Structural Design Basis Review of the HCCP TBM-set Attachment

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1. Introduction

The HCCP (Helium-Cooled Ceramic Pebble) TBM-set to be installed in ITER consists of the TBM-box, the TBM-shield, and the attachment structures connecting them [1]. The attachment is a principal load-transfer component. It transfers the mechanical loads from the box to the shield, and it also has to accommodate the relative deformation caused by thermal expansion during operation. The attachment must therefore be stiff enough to transfer the loads and flexible enough to follow the thermal expansion. These two requirements compete, and the design satisfies them by separating the directions in which stiffness and flexibility are needed.

In a previous study, the thin-plate attachment configuration was assessed by finite element analysis, and candidate geometries were compared with respect to peak stress [2]. That study resolved the stress issue of the initial configuration. It also treated the mass limitation as a constraint that the geometric redesign would satisfy.

This study revisits those results and the design basis behind them. The review covers the mass inventory, the load hierarchy at the bolted interface, the shear transfer path, and the code verification status. The parts that the results actually settle are identified, and the issues that remain to be confirmed are listed together with the approaches proposed to address them, so that it becomes clear which design decisions can be regarded as closed before the final design review. The design is at the preliminary stage, and the items discussed here are being addressed in the ongoing design work.

2. Configuration and Previous Analysis

2.1 Configuration

The configuration described here is the initial thin-plate design, which is the reference for the review of Section 3. The attachment is welded to the back plate of the TBM-box (I/F1 in Fig. 1) and is connected to the front plate of the TBM-shield (I/F2) by preloaded bolts, with conical seating surfaces acting as shear keys. Two attachment units are used, one in the upper and one in the lower part of the interface, and each unit is fastened by four M24 bolts. The box side is welded because the box and the attachment are replaced together as a single assembly. The shield side is bolted for ease of assembly and because the attachment and the shield are made of different materials, so a welded joint at this interface would be a dissimilar weld. Each unit carries two arms, and each arm ends in a stack of thin plates. The stack provides the flexibility against thermal expansion. It bends in the direction of the thermal expansion and remains stiff against the electromagnetic moment.

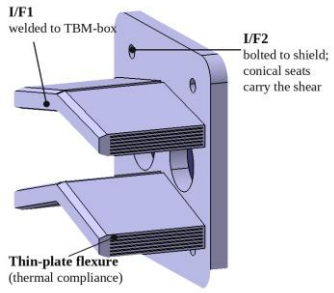


Fig. 1. One attachment unit and its two interfaces

2.2 Design conditions and analysis method

Three operating states are considered: normal operation, baking, and outgassing. The imposed boundary-temperature difference between the box-side and the shield-side regions of the attachment is about 430 °C in normal operation and about 30 °C during baking. The same member is therefore subject to thermal demands that differ by an order of magnitude. In addition to these states, transient electromagnetic events, two seismic events, and the dwell period between pulses are treated as load cases. The configuration is also subject to a mass constraint. The ferromagnetic steel mass of each TBM is limited to 1,300 kg. The limit follows from the toroidal field ripple and not from a structural requirement, and minimizing this mass is a stated objective of the ITER TBM programme [1]. Components required to be non-magnetic are separately limited to a relative permeability of 1.03.

The structural material of the box is the reduced-activation ferritic/martensitic steel EUROFER97, and the shield is made of 316L(N)-IG. The attachment is currently assumed to be EUROFER97 as well. The assessment follows the RCC-MRx code [3], with the design limits and criteria for EUROFER structures in TBM components taken from [4]. The Level A criteria are applied to the normal operating condition. The two seismic combinations are evaluated using the Level C and Level D criteria applicable to their respective loading conditions.

The previous assessment [2] was carried out with ANSYS as a sequential thermo-mechanical analysis on a global TBM-set model. In the thermal step, constant-temperature boundaries and volumetric nuclear heating on the attachment were applied to obtain the steady-state temperature field. In the mechanical step, the temperatures were applied as a body load, the rear end of the TBM-shield was constrained, and the stress in the attachment region was extracted from the global model.

