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Present status of the liquid lithium target facility in the international fusion materials irradiation facility (IFMIF)

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Abstract

During the three year key element technology phase of the International Fusion Materials Irradiation Facility (IFMIF) project, completed at the end of 2002, key technologies have been validated. In this paper, these results are summarized. A water jet experiment simulating Li flow validated stable flow up to 20 m/s with a double reducer nozzle. In addition, a small Li loop experiment validated stable Li flow up to 14 m/s. To control the nitrogen content in Li below 10 wppm will require surface area of a V–Ti alloy getter of 135 m^2. Conceptual designs of diagnostics have been carried out. Moreover, the concept of a remote handling system to replace the back wall based on 'cut and reweld' and 'bayonet' options has been established. Analysis by FMEA showed safe operation of the target system. Recent activities in the transition phase, started in 2003, and plan for the next phase are also described.

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 in a sufficient irradiation volume (500 cm^3) for testing candidate materials and components to be used in ITER and fusion DEMO reactor. To realize such a condition, a 40 MeV deuteron beam with a current of 250 mA is injected into a liquid Li target flowing

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with a speed of 20 m/s. Following the conceptual design activity (CDA) [1,2], a design study with focus on cost reduction without changing the original mission was completed in 1999 [3]. In the end of 2002, a three year key element technology phase (KEP) 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 was completed [4–6]. During KEP, 19 tasks on the Li target system were done. Now, activities in a transition phase started in 2003 are in progress. This paper describes the results of work on the liquid Li target system activities in the KEP and the transition phases.

2. Lithium target system

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

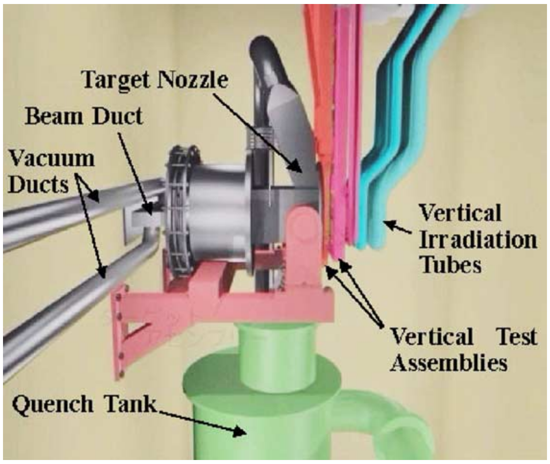

Fig. 1. A three dimensional view of the IFMIF target assembly.

Table 1
Major specifications of IFMIF target system

Items	Parameters
Deuterium beam energy/current	40 MeV/125 mA (nominal) × 2 accelerators
Averaged heat flux	1 GW/m^2
Beam deposition area on Li jet	0.2 m^W × 0.05 m^H
Jet width/thickness	0.26 m/0.025 m
Jet velocity	15 (range 10–20) m/s
Surface roughness of nozzle	<6 μm
Curvature of back wall	0.25 m
Wave amplitude of Li free surface	<1 mm
Flow rate of Li	8 m^3/min (at target section)
Inlet temperature of Li	523 K (nominal)
Vacuum pressure	10^{-3} Pa at Li free surface 10^{-1} Pa in target/test cell room
Hydrogen isotopes content	<10 wppm (<1 wppm:T)
Impurity content	<10 wppm (each C, N, O)
Materials (back wall)	RAF steel or 316 stainless steel
(Other components)	316 stainless steel
Erosion/corrosion thickness	
(Nozzle and back wall)	<1 μm/year
(Pipings etc.)	<50 μm/30 years
Replacement	Every 11 month for back wall No replacement for 30 years (other components)
Availability	>95%

3. Results in the KEP and transition phases

3.1. Water jet experiment

A water flow with the same Reynolds number ($Re = 5 \times 10^5$) as the Li flow can simulate the characteristics of the liquid Li flow. In JAERI, the water jet experiment was conducted to evaluate the effects of surface roughness of the nozzle on the flow behavior. In IFMIF, the pressure above the free surface of the Li is 10^{-3} Pa. The effect of the working pressure on the surface wave growth was investigated in the water jet experiment was operated under 0.01 MPa (0.1 bar) and a flow velocity of up to 20 m/s. The results showed that 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]. The experiment with the 100 μm roughness nozzle showed larger surface waves, for a flow speed above 10 m/s, than the 6.5 μm roughness nozzle. According to measurement of the velocity distribution, the boundary layer changed from laminar flow to turbulent flow with an increase in velocity beyond 10 m/s was observed. Based on these results, the specification of the IFMIF target nozzle roughness is determined to be less than 6 μm.

