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Status of activities on the lithium target in the key element technology phase in IFMIF

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Abstract

This paper describes the status of the liquid lithium (Li) target facility in the key element technology phase (KEP) of the International Fusion Materials Irradiation Facility (IFMIF). The IFMIF is being jointly developed by the European Union (EU), Japan (JA), Russian Federation (RF) and US to provide an accelerator-based D–Li neutron source for testing the candidate materials for fusion reactors. A key issue of the Li target is to obtain a stable liquid Li flow with a speed of 20 m/s under a deuterium beam deposition of 10 MW. In the KEP, 19 tasks for the Li target are proposed and shared by EU, JA and RF. These tasks are a Li simulation experiment by water jet, Li flow experiment, corrosion/erosion, remote handling of the target assembly, and safety analysis. In addition to the KEP tasks, detailed design of the target is being performed.

1. Introduction

The IFMIF is an accelerator-based D–Li neutron source to produce intense high energy neutrons (2 MW/m^2) up to 200 dpa and a sufficient irradiation volume (500 cm^3) for testing candidate materials and components used in ITER and DEMO [1]. To realize such a condition, a 40 MeV deuteron beam with a current of 250 mA is injected into a liquid Li flow with a speed of 20 m/s. Following conceptual design activity [2,3], a design study with focus on cost reduction without changing the original mission has been done in 1999 [4]. In 2000, a 3 year key element technology phase (KEP) was initiated to reduce the key technology risk factors needed to reach the corresponding power handling capabilities in the liquid Li target system, and to satisfy the availability and reliability in endurance tests. For these purposes, 19 tasks are proposed for the Li target system [5]. In this paper, the status of IFMIF-KEP activities on the Li target system is described.

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Table 1
Major specifications of IFMIF target system

Items	Values
Beam deposition area on Li jet	200 mm (width) × 50 mm (height)
Thickness/width of Li jet	25 mm/260 mm
Velocity of Li jet	15 (range 10–20) m/s
Flow rate of Li	130 l/s
Inlet temperature of Li	250 °C
Permissible corrosion thickness	50 μm
Permissible impurity contents	10 wtppm (C, N, O: each)
Tritium generation rate	7 g/year
Materials	
(Back wall)	Reduced-activation ferritic steel
(Other components)	304 stainless steel
Replacement	
(Back wall)	9 month/fpy
(Other components)	No replacement for 20 years

2. Lithium target system

The major functions of the Li target system are to provide a stable Li jet for production of intense neutrons (20 dpa/year) under irradiation of a 10 MW deuterium beam [6]. An average surface heat flux on the free liquid Li flow is 1 GW/m^2. To handle such an ultra high heat load, a high-speed liquid Li jet flow is necessary. Table 1 summarizes the major parameters of the target system. The system consists of a target assembly, a Li main loop and a Li purification system. A block diagram of the Li target system is shown in Fig. 1. The Li loop circulates the Li to and from the target assembly through an Li purification and heat exchange system by an electromagnetic pump. The Li purification system with a cold trap and two hot traps is able to maintain tritium, ^{7}Be and other impurities under permissible levels to realize the required safety condition and to minimize corrosion of the loop materials.

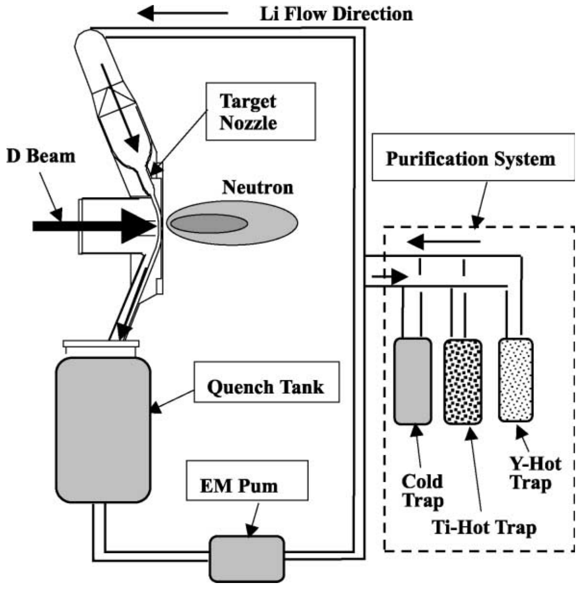

Fig. 1. Block diagram of the IFMIF target system.