The interface loads discussed in Section 3.2 come from a separate load-combination analysis performed for the bolted connection, in which the resultant forces and moments at I/F2 were obtained for each combination of pressure, thermal, gravity, static magnetic, transient electromagnetic and seismic loads.

2.3 Results of the previous assessment

The results are summarized in Table I, normalized to the initial thin-plate design. The relative values are peak von Mises stress and serve as an indicator only. The Level A check in the last column was made on stress intensities linearized along evaluation paths. The initial thin-plate configuration did not satisfy the reported Level A stress-intensity check, which is what motivated the geometry study. Two lightweight variants were obtained by clarifying the primary load path and by introducing localized compliance instead of compliance distributed over large plate areas. Both reduced the peak stress to about half of the initial value and satisfied that check. The one-plate variant was selected for its balance of structural integrity, mass, and manufacturing simplicity.

Table I: Peak stress of the candidate configurations [2]

Configuration	Relative peak stress	Level A check
Model 1 (thin plates)	1.00 (reference)	not met
Model 2 (one plate)	≈ 0.53	met
Model 3 (cylinder)	≈ 0.53	met

These results resolve the reported Level A stress-intensity issue for the configurations and load cases examined. The other elements of the design basis are examined in the next section.

3. Items to be Confirmed in the Present Design Basis

3.1 The mass constraint calls for a material decision

The lightweight variants were also expected to contribute to the mass limitation. The ferromagnetic inventory of the reference design, with the attachment assumed in EUROFER97, indicates that geometry alone may not provide the reduction required (Table II). The box mass is set by its function, and the box without the attachment already accounts for most of the limit, so the margin remaining for the attachment is small. Meeting the limit by geometry would require a reduction of about 70 % of the attachment mass.

Table II: Mass reduction required from the attachment

Item	Relative to the attachment mass
Attachment (EUROFER97 assumed)	1.00
Allowed within the ferromagnetic limit	≈ 0.3
Reduction to be found	≈ 0.7

A reduction of this size is difficult to reconcile with the torsional stiffness that the attachment must keep to transfer the electromagnetic moment. The scaling given in Section 4(e) also shows that the plate thickness cannot be reduced without losing the buckling margin in the same proportion. The mass constraint is therefore better treated as a material selection problem. A non-ferromagnetic steel would remove the attachment from the ferromagnetic inventory completely, and the assembly would fall below the limit without any change of shape.

3.2 The interface force resultant is dominated by steady-state loads

The verification effort has so far been weighted toward the transient events. The load combination results suggest that this weighting can be revisited.

The force resultant at the bolted interface, taken as the vector magnitude of the reaction over one attachment unit, was compared between load combinations (Fig. 2). Each event case adds the named event to the normal-operation loads. With respect to normal operation, the transient electromagnetic cases change the resultant force by about −3 %, because the electromagnetic force acts partly against the thermal and pressure resultant. The seismic cases increase it by about +3 % for the Level C event and by about +5 % for the more severe Level D event. The thermal-only states, baking and outgassing, reach 11 % and 27 % of the normal-operation resultant, but the sign reversal between these two states contributes to the fatigue-relevant load range discussed in Section 3.4. The resultant magnitude is used here as a first indicator only, and the contributions of the individual components are given below.

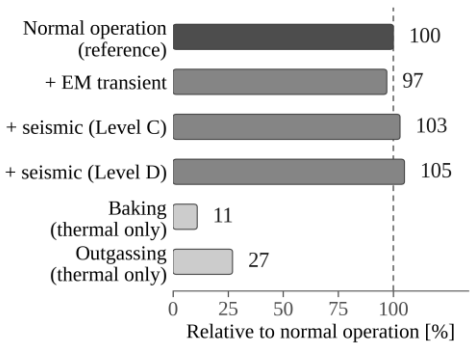


Fig. 2. Force resultant at I/F2 by load combination.

