding ratio (TBR), which is considered to be a key benefit of the SCYLLA© breeder blanket concept [2], and thus UNITY will allow the investigation of various Li:Pb ratios and their associated impact on performance of SiC composites, including corrosion.

Another coolant of interest to KF is FLiBe (Li_2BeF_4), which is one of the molten salt coolant systems being considered for high temperature applications, including high-magnetic field fusion systems and some molten salt reactor (MSR) designs. For fusion, FLiBe is the preferred option of the various fluoride-based molten salts as it allows a higher tritium breeding ratio and has favourable neutronic and thermal-hydraulic properties. FLiBe is very attractive as a tritium breeding material in liquid blanket systems of fusion reactors because of its chemical stability and low electrical conductivity. In its liquid form, it is an ionic salt that can withstand high neutron and gamma radiation fields. However, FLiBe produces TF by neutron irradiation, which is corrosive to structural materials and raises safety concerns regarding tritium permeation. Thus, the selection of structural materials is a critical issue. Beryllium is added as a reducing agent to react with the highly corrosive HF, which is formed from the reaction of lithium fluoride with a neutron. The toxicity of Be makes experimental work difficult. While FLiNaK is not seriously being considered as an in-core coolant (due to the high thermal neutron cross-section of potassium), it is often used as a substitute for FLiBe to avoid safety issues with beryllium handling [27]. Thus, available data on compatibility of SiC composites with FLiBe remains scarce [5], and a summary is provided in Table 2.

TABLE 2. KEY LITERATURE ON SiC-FLiBe COMPATIBILITY

Reference Study	SiC Composite Material	Static/Flowing FLiBe	Time	Temperature
Nishimura (2000) [28]	Monolithic SiC	Static	24, 72 and 240 h	550 °C
Cao (2016) [29]	CVI and CVD SiC	Static(?)	1000 h	700 °C
Pint (2020) [30]	Various CVD SiC: CVD SiC, High-resistivity, Low-resistivity, α-SiC, Graphite + pyrolytic C Various CVI SiC: Hi-Nicalon Type 2 fibers, Tyranno SA3 fibres	Static	500 h 1000 h 1000 h	750 °C 650 °C 750 °C

In the limited range of temperature conditions tested for compatibility of SiC composites with FLiBe thus far, it appears there is little difference in corrosion rates between 650 and 750 °C. Generally the CVD SiC composites seems to be more resistant to corrosive attack than CVI SiC composites, which is similar to the case with exposure to LiPb. As is also the case with LiPb, impurities in FLiBe appear to cause degradation of SiC, as has been demonstrated by the formation of $Ni_{31}Si_{12}$ due to Ni impurities [28]. This results in the release of C into the FLiBe, which could react with other materials exposed to the coolant, such as steels.

Given the lack of experimental data, there are numerous remaining issues to be investigated regarding compatibility of SiC composites with FLiBe, which were summarised by Lee *et al.* [27]:

— Long-term corrosion experiments in flowing FLiBe under neutron irradiation;
— Flowing experiments with a temperature gradient and including SiC composites and structural alloys where dissimilar interactions may occur between SiC and Fe, Ni and Cr;
— Correlation between chemical degradation or corrosion and propagation of micro-cracks, and the time-dependent slow crack growth failure of nuclear- and fusion-grade SiC composites;
— Cover gas solubility and the expected oxygen activity in the salt during service;
— The impact of irradiation on the behaviour of H isotopes in SiC composites;
— The effect of SiC composite microstructure (e.g. grain boundary effects) on corrosion and susceptibility to form localised attack.

Static testing can be carried out in either open or sealed crucibles under an inert cover gas within a glovebox, though due to the affinity for oxygen the open crucible method often leads to higher corrosion rates. The LIBRA experiment being undertaken by the Massachusetts Institute of Technology offers an opportunity for further static testing of SiC composites in a range of environmental and redox conditions after their initial programme goals are realised [31]. Historically, a series of natural circulation FLiBe loops were operated at Oak Ridge National Laboratory through the period 1950-1970s, which examined materials compatibility (excluding SiC composites). Recently the University of Wisconsin Natural Convection FLiBe Loop (NCFL) was recommissioned, and allows testing at temperatures between 500 and 800 °C, with a temperature gradient of up to 120 °C, and flow velocities of ~5 $cm \cdot s^{-1}$ [32].

With the many remaining technical issues to be resolved, KF ultimately plans to install a molten salt loop in UNITY, following successful operation of the LiPb loop. In the meantime, KF has recently commissioned a FLiBe test loop with an inventory of 1 kg, which can operate at temperatures up to 650 ºC. This loop, accompanied by a FLiBe refining system, aims to examine issues around coolant purification, corrosion behaviour under flowing FLiBe conditions, and tritium extraction performance, again using deuterium as a proxy [1].

