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# Conceptual aspects of melting unit vessel cooling by heavy liquid metal coolant

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**Abstract**

The article presents a conceptual analysis of the feasibility of lead–bismuth coolant application for cooling the melting unit steel vessel designed for implementation of a new efficient radwaste reprocessing technique. In support of the lead–bismuth coolant feasibility, the main advantages and specific features of its application are presented, taking into account significant experience acquired in Russia in handling this coolant (nuclear submarines reactor units and circulation loops), availability of job-proved methods and equipment for the coolant quality control, coolant properties ensuring fire and explosion safety and heat removal capability under high temperature and low pressure conditions. Preliminary calculated estimates were made as for temperature distributions during lead–bismuth cooling of the melting unit steel vessel. Calculations were made for the melting unit normal operation, in the presence of refractory coating and slag lining of a certain thickness formed on the vessel inner surface.

Based on the results of the calculated temperature distribution estimates, it can be concluded that lead–bismuth cooling of the melting unit steel vessel in normal operation (i.e. in the presence of refractory coating and slag lining on the vessel inner surface) provides an opportunity to maintain steel surface temperatures which do not exceed the limits at an acceptable flow rate. Data presented in this article have been obtained for the first time and may be useful in designing melting units for radwaste reprocessing.


*Keywords:* Liquid metal coolant; Steel vessel; Heat removal; Melting unit; Surface; Calculation; Lead–bismuth; Temperature.

## Introduction

Currently, new and more efficient technological schemes for radwaste reprocessing are under development in Russia. One of the trends in this respect is the creation of melting units for low and medium metal radwaste reprocessing [1,2]. The melting unit is supposed to use the melting chamber steel vessel with liquid metal cooling. The authors examine the conceptual aspects of the feasibility of lead–bismuth coolant application for the melting unit steel vessel cooling.

The lead–bismuth coolant is efficient in removing heat at high temperatures and low pressures. Due to a high boiling temperature (~1670 °C), its application practically eliminates the heat removal crisis and hazards associated with steam explosions. This coolant is flame-/explosion-proof because of its chemical inertness with respect to water and air, and has a relatively low melting point (~125 °C).

As of today, the lead–bismuth coolant management technique has been mastered which is confirmed by a significant experience acquired in Russia in safe operation of submarine lead–bismuth cooled reactor units and their on-shore test facilities [3,4], long-term operation of research non-isothermal circulation loops, and application of this coolant for new generation fast breeder reactors [5,6].

Based on the existing experience in using the lead–bismuth coolant as well as methods and equipment of its quality control, the authors think it highly advisable to consider

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lead–bismuth cooling of the melting chamber steel vessel for the projects of advanced melting units.

## Lead–bismuth coolant usage specifics

One of the main advantages of the lead–bismuth coolant is a lack of energy release during its chemical interaction with air and water. It is well known that heavy liquid metal coolants, including lead–bismuth, have the lowest stored potential energy in comparison with other coolants [7]. Other things being equal, the higher the value of the coolant stored potential energy, the greater the likelihood of a severe accident and the harder its consequences are. Thus, when the lead–bismuth coolant is used, it ensures safety of the facility by eliminating the very causes of coolant-related severe accidents.

The specifics of the lead–bismuth coolant usage in circulation loops include the following:

(1) Maintaining the specified oxygen potential in the coolant to prevent erosion-corrosion damage to structural steel at a long-term operational lifetime (thousands of hours).
(2) Ensuring cleanliness of the coolant and circulation loop surfaces in order to maintain the design thermal-hydraulic characteristics throughout the operating period.

Up to date, the operating temperatures for the lead–bismuth coolant are within 650 °C, at which the long-term experimental studies have proved the possibility of ensuring the corrosion resistance of steels exposed to the coolant [8].

The specialists of the JSC “SSC RF-IPPE” developed a technology providing corrosion protection of steels and produced equipment for its implementation in various circulation loops including those of nuclear reactors [9,10]. This technology provides conditions in the coolant for forming protective coatings on the structural steel surfaces and ensures their integrity in operation. This is achieved by maintaining the specified oxygen potential in the coolant.

If the lead–bismuth coolant contains dissolved oxygen, protective oxide films are formed on the steel surfaces of the liquid metal circuit and equipment due to lower lead oxygen affinity as compared with the main components of steel (iron and chrome). The oxide films have the following structure: $Me_xO_y$, where Me denotes Fe, Cr and other components of steel.

Due to its inertness to the coolant, good adherence to the steel surface, and the ability to ‘heal’ defects if the coolant contains dissolved oxygen, the protective oxide film prevents the structural steel surface from direct contact with the liquid metal coolant, ensuring the corrosion resistance of steel at a long-term operational lifetime. In this regard, today the ‘oxygen’ technology developed at the JSC “SSC RF-IPPE” is the main method for structural steel corrosion protection in the heavy liquid metal coolant environment, including the projects of advanced fast breeder reactors with heavy liquid metal coolants.

To control the oxygen dissolved in the coolant, the specialists of the JSC “SSC RF-IPPE” developed sensors based on solid oxide electrolyte [11] which are characterized by rapid response, high sensitivity, the ability to work for a long time at high temperatures and thermal shocks, reliability and stability of conductive and mechanical properties in a wide range of temperatures and oxygen partial pressures.

The best method for controlling the oxygen TDA in the coolant is a so-called solid-phase control method, which was also developed at the JSC “SSC RF-IPPE” [10]. Technical implementation of the solid-phase control method is carried out by means of special devices, i.e. mass-transfer devices with a solid oxygen source. Up to date, a considerable experience has been acquired in long-term operation of different mass-transfer devices at the test facilities with lead–bismuth and lead coolants which attests to their reliability, possibility of fine tuning the oxygen insertion rate and absence of negative effects on the loop as a whole [12].

The lead–bismuth coolant properties are such that its direct contact with ambient oxygen (during gas system filling or leakage or equipment repair) may result in solid-phase deposits based on the coolant oxides.

To eliminate the coolant oxide-based deposits, a special technological procedure is used, i.e. hydrogen purification [13] which results in the removal of eutectic components from the deposits. In this case, the deposits are destroyed whereas lead and bismuth are returned to the coolant. Hydrogen purification is carried out using the gas mixtures ‘hydrogen - water steam - inert gas (argon or helium)’. When hydrogen purification is carried out, the hydrogen-containing gas mixture is entered into the coolant flow, whereas slag recovery occurs simultaneously with a mechanical action of the two-component coolant flow, which completely solves the problem of effective cleaning of the circulation loop surfaces. The hydrogen purification method for circulation loops with heavy liquid metal coolants and equipment for its implementation was developed at the JSC “SSC RF-IPPE”.

The efficiency of removing deposits from the coolant and loop surfaces using hydrogen-containing gas mixtures has been repeatedly proven at submarine reactors and various research circulation loops with lead–bismuth and lead coolants. By now, several types of devices have been developed for gas mixture insertion into the heavy liquid metal coolant flow using which it becomes possible to provide efficient purification of circulation loops of various structures and coolant circulation patterns.

It should be noted that hydrogen purification is a rare procedure which is only required when a circulation loop has been polluted with solid-phase deposits. In cases where a circulation loop is operated with a full-pressure gas system, the coolant is not drained or the equipment is repaired, hydrogen purification is not needed.

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