# The Accomplishments of Lithium Target and Test Facility Validation Activities in the IFMIF/EVEDA Phase

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**Abstract**. As part of the Engineering Validation and Engineering Design Activities (EVEDA) phase for the International Fusion Materials Irradiation Facility IFMIF, major elements of Lithium Target Facility and the Test Facility were designed, prototyped and validated. For the Lithium Target Facility, the ELTL lithium loop was built and used to test the stability (waves and long term) of the lithium flow in the target, work out the startup procedures, and test lithium purification and analysis. It was confirmed by experiments in the Lifus 6 plant, that Lithium corrosion on ferritic martensitic steels is acceptably low. Furthermore, complex remote handling procedures for the remote maintenance of the target in the Test Cell environment were successfully practiced. For the Test Facility, two variants of a High Flux Test Module were prototyped and tested in helium loops, demonstrating their good capabilities of maintaining the material specimens at the desired temperature with a low temperature spread. Irradiation tests were performed for heated specimen capsules and irradiation instrumentation in the BR2 reactor. The Small Specimen Test Technique (SSTT), essential for obtaining material test results with limited irradiation volume, was advanced by evaluating specimen shape and test technique influences.

## 1. Introduction

The International Fusion Materials Irradiation Facility IFMIF is developed with the mission to generate materials irradiation test data for design, licensing, construction and safe operation of a fusion DEMO reactor. A facility with such capabilities is part of the EU and Japanese roadmaps for the development of fusion power. This paper deals with the outcomes of validation activities for systems of the so called Test Facility and Lithium Target Facility, as part of the Engineering Validation and Engineering Design Activities (EVEDA) phase under the Broader Approach Agreement between EURATOM and Japanese government, which entered into force on June 2007. A collective overview of achievements by Japanese and European laboratories with JAEA and F4E as respective implementing agencies is given.

In the IFMIF plant [1], the systems of the Accelerator Facility (with two 40MeV 125mA deuteron beams) act together with the systems of the Lithium Target Facility (with a free-surface lithium target) to establish a neutron source with fusion-relevant energy spectrum and enough neutron flux to achieve testing at damage rates equal or higher compared to a future

Fusion Power Reactor. The so called Test Facility provides the irradiation experiments (housing Small Specimen Test Technique (SSTT) material specimens), radiation protection environment and infrastructure to implement the mission of material testing.

At the lithium target, a lithium flow guided on one side by a concave back plate at nominal speed of 15 m/s is generated. The two deuteron beams impinge on the free surface side, releasing a power of 2 x 5MW within the beam footprint area of 20 x 5 cm² in the lithium. Due to the heat release depth profile and to keep the neutron flux as uniform as possible, the thickness of the lithium flow should be maintained at 25mm +/- 1mm.

In the high neutron flux region directly behind the back plate, a calculated volume of about 0.5L is available to irradiate steel specimens to structural damages of 20-50dpa per full power year of IFMIF. Exchangeable irradiation rigs (High Flux Test Module, HFTM) were developed to achieve a high specimen packing density in the limited irradiation volume, and to maintain controlled temperature environments. A high temperature variant (up to 1000°C) was developed in Japan, and a variant for the temperature window (250 - 550°C) of Reduced Activation Ferritic Martensitic (RAFM) steels was developed in Europe.

The IFMIF facility essentially relies on remote handling procedures and equipment to safely and efficiently perform maintenance of the neutron source or the irradiation experiments in the harsh irradiation environment. Many other processes, like handling of small specimens, and ancillary systems like helium loops, or knowledge on application-relevant liquid-metal corrosion, helium heat transfer and especially the essential SSTT technology contribute to the performance of the facility.

Accordingly, validation activities on these critical facilities, components, and technologies were included in the scope of the EVEDA phase [2].

