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Division V - Modelling, Testing and Response Analysis of Structures, Systems and Components

## PURPOSE-DESIGNED & QUALIFICATION STRUCTURAL SUPPORTS FOR ITER CRYOSTAT

Micaël Connesson<sup>1</sup>, Sébastien Diaz<sup>2</sup>, Jeanne Duc<sup>3</sup>, Laura Boutron<sup>4</sup>, Laurent Patisson<sup>5</sup>, Armand Gjoklaj<sup>6</sup>

<sup>1</sup> Technical & Engineering Director, NUVIA France, Lyon, FRANCE ([micael.connesson@nuvia.fr](mailto:micael.connesson@nuvia.fr))

<sup>2</sup> CEO, NUVIA Protection, Morestel, FRANCE ([sebastien.diaz@nuvia.fr](mailto:sebastien.diaz@nuvia.fr))

<sup>3</sup> Project Engineer, NUVIA Structure, Lyon, FRANCE ([jeanne.duc@nuvia.fr](mailto:jeanne.duc@nuvia.fr))

<sup>4</sup> Engineering Department Manager, NUVIA Structure, Lyon, FRANCE ([laura.boutron@nuvia.fr](mailto:laura.boutron@nuvia.fr))

<sup>5</sup> Group Leader for Building & Civil Works Section, ITER Organization, Cadarache, FRANCE  
([laurent.patisson@iter.org](mailto:laurent.patisson@iter.org))

<sup>6</sup> Civil Nuclear Engineer, Building & Civil Works Section, ITER Organization, Cadarache, FRANCE  
([armand.gjoklaj@iter.org](mailto:armand.gjoklaj@iter.org))

### ABSTRACT

The ITER project aims at building a fusion device, twice the size of the largest current devices. The core of the reaction is held in a massive machine, the Tokamak, supported by specifically-designed bearings. The unusual working conditions and load cases on the bearings prohibited the use of classical design and sliding materials.

Therefore, a unique combination of design and qualification process, based on step-by-step experimental approach and on numerical analysis, is implemented in order to provide safety-proved, robust and fit-to-purpose supports for the Cryostat of ITER project.

### INTRODUCTION

The ITER project aims at building a fusion device, twice the size of the largest current devices, with the goal of demonstrating the scientific and technical feasibility of fusion power. It is a joint project between the European Union, China, India, Japan, South Korea, the Russian Federation and the USA. ITER will be constructed in Europe, at Cadarache in the south of France.

The Tokamak Complex Buildings housing the fusion reactor, Tokamak machine, and plant systems is mainly made of a reinforced concrete structure, weighing almost 300 000 tons.

The Tokamak machine (whose envelope is called “Cryostat”), shall be installed within a large and heavily-reinforced concrete support structure. The fusion reaction is expected to occur in a 150 to 300-million-degrees-centigrade plasma, circulating in the heavy magnetic field and the quasi-vacuum of the Tokamak, in the centre of the liquid-helium-cooled (-269°C) superconductor magnets.

To support this massive and extraordinary machine, 18 spherical sliding steel bearings accommodate displacements and mainly transmit the vertical loads of the machine down to the civil structure. These bearings will be called, throughout the article, the “Cryostat Support Bearings” (e.g., CSB).

