Water-LiPb interaction study

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The water-lithium lead interaction implies a direct energy release, which leads to temperature and pressure increase, due to a combined thermal and chemical reaction, and an indirect form of energy release, the hydrogen production, due to secondary chemical reaction involving the initial reaction products. Review and understanding of the knowledge acquired in past studies, experimental works and numerical activities are needed in view of the renewed interest in the Water Cooled Lithium Lead blanket concept and safety issues connected with the fusion reactor design. This paper presents a review of the studies carried out in the past to characterize the potential safety concerns associated with the use of water and lithium-lead eutectic alloy and the main experimental campaign. As results, no code was found able to perform a satisfactory post-test analyses of separate effect experiments without engineering assumptions. Therefore, correlations that model the exothermic reaction and hydrogen production, and the availability of experimental data with more controlled initial and boundary conditions are needed for solving the WCLL blanket safety issues associated with the water-LiPb interaction.

Keywords: water, lithium-lead, SIMMER, WCLL breeding blanket, chemical reaction

1. Introduction

The breeding blankets will be key components of the fusion power plant and their limitations with regard to power density, thermal efficiency and lifetime could determine to a large degree the attractiveness of a power plant. In view of economically sustainable production of electricity, the design of an efficient and reliable balance of plant is a requirement for DEMO design, thus impacting on the choices of blanket coolant and materials. Therefore, as a risk mitigation strategy, it is seen as necessary to foresee the evaluation, and potentially, the development of different concepts of breeding blanket [1].

The Water Cooled Lithium Lead blanket concept has been recently reconsidered for evaluating if it could be a possible breeding blanket option for an early DEMO reactor [1]. It employs sub-cooled water flowing through the cooling tubes at high pressure, removing heat from the high temperature LiPb eutectic alloy maintained at atmospheric pressure [2].

Although the cooling tubes of reference WCLL blanket design for DEMO are double wall to decrease the probability of water leakage into the LiPb breeder, taking into account the number of cooling tubes in the blanket, the probability of water leakage or pipe break is still not negligible. As a consequence, the contact between water and liquid lithium lead alloy is a major safety concern in the design [3].

The paper is subdivided into four main parts. After the introduction, literature review including interpretation of results of past R&D activities is presented. The simulation of the BLAST experiment test No. 5 is reported in the third part with a description of the SIMMER-III model.

2. Literature Survey

Fusion safety tests with lithium-lead alloy breeder material have been conducted by US, i.e. Westinghouse Hanford Company [5], [6] and University of Wisconsin [3], [6], cooperatively with the EC at JRC Ispra [3], [7]. Alloy safety reaction tests [4], [7] were carried out to investigate and to characterize the qualitative behavior of the liquid lead alloy interactions. The performed tests showed that in case of eutectic lithium lead alloy [6] «…although the interaction may be benign in terms of energetics or mobilized radioactivity, hydrogen could be produced from the metal-water interaction.». Piet et al. [3] highlighted that the different contact mode of liquid metal water (i.e. liquid and steam) reactions makes experiments and modeling complicated and numerous. Considering the injection contact mode, the authors postulated that it «…falls into the broad general category of FCI…», including the possibility of vapor explosion, besides the chemical reaction.

The chemical reactions that should be considered as relevant are:

$$2Li + H_2O \Rightarrow Li_2O + H_2 + 186\frac{kJ}{mole\ of\ Li} \quad (1)$$

$$Li_2O + H_2O \Rightarrow LiOH + \frac{1}{2}H_2 + 204\frac{kJ}{mole\ of\ Li} \quad (2)$$

The rate of hydrogen production [8] is dependent upon the chemical kinetics of the reaction, for a known contact area. Experimental data showed that the reaction was a function of the range of initial liquid lithium-lead temperatures investigated, and of temperature achieved in the reaction zone. In particular, R&D activities reported in Refs. [7] and [9], and the experimental

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activities performed in BLAST facility [10] demonstrate that the H_2 production was higher for temperature above 450°C. For reaction temperature below 450°C, LiOH is formed preferentially. For temperature in the reaction zone beyond 450°C, Li_2O is the stable reaction product.