## 2. Validation activities for the Lithium Target Facility

### 2.1. Li-target flow validation

Due to the depth profile of the heat release in the target, with the Bragg peak at 19 mm below the Li-surface depth, the safe beam-target interaction and predictable neutron production depend on a controlled thickness of the free-surface lithium flow in the beam footprint area. The requirements on the thickness of the lithium flow have been specified to 25 +/- 1 mm, thus setting limits for long term thickness drifts as well as amplitude of waves induced by secondary flows and free surface stability. To accordingly validate the free surface target flow, a target with 1:1 length and curvature and scaled down width (1:2.6) was built. This target was integrated into the EVEDA Lithium Test Loop [3] (See section 2.2) where it could be operated with the full range of flow speeds between 10-20 m/s (nominal speed 15 m/s). This target was equipped with extra ports for optical inspection (with high speed video cameras) and especially with a laser probe based on optical comb / time of flight technique for time resolved measurements of the Li-surface position. The laser probe was assessed to achieve a wave height resolution of 16μm at relevant application conditions [4, 5]. Due to the optical setup, samples are obtained whenever a wave crest or floor passes the measurement spot. Experiments were conducted at 250°C for 10, 15 and 20 m/s under beam-operation-relevant vacuum conditions ($10^{-2}$ – $10^{-3}$ Pa) as well as with $10^{5}$ Pa argon cover gas. In all conditions, the tolerance for the wave height was achieved. At 15 m/s and $10^{-3}$ Pa (designated operation point with beam) the mean value of the approximately Rayleigh-distributed wave amplitude was only 0.26 mm. The spanwise profile of the mean thickness of the Li flow shows a wake (maximum elevation about 1.5 mm) near the channel sidewalls (See FIG. 1, right), evolving downstream towards the center. In the center of the designated beam footprint, this elevation occupies less than 30 mm next to the sidewalls, leaving a nearly flat zone for the beam with a thickness spread of about 0.2 mm. The lithium loop was run continuously over 571 h, during which the stability of the loop flow parameters and the lithium flow were measured. The deviations in the mean thickness profile in the beam area were much less than 0.1 mm, and the appearance of the target nozzle remained unchanged, proving very good stability of the Li target flow. Details on the Li-target flow investigations are found in [5-7]

### 2.2. The EVEDA Lithium Test Loop

The EVEDA Lithium Test Loop [3] (ELTL, See FIG. 1) was built in Oarai by JAEA and Mitsubishi Heavy Industries. The construction took 1 year and was finished November 2011. The loop has a height of 20 m and includes a total of 2.5 m³ of Lithium. The Lithium is driven by an Electromagnetic Pump (EMP) which can achieve a volumetric flow rate of about 3000 L/min. The process equipment of the ELTL includes flow meter, heat exchanger, the Target Assembly and Quench Tank in the main loop, additionally a purification loop with a cold trap, an impurity monitoring loop with off-line sampler, as well as vacuum system and cover gas system. The Lithium can be collected in the dump tank.

The operation of the loop including the target flow startup sequence was practiced. The loop starts from argon atmosphere and is coarsely evacuated to 10kPa before Li flow. The liquid Li column is first elevated by the EMP up to the highest point, then the flow through the target is started by voltage increase of the EMP. An evacuation / degassing period of about 3 hours follows until the vacuum pressure stabilizes at $10^{-2}$ to $10^{-3}$ Pa. At this pressure, 250°C and 15m/s steady state flow the equivalent of the "beam-on" conditions in IFMIF are reached [7]

The cold trap was operated in parallel to the investigations on the Li target for 570 hours. The cold trap temperature was set variably 0 – 60 °C below the main loop temperature. The main loop lithium was circulated for several purification and sampling campaigns through the purification loop. A decrease of Ni was observed for decreasing cold trap temperature.

In overall, the ELTL was operated 519 days from acceptance tests to the final validation tests with 3849 hours of Lithium circulation, including modes of continuous day-and-night operations.

*FIG. 1. Left: ELTL lithium loop in Oarai.Right: 2s exposure of the Li flow at 15 m/s.*

### 2.3. Remote handling procedures

Due to the possible corrosion of the Li target nozzle and due to the strong irradiation of the target backplate, either the whole target assembly (TA) or the target backplate (BP) are scheduled for annual replacements. The replacement operations have to be carried out inside the irradiated IFMIF Test Cell under remote handling (RH) conditions. The necessary RH procedures and tools were devised and tested by ENEA using 1:1 size mockups. In the ENEA Brasimone DRP facility, a dedicated test environment simulating the IFMIF Test Cell was set up. In this environment, a support for the target assembly was placed, and the complete target with attached Li-pipes could be handled. A crane with suspended mounting plate, customized lift frames for the TA and BP, a telescopic arm to reach the screw locations, a robotic arm for keeping in place the tools and bolting tools were used for the operations.

The remote handling trials confirmed the feasibility of the planned operations and provide good estimates for the required times: The BP replacement could be performed in less than 2 days, while the whole TA replacement could be done in less than 3 days. Furthermore, a list of detail improvements to make the TA design better suited for RH has been derived.

