Available online at www.sciencedirect.com

ScienceDirect

Journal of Nuclear Materials 367–370 (2007) 1543–1548

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Thermo-structural analysis and design consideration of the replaceable backwall in IFMIF liquid lithium target

H. Nakamura [a,*], M. Ida [a], T. Chida [a], K. Shiba [a], K. Shimizu [b], M. Sugimoto [a]

[a] *Japan Atomic Energy Agency, Tokai-mura, Ibaraki 319-1195, Japan*
[b] *Mitsubishi Heavy Industry, Hyogo 652-8585, Japan*

Abstract

The IFMIF is an accelerator-based intense neutron source for testing candidate materials for fusion reactors. Intense neutrons are emitted inside the Li flow through a backwall. The backwall made of 316L stainless steel or RAFM is attached to the target assembly with a lip seal welded by a YAG laser. Since the backwall is operating under a severe neutron irradiation of 50 dpa/year and a maximum nuclear heating rate of 25 W/cm^3, thermo-structural design is one of critical issues in a target design. Thermal stress was calculated using the ABAQUS code. As a permissible stress, yield strength at 300 °C was used. In the case of the 316 stainless steel backwall, the maximum thermal stress was more than the permissible stress (164 MPa). On the other hand, in case of the F82H backwall, a maximum thermal stress was below the permissible stress (455 MPa). Therefore, F82H is recommended as the backwall material.

---

1. Introduction

International Fusion Materials Irradiation Facility (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 used in ITER and the fusion DEMO reactor [1]. To realize such a condition, a 40 MeV deuteron beam with a current of 250 mA and a total power of 10 MW is injected into a liquid Li flow with a speed of 20 m/s. At the end of 2002, a 3 year Key Element technology Phase (KEP) to reduce the key technology risk factors was completed [2]. Following the KEP, a transition phase is being performed prior to Engineering Validation and Engineering Design Activities (EVEDA) [3]. The major function of the Li target assembly is to provide a stable Li jet with a wave amplitude less than 1 mm up to a speed of 20 m/s. Intense neutrons are emitted inside the Li flow through a thin backwall attached to the target assembly. Since the backwall is operating under a severe neutron irradiation of 50 dpa/year and a maximum nuclear heating rate of 25 W/cm^3, thermo-structural design is one of critical issues in a target design. In a previous study [4], thermal stress analysis of the 316 stainless steel backwall was done to evaluate effects of constraint

---

[*] Corresponding author. Address: IFMIF Development Group, Tokai Research and Development Center, Japan Atomic Energy Agency, 2-4 Shirakata-Shirane, Tokai-mura, Ibaraki-ken 319-1195, Japan. Tel.: +81 29 284 3791; fax: +81 29 282 5551.
E-mail address: nakamura.hiroo@jaea.go.jp (H. Nakamura).

0022-3115/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jnucmat.2007.04.021

condition and thermal transfer coefficient on the thermal stress. This paper describes the latest efforts to optimise the backwall thermo-structural design.

2. Lithium target system and backwall

Design requirements of the Li target system are: heat removal of 10 MW from the deuterium beams, production of a stable Li jet for production of intense neutron irradiation damage more than 20 dpa/year in the high flux test module, control of the impurity levels (T, ^{7}Be, C, O, N), assurance of safety with respect to the Li hazard and tritium release from the Li loop and achievement of system availability of more than 95% during plant lifetime [5]. Major specifications of the IFMIF Li target are summarized in Table 1. The Li target system consists of two main components: the target assembly and the Li loop. A three-dimensional view of the target assembly is shown in Fig. 1. The target assembly and/or backwall must be replaceable by a remote handling system with a setting accuracy of 0.5 mm necessitated by the small gap (2 mm) between the backwall and the test cell assembly.

The backwall is operating under a severe condition of neutron irradiation damage (about 50 dpa/year) and is designed for replacement every 11 months. The target assembly is a stainless steel alloy except for the backwall made of 316L stainless steel or a Reduced-Activation Ferritic/Martensitic (RAFM) steel such as F82H. Two design options for backwall replacement are under investigation. The first is called the ‘Cut and reweld’ option shown in Fig. 1. The backwall is connected to the target assembly by a welded lip seal and a mechanical clamp at the circumference. For replacement of the backwall itself, the overall target assembly with the backwall is removed using a remote handling system to the hot cell area where a YAG laser device will be used for cutting the lip seals of the flanges. The second option is to replace the backwall of the target assembly by a remote handling device [6]. In this case, a ‘bayonet’ type mechanical attachment of the backwall to the target assembly is envisaged. In this paper, the ‘Cut and reweld’ option is considered.

