



Analysis of heavy liquid-metal coolants

Daniel de Souza Gomes¹

¹*dsgomes@ipen.br, Av. Prof. Lineu Prestes,
2242 - Butantã, São Paulo - SP, 05508-000*

1. Introduction

Lead-cooled fast reactors (LFRs) may have an advantage in the public's acceptance of fast reactors, even though sodium-cooled reactors are a far more developed and standard technology. Many nuclear research centers worldwide are developing fast reactor designs using heavy liquid metal coolants (HLMC), such as pure molten lead or lead-bismuth eutectic (LBE) alloys. In contrast, corrosion causes a drawback that attacks fuel cladding and structural materials [1].

The advantages of HLMC are its extremely high boiling point, its chemical inertness in contact with air or water, and its ability to employ natural circulation. Thus, over time, the number of countries creating liquid metal reactors has increased, including Russia, China, the European Union, and the USA. In the 1950s, American research considered that Pb-Bi-cooled fast reactor designs had been abandoned in favor of sodium (Na) and sodium-potassium (NaK) cooling. Russia has dominated the world in lead-cooled reactors since the first naval reactors were built in the 1960s. Thus, the LFRs are a promising technology for producing electricity and hydrogen and managing actinides in a closed fuel cycle, according to the Generation IV International Forum (GIF).

In 2015, the European Sustainable Nuclear Industrial Initiative (ESNII) consortium started to advance at least three designs. The first is the Multi-Purpose Hybrid Research Reactor for High-Tech Applications (MYRRHA), an accelerator-driven system (ADS) achieving 600 MeV linear acceleration cooled by lead-bismuth eutectic (LBE). MYRRHA has a subcritical core coupled to a proton accelerator dedicated to radioisotope production for medical and industrial applications [2]. The ESNII consortium also supports the Advanced Lead-Cooled Fast Reactor European Demonstrator (ALFRED). ALFRED is a pool-type reactor with an electrical capacity of 125 MWe, operating with molten lead in a temperature range of 400 to 480 °C [3]. Table I depicts a few projects developing lead-cooled reactors and their characteristics.

Table I: Characteristics of lead-cooled reactors.

Reactor	BREST-300	ALFRED	CLEAR-I	Westinghouse LFR
Design	4-Loops	Pool-type	Pool-type	Pool-type
Power (MWe)	300	125	4	450
Coolant	Lead	Lead	LBE	Lead
Inlet temperature (°C)	420	400	260	420
Outlet temperature (°C)	535	480	390	650

2. Methodology

The comparative method of studying reactors that operate compared to heavy metal coolants explores their physical properties, such as density, thermal conductivity, specific heat capacity, and heat exchange correlations. The physical properties of liquid metal coolants, such as sodium, lithium, and lead, are also necessary for eutectic alloys of sodium-potassium, lead-lithium, and lead-bismuth.

Early on, the LMFRs used mercury as a liquid metal and then discovered that sodium and lead showed advantages compared with mercury. The Russian Federation's golden age of liquid metals happened from the 1950s to the 1970s. Russia built and operated Project 705 in service from 1971 into the early 1990s, following other (Pb-Bi) reactors based on NATO-named "Alpha" class submarines.

Thus, Russia's experience spans over seven decades. The impact of the Cold War induced several countries to study metal coolants such as lead, Pb-Bi alloy, lithium, cesium, and Na-K alloy early on. Compared with other coolants (gas, water), liquid metals have two significant benefits: low pressure in the system (owing to their high boiling point) and high thermal conductivity because of their electron conductivity. Then, the proposed concept of a pressurized water lead-bismuth-cooled fast reactor (PLFR) was based on the previous LFR concept.

The Westinghouse Lead Fast Reactor (LFR) is a liquid lead-cooled fast neutron spectrum reactor with a ~465 MWe capacity. It is elementary, passively safe, and scalable. After the first few years of operation and testing, the Westinghouse initiative started with the PLFR unit.

The US Advanced Nuclear Systems Plan focused on lead-cooled reactors. Then, the Argonne National Laboratory built the Small Secure Transportable Autonomous Reactor (SSTAR). In 2008, the SSTAR model included a sealed reactor core, which would use rails or ships to move. SSTAR has worked with UN fuel and LBE and has a lifespan of over 30 years. The 10 MWt China Lead-Based Research Reactor (CLEAR-I) conceptual design operated in 2014. It can have critical and subcritical dual-mode operation, comprising Generation IV lead-cooled fast reactor technology and the ADS transmutation system. CLEAR-I employed lead-bismuth eutectic as the primary coolant.