Several small scale tests were conducted at different lithium-lead temperatures, and water pressures [7]. They evidenced that the short-term reaction (~10 ms) is dominated by mixing and pressurization, whereas the long-term reaction is dominated by the chemical aspects. The amount of hydrogen generated was sufficient to blanket the lithium-lead and to reduce the heat transfer between the fluids, thus reducing the pressurization. The reaction went to completion and typically 40-60% of the water was involved in the initial short-term reaction.

A kinetics model was developed by Herzog [8] and extended by Biney et al. [11]. This model is based on the premise that the rate of reaction during the interaction is controlled by the rate of diffusion of lithium atoms and products (Li_2O or LiOH) at the liquid metal surface. Applications of the model showed a very rapid pressurization, a maximum pressure determined by the back pressure and a maximum temperature in the reaction zone equal to 900°C.

The investigations performed in BLAST facility were aimed to simulate large breaks of water tubes, which may occur in the WCLL blanket model for DEMO fusion reactor [6], [9], [10]. The pressure evolutions of BLAST tests evidenced similar trends: geometry and initial conditions mainly determine the behavior of the system and the pressure peaks.

Sardain et al. [12] set up a coarse mesh grid representing BLAST facility. The simulations were focused on the first pressure peak of the tests (few tenths of seconds) because, during this phase, the effects of the chemical aspects, not modeled by the code, affected less the pressure trend. SIMMER code reproduced properly in the experimental pressure peaks, but the fast high one in test n° 9 was not reproduced by the "standard" FCI model of SIMMER-III code. Thus, another approach [12] was used to simulate the fast high pressure peaks the experiment. This consisted in applying the Cigalon model, which is based on the theory and modeling developed for severe accident in light water reactors [13]. The results showed a reasonable prediction of the first peak of test n° 9, but an underestimation of the other cases.

LIFUS5 [14] experimental facility was designed to investigate the consequences of LOCA accidents in liquid metals pools and to operate in a wide range of conditions. Post-test calculations by SIMMER-III [15] code were carried out to assess the code performance in predicting the main parameter trends. The code simulations were performed considering an external energy source, due to the reaction with water, in the range of 5-20% of the maximum energy that can be generated if the overall water mass injected reacts with the lithium. With this engineering assumption, the simulation of the pressure trends are satisfactory from qualitative point of view.

3. Post-test analysis of BLAST test No. 5

BLAST Test No. 5 was chosen for performing the post-test analysis by SIMMER III code, after the review of Refs. [7], [9], [10], and [12]. Figure 1 shows the pressure time trends measured in the reaction, expansion and water-injection vessel during the Test No. 5 from 0 s to 6 s. It shows that the water pressure vessel decreases of about 10% of the initial value during the water injection. The pressures measured in the reaction and expansion vessels do not overshot the water injection pressure. The reaction vessel pressurization highlights the time of water entering in the reaction vessel: it is about 250 ms after the injection valve opening. Later, the pressure increases up to 40 bar in about 100 ms and decreases for 250 ms after that, due to the vent of the vapor and hydrogen in the expansion vessel, as evidenced by expansion vessel pressure increase. The pressure reduction occurs until the saturation pressure at the injection water temperature is reached, i.e. 25 bar. From this time on, the pressure rises simultaneously in the reaction and expansion vessels with a difference corresponding to the pressure drops in the expansion tube.