### 2.4. Steel corrosion in flowing Li

In order to be able to estimate the corrosion of the components of the TA (especially the nozzle and the BP) which are made from the Reduced Activation Ferritic Martensitic (RAFM) steel grades Eurofer-97 or F82H, according corrosion tests in flowing Lithium were performed by ENEA in the Lifus 6 plant [8] for both steels. A rod composed of 8 annular specimens, 4 for each material, was mounted concentrically into a flow channel. The flow velocity of 15 m/s, Temperature of 330 °C and specified nitrogen concentration < 30 wppm were chosen representative for the IFMIF target conditions. The required value of nitrogen concentration in flowing lithium was achieved by employing a hot trap containing a Titanium sponge getter and verified by a validated offline chemical analysis [9]. After the first short term campaign with the duration of 1222 hours of constant flow exposure , weight loss, dimensional change (negligible), surface quality and roughness and SEM-EDS inspections were performed. The maximum corrosion rate of the individual samples was measured (0.23 +/- 0.05) µm/year, with no appreciable difference between the two materials, satisfying the IFMIF requirement of less than 1µm/year. The surface remained smooth and the surface roughness remained essentially unchanged. In comparison to an unexposed specimen, a small depletion of Cr and W from the surface was measured in Li-exposed specimens by EDS. A second corrosion test to about 2000 hours is under work, to be followed by a final one covering 4000 hours of exposure.

## 3. Validation activities for the Test Facility

### 3.1 High Flux Test Modules (HFTM)

Corresponding to different irradiation objectives, two irradiation experiments for the high flux region were developed in EVEDA: the EU design addressing RAFM irradiation in the temperature range 250 – 550°C with vertical irradiation capsules made of RAFM with brazed mineral insulated electrical heaters, and the Japanese design addressing high temperature irradiation up to 1000°C with horizontal ceramic capsules with integrated heaters of refractory metals.

For the EU HFTM [10] manufacturing trials of single components leading up to a full length “double compartment” prototype (See FIG. 2 right) with 6 irradiation rigs were performed. This prototype was tested for thermal-hydraulic and mechanical properties in the HELOKA-LP helium loop at 1:1 hydraulic conditions. The full range of irradiation temperature levels up to 550°C was established. Also agile transient behavior (cool-down with 4K/s), robust temperature control (temperature excursion at instantaneous beam-on power insertion limited to 10K) and low temperature spread (15K in vertical axis and 8K in horizontal axis) were demonstrated, all values better than the requirements. Further work for the EU HFTM encompassed the handling of SSTT specimens under hot-cell conditions (assembly of the densely integrated specimen packing for the capsule, 80 specimens in about 2 hours) and studies on handling and corrosion of the NaK-78 eutectic metal.

For the Japanese HFTM [11], capsules and a full mockup for test in a gas loop were fabricated. The maximum temperature of 1000 °C was achieved for the capsule with excellent temperature homogeneity. In the gas loop operated with nitrogen, temperatures up to 600°C and homogeneities of about 4%, or temperatures up to 900°C with homogeneity of 14% were established. Cool-down transients from 600 to 200 °C were done with about 1K/s.

### 3.2 BR2 irradiation

Three capsules of the EU HFTM and one capsule of the Japanese HFTM were irradiated for three cycles in the Belgian BR2 test reactor [12]. The temperature control (three individually controlled heaters per capsule) worked well under the gamma heating conditions, and homogenous temperatures throughout the capsules were achieved. However several heater circuits failed during the irradiation. It is not fully clear if these failures have to be attributed to irradiation effects (deterioration of insulation) or if they are caused by pre-damaging during the manufacturing (some of the mineral insulated wires were cut and re-connected). Also, the capsule which cycled between 250 and 440°C mechanically failed after 650 thermal cycles and leaked the contained NaK. These experiences have led consequently to a mechanical design improvement of the capsule, such as avoiding of some weld seams and increased bending radii for the electrical heaters.

In the BR2 irradiation campaign, also Cerenkov Fiber Optical Sensors (C_FOS) developed by SCK-CEN and fission chambers [13] were tested. These radiation detectors are destined as instrumentation to characterize the IFMIF neutron source in the startup phase of the facility, and to instrument the High Flux Test Module. About 10% of the anticipated IFMIF dose could be tested. Both detectors showed good linearity.