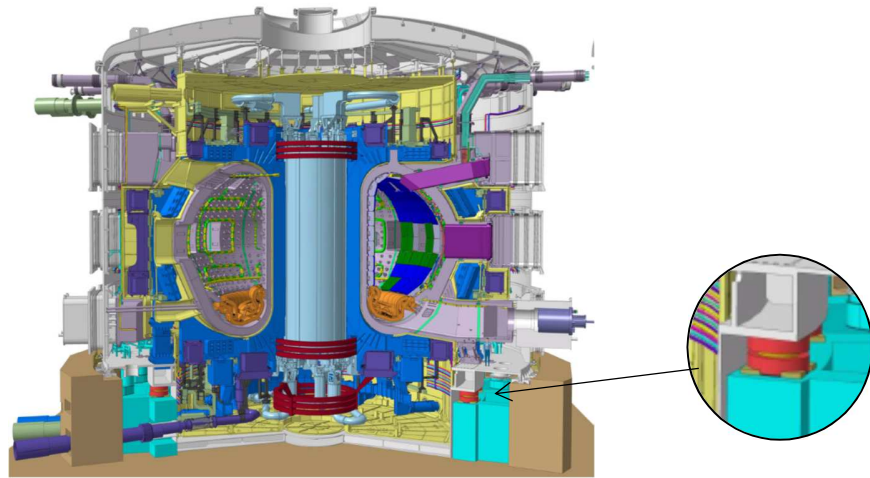


Figure 1. The Cryostat on the CSB

The vertical loads, coming from various load cases due to the Tokamak itself, are combined with horizontal loads and imposed rotations, mainly due to thermal loading (service case but also accidental loss of coolant):

- The nominal vertical load applied to individual CSB is 21MN (approx. 2200tons) and it can increase up to 39.8MN (approx. 4000tons) in accidental case. Both values include safety provisions defined by ITER.
- Cumulated displacement over service life under thermal-“breathing” of the vessel is only 12m.
- Maximum bending moment transmitted under vertical load, horizontal friction resistance and simultaneous imposed rotation should not exceed approximately 5 MN.m.

But the environment of the whole machine is such that the loads transmitted by bearings after sliding must NOT exceed 0.25 friction coefficient during the 60 years of service life. Moreover, these bearings have to withstand very specific and outstanding conditions: normal atmospheric pressure (no vacuum), up to  $10^5$  Gy of  $\gamma$ - & plasma neutron-radiation cumulated dose, temperature as low as  $-100^\circ\text{C}$  under accidental conditions.

And, last but not least, they are Protection Important Components, what implies a dedicated qualification program and associated control in order to underpin the Safety Cases. This qualification program has therefore to cover all the range of loads and conditions.

## DESIGN & QUALIFICATION STRATEGY

### *Tribology and design guiding principles*

The Cryostat Support Bearings are sliding-based bearings, in order to convert the unknown effect on structures of thermal expansion or contraction of the machine into well-known loads and displacement. Stating this fundamental design principle demands a particular focus on the sliding behaviour of the CSB: characterization of the sliding complex will be the corner stone of the qualification program, knowing that, from tribological point of view, sliding phenomenon is driven by two mechanisms: friction and wear.

*Friction* is the motion resisting force, at a certain moment in the process of motion, between the two surfaces in contact. In the basic friction mechanisms, no material removal is involved. Two friction coefficients are defined:

- Static friction coefficient which characterises the energy needed to start the movement from immobile to mobile.
- Dynamic friction coefficient which characterises the energy needed to keep moving.

*Wear* is the process of matter detachment from one surface. It is different from friction in the sense that it is not taking place at a specific moment but during a time period, while the surfaces are in moving contact. The major phenomena which can pollute the friction coefficient are the appearance of scales, stick slip effect and wear during movement. The design of the CSB and the sliding complex definition must address this tribological principles.

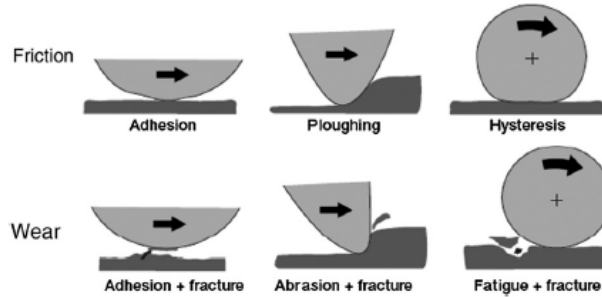


Figure 2. Friction and wear phenomena as per Window et al. (2011) should be addressed during qualification campaign of sliding complex

Keeping in mind the stakes for the sliding complex, the design process goes on by conjugating the other design constraints of the supporting system:

- i. The CSB must enable 5 Degrees Of Freedom, rotations and horizontal translations (rotation in the 3 directions like a spherical hinge and translation in 2 directions), implementing the sliding complex with proper geometry. Other structures (shear keys, vertical skirts supports, by instance) will limit the movements of the machine.
- ii. On the one hand, the extension of the range of loads, the temperature and service-life conditions, mean that classical, soft sliding materials cannot be used for the application: CM1, CM2 sliding materials become either brittle at cold temperature or lose their properties under high-energy radiation. On the other hand, the friction and wear behaviours of the sliding complex must be thoroughly understood.
- iii. The CSB must be tested full scale and full range. Not only their dimensions must be compliant with testing rigs but also their design has to take into account that the resisting friction coefficient of the bearings will be tested for translation DOF and rotation DOF. Therefore, the geometry of the CSB was defined so that 2 bearings could be stacked, upside-down, creating thus a real spherical hinge.