3. Status of KEP activities

3.1. Water jet experiment

A water jet experiment is conducted in JAERI to simulate characteristics of the liquid Li flow with the same Reynolds number as the Li flow under low pressure condition and to evaluate the effect of surface roughness of the nozzle on the flow behavior. In the IFMIF conditions, the pressure above the free surface of the Li flow is 10^{-3} Pa. In previous experiments [7], a stable flow with small surface waves of amplitude less than 1 mm was observed under 0.1 MPa (1 bar). To investigate the effect of the working pressure on the surface wave growth, the water jet experiment under 0.01 MPa (0.1 bar) was performed up to a flow velocity of 20 m/s. As a result, the working pressure is not a cause of the surface wave growth. Following this study, the effect of nozzle roughness on the flow stability was also evaluated using acrylic nozzles with wall roughness of 6.5 and 100 μm [8]. Dimensions of the nozzle exit are 10 mm in height and 100 mm wide. As shown in Fig. 2, the experiment with the nozzle with 100 μm roughness showed larger surface waves beyond a flow speed of 10 m/s than the nozzle with 6.5 μm roughness. Measurement of the velocity distribution shows that the boundary layer changes from laminar flow to turbulent flow with an increase in velocity beyond 10 m/s. These results provide a guideline for a fabrication of the IFMIF target nozzle.

In the replaceable back wall option, one of the design issues is a small discontinuity in the back wall, which might influence the jet stability. To investigate the jet stability in the presence of a replaceable back wall, the water experiment is also under way in ENEA. The design of the water jet mock-up was oriented in order to assure the change of few parameters such as a back wall curvature (25–45 cm) and a step at the nozzle joint (−0.1 to +0.1 mm) that could cause the flow instability. In high-speed flow, cavitation must be avoided because it is a source of damage and jet instability. In the experiment, cavitation noise will be measured by a high sensitivity detector call as CASBA (cavitation and sub-cooled boiling apparatus) developed by ENEA.

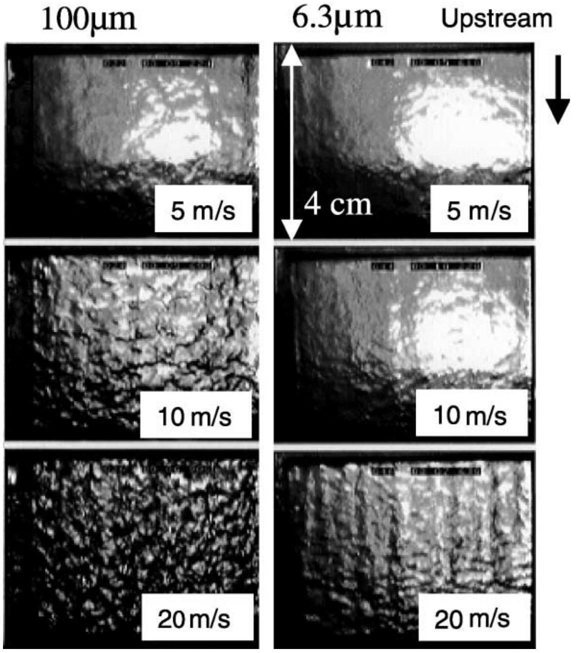

Fig. 2. Free surfaces observed at viewing ports 150 mm downstream from nozzle exit, which correspond to location of IFMIF beam footprint.

3.2. Lithium loop experiment

To validate the stability of Li flow up to a speed of 15 m/s with a double reducer nozzle, which has the same dimensions as the one in the previous water jet experiment, modification of the existing Li loop is under way in Osaka University. Details of the Li loop experiment are described in [8,9]. Major diagnostics under consideration are a high-speed video camera, Li thickness monitors and a laser surface wave monitor. Corrosion/erosion behavior of the nozzle material under flowing Li will be observed after the experiment. In the Li flow, cavitation occurrence will be measured by the CASBA. After the Li loop modification, the experiment will be started in July 2002.

3.3. Lithium purification system

This task is aimed at development of a Li purification system, including removal systems and monitors. In the Li loop, non-metallic impurities to be controlled are divided into two groups. The first group consists of radioactive impurities such as tritium and ^{7}Be generated by the D–Li reaction. From a safety point of view, these elements should be reduced as low as possible within realistic limits. ^{7}Be can be trapped easily by a cold trap. However, a yttrium-hot trap is needed to reduce tritium concentration below 63 wt ppm (= 440 appm) because the solubility of hydrogen isotopes in the Li at 473 K is about 63 wt ppm. The second group consists of carbon, nitrogen and oxygen that are generated from the loop materials. Among these impurities, oxygen and carbon can be easily removed by a cold trap because their solubility in Li is low near the melting point of the Li. On the other hand, nitrogen cannot be removed by the cold trap because the solubility is high. Therefore, control of the nitrogen needs a hot trap with getter material that reacts with nitrogen. In addition, nitrogen reduction is essential for removal of tritium by the yttrium-hot trap since yttrium nitride layer will diminish tritium absorption.

