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The LIBRA Experiment: Investigating Robust Tritium Accountancy in Molten FLiBe Exposed to a D-T Fusion Neutron Spectrum

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Abstract — *The Liquid Immersion Blanket: Robust Accountancy (LIBRA) experiment will be a first-of-a-kind experiment to explore and develop the liquid immersion blanket (LIB) concept. The LIB is a radically simple molten–LiF-BeF$_2$ (FLiBe)–salt tritium breeding blanket for deuterium-tritium (D-T)–fueled fusion power plants (FPPs) achieving a high tritium breeding ratio (TBR) in neutronics models. However, tritium breeding in FLiBe is inherently difficult to study experimentally. As a result, the coupled issues of FLiBe radiochemistry and tritium (T) transport are poorly understood. LIBRA approaches this challenge by simulating an FPP blanket environment using a D-T neutron generator and $\approx$ 1000 kg of FLiBe. LIBRA will investigate T breeding, containment, and extraction, coupled with FLiBe redox control and radiochemistry. The primary goal of LIBRA is to demonstrate robust T accountancy in blanket prototypical conditions. Here, T accountancy encompasses accurate predictions of T breeding in the FLiBe; detection and measurement of all T bred in LIBRA; and speciation of the T extracted from the FLiBe. Initial neutronics simulations of LIBRA indicate that a global TBR of $\sim$1 is possible, where the TBR is defined as the number of tritons bred and extracted from FLiBe relative to the number of neutrons produced by D-T fusion reactions in the neutron generator. In this paper, we present the LIBRA concept and its scientific goals in the context of T breeding experiments. We also consider the potential impact of the LIB on the future fusion power industry, motivating further development of FLiBe-based T breeding research activities such as LIBRA.*

Keywords — *FLiBe, tritium breeding, tritium accountancy, liquid immersion blanket, fusion power.*

Note — *Some figures may be in color only in the electronic version.*

I. INTRODUCTION

The growing fusion industry aims to deploy full-scale fusion power plants (FPPs) in the 2030s. If successful, deuterium-tritium (D-T)–fueled FPPs, such as Commonwealth Fusion Systems' ARC concept or Tokamak Energy's spherical tokamak, could play a major role in accelerating decarbonization.[1–3] This will require many breakthrough engineering advances, including the development of highly efficient tritium (T) breeding systems.

Tritium is scarce and extremely expensive, so any D-T FPP will need to breed its own T fuel. This is accomplished by exploiting the interaction between the neutrons created as a by-product of the D-T fusion reaction in the plasma and lithium (Li) in the T breeding blanket, particularly the isotope ^{6}Li (< 8% natural abundance):

$$^6_3\mathrm{Li} + ^1_0\mathrm{n} \rightarrow ^4_2\mathrm{He} + ^3_1\mathrm{H} \ . \tag{1}$$

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Conventional breeder choices include ceramic solids, like $LiTi_2O_3$, and liquids, like the metal $Pb_{83}Li_{17}$ with a melting point of 235 C and Li-containing salts like LiF-BeF_2 (FLiBe) or LiF-NaF-KF (FLiNaK) with melting points around 460 C.

The achievable tritium breeding ratio (TBR), defined as the number of tritons produced in the breeder per fusion neutron produced in the plasma, associated with conventional blanket designs is estimated at 1.05 to 1.15 (Ref. 4). This is too low to support a fusion power industry in the near term. Tritium doubling time t_D is defined as the time an FPP requires to breed enough excess T to start the next FPP. A robust fusion power industry needs $t_D < 3$ yr, which corresponds to a TBR of > 1.15 under conservative plasma physics assumptions.[4] The lower TBRs of existing blanket designs will lead to long T doubling times of 3 to 10 yr that inherently limit the penetration of fusion power onto the energy market.

This is illustrated in Fig. 1a, which presents a hypothetical scenario in which FPPs are ready for deployment in 2030 and the operation of new plants is limited only by T availability. It is assumed that with the exception of the startup of the first FPP, all T for new plants is bred by an earlier plant. A simple doubling-time model is plotted for three D-T FPP concepts:

$$P_{tot} = 2^{t/\Lambda} \cdot P_{\mathrm{FPP}} \quad , \tag{2}$$

where

P_{tot} = maximum fusion power on the grid

P_{FPP} = output of the individual plant

t = number of years since the first FPP was completed

Λ = tritium doubling time associated with the FPP breeder design.

If blankets achieve a 5-yr doubling time, it will take nearly 50 yr from the start of the first FPP to reach 1 TW of fusion power on the global electrical grid. For fusion to have a chance at contributing to grid decarbonization within a generation, significant advancements in blanket technology and increases in the efficiency with which T can be bred and extracted are required.

In particular, the fusion community must develop blankets that prioritize the following design principles[4]:

1. *High TBR (* > 1.2), where TBR is defined as the ratio of T produced in the breeding blanket to T consumed as fuel in the plasma (or, equivalently, tritons produced in the blanket to neutrons produced in the plasma).

2. *Low breeder blanket cost*, to improve the economic viability of commercial fusion power.

3. *Low T inventory in the blanket*, to improve safety and ease regulatory burdens.

The liquid immersion blanket (LIB), first proposed in Ref. 5 as part of the ARC FPP design, is an example of

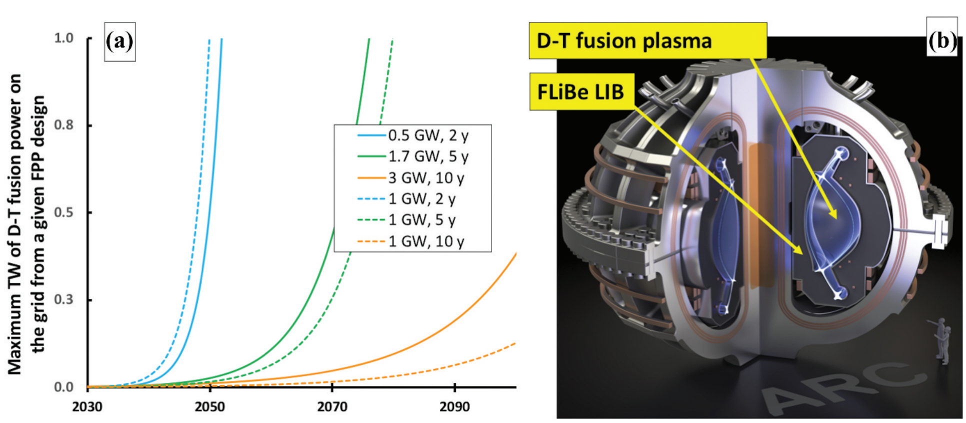


Fig. 1. (a) Fusion power expansion will be limited by the T inventory doubling time of the breeder blankets in use. Assuming the first plant in 2030, the maximum terawatts from fusion power, as given by Eq. (2), is plotted for example P_{FPP} values (0.5 GW for ARC, 1.7 GW for ARIES-AT, and 3 GW for DEMO) and doubling times. A 5-yr doubling time is given as the reference case for an example FPP in Ref. 4. Dashed lines show results for P_{FPP}=1 GW. (b) The LIB design achieves a high TBR and low T inventory doubling time compared to other blanket designs in the literature. The LIB surrounds the VV and plasma, in contrast to conventional FPP designs in which the blanket is inside the VV. ARC will target a 2-yr doubling time. It was originally proposed for ARC (Ref. 5), but the principle is adaptable to other D-T FPP concepts. ARC rendering courtesy of Commonwealth Fusion Systems.

a blanket concept that follows this paradigm. The LIB emphasizes lower cost, higher TBR, and lower T inventory compared to conventional breeder technology being studied under the framework of the ITER Test Blanket Module program or the U.S. Fusion Blanket and Tritium Fuel Cycle program. It is a radically simple blanket design that consists of a large blanket tank of molten FLiBe salt that surrounds the vacuum vessel (VV) and plasma. A LIB is conceptualized in the rendering of ARC in Fig. 1b, although it should be noted that the LIB design can also be incorporated into other D-T fusion concepts.

The LIB contains a minimum of structural material other than the blanket containment tank and support structures for the VV, allowing the breeding volume to be optimized in a small space. The molten FLiBe is liquid and not susceptible to damage associated with neutron irradiation of solids. The liquid breeder can also be used as a working fluid to extract heat from the VV. If deployed in an FPP design like ARC, the LIB is highly complementary to demountable magnet technology, which enables access to the VV for maintenance and/or replacement.[5] The LIB does not need to be disassembled and reconstructed nor does it need to be replaced.