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	$0.2\ \mathrm{m}^{W} \times 0.05\ \mathrm{m}^{H}$
Jet width/thickness	0.26 m/0.025 m
Jet Velocity	15 (range 10–20) m/s
Curvature of backwall	0.25 m
Inlet temperature of Li	250 °C (nominal) to 300 °C
Vacuum pressure	10^{-3} Pa at Li free surface
Materials	
Backwall	316L stainless steel or RAF steel
Other components	316L stainless steel
Erosion/corrosion thickness	
Nozzle and backwall	<1 μm /year
Pipings, etc.	<50 μm /30 years
Replacement	Every 11 month for backwall No replacement for 30 years (other components)

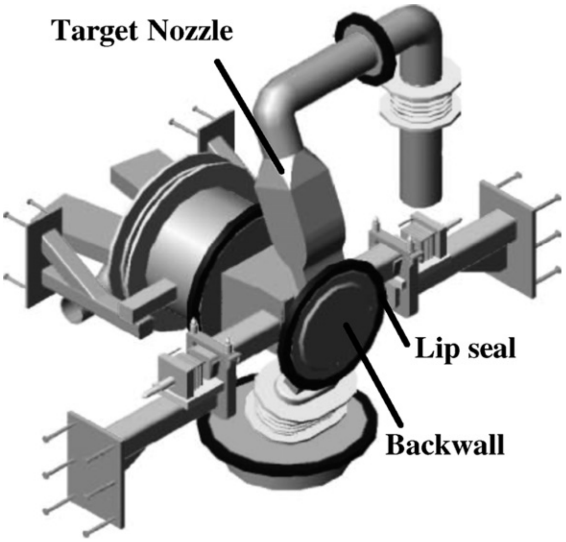

Fig. 1. Three-dimensional view of target assembly and backwall.

3. Thermo-structural analysis and design consideration

3.1. Calculation model and conditions

Deformation and thermal stress of the backwall due to nuclear heating by neutron irradiation was estimated by using the ABAQUS code under linear analysis. In this study, creep and irradiation swelling were not considered in the deformation calculation although these need to be evaluated in a future study. Fig. 2 shows the calculation models of the backwall and volumetric neutron heating distribution. Its shape is nearly a disc with a diameter of

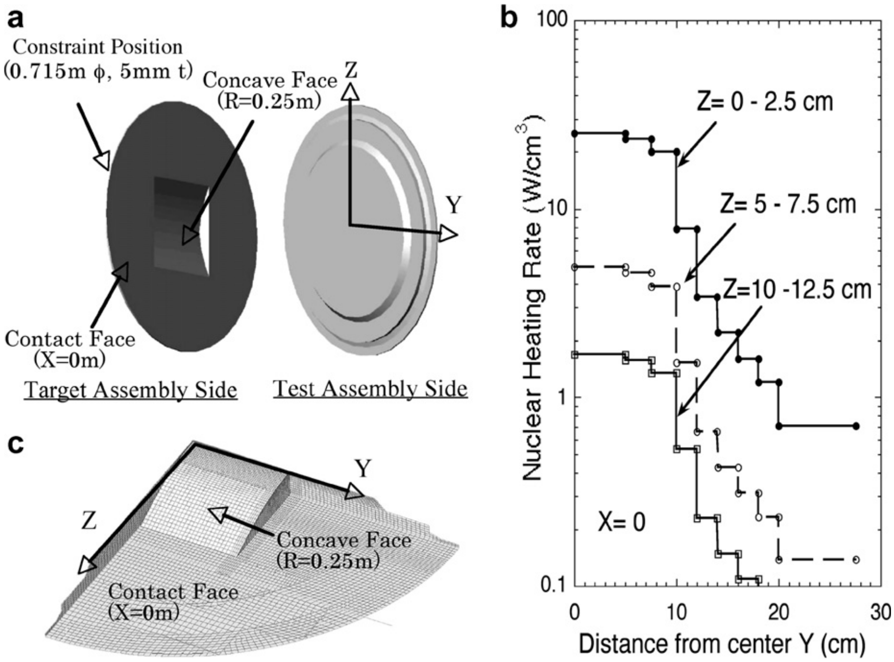

Fig. 2. Backwall models and calculation conditions for the thermal stress analysis: (a) backwall model, (b) nuclear heating rate and (c) ABAQUS 1/4 model.