### 3.3 HELOKA-LP helium loop

The HELOKA-LP helium loop [14] (See FIG.2 left) was built at KIT as testbed for the HFTM, as well as to gain experience with low pressure helium loops which are needed in IFMIF for the cooling of all test modules and some test cell components. The loop can circulate 120g/s of helium and provide 0.3 – 0.6 MPa abs. pressure and room temperature up to 300°C at the inlet of the test section. It is thus capable to supply a full scale High Flux Test Module. The loop has been used for an extensive test programme of the double-compartment HFTM prototype, including start-up procedures, steady state stability tests, cool-down transients, and loss of coolant scenarios. The loop’s operational record is now used to support reliability and availability studies for the IFMIF ancillary systems.

*FIG. 2. Left:HELOKA-LP helium loop at KIT. Right: Double compartment prototype of the HFTM during installation*

### 3.4 Creep Fatigue Test Module (CFTM)

A creep fatigue test module, in which 3 creep fatigue samples can be in-situ tested in the radiation field directly behind the HFTM was developed and tested at CRPP-EPFL Switzerland. Special attention was given to the design of the sample holder to allow easy and precise alignment of the specimens. A full testing machine with servo-moto controlled actuators and radiation hardened elongation sensor were built. The test frame was tested with load cycles over 3 months running load cycles with 12.5kN force and 0.2mm displacement amplitudes. The setup was tested in a vacuum vessel with HF Eddy current heating of the specimens and nitrogen cooling at temperature 100-550°C.

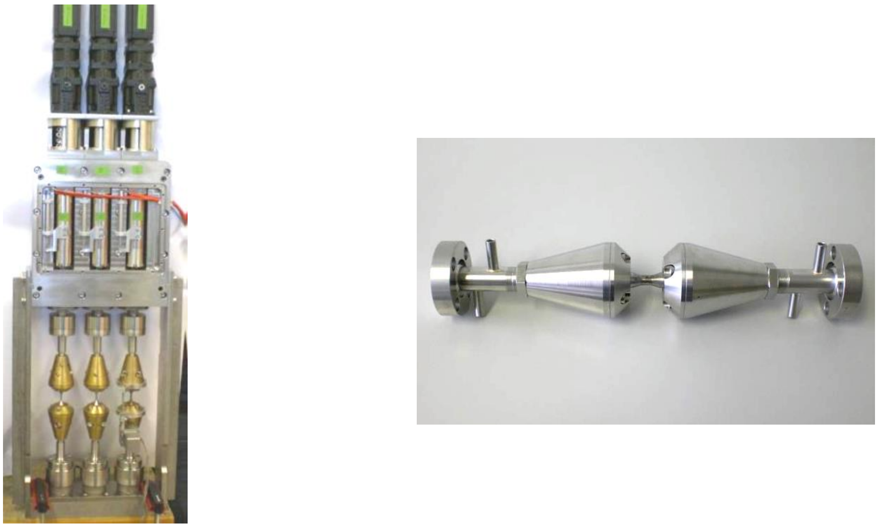

*FIG. 3. Left:CFTM test frame. Right:Detail of specimen holder with tungsten heater bodies*

### 3.5 Small Specimen Test Technique

Since the volume available for specimen irradiation in the IFMIF High Flux Test Module is only 0.5L or less, it is essential that miniaturized specimens are used. A single capsule of the EU HFTM houses 86 specimens, including flat tensile, Charpy / bend bars, fracture toughness and fatigue specimens, which can be used to characterize one or two alloys at one temperature level and one damage dose. However, it must be assured that the correspondence between the results obtained with SSTT and conventional size specimens is reliable. The work performed by JAEA in IFMIF EVEDA [15] addressed the applicability of the Master Curve for RAFM steels, effect of size and shape of miniaturized fatigue specimens, and the crack growth rate with wedge-opening load (WOL) specimens. It was found that results of Eurofer-97 and F82H did not fully align with the classical master curve approach. Optimized functions $K_{JC}(T)$ were developed for the 1CT specimen shape. An new testing machine for fatigue tests with SSTT was developed, with improved attachment for the extensometer to the specimen, and protection against vibrations. The fatigue results showed no significant specimen size effect, but hourglass type specimens showed a shorter crack initiation life for smaller diameters.

### 4. Conclusions

A broad range of validation activities were performed on the scale of experimental facilities, component tests and laboratory experiments for the Lithium Target Facility and the Test Facility of IFMIF during the EVEDA phase. These activities have provided valuable feed back to the associated design processes already during the Engineering Design Activities, as well as for the following development steps of IFMIF. The technical maturity of the most critical technologies could be demonstrated, and the lessons-learned allow a targeted further development to make IFMIF a reachable, efficient and reliable materials science facility as essential step on the roadmap to Fusion energy.

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