The LIB has not progressed significantly from the basic concept proposed in the 2015 introduction of the Massachusetts Institute of Technology (MIT) ARC design,[5] largely due to the radiochemical challenges involved in testing it: maintaining >500 C temperatures, access to laboratories equipped for beryllium (Be) and HF handling, access to fusion neutron sources and laboratories capable of the associated safety concerns, and safe handling of radioactive T. Showing T accountancy—the experimentally validated measurement of how much T is produced in and extracted from the breeding system—is paramount to validating and designing a T breeder technology. No existing experiment is capable of carrying out this work for the LIB except the Liquid Immersion Blanket: Robust Accountancy (LIBRA) experiment, which is a leap forward on the critical path for first FPP operation.[6]

II. OVERVIEW OF THE LIBRA PROJECT

II.A. Past Work on FLiBe and Tritium Breeding

Experimental work on T breeding is mostly limited to testing small volumes (< 1 L) of Li-based breeding materials using fission spectrum neutrons from research reactors. Ceramic T breeders[7–79] and liquid metals[51,80–88] are the most common breeder choice, with a few tests using small amounts (< 1 kg) of molten FLiBe salt.[68,88–95] Of the experiments surveyed in the literature, 84% used solid Li ceramic as the breeder material, 11% used liquid PbLi, and 5% used molten FLiBe.

Only a few T breeding experiments (< 5% of experiments surveyed from the literature) have used 14-MeV D-T fusion neutron sources.[8,29,55,63,96] The limited experimental work on FLiBe T breeding is not surprising: In addition to the handling challenges of FLiBe due to Be toxicity and the potential for hydrogen fluoride gas formation, the urgency for FLiBe T breeding research prior to the introduction of the LIB has been limited. There are six test blanket modules (TBMs) planned as part of the ITER fusion program. Four will use Li ceramic breeders (Li_2SiO_4 or Li_2TiO_3), and two will use PbLi. (Note, however, that all four of the ceramic concepts will use Be in the design as a neutron multiplier.) FLiBe is absent from the present U.S. blanket research and development program, as well.

Past FLiBe breeder tests fall mostly within the context of the Japanese INTREXFLIBE (Ref. 68) and Japanese/American JUPITER-II programs.[97] These campaigns supported development of FPP designs like the Force-Free Helical Reactor[98,99] (FFHR), which proposes FLiBe or FLiNaBe as a breeding material in a cartridge-style blanket.[100]

FLiBe T breeding work is mostly limited to single-effect studies (Fig. 2). In addition to a small number of FLiBe T breeding studies, the INTREXFLIBE and JUPITER-II programs also studied the chemistry and kinetics of released T (Refs. 68, 94, 96, and 101 through 104); T permeation, diffusion, and solubility[88,93,105–112]; T extraction[113–115]; studies of T control in a full-scale blanket[116,117]; and T-related materials challenges.[92,118] However, experiments never progressed beyond small-scale handling of FLiBe, and the development of full-scale FLiBe T breeding blankets largely stagnated. Today, fluoride salts are of interest to the growing small modular fission reactor industry, leading to a small but growing body of work on redox control in FLiBe (Refs. 119 through 124) and structural material corrosion.[125–138] The Molten Salt Reactor Experiment (MSRE) at Oak Ridge National Laboratory (ORNL) in the 1960s is still the only large-scale, integral U.S. project to successfully utilize commercial-scale amounts of FLiBe (Refs. 139 and140). While fission reactor designs that utilize FLiBe as a working fluid aim to minimize, not maximize, T breeding in the salt, T production and transport remain key safety and operational issues.

		Radiation		T accountancy				T kinetics			FLiBe chemistry			
		Neutrons	14 MeV fusion spectrum	Tritium	Measure TBR	Complementary neutronics	T extraction, detection, & speciation	T transport in Flibe	T diffusion at gas /liquid IF	T diffusion through solids	Redox control	Material compatibility	Sparging fluid effects	> 1 L flibe
LIBRA		Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
INTREXFLIBE [68]	[99]	Y	Y	Y	N	N	Y	N	Y	N	N	Y	Y	N
	[94]	Y	N	Y	N	N	Y	N	N	N	N	N	N	N
	[101]	Y	N	Y	N	N	Y	Y	Y	N	N	N	Y	N
	[102, 103]	Y	N	Y	N	N	Y	N	Y	N	N	N	Y	N
	[105]	Y	N	Y	N	N	Y	N	Y	Y	N	N	N	N
	[118]	N	N	N	N	N	N	N	N	N	N	Y	N	N
JUPITER II [97]	[107, 108]	N	N	N	N	N	N	D, H used as sub. for T			N	N	N	N
	[112]	N	N	Y	N	N	Y	Y	N	N	N	N	N	N
	[89]	Y	N	Y	N	Y	Y	Y	N	N	N	N	N	N
Redox experiments	[120-122]	N	N	N	N	N	N	N	N	N	Y	N	N	N
	[123]	N	N	N	N	N	N	N	N	N	Y	Y	N	N
FLiBe corrosion studies	[125, 126]	N	N	N	N	N	N	N	N	N	N	Y	N	~
	[133]	Y	N	Y*	N	N	N	N	N	N	N	Y	N	N
	[104, 129–132, 134, 136–138]	N	N	N	N	N	N	N	N	N	N	Y	N	N

Non-experimental papers or papers using FLiNaK were not included. * FLiBe was Li-7 enriched to reduce T production ~ Loop tests with flowing FLiBe.

Fig. 2. Prior experimental work in FLiBe T breeding is limited, making it difficult to validate the LIB concept with existing research. Successful FLiBe T breeding in an FPP requires competency in four interdependent categories: operation in a fusion neutron environment, accurate T accountancy, understanding of T kinetics in FLiBe, and FLiBe chemistry control. LIBRA aims to integrate all four in a LIB-prototypical environment.

No FLiBe experiment has tested integrated corrosion, T speciation, T containment, and T recovery under prototypical FPP blanket conditions (Fig. 2). To date, experiments with FLiBe have not progressed beyond basic detection of T to show true TBR measurement and T accountancy. Such tests require accurate radiochemical conditions, such as high salt temperatures, hazardous materials, and high-energy D-T fusion neutrons, which incur significant cost and require access to specialized facilities. Since FLiBe is not under consideration for any of the DEMOnstration nuclear fusion reactor (DEMO) designs planned to follow ITER, it is not surprising that experimental FLiBe T breeding work has been limited up to now. Furthermore, it is difficult to obtain large volumes of FLiBe, in part because demand has been low and capable production facilities are limited to making small batches due to the hazardous handling conditions. However, new capabilities for industrial production of FLiBe (in tons per year) are becoming available through supply chain development in the molten salt fission reactor community, creating a high leverage opportunity for the fusion community to reconsider the benefits of FLiBe T breeding.

II.B. LIBRA Design

LIBRA (Fig. 3) is designed to replicate a prototypical FPP blanket environment in a cost-effective, laboratory-scale experiment. It is an integrated experiment for validating T breeding and accounting science, studying FLiBe thermomechanical and radiochemical behavior, refining chemistry control methods for industrial volumes of FLiBe, and demonstrating robust safety practices.

In LIBRA, a D-T neutron generator is completely surrounded by a cylindrical tank of molten FLiBe salt (Fig. 3a). A 10^{10} n/s generator will be purchased for LIBRA from Phoenix, LLC. This neutron generator provides the highest commercially available 14-MeV neutron rate in a form factor appropriate for T breeding tests.

The neutron source acts as an analog to the neutron source in an FPP (the plasma) being surrounded by the FLiBe blanket: Neutrons from D-T fusion reactions (born at 14.1 MeV) have a much harder spectrum than neutrons from fission reactions in a fast reactor (born at 2 MeV), and it is therefore scientifically limiting to rely on fission reactors as a neutron source. To be fair, the commercial neutron generator that will be used in LIBRA does not approach the fluence or flux of an FPP like ARC ($\approx 10^{21}$ n/s), which would be needed to truly match FPP rates and levels of radiation damage in solid materials, radiolysis in the molten salt, and dynamic tritium breeding concentrations. However, LIBRA will still provide an analogous neutron energy spectrum to the LIB in ARC (see Sec. III) using equipment that is commercially available today.