The force resultant is therefore dominated by the steady-state combination of internal pressure, thermal load, gravity, and the static magnetic force. The examined transient electromagnetic and seismic events modify it by no more than about 5 %. Relative to the normal-operation values of the same components, the transient electromagnetic load still contributes about 17 % of the vertical shear and 13 % of the resultant moment, so its effect appears in the individual components even though it is not visible in the resultant magnitude. On the basis of the resultant magnitude the seismic combinations are unlikely to govern the preliminary sizing, and the applicable Level C and Level D limits further support this. Component-wise checks on the bolts and the contact surfaces are still required before the governing combination is identified.

This is different from the usual situation reported for in-vessel components, where the transient electromagnetic loads are the dominant design load [5]. The large temperature difference and the internal pressure carried by this interface explain the difference. Design and verification effort is therefore better directed to the steady-state combination, with the transient electromagnetic contribution retained in the sizing of the shear path.

3.3 The shear transfer path is to be quantified

The design assumes that the flat plate surfaces are not in contact and that the transverse shear is transferred entirely through the conical seating surfaces. Friction is not credited as a load path. The baseline concept therefore relies on form-fit load transfer through the preloaded conical seats. Fitted bolts acting in bearing are an alternative concept and are not credited in the present load path.

The geometry of the conical seats, their contact area, and the resulting bearing stress are to be evaluated as the design proceeds. The bolt margins of the preliminary sizing depend on this element carrying the shear as assumed. The assumption itself was taken from a European TBM shield design and is to be confirmed for the HCCP shield.

3.4 Code verification items to be completed

The bolted connection was sized against the RCC-MRx framework at a level suitable for the preliminary design stage. Several quantitative items are to be completed (Table III), among them the joint stiffness ratio governing the load sharing between bolt and joint, which was assumed at this stage and is to be computed. Beyond these items, the sizing was made from the interface reactions of a global model in which the bolts and their preload are not represented, so prying, bolt-hole stress concentration, and the opening and slip of the contact faces are to be included in the detailed evaluation. The normal-operation thermal load used in the sizing was obtained by interpolating the baking and outgassing results, and a dedicated analysis is planned.

Table III: Verification items to be completed

Item	Required input
Differential thermal expansion	dedicated thermal analysis
Bearing pressure at the shear key	seat geometry, contact area
Thread stripping	clamp length, thread engagement
Mechanical fatigue	cycle definition, stress range
Joint stiffness ratio	bolt and joint stiffness

Fatigue needs particular attention. Because the interface load reverses sign between operating states, the transitions between normal operation and dwell, and between outgassing and baking, produce a stress range at the interface. The preload limits the range seen by the bolts as long as the joint faces remain closed, while the attachment and the conical seats are subject to a contact-pressure range and to possible unloading, so the fatigue assessment is to be included.

4. Recommendations

Items (a) and (b) address the mass constraint of Section 3.1, (c) the shear transfer path of Section 3.3 and (d) the code verification items of Section 3.4, while (e) follows from the conclusion of Section 3.1 that geometry is not the way to reduce mass. The load hierarchy of Section 3.2 does not call for a separate action, but it sets the weighting between the others. Item (c) requires the least effort and is proposed as the immediate action.

(a) The mass constraint should be treated as a material decision and not as a geometry problem. Full substitution to austenitic steel satisfies the limit, but it raises the thermal expansion coefficient appreciably with respect to EUROFER97 and moves the dissimilar joint to the box-side interface, which is welded. A hybrid arrangement keeps the homogeneous weld at the box side and places the material transition at the cooler end of the attachment. The hybrid satisfies the mass limit only if the converted part covers about 70 % of the attachment mass, which is the same fraction identified in Section 3.1. Whether it does is to be established from the mass distribution within the attachment. Both options also change the load basis of Section 3.2, because the ferromagnetic contribution of the attachment is removed and the thermal load is expected to change, so the load combination has to be repeated. In both cases the relative permeability of the austenitic parts has to be verified after fabrication, because cold work and welding can increase it.

(b) The decisive criterion for the material decision is the feasibility of the joint, not the stress margin. The dissimilar butt weld required by the reference geometry is a thick and long structural weld, for which fabrication experience is limited. The post-weld heat treatment is a

further open point, because the condition that restores the heat-affected zone of the ferritic/martensitic side, reported for a comparable joint between a RAFM steel and an austenitic steel [6], has to be reconciled with the tempering condition of EUROFER97 [7]. No directly applicable qualified route for this weld was identified within the RCC-MRx framework used here.