0.715 m. Its Li flow side has a concave face with a radius of 0.25 m. The analysis was performed for a 1/4 section ($0\,\mathrm{m} < Y$, $0\,\mathrm{m} < Z$) of the backwall because of its symmetry. The maximum value of the nuclear heating rate was 25 W/cm^3 at beam center ($Y = 0$ m, $Z = 0$ m). In a previous study, two cases for the boundary condition were considered at the lip seal of the backwall. One is constraint for all degrees of freedom, and the other is that only in the X direction. Since the former constraint is not acceptable due to high thermal stress, the latter constraint was used in this analysis. Temperatures of the target assembly and liquid Li were both 300 °C, and the convection heat transfer coefficient between Li and the backwall was 34 kW/m^2 K, estimated as the minimum value from experimental results [7]. Emissivity of the backwall was 0.3. The temperature of the vertical test assembly (VTA) was assumed to be 50 °C because the effect of VTA temperature between 50 °C to 150 °C on the backwall temperature was found to be negligible. In this analysis, the high-speed Li flow pressure (0.04 MPa) on the backwall is not neglected because induced mechanical stress is less than a few % of the permissible thermal stress.

Contact heat transfer coefficients between the backwall and the target assembly were 15.8, 79 and 158 W/m^2 K depending on the contact pressure of the clamping mechanism, which was assumed to be 0.1, 0.5 and 1 MPa, respectively. To evaluate the effects of the backwall thickness on the thermal stress and deformation, the minimum thickness of the backwall was selected to be 1.8 mm (reference value), 3 mm and 5 mm. In the backwall, an inelastic deformation of the backwall is not allowed to realize a stable high-speed Li flow and, therefore, a permissible stress of the backwall is defined by yield strength. To prevent deterioration of the high-speed Li flow, the deformation of the backwall needs to be as small as possible. Permissible deformation value will be defined by a future study on Li flow stability.

3.2. Results and discussion

3.2.1. Thickness and contact heat transfer coefficient

In the previous analysis of the 316L stainless steel (Fe plus Cr: 16–18%, Ni: 12–15%, Mo: 2–3%, Mn: <2%, Si: <1%, C: <0.03%, in wt%) backwall with a minimum thickness of 1.8 mm and a contact heat transfer coefficient of 158 W/m^2 K between the target assembly body and the backwall, the maximum thermal stress and deformation at the center of the backwall were about 260 MPa and 0.3 mm, respectively [4]. The temperature at the center of the backwall was about 300 °C, close to the Li temperature. The

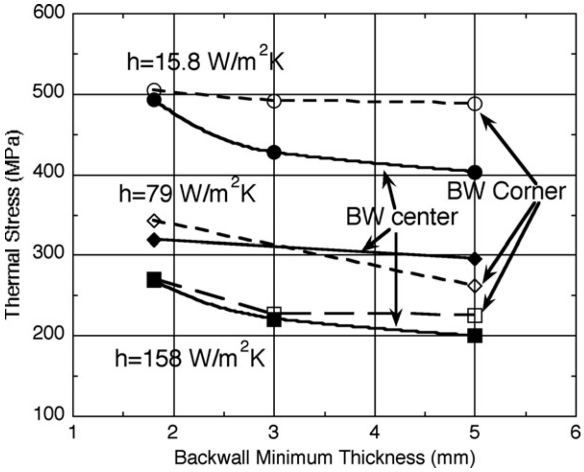

Fig. 3. Effect of the 316L backwall minimum thickness on thermal stress.

calculated thermal stress was beyond the permissible value of 164 MPa at 300 °C for 316L stainless steel. Although the permissible deformation value is not yet defined, to mitigate the thermal stress and deformation, the effects of the minimum thickness of the backwall and the contact heat transfer coefficient on the thermal stress was evaluated as shown in Fig. 3. Increasing the minimum thickness of the backwall, the thermal stresses decrease and are close to constant values. However, in a range of 15.8–158 W/m^2 K, which corresponds to a contact pressure of 0.1–1 MPa, the induced thermal stresses are still above the permissible value, even in the 5 mm case. Considering realistic design conditions on the contact heat transfer coefficient and the minimum backwall thickness, 316L stainless steel is not recommended for the backwall application in the IFMIF.

3.2.2. Backwall material

Considering the advantages of reduced radioactivity and higher mechanical strength than 316L stainless steel, a Reduced-Activation Ferritic/Martensitic (RAFM) steel such as F82H (Fe plus Cr: 8%, W: 2%, V: 0.14%, Ta: 0.04%, C: 0.1%) was selected as a candidate material. Using the reference configuration with a minimum thickness of 1.8 mm, a thermal stress analyses was done. Figs. 4 and 5 show contour of the temperature and the von Mises stress of the F82H backwall, respectively. High thermal stresses are observed at the center and corner of the backwall. Fig. 6 shows the von Mises stress and the deformation as a function of the contact heat transfer coefficient between the backwall and the target assembly. For a comparison, results of the 316L backwall are also shown. Lower thermal stress and lower deformation of the F82H than of the 316L is caused by higher thermal conductivity and lower thermal expansion coefficient of the F82H than of the 316L. According to the IEA data base [8], the yield strength of F82H is 455 MPa at 300 °C. Even in the case of reference condition (15.8 W/m^2 K), the von Mises stress is below the permissible value.