Sparge and sweep gas systems are used to remove T directly from the salt and tank interstitial, respectively,

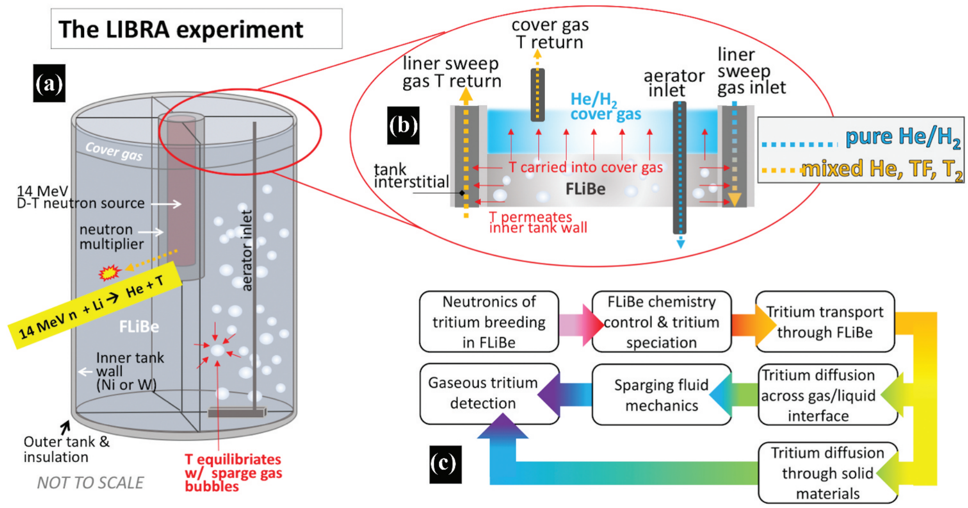


Fig. 3. (a) The D-T neutron generator is surrounded by a cylindrical tank of FLiBe (~1-m diameter). The tank is divided into four independent quadrants, each with its own sparging and sweep gas system. There is an interstitial between the sectored tank liner (in contact with the FLiBe) and the outer tank through which a sweep gas can be passed. (b) Tritium is carried to the detection system via the cover gas or via liner sweep gas return. (c) LIBRA enables an integrated understanding of T breeding and kinetics in FLiBe molten salt.

for detection and collection (Fig. 3b). Sparging nozzles at the bottom of the tank bubble inert gas (~0.5-mm diameter) through the FLiBe and carry T (in the more insoluble form of T_2 or HT; see Sec. IV.B) to the cover gas in the tank headspace above the salt. The cover gas is then exhausted to a continuous T detection system that cumulatively quantifies the extracted T. LIBRA will use a variable He/H_2 mixture as the sparge and sweep gas. A controllable HF flow will be integrated into the sparge gas line to enable in situ hydrofluorination, as this is the standard method of FLiBe purification in the studies described in Sec. II.A. Temperature control will be accomplished with high-temperature heating cords within the interstitial volume and thermocouples in the FLiBe.

Tritium detection will be performed with ion chambers in series with water bubblers. Tritium accumulates over time in the ion chambers due to slow liquid-gas transfer of T from the salt and the low overall concentration of T in the salt. The gas flow rate limit is set by the 50 L/min upper limit of the water bubbler throughput. The sensitivity of the ion chambers is 1 $\mu Ci/m^3$ in the individual gas streams. Estimates of the time to reach this threshold is between 1 to 6 h, depending on the T speciation. To make accurate TBR calculations, precise neutron energies and fluence measurements are needed. The tanks will therefore be outfitted with various activation foils and wires to record the neutron irradiation conditions for each experimental test. An array of neutron diagnostics will be used for commissioning the neutron generator and for general radiation monitoring. Scintillation and ^{6}Li detectors will be used outside of the tanks to monitor the neutron spectrum in real time during T breeding tests. Helium-3 detectors will be used for general neutron monitoring around LIBRA.

LIBRA will be divided into four quadrant tanks (QTs), QT1 through QT4, which have identical volumes, sparging/sweep gas systems, T and neutron detection capabilities, redox control systems, and temperature control systems. However, each quadrant operates independently of the others, so that QT1 through QT4 can be assigned to different scientific goals in a single experimental campaign. This enables more rapid generation of experimental data and, critically, allows comparative experiments to be performed simultaneously in identical conditions.

As an example, consider the first planned experimental measurement of the TBR in the LIBRA system. QT1 and QT2 will be lined with tungsten (W), a leading material candidate for the FPP vacuum vessel–first wall (VV-FW), which has low T permeability relative to nickel (Ni) and which is expected to have high corrosion resistance to FLiBe. QT1 and QT2 will be identical, providing a built-in replicability study. QT3 will be lined with pure Ni, which has higher T permeability than W and good corrosion resistance in fluoride salts.[133] Metallic Be will be added to the FLiBe in QT1, QT2, and QT3 for redox control[120–122] and to ensure that generated T is present in the system as HT instead of corrosive, difficult-to-extract TF. Though the redox potential target is not explicitly set for LIBRA, the literature indicates that the Be metal reduction will set the minimum redox potential to −902.5 kJ/mol F_2 and the hydrofluorination purification process will set the maximum potential to −590 kJ/mol F_2 (Ref. 141). Comparing T measurements in QT3 to measurements from QT1 and QT2 enables a quantitative analysis of T extraction pathways in the system; as shown in Fig. 3b, T is sent to the detectors via the cover gas (T enters the cover gas directly from the FLiBe salt, a process enhanced by the sparging gas) or via the sweep gas in the interstitial space between the outer tank and the tank liner (T enters the interstitial via permeation of the inner tank liner). Finally, QT4 will be lined with W like QT1 and QT2, but impurities will be deliberately added to the FLiBe in QT4, so that we can measure how T extraction efficiency changes with salt purity. The quadrant system enhances the capabilities of the system without sacrificing time.

Table I describes the technical performance targets for the LIBRA experiment and shows how they improve on the available data from FLiBe T breeding experiments in the literature. LIBRA aims to go beyond basic studies of T breeding and kinetics in FLiBe. It is designed to achieve results that validate and advance the LIB concept, for example, demonstrating fast T equilibration time in the FLiBe (necessary to keep T inventory low in the LIB) and the ability to measure a high TBR as a global quantity. LIBRA's approach to achieving robust T accountancy hinges on four key design choices and two key risk management strategies, described below.

II.B.1. Key Design Choice 1: Use an FPP-Relevant Size, Design, and Materials

In LIBRA, the structural material present between the neutron source and the FLiBe is minimized to maximize T breeding in the salt. This is one of the guiding design principles of the LIB: Solid structural components are mostly eliminated, which minimizes parasitic neutron absorption and allows more of the system volume to be dedicated to breeder material, enhancing global TBR. Furthermore, because the molten FLiBe is liquid, it conforms to arbitrarily complex geometries and eliminates empty volume for neutrons to escape.

The size of LIBRA was selected to provide the minimum FLiBe breeder thickness required to maintain the correct neutron energy spectrum throughout the test volume while also enabling a TBR of ≈ 1. Fusion neutrons are scattered and moderated as they pass through the FLiBe. In order to accurately represent the FPP LIB, a radial thickness of several mean free paths (~7 cm for 14.1-MeV neutrons in FLiBe) of breeding material is required. Calculations indicate that this thickness is ~40 cm for LIBRA (see Sec. III). Any additional thickness of FLiBe would increase the overall TBR, but with diminishing scientific returns for the associated increase in cost and size.

II.B.2. Key Design Choice 2: Match the LIB Radiochemical Environment

LIBRA provides a close match to the expected LIB radiochemical environment by using the intended breeder material (FLiBe) and neutron spectrum (14-MeV D-T neutrons) instead of substitutions like FLiNaK and fission neutrons. FLiNaK is easier to procure, contains comparable amounts of Li breeder, and circumvents the issue of Be toxicity. However, we do not anticipate that a future LIB would use FLiNaK instead of FLiBe, although it is theoretically possible, because Be acts as a neutron multiplier and enhances T breeding. A FLiNaK LIB would need to be much larger to achieve the same T inventory, increasing plant size and cost (see Sec. III and Fig. 6). Therefore, LIBRA must use FLiBe in order to be truly radiochemically relevant to the LIB, as T transport and behavior are highly dependent on its chemical form, which in turn is coupled to salt chemistry. Each QT will

TABLE I

Technical Performance Targets for LIBRA Compared to FLiBe T Breeding Experiments in the Literature

Target	Literature	LIBRA Experiment
Neutron energy spectrum	Arbitrary	Matches LIB spectrum
Tritium equilibration time	~7 days	< 1 day
Validated global TBR	n/a[a]	> 1
Breeder volume	0.001 m^3	0.5 m^3
Redox potential	Variable	Controllable
Corrosion rate	0 to 25 µm/yr	< 5 µm/yr

[a]n/a = not measured.

be equipped with salt monitoring systems capable of measuring and adjusting impurity and redox levels.

It is impossible for a fission spectrum to replicate the high-energy fusion neutron environment of an FPP. Furthermore, use of fission neutrons limits experimental flexibility and speed and dictates small experimental salt volumes. Fusion neutron sources are commercially available, have the correct energy spectrum, and can be used in an arbitrarily large breeder volume.

II.B.3. Key Design Choice 3: Measure the TBR as a Global Quantity

The TBR in a power plant is a global quantity dependent on both total T consumption and total T production. This means T must be measured throughout the entire system and that total neutron fluence must be precisely characterized. No experiment to date has measured the global TBR for any breeder concept. To ensure full capture of releasable T in LIBRA, the T will be monitored in three pathways: (1) directly from the FLiBe, (2) permeation through to the tank wall interstitials, and (3) permeation completely out of the LIBRA apparatus.