A power LFR system ranges from 50 to 150 MWe, employing a modular system from 300 to 400 MWe or even a monolithic plant producing 1200 MWe. The fast neutron spectrum permits net breeders, net burners, or the use of standard fuels. Besides, molten lead or lead-bismuth alloy coolants offer passive system implementation. Also, it permits modular reactors and fuel cycle flexibility for use within a closed fuel cycle. The boiling point for lead or lead-bismuth eutectic (LBE) is higher, showing a weight fraction of (Pb 44.5–Bi 55.5)% [4]. Other referenced alloys are PbLi (Pb 99.32-Li 0.6) wt.% and NaK (Na28-K78) wt.%. This characteristic offers an improved safety margin and the ability to operate at higher temperatures. Besides, lead alloys, like sodium, do not react exothermically with water [5]. Thus, the heat transfer correlations for HLMS depend on the Peclet number. Table II depicts the liquid metals used as coolants and their thermal properties at an operating temperature of 450 °C for the molten liquid phase.

Table II: Liquid metal fluid properties.

Physical properties	H ₂ O	Na	NaK	Pb	LBE	PbLi
Melting point (°C)	0.0	97.8	-12.6	337	125	235
Boiling point(°C)	100	882	784	1748	1654	-
Liquid density (g/cm ³)	0.9971	0.8558	0.759	10.580	10.195	9.326
Thermal conductivity (W/m K)	0.670	72.36	26	16.6	13.12	51
Heat capacity (J/kg °C)	4182	1282.4	873	146.7	142.9	175
Kinematic viscosity(mm ² /s)	0.15	0.32	0.24	0.21	0.89	0.13
Prandtl number	6.137	0.0049	0.0063	0.0197	0.0165	0.027

ADS like MYRRHA deliver environmental gains using the boiling point of over 1650 °C and the low Prandtl and Peclet numbers from LBE. However, in ADS systems containing polonium, alpha decays 210Po from 210Bi. Under development, the Russian reactor BN-1200 represents a sodium-cooled fast breeder project to produce 1200 MW at a temperature of 410 °C. Other plans include the Japan Sodium-cooled Fast Reactor (JSFR) with 750 MWe operating at 550 °C and the China Fast Reactor 600 (CFR-600) with 600 MWe. However, the SFRs need an intermediate heat exchanger between the reactor core and steam generator because sodium reacts violently with water.

While SFRs have worked with sodium, eutectic sodium-potassium (NaK) is attractive because it is liquid at room temperature. In the 1980s, the Russian Radar Ocean Reconnaissance Satellites used NaK as a coolant, spreading NaK droplets in space. Figure 1 depicts metal liquid density and thermal diffusivity. Figure 2 displays the thermal conductivity and heat capacities of a few liquid metals.

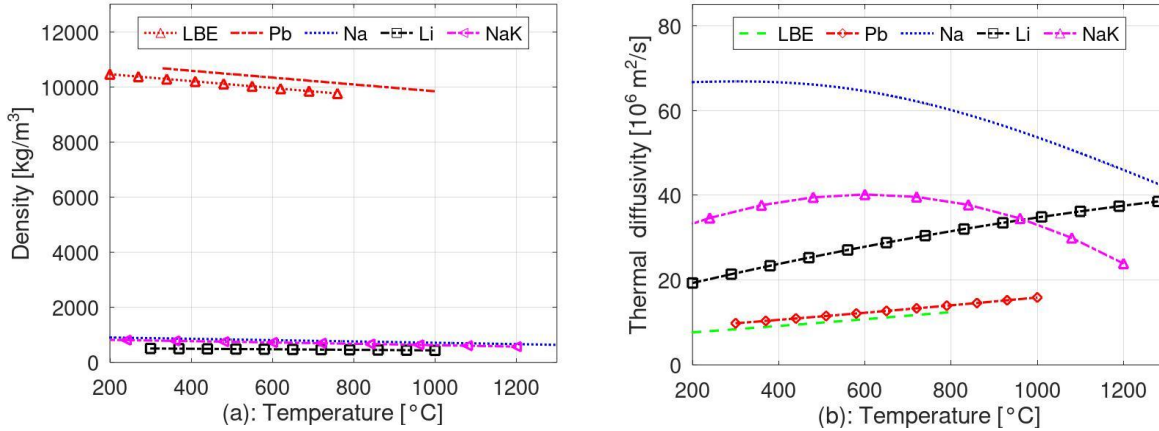


Figure 1: (a) density of liquid metals and (b) thermal diffusivity of a few liquid coolants