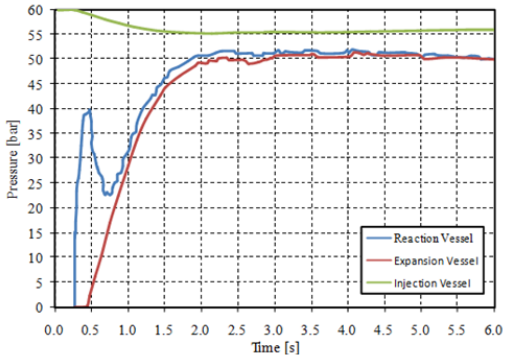

Fig. 1. BLAST test No. 5: pressure time trends in the water-injection, reaction and expansion vessel.

The numerical analysis of Test No. 5 [16] was performed modeling BLAST facility by SIMMER-III code. This version of the code is two-dimensional (R-Z) and axisymmetric. The nodalization models the reaction vessel, expansion tube and expansion vessel, as depicted in Figure 2. The geometrical domain is composed by 16 radial and 73 axial cells. The radial and axial dimensions have different scales to better depict the geometry of the model. A zoom of the injection region is available in the right of Figure 3.

Two main issues are identified in Refs. [7], [10], and [12], relevant for setting up the nodalization and for performing the post-test analysis: the definition of the filling level of the lithium lead, and the geometrical description of the water injection line, of the injector (e.g. length, diameter, curves, valves etc. of connecting pipes) and of the injection procedure. The level of lithium-lead eutectic alloy is an important initial

condition that determines the compressibility of the facility and affects the pressure transient behavior and the injected mass of water. The effect of the water system geometry was addressed performing a sensitivity analysis on the equivalent pressure drop in the injection line. The overall pressure drop is the result of the sum of three singular energy loss coefficients, see Figure 3 right side.

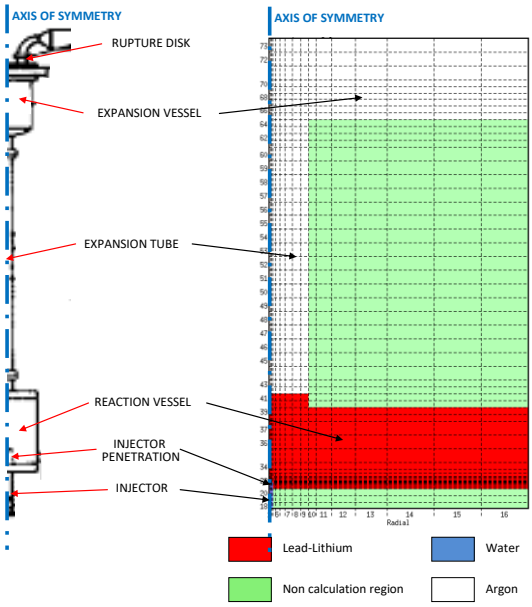

Fig. 2. BLAST facility nodalization by SIMMER III code: overall view.

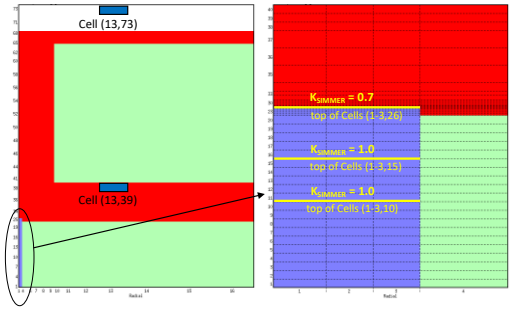

Fig. 3. LiPb level in BLAST facility and reference cells (left), outline of the orifice coefficient positions and values, and water injector tube detail (right).

No correlation is available in SIMMER-III to simulate the exothermic effect and hydrogen production due to chemical reaction between water and lithium. Therefore, an engineering approach was applied, based on an iterative procedure and the experience acquired in the simulations of LIFUS5 experiments [14]. The assumption is that maximum 20% of the injected water reacts with lithium and, thus, the energy released during the test and affecting the pressure trends is bounded by this value. Then, a heat source is imposed as function of the injected water and accounting for the water flow paths.