The most important scientific tools in LIBRA, then, are the T and neutron diagnostic systems. To minimize uncertainty, LIBRA will employ multiple diagnostics per relevant quantity. Active T detection comprises ionization chambers with final T capture by liquid scintillation bubblers. Passive environmental T detection on and near the LIBRA system (e.g., swipes) will also be used. Neutron fluence will be measured with activation foils, fission chambers, liquid scintillators, and ^{3}He-based detectors. All of these will be validated against numerical neutronics simulations. This redundant diagnostic strategy provides the reliable measurements necessary to accurately measure the TBR.

II.B.4. Key Design Choice 4: Prioritize a Modular Design

The modularity of the four quarter tanks in LIBRA provides experimental flexibility and replicability. The functionality and diagnostics of each quadrant are identical, but the tank sparging, sweep gas, and detection systems operate independently of each other.

The LIBRA facility will be located in the MIT Vault Laboratory (Fig. 4), which has the necessary shielding and infrastructure to support an experiment utilizing a D-T neutron generator. The LIBRA tank will be housed in a negative pressure enclosure with HEPA filtration to contain any Be or T that enters the environment from the experimental system. The enclosure serves as the final

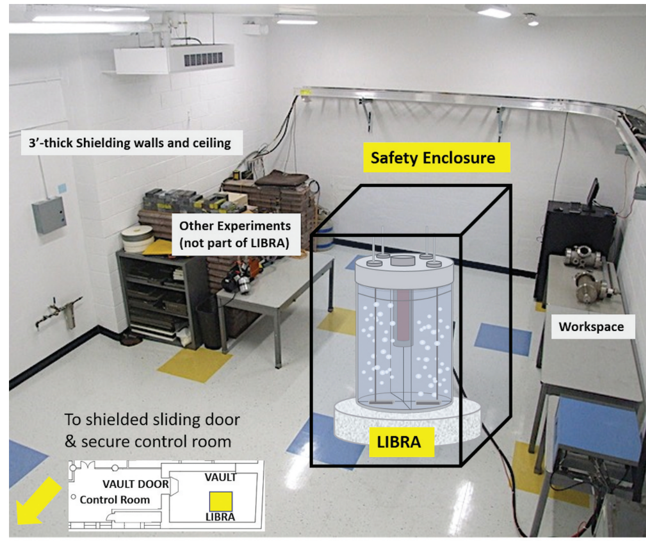


Fig. 4. The MIT vault laboratory, pictured, is under consideration for LIBRA siting. The LIBRA laboratory site will require sufficient neutron shielding and a secure control room for remote monitoring.

T containment barrier for any T that permeates completely out of LIBRA. Safety controls will be implemented to monitor for hazardous gas leakage (HF, T), and environmental swiping will be conducted on a regular schedule to monitor surfaces inside the enclosure. A second laboratory space, equipped for safe handling and analysis of FLiBe, is under construction near the Vault Laboratory.

Table II summarizes the expected risks to achieving LIBRA's technical targets and outlines the high-level strategy for mitigating these risks. Note that the case for achieving a TBR of > 1 in the current design is computationally validated in Sec. III. LIBRA's chemistry is further considered in Sec. IV.

II.C. LIBRA in Context

Figure 5 places LIBRA in the context of other T breeding experiments that used, or will use, fusion spectrum neutrons and considers these experiments in the context of the NASA technology readiness level (TRL) framework.[142] Figure 5 highlights four past experiments in particular:

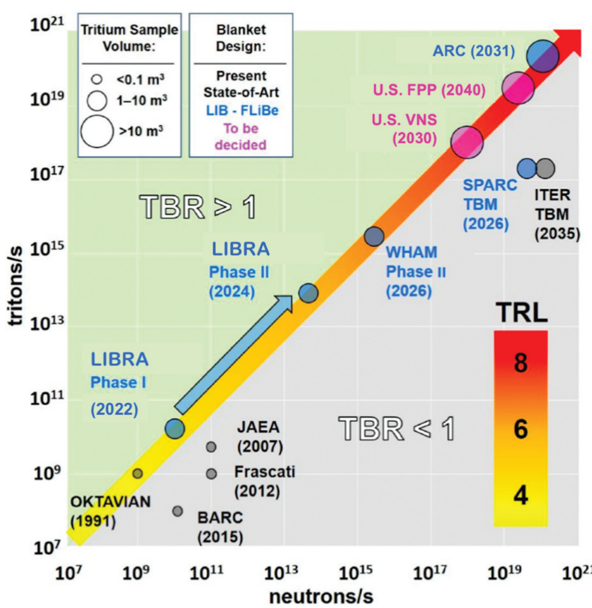
1. *OKTAVIAN, 1991*: The TBR was measured in solid Li spheres exposed to the OKTAVIAN 14-MeV neutron source, sometimes in conjunction with a Pb or Be neutron multiplier and a C reflector.[11,63]

TABLE II

Risks to Achieving the LIBRA Technical Targets and Proposed Mitigation Strategies

Technical Target	Science Risk	Mitigation Strategy
TBR > 1	Insufficient neutron economy	→ High FLiBe volume, effective neutron multipliers near source
Uncertainty: as low as reasonably achievable	Tritium detection sensitivity and accuracy limits	→ Employ multiple established and novel detection methods
	Unmeasured T trapped or T lost from system	→ Monitor various T extraction pathways; increase T extraction rate with high temperature and H_2 addition
	Improper neutron spectrum	→ Compact accelerator-based 14-MeV neutron source
	Uncertain neutron fluence	→ Distributed neutron foils and counters, in situ calibration
Tritium measurement time ~1 day	Low efficiency of gas sparging due to high TF to T_2 ratio	→ Lower FLiBe redox potential to promote T_2 versus TF; this decreases T solubility and enhances sparge recovery
	Low efficiency of gas sparging for T_2	→ Sweep gas recovery of T_2 permeated into tank interstitial volume
Radial build = 0.25 m	Insufficient neutron moderation and shielding at that size	→ High FLiBe-to-structure ratio, modular thin-walled tanks, ~4π sr[a] coverage; increase reflector/moderator outside tanks
Corrosion rate ≤ 5 m/yr	Impurities in FLiBe drive enhanced corrosion	→ Tungsten and nickel tank linings → On-line chemistry control of FLiBe
FLiBe redox potential control	Redox potential overly oxidizing	→ Add Be/beryllides as reducing agent
	Redox potential resists control with large FLiBe volume	→ Hydrofluorinate sparge gas for on-line purification

[a]sr = steradians.



Level	NASA TRL definition for spaceflight technologies	Applying the TRL framework to the LIB
TRL 9	System "flight proven" through successful mission operations	Many LIB-equipped FPPs are operating successfully
TRL 8	Actual system completed and "flight qualified" through demonstration	T breeding and extraction demonstrated on an FPP with the first full-scale LIB
TRL 7	System prototype demonstration in a space environment	LIB test blanket module is deployed and tested on a DT-tokamak with Q>1
TRL 6	System prototype demonstration in a relevant environment	LIBRA PHASE II: scale up the system
TRL 5	Component/breadboard validation in a relevant environment	LIBRA PHASE I : demonstrate global TBR > 1 in a radiochemically relevant environment
TRL 4	Component/breadboard validation in a laboratory environment	T successfully extracted from FLiBe following neutron irradiation INTREXFLIBE, JUPITER-II, etc.
TRL 3	Proof-of-concept demonstrated	Analysis demonstrates validity of LIB concept LIB/ARC introduced in 2015 (Sorbom et al.)
TRL 2	Technology concept formulated	The LIB concept is created
TRL 1	Basic principles observed and reported	Interactions between neutrons and the lithium in FLiBe create tritium

Fig. 5. The TRL framework was developed by NASA to describe how new ideas move from basic concepts to real-world implementation.[142] LIBRA accelerates the TRL of the FLiBe-based LIB and demonstrates an FPP-relevant global TBR. TRL 5+ for the LIB is associated with global TBR ≥ 1 and progressively higher neutron fluences. LIBRA Phases I and II make more advanced tests possible (e.g., a mock-up on a tandem mirror device, such as a future iteration of WHAM, or a TBM on a burning plasma tokamak like SPARC). These in turn enable high TRL applications of the LIB, such as deployment on ARC or a national pilot plant.