At ENEA, water experiments are being in progress on a quasi full-scale simulacrum, called HY-JET, of a double reduced (SHIMA) nozzle with a curved replaceable back plate vertical target flow. Tests performed with a back wall curvature of 45 cm and a roughness of 0.8 μm and no stair at nozzle-back wall joint have been carried out. It was demonstrated that in laminar flow, below 2.5 m/s, some diagonal wakes remain attached to the lateral tray walls and these wakes disappear above the transition to turbulent flow. At higher velocity, approaching 10 m/s, the flow assumed the fully developed turbulence pattern with sparkling bubbles on the bulk, remaining well attached to the back plate. In the turbulence flow region, the lateral instabilities have procured overcoming of flow beyond the lateral tray walls. The Gortler vortexes are not clearly evidenced due to superimposition with the lateral instabilities. Cavitation noises on both the flow straightener-orificed plates and at the outlet the nozzle respectively at 5 and 10 m/s have been detected by ENEA CASBA-2000 patented accelerometer, with the resonance signal resulting almost linear with the nozzle velocity.

In addition, a water experiment is in progress in IPPE at Obninsk to investigate the effect of structural vibration on the flow stability.

3.2. Lithium loop experiment

Following the water jet experiment, the existing Li loop facility at Osaka University has been modified to validate the stability of Li flow with a double reducer nozzle, which has the same dimensions as the nozzle in the previous water jet experiment. In this experiment, a horizontally aligned test channel was provided, although in IFMIF Li flows vertically. Gravity force is not dominant since surface tension is the dominant force on the surface stability. Various Li loop design key features were taken into account including nozzle fabrication, gas bubble entrainment, cavitation, and wetting issues. Major diagnostics were a high speed video camera, Li thickness monitors and a laser surface wave monitor. In the Li loop experiment, a Li velocity up to 14 m/s was obtained under an Ar cover gas and 8.5 m/s under vacuum conditions. Surface observations of Li free surfaces were taken by a CCD camera at 150 mm downstream from the nozzle exit. In this way a relatively calm flow with neither violent waves nor splashing of the fluid was observed. Details of this experiment are described in Ref. [9]. However, after several operating campaigns, surface waves called wake were observed. The origin of the wake seems to be small Li solid particles deposited on the nozzle surface [10]. Characterization of the deposited Li is under way. In IPPE, a small Li loop is being constructed with a concave vertical flow and the same nozzle cross-section as the Osaka Li loop. The experiment will start in spring 2004. Li flow stability and operational characteristics for the vertical concave flow will be investigated.

3.3. Lithium purification system

In the Li loop, two classes of impurities are to be controlled. The first group consists of radioactive impurities such as tritium and ^{7}Be generated by neutrons from the D–Li reaction, and neutron irradiation activated corrosion products (CP). From the viewpoints of maintenance and safety issues, these elements should be reduced as low as possible in a realistic design. A cold trap can reduce ^{7}Be and activated CP in the loop. However, to reduce tritium concentration below 1 wppm a yttrium hot trap is needed because the solubility of hydrogen isotopes in the Li at 473 K is about 63 wppm. The second group of impurities consists of carbon, nitrogen and oxygen that enter from the loop materials. Among these impurities, oxygen and carbon can be removed by a cold trap, but, the control of the nitrogen needs getter material that reacts with nitrogen. In addition, nitrogen reduction is essential for prevention of deterioration of the yttrium-hot trap due to formation of nitride surface layers.