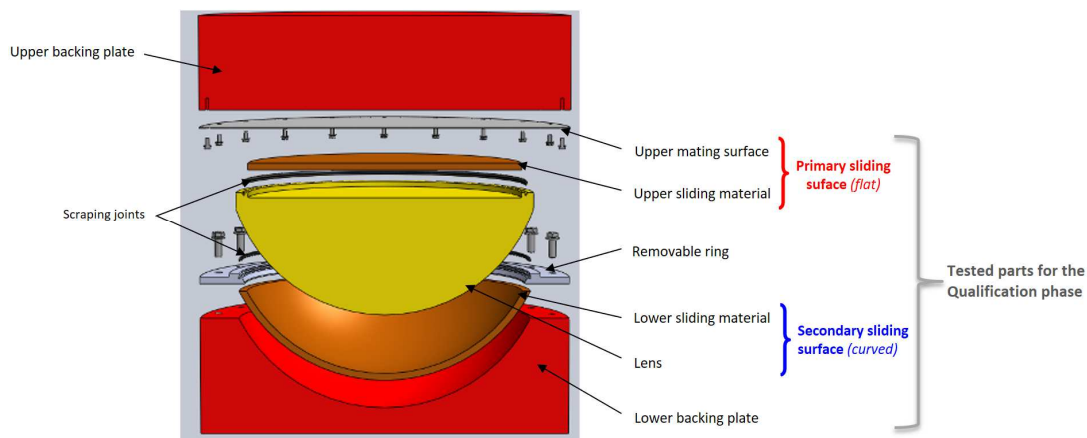


Figure 3. Exploded cross-section of the CSB

Nevertheless, the design loading configuration is a tri-axial loading: the vertical load  $N$  is combined simultaneously with a horizontal load  $H$  and a bending (rotation) moment  $M$ . Such testing bed does not exist, especially over the full load range ( $N = 41\text{MN}$ ).

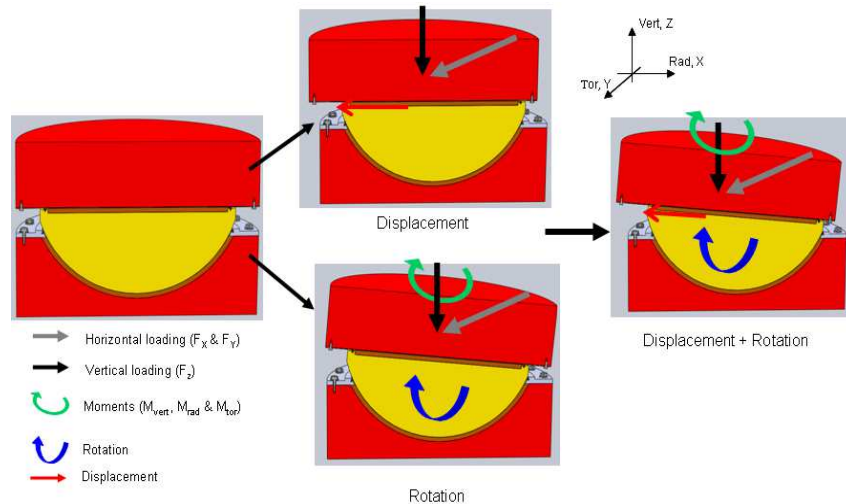


Figure 4. Tri-axial loading conditions represented on a cross-section of the CSB

### *From existing standards toward a dedicated dual approach*

Requirements and approach from different existing standards were scrutinized.