2. *Japan Atomic Energy Agency (JAEA), 2007*: A water-cooled breeder blanket mock-up consisting of two Li_2TiO_3 layers and three Be multiplier layers was tested at the JAEA fusion neutron source facility.[55,56]
3. *Frascati, 2012*: Two ITER TBM concepts, the helium-cooled pebble bed and the helium-cooled lead lithium concept, were tested at the Frascati neutron source to validate neutronics studies.[8]
4. *Bhabha Atomic Research Centre (BARC), 2015*: The Indian lead lithium cooled blanket, which will use Li_2TiO_3 pebbles as a breeder and liquid PbLi eutectic as a secondary breeder, as well as coolant and multiplier, was tested at BARC. A mock-up TBM assembly was built and irradiated with 14-MeV neutrons from a SODERN neutron generator.[29]

Like LIBRA, these experiments utilized neutron sources with lower neutron fluences (10^9 to 10^{11} n/s) than are anticipated in burning plasma D-T tokamaks (10^{18} n/s and higher), since we are limited by the capabilities of available D-T neutron generators. The three blanket TBM mock-up experiments included here (JAEA, Frascati, and BARC) did not, however, demonstrate a TBR of > 1; the only experiment that has done so (OKTAVIAN) was a highly optimized geometry that is not representative of a breeder blanket design (a solid sphere of Li, with layers of neutron reflectors and multipliers).

LIBRA aims to bridge the gap between the current state of the art (single-effect tests in small FLiBe volumes, as described in Fig. 2) and future TBMs for the LIB (proposed for installation on future burning plasma tokamaks, such as SPARC), which will be far more expensive and which are years away from becoming reality. It will also serve as the TBM mock-up for the FLiBe-based LIB, much as the BARC, Frascati, and JAEA experiments plotted in Fig. 5 serve to test the TBM concepts that are planned for eventual installation on ITER (Ref. 143). Phase I, described here, will operate at a neutron fluence many orders of magnitude below what is anticipated in ARC, but it aims to be the first mock-up to achieve a TBR approaching or exceeding one. Future iterations of LIBRA (Phase II) will use more powerful neutron generators and larger FLiBe volumes to achieve a TBR exceeding 1 at neutron fluences that are more relevant to FPPs. LIBRA paves the way for LIB mock-ups on devices like the Wisconsin HTS Axisymmetric Mirror (WHAM), currently under development at the University of Wisconsin–Madison,[144] and LIB TBMs on the SPARC tokamak, currently under construction in Devens, Massachusetts.

III. PRELIMINARY NEUTRONICS CONSIDERATIONS FOR LIBRA

In initial neutronics studies, FLiBe was compared against other liquid breeder alternatives, such as PbLi and FLiNaK, using the OpenMC particle transport code.[145] In the LIBRA geometry, FLiBe was found to provide an ~11% increase in T breeding relative to PbLi. In Fig. 6, LIBRA was modeled with both FLiBe and FLiNaK for varying Li enrichment levels, Pb multiplier thicknesses, and salt breeder thicknesses. These results show that a FLiNaK breeder requires a larger LIBRA radial build to achieve the same TBR (a result that extends to the LIB in an FPP). For example, a TBR of ~1 can be achieved using 10%-enriched FLiBe with 0.5-m salt thickness and a < 5-cm Pb thickness. Using 10%-enriched FLiNaK, LIBRA would need a > 1-m salt thickness and a > 5-cm Pb thickness. FLiBe was thus chosen for study in LIBRA because it is the most compelling breeder choice for the LIB: It enables a high TBR without requiring expensive Li enrichment or increasing plant radial build.

LIBRA aims to achieve a blanket-prototypical radiation environment in its volume of FLiBe salt. The fusion neutron energy spectrum in an FPP ranges from high-energy "fast" neutrons near the fusion core, where neutrons emerge from the D-T reaction at 14.1 MeV, to thermalized lower-energy neutrons at the outer edge. The expected spectrum as a function of location is determined by system

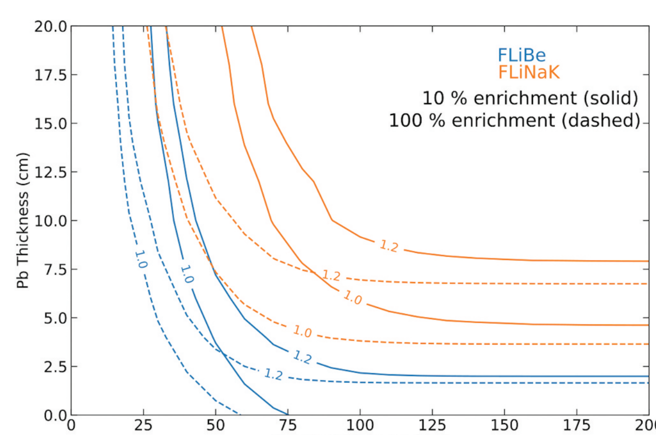


Fig. 6. FLiBe is a more efficient T breeder than FLiNaK. OpenMC simulations of LIBRA show that increases in breeder thickness and neutron multiplier thickness are required to achieve a given TBR with FLiNaK instead of FLiBe.

geometry and material. LIBRA is designed such that its radial neutron energy spectrum closely matches that of a compact LIB in an FPP ($< 1\%$ deviation).

OpenMC simulations of the LIBRA system were used to determine the minimum radial thickness of FLiBe needed for accurate representation of the LIB, which is about 40 cm. Figure 7a shows the output of an OpenMC simulation of an example LIBRA system. The 10^{10} n/s neutron source is located at the center of the cylindrical tank's volume and surrounded by a 5-cm Pb layer for a neutron multiplication boost. The tank in the simulation has a radius of ≈ 65 cm and a height of 1.7 m, which is larger than required for the initial LIBRA build. Tritium in the FLiBe is concentrated closest to the neutron source. The simulation shows that a FLiBe thickness of about 40 cm, corresponding to a tank radius of about 50 cm, is adequate to achieve most of the T that is bred at this fluence (indicated by the dashed line). This is shown quantitatively in Fig. 7c: At the chosen FLiBe thickness, we can still theoretically achieve a TBR > 1 while still aiming to minimize the overall FLiBe volume, tank size, and cost.

The mean free path of 14-MeV neutrons in FLiBe is ~7 cm, so a 40-cm radial FLiBe thickness spans > 5 neutron mean free paths. This thickness is also where the neutron spectrum begins to deviate less from the true LIB neutron environment. The root-mean-square (RMS) deviation of the neutron energy spectrum as a function of FLiBe thickness falls below 1% in the 35 to 40-cm range (Fig. 7b). At smaller FLiBe thicknesses, LIBRA's neutron energy spectrum would not be adequately representative of the neutron energy spectrum in the LIB, limiting LIBRA's usefulness as a blanket mock-up. Thus, the 40-cm FLiBe thickness is chosen. The neutron energy spectrum hews closely to that expected in a real LIB, a TBR in excess of 1 (a significant target milestone for a T breeding experiment) is possible, and the FLiBe volume/tank size is larger than required to achieve both of these targets.

Further OpenMC simulations spanned a wide range of multiplier materials and thicknesses, tank dimensions, liquid breeder compositions, and reflectors. These were used to determine the present baseline configuration of LIBRA, described in Table III. Tank liner thicknesses, outer tank thickness, and material are still under consideration.

IV. FLIBE CHEMISTRY AND TRITIUM BEHAVIOR IN LIBRA

IV.A. Tritium Extraction Pathways in LIBRA

The primary pathway by which T is extracted from LIBRA is the sparge pathway. Preliminary calculations predict that sufficiently small sparging bubbles (≤ 5 mm) will reach concentration equilibrium with the T in the FLiBe by the time they reach the headspace cover gas in the LIBRA tank. The T concentration equilibrium is dictated by Henry's Law, which sets the interface condition at the liquid-gas interface of the bubble:

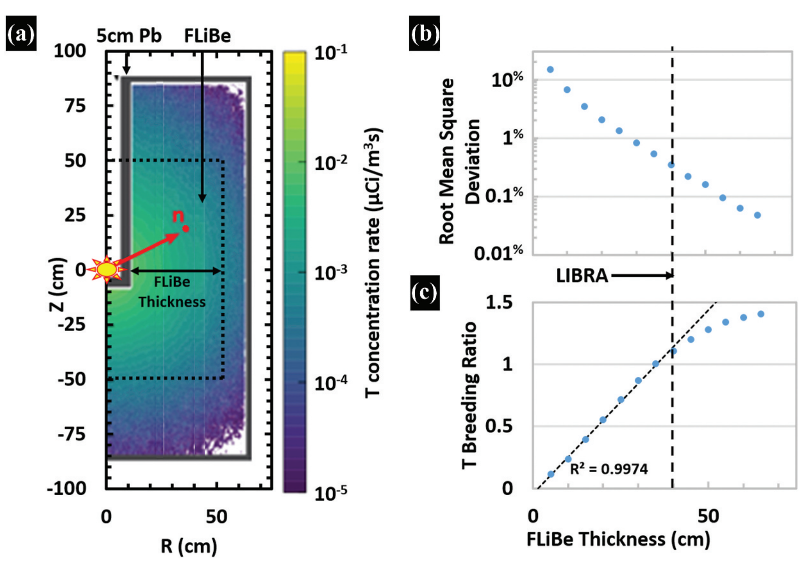


Fig. 7. These figures illustrate why a FLiBe thickness of 40 cm was chosen for the Phase I LIBRA experiment. (a) Schematic of the cylindrical LIB cross section showing the distribution of T breeding rate in FLiBe with a 10^{10} n/s source. Tritium production is concentrated near the neutron source. (b) RMS deviation in neutron energy spectra is plotted as a function of FLiBe thickness. It falls below 1% at about 35 cm. (c) LIBRA TBR is plotted as a function of FLiBe thickness. It exceeds 1 at about 40 cm.