FIG.2. FLiBe test loop.

Finally, the use of pure Li as a coolant is also of interest for self-cooled fusion breeder blanket designs, given its high temperature operation range and potential to reach high TBR without the need for ^{6}Li enrichment. It is well known that SiC composites are incompatible with pure Li [33], and as such vanadium alloys are commonly used as the structural material in concepts containing pure Li coolant. However, various issues such as the manufacturability of vanadium and its high tritium retention mean its development has been limited thus far. Therefore, KF plans to investigate alternative materials that could be compatible with pure Li coolants, such as Mo. A pure Li test loop with an inventory of 3.7 kg is currently under construction, and is scheduled to enter operation in 2024. The loop will be constructed of 9Cr-1Mo ferritic steel and nickel-free steel (SS430), which allows higher operating temperatures (~600 ºC) compared with previously operated loops. Impurity levels will be controlled using a series of cold traps and flow rates through the corrosion testing sections are expected to be ~10 $L{\cdot}min^{-1}$ [1].

CONCLUSIONS

Development activities and operation of LiPb, FLiBe and pure Li coolant loops are ongoing at Kyoto Fusioneering Ltd to support the advancement of high temperature breeder blanket concepts, such as SCYLLA©, which utilise advanced structural materials including SiC composites. While existing literature suggests SiC composites and LiPb are compatible, there remain gaps in our understanding, particularly around high temperature performance, influence of irradiation, potential for Li:Pb optimisation, and the behaviour of new grades of SiC composites being developed in-house. The available data on SiC composites and FLiBe compatibility is more scarce, which leaves many technical issues unanswered. Finally, compatibility of SiC composites with pure Li is known to be poor, and significant challenges remain to be resolved with vanadium alloys, thus KF plans to investigate alternative materials such as Mo.

KF's existing and planned LiPb, FLiBe and pure Li loops, especially those incorporated into UNITY, serve as platforms for collaboration with a wide range of fusion programmes being led by both public and private developers.

REFERENCES

[1] Baus, C. *et al*., 'Kyoto Fusioneering's Mission to Accelerate Fusion Energy: Technologies, Challenges and Role in Industrialisation', *Journal of Fusion Energy*, **42** 10, (2023).

[2] Pearson, R. *et al*., 'Overview of Kyoto Fusioneering's SCYLLA ("Self-Cooled Yuryo Lithium-Lead Advanced") Blanket for Commercial Fusion Reactors', *IEEE Transactions on Plasma Science*, **50** 11, (2022).

[3] Takeda, S. *et al*., 'UNITY: Kyoto Fusioneering's Unique Integrated Testing Facility for Fusion Power Generation', *Fusion Science and Technology*, (2023).

[4] Konishi, S. *et al*., 'Recent Research Progress and Prospects of SiC/SiC Composites', *Journal of Plasma Fusion Research*, **98** 8, 335-337, (2022).

[5] Mouche, P. A., "SiC Compatibility", in *Comprehensive Nuclear Materials*, Elsevier (2020).

[6] Barbier, F. *et al*., 'Compatibility of materials for fusion reactors with Pb-17Li', *Journal of Nuclear Materials*, **307-311**, 1351-1354, (2002).

[7] Pint, B. A. *et al*., 'Investigation of Pb-Li compatibility issues for the dual coolant blanket concept', *Journal of Nuclear Materials*, **367-370**, 1150-1154, (2007).

[8] Zhu, Z. Q. *et al*., 'Preliminary experiment on compatibility of SiCf/SiC composites in static liquid LiPb at 700 °C', *Fusion Engineering and Design*, **84** 7-11, 2048-2051, (2009).

[9] Zhao, S. *et al*., 'Compatibility of PIP SiCf/SiC with LiPb at 700 °C', *Fusion Engineering and Design*, **85** 7-9, 1624-1626, (2010).

[10] Ling, X. *et al*., 'Compatibility of SiC with static liquid LiPb at 800 °C', *Fusion Engineering and Design*, **86** 9-11, 2655-2657, (2011).

[11] Park, C. *et al*., 'Compatibility of SiCf/SiC composite exposed to liquid Pb-Li flow', *Journal of Nuclear Materials*, **417** 1-3, 1218-1220, (2011).

[12] Tosti, S. *et al*., 'Design and manufacture of an oven for high temperature experiments of erosion-corrosion of SiCf/SiC into LiPb', *Fusion Engineering and Design*, **88** 9-10, 2479-2483, (2013).

