# Material Compatibility with LIQUID METAL and mitigation strategies: Removal of activation corrosion product

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The compatibility of solid materials with liquid metals is an important research field towards the development of fission and fusion reactors alike. Corrosion is a complex phenomenon which includes different mechanisms and depends on many parameters of the fluid. In particular, fluid temperature has a big impact on the corrosion rate as the solubility of alloying elements in the fluid increases with it (Figure 1, Figure 2). Liquid metals generally present high solubility to common alloying elements of steels, such as chromium, nickel, aluminium, silver and copper. These impurities can precipitate in the coldest spots of the system where their solubility decreases and they can form plugs that can reduce the flow. Moreover, these elements can be activated under neutron irradiation, contributing to the Operational Radiation Exposure and increasing the radioactive inventory that can be mobilized in case of accident.

Moreover, the corrosion products solubilised in the liquid metal can precipitate in the cold part of the reactor and produce an increase of pressure drops with impact on the performance of the main components.

Therefore, strategies to mitigate corrosion and remove the corrosion product have to be conceived and put in practice. The common approach for fission and fusion systems is to use a combination of these techniques:

* using corrosion resistant materials and low activation materials;
* minimizing the corrosion rates by controlling the liquid metal chemistry;
* reducing liquid metal velocity and temperature (when possible);
* purifying the liquid metal;
* depositing a protective coating on the exposed surfaces.

This work focuses on the control of lead and its alloys chemistry: pure lead and Lead-Bismuth Eutectic (LBE) are candidate coolants for the so-called fourth generation of fission reactors, while LiPb is used as breeder materials in several concepts of Breeding Blankets for fusion reactors (e.g. the Water-Cooled Lithium Lead).



Figure 1: solubility of several elements in LBE [1].

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Figure 2: solubility of chromium, nickel and iron in lead, lithium and lead-lithium alloy [2].

For fusion applications, the reduced activation ferritic/martensitic (F/M) steel EUROFER is currently considered the reference structural steel for LiPb breeding blankets in the future European DEMO reactor. Its application requires a better understanding of material compatibility related to physical/chemical corrosion phenomena in the 450-550°C temperature range. The impact of corrosion includes deterioration of the mechanical integrity of the blanket structure due to the wall thinning. Furthermore, serious concerns are associated with the transport of activated corrosion products (ACP) by the LiPb coolant. The current EUROfusion approach foresees the use of alumina coatings to protect EUROFER from the aggressive LiPb environment in the future DEMO reactor [3].

In fission, instead, in parallel to the adoption of corrosion resistant materials (Ferritic/Martensitic Steels, also in the Oxide-Dispersion Strengthened version, vanadium alloys, refractory materials), the use of stainless steels is still under consideration by implementing a strict control of the oxygen concentration in the lead alloys. Indeed, a protective continuous oxide layer can form at certain oxygen concentrations. Concentrations below this threshold would not be able to prevent the dissolution of the alloying elements, while a content of oxygen higher than the solubility limit would oxidize the coolant itself [4].

However, the research in both fusion and fission is also investigating the removal of corrosion activated products with a purification system. This system is essentially composed by a cold trap (*CT*) [5] consisting in a heat and mass transfer device, where a supersaturated solution of impurities is generated as the result of LiPb cooling, causing the crystallization of the impurities both on the immovable surfaces and in suspension. The principle of the *CT* is to maintain the impurity equilibrium concentration in the loop below the LiPb solubility at lowest temperature (*Tlow*) foreseen in the plant (*Tct* < *Tlow*). Such an apparatus has the purpose of collecting the impurities generated during the operation, avoiding therefore, the corrosion products precipitating in the loop.

For a generic system solute/solvent system with a source term and provided with a purification apparatus, the impurities concentration *C(t)*, in ppm, can be obtained from a balance equation:

  (1)

where *M* is the LiPb total mass in the system (kg),  is the mass flow in the *CT*,  the *CT* efficiency and *C∞* the asymptotic concentration (t🡪∞) defined as:

  (2)

where *S* is the source term (g/s),  represents the iron solubility at the minimum *CT* temperature, *Tct* (being the iron the main component of F/M steel). Concerning the *CT* efficiency, it can be generically defined as:

  (3)

and in an initial assessment, it is assumed to have the same form of the *CT* efficiency defined for the sodium purification system:

  (4)

where τ represents the fluid resident time (min) in the *CT* and *p, q* are coefficients set equal to 122 and 3.4 respectively for sodium *CT* [6]*.* The appropriateness of such a correlation for LiPb corrosion system should be evaluated experimentally with chemical analysis of LiPb sampling upstream and downstream the *CT*. Referring to the schematic of Figure 3. The following thermal balance can be written:

  (5)

then,

  (6)

From eq. 6 it is possible to derive the mass flow rate repartition through the *CT*.



Figure 3: Mass flow rates repartition and temperatures

Finally, once fixed the residence time and the mass flow rate through the *CT* through Eq. 7 it is possible to derive the volume of the *CT*:

  (7)

Available experimental data on the corrosion rate for F/M steels in flowing LiPb show a large dispersion, predicting values at high temperatures (450-500 °C) from 5 µm/y to a few hundred µm/y [7]. The same issue is observed for the solubility of iron in LiPb: data from different correlations are affected by a dispersion of several order of magnitude [8]. Moreover, detailed information about experimental conditions, such as the LiPb flow velocity and the amount of impurities dissolved in the LiPb alloy, are often missing. This lack of data precludes also a rational design of a LiPb purification system affecting the impurities source term *S* in Eq. 2 and the maximum solubility value  above which precipitation occurs (Eq. 2).

The plots reported in Figure 4-Figure 7 show the variation with temperature of density and specific heat [9], which are the two properties that influence the cold trap design, for lead alloys and their percentage difference. With the exception of the specific heat of LiPb, which is about 30% higher than that of lead and LBE, these properties are similar for the alloys, allowing to extrapolate many results on cold trap testing and design.

Many facilities are being used to further investigate this topic. Among them, COSTA [10], CORRIDA [11] and PICOLO loop [12][13] at KIT (Germany), LECOR [14], BID1 [14] and IELLLO [15] at ENEA Brasimone (Italy), CRAFT [16] at SCK-CEN (Belgium), OLLOCHI [17]at JAEA (Japan) are used to investigate corrosion in static or flowing lead, LBE or LiPb. COSTA and CORRIDA are also used to investigate oxygen sensors and oxygen control. Cold traps are under investigation in CRAFT facility and in the frame of FP9 EUROfusion project at CV Rez in the MELILOO loop [18].

Moreover, numerical codes, such as OSCAR [19] and PACTITER [20], are under development and validation to predict the amount of Activation Corrosion Products and their transport in the loops.

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| C:\Users\admin\Desktop\Revisione di letteratura strumentazione Pb\Density_HLM.emfFigure 4 Comparison between HLM density | C:\Users\admin\Desktop\Revisione di letteratura strumentazione Pb\Comparison_Density_HLM.emfFigure 5 Percentage difference between densities |
| C:\Users\admin\Desktop\Revisione di letteratura strumentazione Pb\Specific_heat_HLM.emfFigure 6 Comparison between HLM specific heat | C:\Users\admin\Desktop\Revisione di letteratura strumentazione Pb\Comparison_Specific_heat_HLM.emfFigure 7 Percentage difference between specific heat |

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