TABLE III

LIBRA Phase I Baseline Design, as Informed by OpenMC Neutronics Studies

Tank height	1 m
Tank radius	0.5 m
Neutron source fluence	10^{10} n/s
Neutron multiplier	Pb
Neutron multiplier thickness	5 cm
Breeder material	FLiBe
FLiBe thickness	0.4 m
Neutron reflector	Pb
Neutron reflector thickness	3 cm
Target global TBR	1

$$c_{HT,F}\left[\frac{\mathrm{mol}}{\mathrm{m}^3_{salt}}\right] = k_H\left[\frac{\mathrm{mol}}{\mathrm{m}^3_{salt}\cdot \mathrm{Pa}}\right]P_{HT}[\mathrm{Pa}] \quad , \tag{3}$$

where P_{HT} = partial pressure of HT in the gas, $c_{HT,F}$ = concentration of T in the salt, and k_H = Henry's Law constant for the system. Therefore, if the salt is sparged at a steady flow rate, the rate at which T is extracted via the cover gas outlet is proportional to the amount of T remaining in the FLiBe.

The secondary pathway (the sweep pathway) by which T is extracted from LIBRA is via T permeation through the metallic inner wall of each quarter tank. The permeated T will be captured by the sweep gas flowing through the tank interstitial volume (Fig. 3b). This diffusion process is governed by Sievert's law and is proportional to (1) the square root of the partial pressure of T in the salt and (2) the liner material's permeability to T. The sparge and sweep recovery of T can be calculated using these assumptions.

In Fig. 8, we show example calculations of the fraction of T remaining in the FLiBe as a function of time since the neutron generator is shut off. The relative amounts of T leaving via the two main extraction pathways (sparging through salt versus sweep gas in the tank interstitial) depend on the sparge gas flow rate, the thickness of the permeation barriers used in the tanks, the liner material, and the salt/material temperature. This dual measurement system provides the ability to measure the ratio of T permeating through the liner versus T that enters the cover gas, and this is a useful metric for understanding system-wide T transport under different environmental parameters. The data from LIBRA will be analyzed in conjunction with the MELCOR-TMAP code developed at Idaho National Laboratory (INL), which combines MELCOR (developed by the U.S. Nuclear Regulatory Commission to model accidents in fission

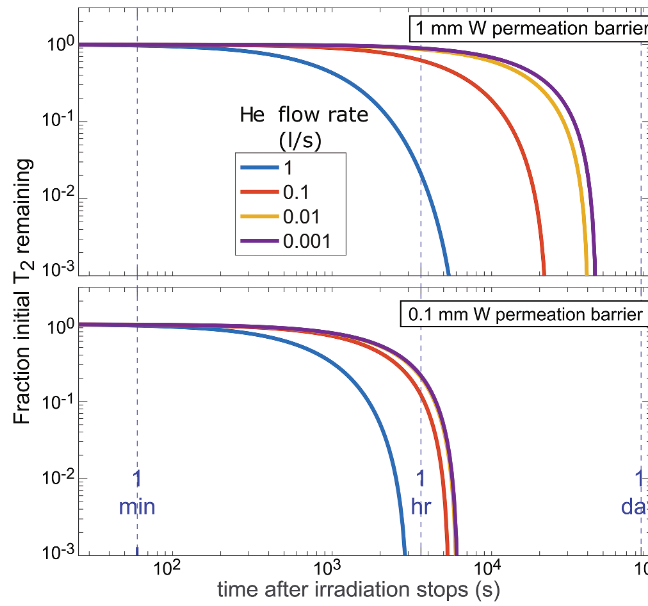


Fig. 8. Modeled T removal with variable FLiBe sparge rates and permeation thickness.

reactors) with TMAP (Tritium Mitigation Analysis Program, developed by INL) to model accident scenarios in fusion reactors and which was modified to include systems with FLiBe as the working fluid.[146] Note also that the T confinement and extraction pathways (e.g., sparging versus permeation) must account for the balance of T_2 versus TF expected in the system.[93,147] LIBRA will accomplish this using a similar setup to that used in the INTREXFLIBE experiments.[94,102,103,105] To distinguish between T_2 and TF, the exit gas split into two lines. Line 1 went to an aluminum reduction bed where condensable TF was converted to HT before being passed to an ionization chamber, so that all T measured in Line 1 was in HT form. Line 2 used a molecular sieve bed to capture all TF before passing the remaining gas to a second ionization chamber, which measured only the T that was in HT form when it left the salt. In this way, it will be possible to measure the ratio of HT:TF in the sparge and sweep gas exiting LIBRA.

IV.B. Tritium Chemistry

As detailed in Sec. II.A, there is a relatively small body of experimental work investigating T behavior in FLiBe. Literature values for the temperature-dependent solubility and diffusivity of hydrogen isotopes and their compounds (H_2, D_2, T_2, HF, DF, and TF) in FLiBe vary by several orders of magnitude,[148] making it difficult to develop analytic models of T behavior in a full-scale FLiBe breeding blanket. LIBRA will measure these values experimentally in LIB-relevant conditions and add to efforts to improve this data set (e.g., MSTTE at INL) (Ref. 149).

Tritium speciation depends on salt redox potential and impurities from corrosion or incomplete salt purification. The T_2:TF ratio in the FLiBe will be strongly dependent on the He/H_2 composition of the sweep gas.[105,141] When the concentration of He in the gas increases, the system is more oxidizing, and T_2:TF decreases. Adding sufficient amounts of H_2 to the sparge and sweep gas will ensure that the T in LIBRA forms T_2 and HT, which are less corrosive to structural materials[116] and easier to extract from the FLiBe than TF is. TF is $\sim 100\times$ more soluble than T_2 in FLiBe at 600 C (Ref. 108), and as a result, a low T_2:TF ratio leads to high system T inventory.[102] However, T_2 easily diffuses through many metals, making containment more challenging.

Studying the impact of FLiBe purity on the T_2:TF will be an important goal of LIBRA, per the description of initial experimental campaigns in Sec. II.B. While the effects of sweep/sparge gas composition have been well validated by prior experiments, data on the effects of impurities on T speciation in the FLiBe are lacking, and the FLiBe purification standard for a full-scale LIB is currently undetermined.

LIBRA will use corrosion-resistant W and Ni tank liners to minimize the confounding effects of structural material corrosion on the redox potential[150] in initial experimental campaigns. Impurities will be intentionally added to the salt in one or more QTs to assess their impact on redox control and T speciation. These data will be used to develop an initial FLiBe purification standard for use in the LIB: We must determine the initial minimum purity required from FLiBe suppliers and the level of online impurity control that the LIB must maintain. Since the MSRE, some groups have worked on improving FLiBe production and purification methods, but only in small volumes,[151–154] and opportunities for the commercial purchase of FLiBe are presently very limited. Development of a FLiBe purity standard for the LIB will help optimize the economics of the nascent FLiBe supply chain and enable the design of large-scale redox control systems for the LIB.

LIBRA will employ a Be redox control system. Redox control of FLiBe via addition of metallic Be has been well validated in smaller amounts of FLiBe (Refs. 92, 93, 112, and 119 through 124). LIBRA will also test more speculative methods for added Be redox control, such as adding beryllides that alter hydrogenic solubility in salts.[155] To a lesser degree, the ratio of HF:H_2 can also influence the redox condition.[156] The adequacy of the redox control system will be tested during initial T breeding experiments via active monitoring of salt conditions and posttest monitoring of material corrosion and salt chemistry.

LIBRA will enable better understanding of how these different factors—gas composition, FLiBe impurities, and Be addition—will impact LIB performance. Successful performance in LIBRA and in the LIB are indicated by a high global TBR, robust T accountancy, low T inventory, and minimized corrosion rates.

IV.C. Materials Considerations

It has been well established that high impurity levels in molten fluoride salts enhance corrosion of structural materials.[92,138,157] Redox and salt chemistry control can be used to minimize corrosion of materials in contact with the FLiBe. This will be an important design goal of the LIB, which is likely to have a greater variety of materials in contact with the salt.