[13] Pint, B. A. *et al*., 'Pb–Li compatibility issues for DEMO', *Journal of Nuclear Materials*, **442** 1-3, S572-S575, (2013).

[14] Park, C. *et al*., 'The effect of wall flow velocity on compatibility of high-purity SiC materials with liquid Pb-Li alloy by rotating disc testing for 3000 h up to 900 °C', *Fusion Engineering and Design*, **136** A, 623-627, (2018).

[15] Pint, B. A. *et al*., 'Compatibility of SiC with ODS FeCrAl in flowing Pb-Li at 600°–700 °C', *Fusion Engineering and Design*, **166**, 112389, (2021).

[16] Romedenne, M. *et al*., 'Evaluation of the interaction between SiC, pre-oxidized FeCrAlMo with aluminized and pre-oxidized Fe-8Cr-2W in flowing PbLi', *Journal of Nuclear Materials*, **581**, 154465, (2023).

[17] Borgstedt, H. U. *et al*., 'Corrosion testing of steel X 18 CrMoVNb 12 1 (1.4914) in A Pb-17Li pumped loop', *Journal of Nuclear Materials*, **155-157** 2, 728-731, (1988).

[18] Konys, J. and Krauss, W., 'Corrosion and precipitation effects in a forced-convection Pb–15.7Li loop', *Journal of Nuclear Materials*, **442** 1-3, S576-S579, (2013).

[19] Yoon, J. S. *et al*., 'Development of an experimental facility for a liquid breeder in Korea', *Fusion Engineering and Design*, **86** 9-11, 2212-2215, (2011).

[20] Utili, M. *et al*., 'The European Breeding Blanket Test Facility: An integrated device to test European helium cooled TBMs in view of ITER', *Fusion Engineering and Design*, **84** 7-11, 1881-1886, (2009).

[21] Smolenstev, S. *et al*., 'Construction and initial operation of MHD PbLi facility at UCLA', *Fusion Engineering and Design*, **88** 5, 317-326, (2013).

[22] Martelli, D. *et al*., ‘Design of a new experimental loop and of a coolant purifying system for corrosion experiments of EUROFER samples in flowing PbLi environment’, *Fusion Engineering and Design*, **124**, 1144-1149, (2017).

[23] Huang, W. *et al*., ‘Status and initial experiments of DRAGON-V facility for lithium-lead blanket technologies of hydrogen fusion reactors’, *International Journal of Hydrogen Energy*, **47** 94, 39931-39942, (2022).

[24] Taylor, C. N. *et al*., ‘The Tritium Extraction eXperiment (TEX): A forced convection fusion blanket LiPb loop’, *Fusion Engineering and Design*, **192**, 113737, (2023).

[25] Garcinuño, B. *et al*., ‘The CIEMAT LiPb Loop Permeation Experiment’, *Fusion Engineering and Design*, **142** A, 1228-1232, (2019).

[26] Noborio, K. *et al*., ‘High temperature operation of LiPb loop’, *Fusion Science and Technology*, **60** 1, 298-302, (2011).

[27] Lee, J. J. *et al*., ‘Chemical compatibility of silicon carbide in molten fluoride salts for the fluoride salt-cooled high temperature reactor’, *Journal of Nuclear Materials*, **524**, 119-134, (2019).

[28] Nishimura, H. *et al*., ‘Compatibility of structural candidate materials with LiF–BeF$_2$ molten salt mixture’, *Journal of Nuclear Materials*, **283-287** 2, 1326-1331, (2000).

[29] Cao, G. *et al*., ‘Corrosion of Candidate Materials in Molten FLiBe Salt for Fluoride-Salt-Cooled High-Temperature Reactor (FHR)’, *Transactions of the American Nuclear Society*, **114** 1, 1232-1234, (2016).

[30] Pint, B. A. *et al*., ‘Capsule Testing of SiC in FLiBe Salt’, ORNL/LTR-2020/1656, Oak Ridge National Laboratory, USA, 2020.

[31] Ferry, S. E. *et al*., ‘The LIBRA experiment: Investigating robust tritium accountancy in molten FLiBe exposed to a D-T fusion neutron spectrum’, *Fusion Science and Technology*, **79** 1, 13-35, (2022).

[32] Britsch, K. *et al*., ‘Natural circulation FLiBe loop overview’, *International Journal of Heat and Mass Transfer*, **134**, 970-983, (2019).

[33] Yoneoka, T. *et al*., ‘Compatibility of SiC/SiC composite materials with molten lithium metal and Li16-Pb84 eutectic alloy’, *Materials Transactions*, **42** 6, 1019-1023, (2001).