(c) The shear key should be quantified. Determining the seat geometry, the contact area, and the bearing stress removes the largest single uncertainty in the connection. It provides the input required to close the bearing pressure item of Table III and to support the fatigue assessment.

(d) The interpolated thermal load should be replaced by a dedicated analysis, so that the load basis of the connection becomes an analysis result rather than an interpolated estimate. This also provides the input required to close the differential thermal expansion item, and it follows from the load hierarchy of Section 3.2, where the steady-state load combination dominates the force resultant.

(e) Geometry optimization should be kept as a separate task that addresses stress, buckling, and fatigue instead of mass. For an idealized plate flexure of thickness t and length L under an imposed end displacement δ, the bending stress scales as $Et\delta/L^2$. Increasing the length is therefore more effective than reducing the thickness. The ratio of this stress to the buckling stress depends only on δ/t for a given buckling coefficient, so the thickness has a lower bound that cannot be removed merely by increasing the flexure length. These relations are scaling arguments for design guidance, not design criteria.

5. Conclusions

The design basis of the HCCP TBM-set attachment was reviewed against the results of the previous assessment. The reported Level A stress-intensity issue is resolved for the configurations and load cases examined, where the two lightweight variants reduce the peak stress to about half of the initial value. Fatigue, buckling and the detailed joint checks lie outside that conclusion. The stress result does not discriminate between the two variants, and the one-plate variant was selected on grounds of mass and manufacturability.

Four items are to be confirmed as the design proceeds. Meeting the ferromagnetic mass limit by geometry alone would require a reduction of about 70 % of the attachment mass, which is difficult to reconcile with the stiffness the member has to keep. The interface force resultant is dominated by the steady-state combination of internal pressure, thermal load, gravity and the static magnetic force, and the examined event loads change its magnitude by no more than about 5 %. This differs from the load hierarchy usually reported for in-vessel components, and the verification effort should be weighted toward the steady state instead of the transient events. The baseline concept transfers the transverse shear by form-fit through the preloaded conical seats, whose geometry and bearing demand remain to be quantified. Fitted bolts acting in bearing are retained only as an alternative. Several items of the bolted-connection verification also remain to be completed, among them the differential thermal expansion and the fatigue assessment.

The proposed approach is to treat the mass constraint as a material decision, for which the decisive criterion is the feasibility of the dissimilar joint and not the stress margin, to quantify the shear key as the immediate action, and to replace the interpolated thermal load by a dedicated analysis. Geometry optimization is kept as a separate task addressing stress, buckling and fatigue. These items define what has to be closed before the final design review. Work on them is in progress and will be reported with the corresponding analyses.

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REFERENCES

[1] L.M. Giancarli, et al., Overview of the ITER TBM Program, Fusion Engineering and Design, Vol. 87, pp. 395-402, 2012.
[2] S.D. Park, et al., Structural design assessment of the HCCP TBM-set attachment, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 6-8, 2026.
[3] AFCEN, RCC-MRx: Design and Construction Rules for Mechanical Components of Nuclear Installations, 2018 Edition, AFCEN, Paris, 2018.
[4] G. Aiello, et al., Assessment of design limits and criteria requirements for Eurofer structures in TBM components, Journal of Nuclear Materials, Vol. 414, pp. 53-68, 2011.
[5] A.R. Raffray, et al., The ITER blanket system design challenge, Nuclear Fusion, Vol. 54, 033004, 2014.
[6] H. Fu, et al., Effect of post-weld heat treatment and neutron irradiation on a dissimilar-metal joint between F82H steel and 316L stainless steel, Fusion Engineering and Design, Vol. 98-99, pp. 1968-1972, 2015.
[7] G. Stornelli, et al., Grain refinement and improved mechanical properties of EUROFER97 by thermo-mechanical treatments, Applied Sciences, Vol. 11, 10598, 2021.