There are very few corrosion studies available for common structural materials in pure FLiBe as the majority of nuclear materials work in FLiBe is concerned with fueled-FLiBe salts for molten salt reactors. Fueled FLiBe is far more corrosive than pure FLiBe, as the fissile compounds are essentially impurities. The majority of studies are static exposure tests in relatively small volumes of FLiBe, although there are limited experimental observations made from the Type 316 stainless steel and Hastelloy-N pipes in MSRE (Refs. 127 and 140) and from Hastelloy-N and Inconel 600 loops built at ORNL in the 1950s (Ref. 135) (although the latter used 71:29 LiF:BeF_2, not 1:1). Known weight loss and corrosion rate data are plotted in Fig. 9. It is difficult to make cross-comparisons between different data sets plotted in Fig. 9 due to variation differences in crucible material, sample surface area, FLiBe purification standards, and FLiBe volumes across experiments. In general, there is a significant need for materials compatibility studies in pure FLiBe. There is a larger body of work on compatibility testing in other fluoride salts (e.g., FLiNaK; see Ref. 157) that can be used to make informed decisions about how a given alloy is likely to respond to FLiBe.

However, this lack of data will be a challenge for the design of the LIB, especially because exposure to the neutron fluence from the plasma is likely to further compound corrosion mechanisms. LIBRA is an opportunity to expand the experimental data on material compatibility in a large volume of high-temperature FLiBe. We will be able to report on the long-term behavior of the experimental

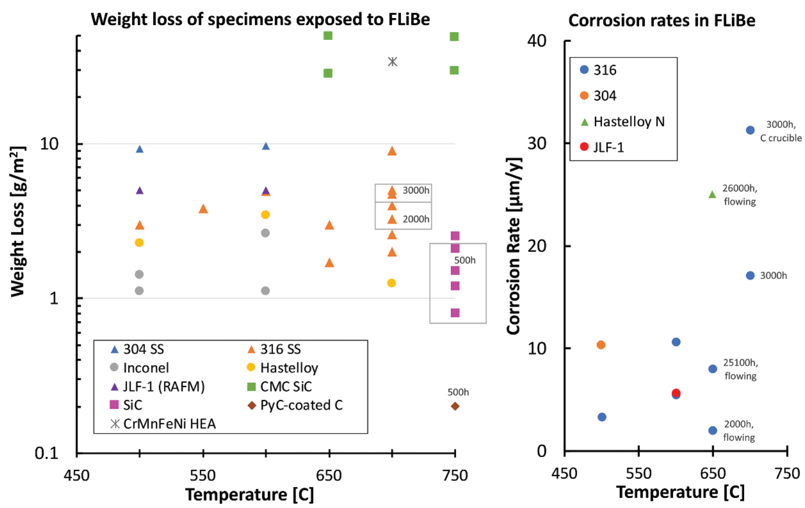


Fig. 9. Published corrosion data for materials in pure FLiBe are very limited and shown in these two plots. Exposure time is 1000 h, and tests were static unless otherwise noted. Crucibles were generally made of the same or similar materials to the samples. SiC and PyC-coated C used Mo capsules; CrMnFeNi high entropy alloy (HEA) used Type 316 stainless steel. (a) Weight loss citations in inset—Type 304 stainless steel: Ref. 131; Type 316 stainless steel (316, 316 L, and 316 H): Refs. 131, 132, 134, 138, and 160; Inconel (600 and 625): Ref. 130; Hastelloy (C-276 and N): Refs. 130 and 140; JLF-1, a reduced-activation ferritic-martensitic steel: Ref. 129; CMC SiC, SiC, and PyC-coated Si: Ref. 161; CrMnFeNi HEA: Ref. 137. (b) Corrosion rate citations in inset—Type 304 stainless steel: Ref. 131; Type 316 stainless steel: Ref. 130; JLF-1: Ref. 129; Hastelloy: Ref. 130.

structural materials (e.g., tank lining, gas line fittings) exposed to the FLiBe over a range of environmental and redox conditions. After initial T breeding goals are attained, one or more quarter tanks can be assigned to coupon exposure tests for materials under consideration for FLiBe-facing components in a LIB-equipped FPP.

IV.D. Tritium Accountancy

Robust T accountancy requires certainty in modeled and measured T. High-fidelity validation of T production, transport, and extraction is necessary to realize the techno-economic advantages of the LIB detailed in Sec. V.

For every experimental run, T breeding will first be modeled neutronically using OpenMC or MCNP. A detailed computer-aided-design model of the finalized LIBRA design will be built for use in these neutronics computations. However, OpenMC and MCNP rely on nuclear cross-section libraries with inherent uncertainties (typically 5% to 10%) (Ref. 158). It is beyond this project's scope to eliminate library uncertainties, but high-fidelity models of LIBRA will be developed and refined to minimize uncertainties in neutronics studies. Experimental uncertainties in T measurements will be influenced by T speciation and subsequent transport throughout the device, which are affected by interactions between the T, the salt, and structural materials. Tritium will be monitored through three containment layers (inner tank wall, outer tank wall, and LIBRA enclosure) to fully capture all T bred in the system using the detection systems described in Sec. II.B. Experimental uncertainties are also likely to arise due to the sensitivity limits of available T diagnostics. The LIBRA T breeding experiments will help us better understand these limitations. This information will aid in the development of novel T diagnostics that can be validated in LIBRA and scaled up for use in the LIB. For example, LIBRA will be used to test new designs of permeator probes (comprising a thin tube that carries sweep gas to a permeator window) that could allow for spatiotemporally resolved measurements of T concentrations as well as more rapid T extraction. Scintillation-based detectors for in situ measurements of T in the FLiBe will also be designed and tested as a means of providing direct, real-time T breeding data.

V. IMPACT OF THE LIB

LIBRA will rapidly advance the TRL of the FLiBe-based LIB, which itself is beneficial to FPP economics, operation, and regulation. Here, we consider the motivation for the LIB—and thus of LIBRA—more fully.

V.A. Benefit 1: The LIB Enables a Smaller, High-Power-Density FPP

The LIB can achieve higher TBRs than other blanket designs at a smaller blanket size. This reduces the accumulated radial build of the plant from the fusion core outward (plasma-facing wall to magnet shield), which improves performance in tokamak FPPs. This is illustrated in Fig. 10. To first order, the engineering power density $(P/V)_{Eng}$ (where P is power and V is volume) scales inversely with blanket thickness Δ_{Bl}. Conventional solid breeder blankets have $\Delta_{Bl} \sim 1.5$ m, measured from the first wall to the magnet shield. The improved moderation and breeding capabilities of the LIB enables a 50% reduction in Δ_{Bl} to 0.75 m.

V.B. Benefit 2: Less Costly, Easier Replacement of Major FPP Components

High heat fluxes and radiation fields on near-plasma components will require replacement during the FPP's operating lifetime. Conventional designs will likely require replacement of blanket components, as they are integrated with the first wall. Alternatively, the LIB minimizes blanket component replacement with a separable first wall. Since it is a liquid, it does not sustain radiation damage, and Li depletion will not significantly impact T production rates over the operating lifetime of an ARC-type FPP. In FPP designs where the VV is a lifetime component and the blanket components are internal to the VV, the blanket is replaced during maintenance periods, constituting $\approx 70\%$ of the solid material in the radial build of the plant. By combining the VV with the first wall, the FLiBe and FLiBe tank material are considered lifetime components. The VV-FW is replaced during maintenance, corresponding to $< 20\%$ of solid material in the radial build (see Figs. 1b and 10). Because the LIB is entirely liquid, it can be pumped out to holding tanks during maintenance to enable VV removal and replacement. This also opens up design constraints on the VV-FW because it needs to maintain performance only for its component lifetime, and not the FPP lifetime.

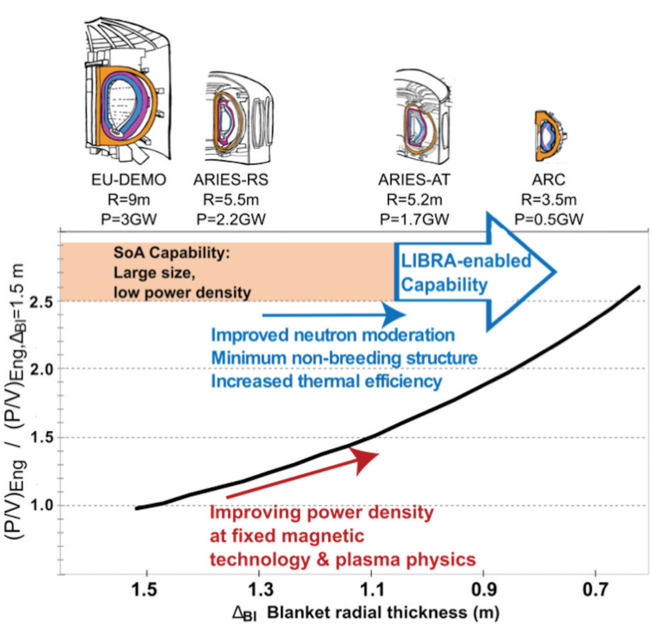


Fig. 10. Power density achieved for core engineered components (magnet and blanket), normalized to blanket thickness Δ_{Bl}=1.5 m. Example FPP designs, with the locations of the toroidal magnets (orange), VV (pink), and blanket (blue) indicated in color, are depicted above at the appropriate Δ_{Bl}. Images based on schematics from EU-DEMO (Ref. 162); ARIES-RS (Ref. 163); ARIES-AT (Ref. 164).