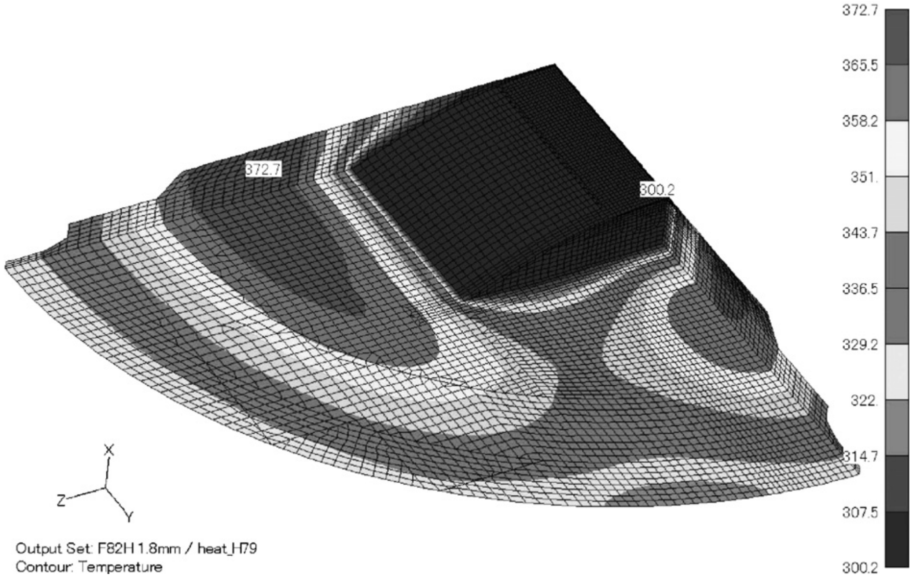

Fig. 4. Contour of temperature of the backwall (F82H, $t_{\min} = 1.8$ mm, $h = 15.8$ W/m^2 K).

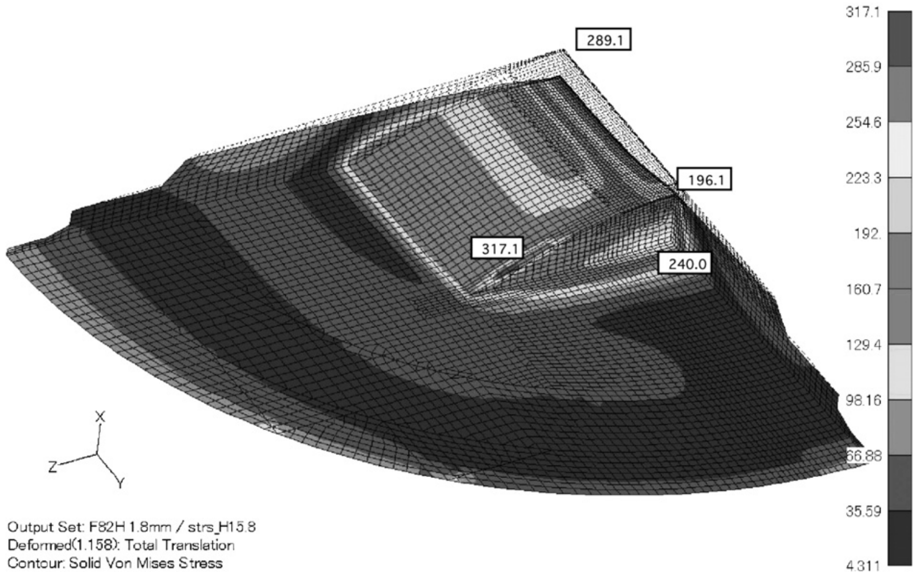

Fig. 5. Contour of the von Mises stress of the backwall (F82H, $t_{\min} = 1.8$ mm, $h = 15.8$ W/m^2 K).