An evaluation of titanium, vanadium, V–Ti alloy and chromium as candidate materials to control nitrogen concentration in Li has been performed in the University of Tokyo [11]. The concentration of nitrogen in the as-received Li was about 50–100 wppm. These materials were soaked in liquid Li at temperatures between 673 and 823 K for about 1 month. As a result, V–Ti alloy, especially V–10%Ti, showed a higher absorption of nitrogen than pure Ti or V. Next, transient absorption characteristics of V–Ti alloy and Cr have been measured for1 week in Li with nitrogen contents of 360 wppm. Cr showed higher absorption capability than V–10%Ti in high nitrogen contents around 100 wppm. The absorption mechanism is dominated by diffusion processes. Due to formation of Li_9CrN_5, more stable than Li_3N, Cr seems to be promising as the getter material for high nitrogen contents. However, a minimum limit of nitrogen content in Li by Cr gettering is about 65 wppm since formation of the compound nitride saturates in this content. Therefore, control of the nitrogen content below 10 wppm will require the V–Ti alloy getter. The recommended combination is Cr getter for the high nitrogen content regime and V–Ti alloy for the low nitrogen regime. The required surface area of the V–Ti alloy getter is estimated to be 135 m^2 for a Li inventory of 9 m^3, an initial nitrogen content of 50 wppm and a getter temperature of 873 K. To control tritium in Li, yttrium getter experiments have been started.

In ENEA, evaluation of the main impurities and definition of a strategy for trapping impurities in the primary Li loop have been studied. 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 are being conducted. For monitoring the impurities, on-line resistivity techniques for N, electrochemical sensors for H, O and N, diffusion carbon meter and analytical techniques are being evaluated.

Soluble getter experiments using Ca and Al have been started in IPPE. Preliminary results show oxygen was reduced from 100 to 1 wppm by Ca and nitrogen was reduced from 500 to 2 wppm by Al, respectively. In these methods, solid oxide and nitride in Li need to be removed by a cold trap. Further study is needed to obtain additional technical data for the IFMIF purification system design.

3.4. Erosion/corrosion

AISI 316 stainless steel will be used for the IFMIF Li loop and a reduced-activation ferritic/martensitic (RAF) steel can be used for the back wall. Li corrosion data, especially, on the RAF is very limited. Li corrosion data is especially needed for maintenance design of the target components to estimate the loop content of radioactive corrosion products. Li corrosion is strongly influenced by the presence of non-metallic impurities such as oxygen, carbon and especially nitrogen in the liquid metal. 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 of the loop flow.

Erosion/corrosion characteristics of stainless steel tubing in the Osaka Li loop prior to the modification was analyzed by optical microscope, SEM, EDS, XRD and XPS. Total Li circulation time was 186 h at about 573 K. Li flow velocity was 0.7–2.3 m/s. Severe corrosion at grain boundaries and large dissolution of Cr at the surface were observed. This may show that a relatively large amount of nitrogen is dissolved in the Osaka Li loop. Dissolution of Cr and Ni from the steel results in the formation of a thin spongy ferrite layer. In ENEA, modification of the existing corrosion loop (LIFUSE III) to add a test section has been completed. Corrosion data with a maximum velocity of 10 m/s will be obtained. In IPPE, rotating sample experiment with AISI 316 type stainless steel and RAF steel has been started. Measurements of corrosion data under a surface velocity up to 20 m/s are planned.

3.5. Remote handling system

The back wall will be operated under severe condition of neutron irradiation damage (about 50 dpa/year), therefore, the back wall is designed for replacement every 11 months. Two design options for the back wall replacement are under investigation. The first option called the ‘cut and reweld’ concept is based on the removal of the overall target assembly including the back wall to the hot cell area for replacement of the back wall itself. A YAG laser device will be used to cut the lip seals of the flanges. The remote handling system to exchange the target assembly is integrated into the universal robot system (URS) of the IFMIF test facilities. The conceptual study of the procedure for the target assembly transfer system to the hot cell has been completed.

The second option is based on the ‘bayonet’ concept which allows the replacement of the back wall of the target assembly using a remote handling device [7]. This solution has in principle the advantages of intrinsic simplicity, the reduction of the target replacement time and the possibility of back-plate replacement without removing the vertical target assembly. In fact this solution enables back-plate replacement operations while working laterally to the target. The back-plate mock up design utilizes an innovative closing system which transmits the force required to ensure the tightness through three sliding wedges mounted in the lower, upper and lateral side; on the remaining side the target is closed by bolts [12]. The seal is ensured by using a metallic gasket. The feasibility of the back wall bayonet concept has been assessed. The manufacturing of a back-plate mock up has been completed and technological tests have demonstrated its capability to satisfy the working conditions (i.e. leak tight at operating temperature). Remote handling testing has proved the accomplishment of procedure specifications and maintainability requirements.