To control nitrogen concentration in liquid Li by the hot trap, a task is being performed in the University of Tokyo [10] for an evaluation of advanced materials. In this task, titanium (Ti), vanadium (V), V–Ti alloy and chromium (Cr) have been investigated. The purities of these materials are over 99.9%. Impurities are <200 wt ppm C, Fe, Mg, <50 wt ppm Cl in the Ti and 107 wt ppm C, 105 wt ppm Nb, 380 wt ppm Si, <50 wt ppm Ti, <100 wt ppm Zr in the V and 100 wt ppm O, 20 wt ppm Fe, <10 wt ppm Cu, Al, Si in the Cr. V–Ti alloy is made of the above Ti and V metals. The concentration of nitrogen impurity in the as-received Li was about 50–100 wt ppm. Due to formation of Li_9CrN_5, more stable than Li_3N, Cr seems to be promising as the getter material for high nitrogen content. These materials were soaked in liquid Li at temperatures between 673 and 823 K for about 1 month. Before and after the experiment, the weight of the specimens was measured. Surface characteristics have been measured by XRD and EPMA. As a result, V–Ti alloys, especially V–10%Ti, showed a higher absorption of nitrogen than pure Ti and V. Next, transient absorption characteristics of V–Ti alloy and Cr have been measured during 1 week under nitrogen contents of 360 wt ppm. Cr showed higher absorption capability than V–10%Ti in high nitrogen contents around 100 wt ppm. The absorption mechanism is dominated by diffusion processes.

Behavior of impurities (mainly C, N, O) in the primary Li loop, evaluation of the main impurities and definition of a strategy for trapping have been studied in EU. Basic tests of the cold and the hot traps for removal of the impurities, and the on-line monitoring (H, C, N) in stagnant Li will be performed. For monitoring the impurities, on-line resistivity techniques for N, electrochemical sensors for H, O and N, diffusion carbon meter and analytical techniques could be used.

3.4. Corrosion

In the IFMIF, a reduced-activation ferritic/martensitic (RAF) steel will be used in the back wall. Li corrosion data, especially, on the RAF is very limited. Even if the anticipated operating temperatures within the

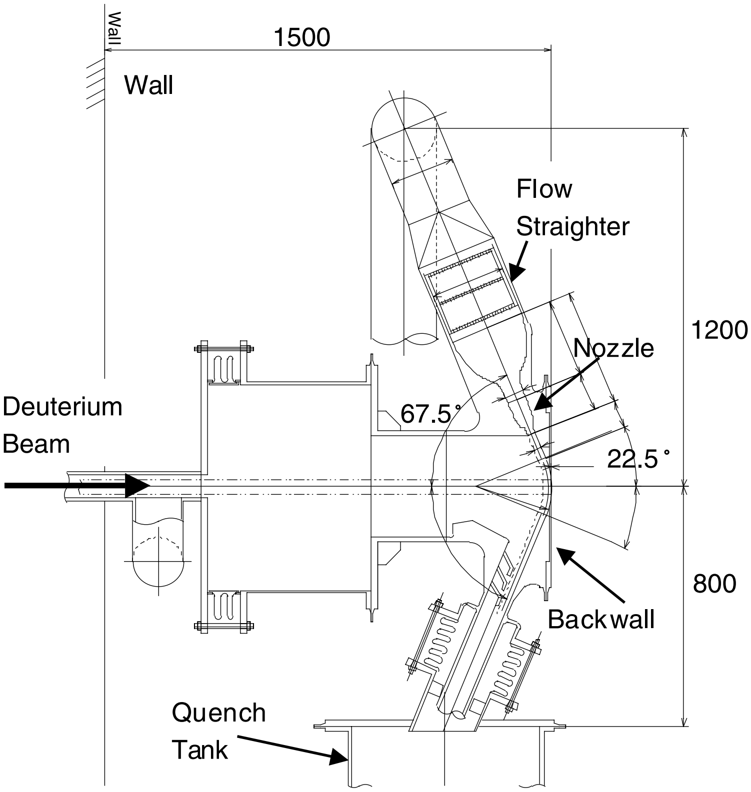

Fig. 3. Cross section of target assembly.

target and the loop are relatively low, both effects of corrosion and liquid metal chemistry have to be controlled and assessed. In fact, as in the case of sodium, Li corrosion is strongly influenced by the presence of non-metallic impurities such as oxygen, carbon and especially nitrogen in the liquid metal [11]. Solubilities of non-metallic elements in Li at 573 K are 87 wt ppm for oxygen, 8604 wt ppm for nitrogen and 23 wt ppm for carbon. From a thermodynamic point of view, formation of binary compounds (Li_2O, Li_3N, Li_2C_2) is possible. The reactivity of nitrogen is enhanced in liquid Li because of the formation of ternary compounds (Li_9CrN_5) at grain boundaries. Moreover, formation of solid Li_2O may cause plugging. In the KEP, modification of the existing loop and test section design will be done.