Hereafter, the code results of two simulations are presented. They are achieved using the same nodalization, set up with the same boundary conditions with the exception that, one run neglects the chemical reaction among water and LiPb, according with the code capabilities; the other run employs the assumptions discussed above, thus an external heat source is implemented in the simulation. The comparisons of the results are referred to the pressures in the reaction and expansion vessels. The trends are calculated in the cells having coordinates (13, 39) and (13, 73), highlighted in Figure 3.

Figure 4 shows the results of the simulation, where the heat generation is neglected. The code results, notwithstanding qualitatively similar with the experimental trends, appear largely underestimated. A "pumping effect" is observed by the second small peak of pressure in the reaction vessel. The first pressure peak, predicted by the code in the reaction vessel, is more than 10 bar lower the experimental value. The predicted pressure in the system is stabilized at about 20 bar less than in the experiment. The results of the simulation evidence the underprediction of the energy in the system (chemical reaction neglected).

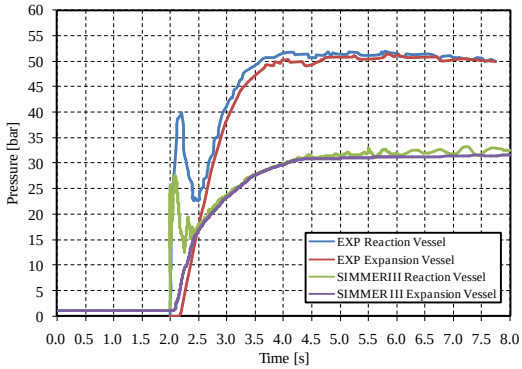

Fig. 4. RUN3 results: Experimental and calculated pressure trends without heat generation.

The experimental and calculated pressure time trends considering the heat generation are shown in Figure 5. This code simulation highlights good prediction of both pressure trends. The first pressure peak calculated by the code is slightly anticipated, but its absolute value is in excellent agreement with the experimental one. The intermediate "pumping effect" is not predicted by the code. The predicted pressure stabilization and its value at the end of transient are both in excellent agreement with the experimental data. The code prediction appears adequate. The main parameter trends are simulated correctly in time, and from qualitative and quantitative point of views. The "well known" code models deficiencies (i.e. those connected with the chemical interaction between lithium and water) have been satisfactory overcome with the heat source procedure based on an iterative method and the experience acquired in previous simulations (i.e. LIFUS5). In any case, the application of this approach is limited if different initial and boundary conditions from the experimental database available are considered.

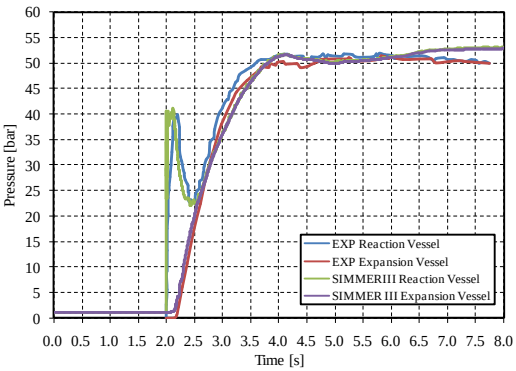

Fig. 5. RUN3 results: Experimental and calculated pressure trends with heat generation.

4. Discussion and conclusions

The LiPb-water interaction implies a direct energy release, which leads to temperature and pressure increase reaction and an indirect form of energy release, the hydrogen production. Considering the "in TBM LOCA" the WCLL blanket will be subjected to the pressure transient, governed by mixing and pressurization, to the chemical reaction contributing to pressure and temperature increases, and to the release of radioactivity products.

The review of the literature and of research activities carried out in the past brings to the conclusion that the phenomena and processes occurring during the LiPb-water interaction were reasonable understood, although the available documentation is not complete. The chemical and thermodynamic interaction are characterized from qualitative point of view. From the experiments, there are indications that the chemical and physical interactions are self-limiting: the steam pressurization, the hydrogen generation and the production of lithium oxide and hydroxide partially insulated the melt against water.