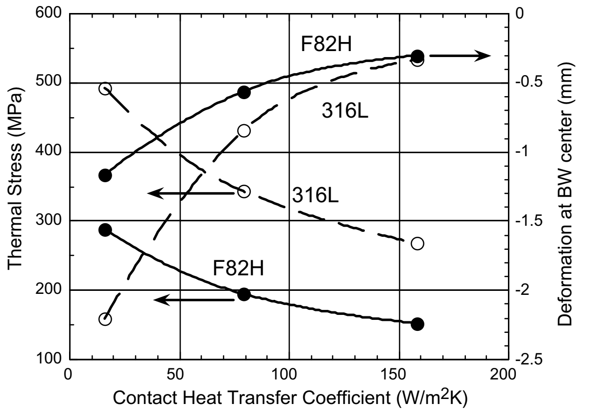

Fig. 6. Effect of the contact heat transfer coefficient on the von Mises stress and deformation of the 316L and F82H backwalls with a minimum thickness of 1.8 mm.

The deformation of the F82H backwall is 0.3–1.1 mm in the range of the contact heat transfer coefficient (15.8–158 W/m^2 K). On the other hand, the von Mises stress of the 316L is above the permissible value, 164 MPa. The deformation of the 316L backwall is 0.3–2.4 mm. Therefore, from the viewpoint of thermo-structural design, F82H is recommended as a backwall material.

4. Future data needs

To apply F82H to the backwall, one of design issues is lip seal welding between the F82H and the 316L stainless steel target assembly because welding these two steels is difficult. To address this issue, use of an interlayer between the target assembly lip and the backwall lip is being considered. In the reference configuration of the 'Cut and reweld' backwall, neutron irradiation at the lip seal location at full performance of the IFMIF is estimated to be 0.1–1 dpa/year, although neutron irradiation at a center of the backwall is 50 dpa/year. In this condition, the He generation rate is about 1–10 appm. Rewelding characteristics of the irradiated lip seal needs to be evaluated. To mitigate the deformation of the backwall, optimization of the backwall configuration is under investigation. Moreover, further study on a constraint condition of the backwall is under way.

In a next phase of the IFMIF project (EVEDA), engineering design and validation on the replaceable backwall will be performed.

5. Summary

Thermo-structural analyses of the 'Cut and reweld' type replaceable backwall made of 316L stainless steel and F82H have been done using the ABAQUS code. In the case of the 316 stainless steel backwall, the von Mises stress was higher than a permissible value of 140 MPa. However, for a F82H backwall, the von Mises stress was less than a permissible value of 455 MPa. Therefore, F82H is recommended as the backwall material.

Acknowledgements

Appreciation is given to all members of the IFMIF international team for their contributions to this work. The IFMIF executive subcommittee has been highly impressed with dedication and enthusiasm of the IFMIF team. They are also grateful to Drs M. Seki, S. Seki, and H. Takatsu for their support and encouragement.

References

[1] A. Möslang, U. Fischer, V. Heinzel, P. Vladimirov, R. Ferdinand H. Klein, B. Riccardi, M. Gasparotto, H. Matsui, M. Ida, H. Nakamura, M. Seki, M. Sugimoto, H. Takeuchi, T. Yutani, T. Muroga, R.A. Jameson, T. Myers, J. Rathke, T.E. Shannon, S. Païdassi, V. Chernov, in: Proc. 19th Fusion Energy Conference, France, October 2002, IAEA-CN-94/FT1-2.

[2] IFMIF International Team (Ed.), H. Nakamura, M. Ida, M. Sugimoto, M. Takeda, T. Yutani, H. Takeuchi, JAERI-Report, JAERI-Tech 2003-005, March 2003.

[3] H. Takatsu, M. Sugimoto, S. Jitsukawa, H. Matsui, these Proceedings.

[4] M. Ida, H. Nakamura, K. Shimizu, T. Yamamura, Fusion Eng. Des. 75–79 (2005) 847.

[5] H. Nakamura, B. Riccardi, K. Ara, L. Burgazzi, S. Cevolani, G. Dell'Orco, C. Fazio, D. Giusti, H. Horiike, M. Ida, H. Ise, H. Kakui, N. Loginov, H. Matsui, T. Muroga, Hideo Nakamura, K. Shimizu, H. Takeuchi, S. Tanaka, Fusion Eng. Des. 66–68 (2003) 193.

[6] B. Riccardi, M. Martone, C. Antonucci, L. Burgazzi, S. Cevolani, D. Giusti, G. Dell'Orco, C. Fazio, G. Micciche, M. Simoncini, Fusion Eng. Des. 66–68 (2003) 187.

[7] N. Uda, A. Miyazawa, S. Inoue, N. Yamaoka, H. Horiike, K. Miyazaki, J. Nucl. Sci. Technol. 38 (2001) 936.

[8] A.-A.F. Tavassoli, J.-W. Rensman, M. Schirra, K. Shiba, Fusion Eng. Des. 61&62 (2002) 617.