3.6. Diagnostics

Loop operating parameters must be known to control the Li target system during operation. Conceptual design of monitors for the Li temperature, Li flow velocity, Li thickness, and displacement of the target assembly and the back wall has been completed. Temperature of the Li free surface is measured by infra-red (IR) cameras, thermocouples and ultrasonic sensors. The IR camera is used to monitor the location of the deuterium beam footprint and surface temperature of the Li. The thermocouples are used to measure the Li temperature of the flow and to calibrate the IR camera. The Li flow velocity and thickness are measured by the ultrasonic sensors. Ultrasonic sensors are also used to measure the Li temperature inside the flow. The displacement of the target assembly and back wall are measured by a laser diagnostics with a spatial resolution of 0.1 mm, located 15 m from the Li target.

3.7. Transient and safety analyses

To evaluate the transient thermal behavior of the Li loop during beam trip or start-up, a numerical analysis has been carried out by FLOW-3D finite element code. As a result, without control of the heat exchanger system, the Li temperature at the exit of the Li cooler falls below the solidification temperature of Li (453 K) after 380 s. On the other hand, with control of the heat exchanger system, the exit temperature of Li can be maintained above the solidification temperature. To define the liquid Li jet thermal-hydraulic conditions for the present design requirements, analysis using the RIGEL code has been carried out [13]. Boiling margin, defined as 'saturation temperature–local temperature', showed a minimum value of 308 K at the free surface just below the beam footprint while in the Li bulk the boiling margin is more than 673 K due to the increase of the saturation temperature by centrifugal force.

A safety analysis of the target system to identify potential failures used the failure mode effect analysis (FMEA) approach. The goal was to identify potential accidents in the plant or simply find conditions that would stop the operating phase [14]. In particular FMEA has identified as the major hazard relative to the target system the radioactive material generated in the Li loop (tritium and ^{7}Be) and the risk related to the liquid Li loop operation. Concerning the radioactive materials safety issue, the majority of the tritium and other radioactive materials and impurities are removed by trapping and kept under control by the impurity monitoring loop. Concerning the risk associated with Li, the vacuum condition of the test cell and the confinement system, combined with the controlled argon gas atmosphere of the Li cell, assure the countermeasures against Li fire risk due to Li-air reaction. Moreover, the floors and the walls of the Li cells are covered with steel liners to prevent Li-concrete reactions. All Li components (tanks, lines, valves, valve bonnets, etc.) are provided with leak detectors. In addition to the Li fire control system, oxygen meters are used to monitor the oxygen concentration in the argon gas. The main conclusions of the safety analysis are that, in the light of plant modification submitted in the reduced cost version of the design, target safety is assured and environmental impact is negligible: potential target-related hazards due to tritium production and Li operation are very low.

4. Future research issues

Following the KEP and the transition phase (2003–2004), in the next phase, the engineering validation and engineering design activities (EVEDA), engineering validation of the target system for prolonged operating time (more than 10 000 h) will be performed during 2005–2009. These activities include (1) 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 will be investigated, (2) validation of the Li loop layout to verify the absence of cavitation and the operation under vacuum condition of 10^{-3} Pa, (3) validation of compatibility of the Li loop materials while maintaining a low impurity level of 10 wppm for each impurity species, (4) validation of the Li purification system and target diagnostics and (5) demonstration of safe operation of the IFMIF Li loop.

5. Summary

Nineteen KEP target system tasks were conducted by the IFMIF team. The KEP tasks included stability of Li flow, damage/corrosion by Li flow, Li purification, Li vaporization, safety analysis, loop integrity and remote handling. Work is continuing in these tasks areas. The water jet experiment on the nozzle roughness is completed. To confirm stability of the Li flow with the double reducer nozzle, stable Li flow up to a speed of 14 m/s has been validated. Evaluation of candidate materials for nitrogen getter has been done. Remote handling system concepts have been assessed. Detailed design is being performed to update the design of the target system and components. Following the KEP and the transition phases, a five year EVEDA phase will validate those critical technologies. Construction of the IFMIF will be started after the EVEDA.

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