Numerical simulations of BLAST Test No. 5 performed by SIMMER-III code demonstrated that first pressure peak was well predicted, as well as the overall pressure trends in the reaction and expansion vessels. Although the iterative procedure set up to evaluate the chemical reaction during the experiment provided satisfactory results, it required large analyst effort and CPU time, and the results depend on the initial and boundary conditions.

Concluding, no code was found able to perform safety analyses without engineering assumption, and was not able to simulate the chemical reaction. The separate effect experiments (BLAST and LIFUS5) are few and not sufficient to perform validation activity, therefore specific experimental activities are needed to improve the understanding of the phenomena and the processes involved in the tube rupture postulated event scenario. The experimental campaign shall be designed for validation purpose, and therefore with controlled initial and boundary condition. The tests shall provide reliable data to be used in validation of a computer code aimed at preforming WCLL safety analysis investigations. The availability of a model for the chemical reaction and hydrogen production is needed.

References

[1] European Fusion Development Agreement, Fusion Electricity: A roadmap to the realization of fusion energy, EFDA 2012.

[2] J. Aubert, et al, WCLL DESIGN, WCLL Workshop, Paris, 7-8 October 2013.

[3] S. J. Piet, et al, Liquid metal chemical reaction safety in fusion facilities, Fusion Engineering and Design 5 (1987) 273-298.

[4] D. W. Jeppson, L. D Muhelestein, S. Cohen, Fusion reactor breeder material safety compatibility studies, Nuclear Technology / Fusion 4 (1983), 277-287.

[5] D. W. Jeppson, L. D Muhelestein, Safety considerations of lithium-lead alloy as a fusion reactor breeding material, Fusion Technology 8 (1985), 1385-1391.

[6] M. L. Corradini, D. W. Jeppson, Lithium alloy chemical reactivity with reactor materials: current state of knowledge, Fusion Engineering and Design 14 (1991) 273-288.

[7] H. Kottowski, et al., Studies with respect to the estimation of liquid metal blanket safety, Fusion Engineering and Design 14 (1991) 445-458.

[8] J.P. Herzog, M.L. Corradini, Modelling of lithium lead/water interactions in a fusion reactor design, University of Wisconsin UWFDM-559, August 1984.

[9] H. Kottowski, G Kuhlbörsch, Li17Pb83 and Li7Pb2 water interaction, Programme Progress Report on Fusion Technology and Safety, CEC, JRC - Ispra, Italy, pp82-85, 1986.

[10] C. Savatteri, A. Gemelli, Lithium-lead/water interaction. Large break experiments, Fusion Engineering and Design 17 (1991) 343-349.

[11] P.O. Biney et al., A mass transport model for hydrogen generation during lithium-lead/water interactions, Proc. IEEE Meeting on Fusion Energy, Knoxville, October 1989.

[12] P. Sardain, et al., Modelling of the Pb17Li/water interaction within a blanket module, Fusion Engineering and Design 51-52 (2000) 611-616.

[13] M. L. Corradini, et al, Vapor explosion in light water reactors: a review of theory and modeling, Progress in Nuclear Energy, Vol. 22, pp 1 - 117, 1988.

[14] A. Ciampichetti et al, Water large leaks into liquid Pb-17Li: first experimental results on LIFUS 5 facility, Fus. Eng. Des. 69 (2003) 563-567.

[15] S. Kondo, et al, SIMMER III: A Computer Program for LMFR Core Disruptive Accident Analysis. Research Document, O-arai Engineering Center, Japan Nuclear Cycle Development Institute, JNC TN 9400 2003-071 (2003).

[16] A. Pesetti, N. Forgione, A. Del Nevo, Post-Test Analysis of the Water-PbLi Interaction in the BLAST Experiments by SIMMER III Code, EFDA - WP13-SYS-04-T06 project, ENEA DM-N-N-042 Rev. 0, 15 August 2013.