V.C. Benefit 3: Higher Temperatures Reduce LCOE

Higher operating temperatures and thermal efficiencies η_{elec} reduce the levelized cost of electricity (LCOE) associated with fusion power. An FPP with a FLiBe LIB will inherently have a high operating temperature due to the high melting temperature of nonpressurized FLiBe (> 450°C). LIBRA can operate over the same temperature range as the LIB (≈ 500°C to 800°C), which corresponds to $\eta_{elec} \approx$ 38% to 48%, as plotted in Fig. 11. Outlet temperatures associated with conventional blankets (≈ 200 C to 650 C) correspond to $\eta_{elec} <$ 20% to 45%.

V.D. Benefit 4: Lower Tritium Inventory Reduces Licensing Burden

A high TBR must be balanced against the need to minimize T inventory. This ensures safe plant operation and ease of licensing and siting. Conventional blanket concepts have longer T recovery times than the LIB, which increases site inventory. If the site inventory exceeds 1 kg, there will be more intense restrictions on the allowable T losses throughout the FPP. If acceptable T release is limited to 1 g, FPPs with conventional state of the art blankets (10 kg of on-site T at any given time) would have to design the plant such that $< 0.01\%$ of the T inventory was released annually, which will likely be a difficult standard to meet. An ARC-type device with a LIB breeding blanket would have a T inventory of ≤ 0.1 kg, meaning that the plant would be designed for $< 1\%$ T loss. The LIB aims to have a rapid T cycle (breeding $\rightarrow$ recovery $\rightarrow$ reinjection) that minimizes T inventory on-site at any given time.

The total amount of releasable T on-site also dictates the minimum distance from the tokamak to the FPP site

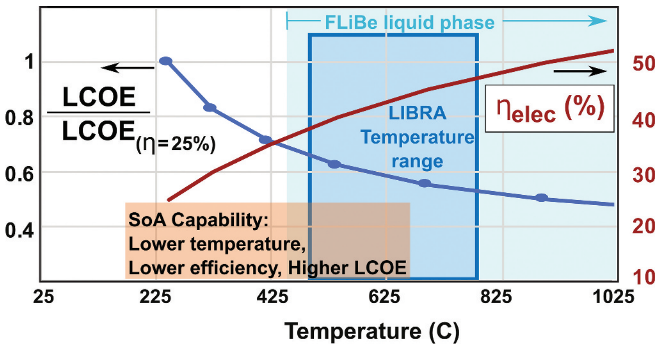


Fig. 11. Relative LCOE of FPP and electrical conversion efficiency η_{elec} versus operating/outlet temperature.[165] The LIB (darker blue window) enables higher η_{elec} and decreased LCOE relative to SoA conventional blankets (orange window).

boundary. For site inventories of just a few kilograms of releasable T, the site radius becomes approximately kilometers under conservative accidental release scenarios.[159] This makes it very difficult to site FPPs near population centers where power demands are highest. The smaller inventory associated with the LIB eases constraints on siting.

V.E. Benefit 5: Shorter T Inventory Doubling Time for Faster Market Penetration

Rapid T recovery, high TBR, and low overall inventory mean that the LIB-enabled FPP can produce its own T fuel and enough excess T fuel to start a second FPP in < 2 yr without incurring extreme regulatory burdens. This fast doubling time is necessary if fusion power is to be relevant to decarbonization efforts in this generation (Fig. 1b). For 0.5-GW ARC-type, LIB-equipped FPPs, the upper limit on possible generating capacity by 2050 is > 1 TW, roughly 6% of projected world electricity production capacity and a $1000\times$ increase over what is possible with conventional blankets.

The economic and regulatory benefits of the LIB relative to conventional blanket designs are summarized in Table IV and further detailed in Fig. 12. Figure 12a plots the initial startup T inventory as a function of the TBR for DEMO, ARIES-AT, and the proposed ARC. The LIB-equipped ARC has a startup inventory that is seven to nine times lower than that of DEMO and four to five times lower than that of ARIES-AT. By achieving a higher TBR and a faster T recovery time, the LIB (as validated by LIBRA)

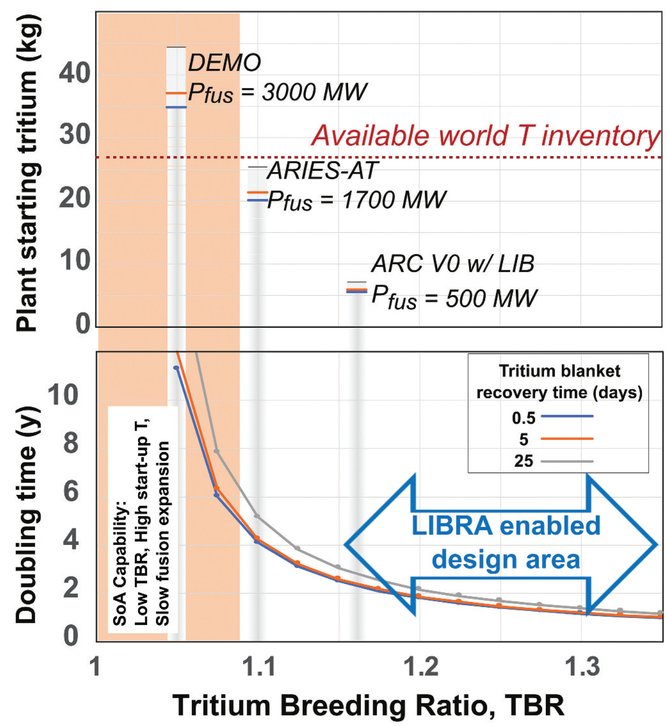


Fig. 12. Aggressive TBR designs are required to accelerate the fusion energy economy. Shown are the FPP T performance versus TBR and T blanket recovery time. (a) Required starting T for various plant powers: DEMO (Ref. 166); ARIES-AT (Ref. 164); ARC (Ref. 5). Smaller FPP size and lower required startup inventory provide more margin before consuming the world's supply of T. (b) FPP T doubling time.

TABLE IV

Conventional Versus LIB-Enabled FPP*

	Conventional	LIB Enabled
First plant T cost	~\$1 billion	~\$0.1 billion
Starting T inventory	> 5 kg	< 1 kg
Tritium doubling time	> 5 years	< 2 yr
Generating capacity in 2050	~10 GW	~500 GW

*Conventional FPP (DEMO-class tokamak, Li ceramic blanket) versus LIB-enabled (ARC-class tokamak, FLiBe LIB). Assumes the first 1-GW(electric) FPP starts in 2030 and the fusion power industry is growth-limited only by T fuel supply.

achieves a much faster doubling time and lower startup inventory.

VI. CONCLUSION

LIBRA is the key to showing that high TBR and rapid T recovery times can be achieved in an experimentally simulated LIB environment. The FLiBe-based LIB has a higher TBR and shorter doubling time than any conventional blanket design while still minimizing total plant inventory. However, FLiBe T breeding research has stagnated, and there are many open research questions that must be addressed, quickly, in order to make the LIB relevant to the nascent fusion power industry by 2030. LIBRA is a time- and cost-efficient way to launch this process.

In the near term, detailed engineering plans of the LIBRA facility will be completed. Before LIBRA is completed, small-scale FLiBe experiments will be carried out in parallel with the preparation work to establish safe handling procedures and validate equipment. We plan to share these results as well as progress on the LIBRA facility construction as we move toward the first LIBRA Phase I experimental campaigns.

In the longer term, the LIBRA facility will be modified to pursue more ambitious scientific goals. The tanks will be expanded to accommodate larger FLiBe volumes, and a higher-fluence neutron source (up to 5×10^{13} n/s, currently under development) will be installed. LIBRA Phase II (Fig. 5) will aim to achieve higher T breeding rates and a TBR of > 1.3. Methods to verify continuous, volumetric T breeding and recovery will be validated and refined. Eventually, LIBRA will provide the foundation for the design of a LIB test blanket module for installation on a burning D-T plasma device.

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