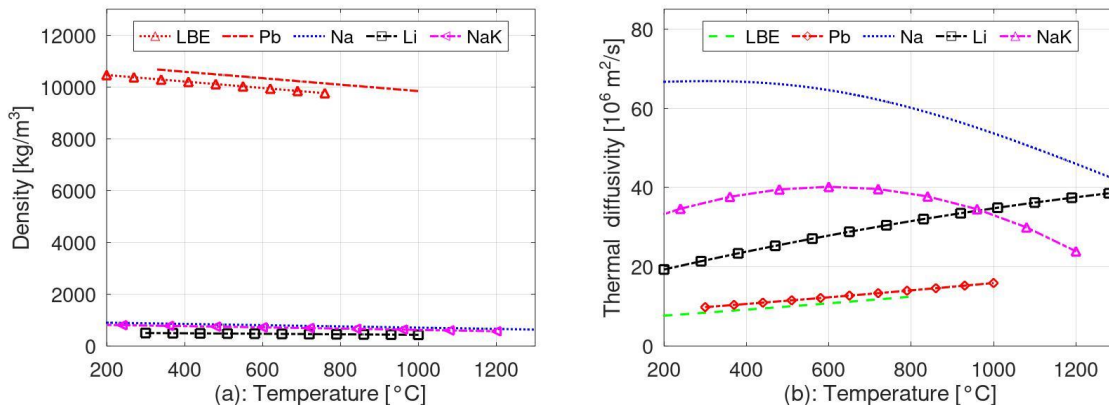


Figure 2: Liquid metals (a) thermal conductivity and (b) heat capacity

In America, the code tools for HML employed are the Multiphysics Object-Oriented Simulation Environment (MOOSE) and RELAP5-3D, with the addition of the ATHENA module. Europeans have used the French system to analyze thermal hydraulics during an accident at a reactor and for safety evaluation (CATHARE). Meanwhile, Germany uses the Analysis of Thermal Hydraulics of Leaks and Transients (ATHLET) to simulate HML.

3. Results and Discussion

A cost analysis of nuclear units must consider many factors, including thermodynamic cycles and coolants, such as light water (H₂O), heavy water (D₂O), helium, carbon dioxide (CO₂), and liquid metals. Liquid metals comprise alloys with low melting and high boiling points through eutectic compounds in the liquid phase at room temperature. Also, HLM is more adaptable for fast-breeder reactors and ADS. HLM has a good heat transfer capability and can operate near atmospheric pressure.

However, fast reactor designs that need HLMC, such as Pb, LBE, Na, and NaK, depend on a low neutron cross-section and lower moderation power, permitting a breeder ratio greater than one.

HLM convective heat transfer shows results from small values for the Prandtl number for liquid metals (<0.1). The Prandtl number for HLM is near zero. The Nusselt number depends on the Peclet number for a zero Prandtl number. Nusselt varying from 0 to 3000; the Peclet number shall vary from 5 to 27. Figure 3 depicts kinematic viscosity and the Prandtl number for HLM.

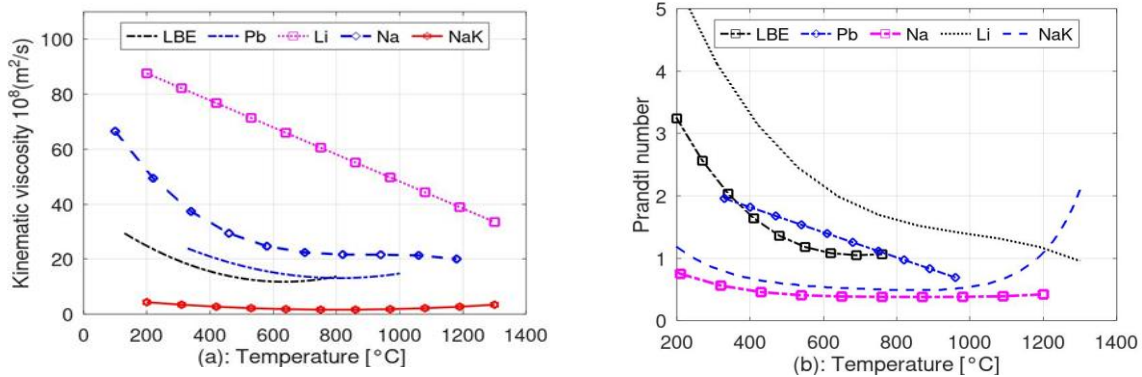


Figure 3: Heavy liquid metals: (a) Kinematic viscosity and (b) Prandtl number.

4. Conclusions

Today, metal-cooled reactors are one of the most promising for the evolution of the world's nuclear power. Early propulsion submarines operated at low-capacity factors and lower temperatures than GIF designs. Naval submarines worked an epithermal (not fast) neutron spectrum. Several designs are being developed using lead, such as ALFRED and BREST reactors, lithium-beryllium alloys adopted in MYRRHA, and CLEAR-I. Besides, many fuels, such as UO_2 , $(\text{Pu-U})\text{O}_2$, metallic, and nitride fuels, are possible. The LBE option should be avoided, and the less corrosive properties of Pb help the use of high-temperature materials, corrosion-resistant materials such as silicon carbide composites, self-passivating steels, and outer layers (SiO_2 or Al_2O_3)

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