3.5. Transient analyses of Li loop

To evaluate the transient thermal behavior of the Li loop during beam trip or start-up of the IFMIF, analysis has been done by simulation code based on finite element method in JAERI. As a result, without control of the heat exchanger system, the Li temperature at the exit of the Li cooler becomes less than the solidification temperature of Li (180 °C) after 380 s. On the other hand, with control of the heat exchanger system, the exit temperature of Li is maintained above the solidification temperature.

To define the thermal-hydraulic conditions of the liquid Li jet for the present design requirements, the analysis by means of the RIGEL code is under way in EU. Final results will be expressed in terms of temperature and velocity distribution of the jet, evaluation of the evaporation rate at the free surface, and pressure distribution in the jet under non-boiling conditions. The boiling margin is defined as ‘saturation temperature–local temperature’. The minimum boiling margin is 35 °C at the free surface just below the beam footprint. Inside the Li flow, the boiling margin is more than 400 °C due to the increase of the saturation temperature by centrifugal force. The results of the activity will give the main parameters for the definition of the jet stability tests.

3.6. Li target safety analysis

In the safety analysis, there are two major hazards in the target system. One is the tritium and ^{7}Be accumulation in the Li loop. The other is the risk related to the liquid Li loop operation. Safety analysis and deterministic evaluations during thermal-hydraulic transients will be performed to verify the safety criteria. In these analyses, the new reduced cost version of the design has been taken into consideration. The reduction from 2 to 1 Li loop reduces the necessary mass of Li from 21 to 9 m^3, which more than halves several risks, such as fire. Hazard analysis related to the Li target has been performed by applying the failure mode and effect analysis [12]. The main conclusions of this work are that, in light of the modifications submitted in the reduced cost version of the design, target safety is fulfilled and environmental impact is negligible. A transient accident analysis phase has been initiated with computer code nodalization. The ATHENA code is used for loss of coolant accident and loss of flow accident or other events. Radiological hazard analysis has been preformed during an earlier phase and the IFMIF facility is categorized into four zones according to their radiation hazard potential. Potential target related hazards due to the radioactive materials and the Li operation are very low.

3.7. Design of Li target assembly

Design activities of the Li target assembly related to remote handling are in progress. Fig. 3 shows a cross section of the latest target assembly considering a replacement by the remote handling arm. Since the back wall made of RAF steel is used under the most sever condition of neutron irradiation around 50 dpa/year, the back wall is designed for exchange in nine months. There are two design options on the back wall replacement. The first option is to remove the overall target assembly with the back wall and move to the hot cell area for replacement. The second option is to replace the back wall at the target assembly by a remote handling device.

4. Future research issues

Following the KEP activities which will be accomplished in 2002, the future research issue in IFMIF next phase is engineering validation of the target system over prolonged operation of more than 5000 h. The issues are (i) validation of the Li flow stability with a IFMIF scale nozzle and a concave back wall, transient behavior of the Li flow simulating IFMIF operation, (ii) validation of the Li loop layout without cavitation under a vacuum condition of 10^{-3} Pa, (iii) validation of compatibility of the Li loop materials under low impurity level of 10 wt ppm, (iv) validation of the Li purification system and diagnostics and (v) examination of operational safety of the IFMIF Li loop. For these purposes, a Li test loop will be constructed in the next phase. Parameters of the proposed prototype Li loop are selected to be the same as the IFMIF except for the jet width. The maximum flow speed is 20 m/s. Considering the effect of waves from the sidewall on surface behavior in the center region at 15 cm from the nozzle exit, 10 cm is selected as a Li flow width of the prototype Li loop to save total cost without reducing the purpose of the prototype.

5. Summary

For the target system, 19 KEP tasks are being pursued by the IFMIF team. The KEP tasks include stability of Li flow, damage/corrosion by Li flow, Li purification, Li vaporization, safety analysis, loop integrity and remote handling are in progress. The water jet experiment on the nozzle roughness is completed. To confirm stability of the Li flow with the double reducer nozzle, modification of an existing Li loop is in progress. The detailed design is being performed to update the design of the target system and the components. The KEP activities will be accomplished in 2002. After the KEP, a 5 year EVP will validate those critical technologies. Construction of the IFMIF will be started after the EVP.

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