Among the standards and reference scientific literacy, the following were found relevant:

- (i) The EN15129, covering “Anti-seismic devices”;
- (ii) The EN1337, related to “Structural bearings”, Part 2 for “Sliding elements” and Part 7 for “Spherical and cylindrical PTFE bearings”
- (iii) Technical guides or scientific publication, gathering feedbacks from other projects, such as Gasparotto et al. (2005)

None of these standards, guide or papers are strictly applicable but all of them bring relevant guidelines.

EN1337 deals with material qualification and design of structural bearings, only under static loads and for CM-1, CM-2 sliding materials. Part 2 describes relevant testing protocol for these materials, from which the qualification of the sliding material dedicated to CSB is inspired. Part 10 focuses on spherical bearings “allowing rotation between two members of a structure and transmitting the loads”, with normative analytical design formula which will be, as much as possible, used for the design of the CSB.

EN15129, applicable to “Anti-seismic devices”, covers devices which dissipate seismic energy and recenter the system after a seismic event. EN15129 prescribes a two steps approach:

- The first step is called “Initial Type Tests” and enables setting the reference mechanical characteristics for the device. In the specific configuration of sliding materials, it describes testing protocol, aiming at demonstrating the capacity and robustness of the isolator. The tests are performed on the material itself and on small-scaled or full scale isolators.
- The “Factory Production Tests” are the second step of the process: production tests are performed during the manufacturing phase with an adapted testing control frequency and test plan, to check that there is no drift during the fabrication, in comparison with the reference ITT results.

As a conclusion, the CSB are not covered by any existing standard. They cannot be tested full scale on the full range of loading. A dual approach must be defined to qualify the CSB, adapting relevant requirements of the standards, combining testing and numerical analysis.

## GRADED & DUAL QUALIFICATION APPROACH

### *Qualification of the sliding complex*

The qualification strategy adopted for these bearings relies first on the qualification of the Sliding Material, in the spirit of the standards. Similar “sliding material” testing campaign can be found in Hathiramani et al. (2009), by instance.

An extensive, step-by-step, 2-years testing program was performed on a set of eligible sliding materials. The material performances were tested through sliding tests so as to study the material friction and wear behaviours and, thus, select the most robust sliding complex. It had to pass tests under the following conditions:

- Various speeds under high normal pressure (up to 200 MPa) through horizontal sliding tests, to simulate the real working conditions. Robustness of the sliding complex against creep and stick-and-slip was also to be demonstrated;
- Ambient & cryogenic temperature (-100°C);
- Various strokes and cumulated displacement, up to 8 times the cumulated estimated service-life distance through wear tests;
- Ageing conditions, specifically defined depending on the ageing mechanism to which the sliding complex was subjected to, through ageing tests;
- Before and after radiations exposure.

### SLIDING MATERIAL TESTS

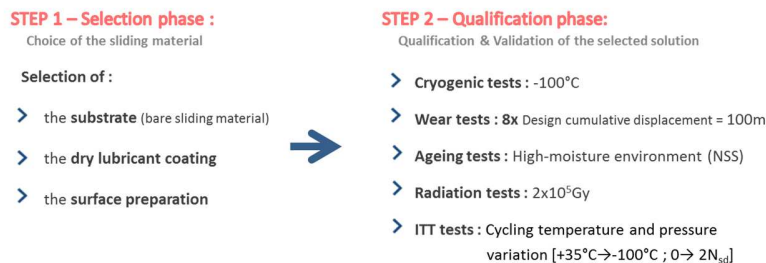


Figure 5. Synthetic Sliding Material testing program

Such conditions cannot be reproduced with classical tribometers, so that a dedicated testing bench was designed and qualified for this campaign. This testing bed, as the other testing bed designed for the project, was commissioned through a specific calibration process derived from the state-of-the-art (refer to Antaluca (2005), where peak edges effect affecting small ‘coupon’ tests is addressed) and the standards: third party assessment, “benchmark” tests with standard tabulated friction material such as EN 1337-2 PTFE or equivalent and qualification standard deviation of the monitoring system were some of the critical steps to certify the accuracy of the friction coefficient of the sliding complex.

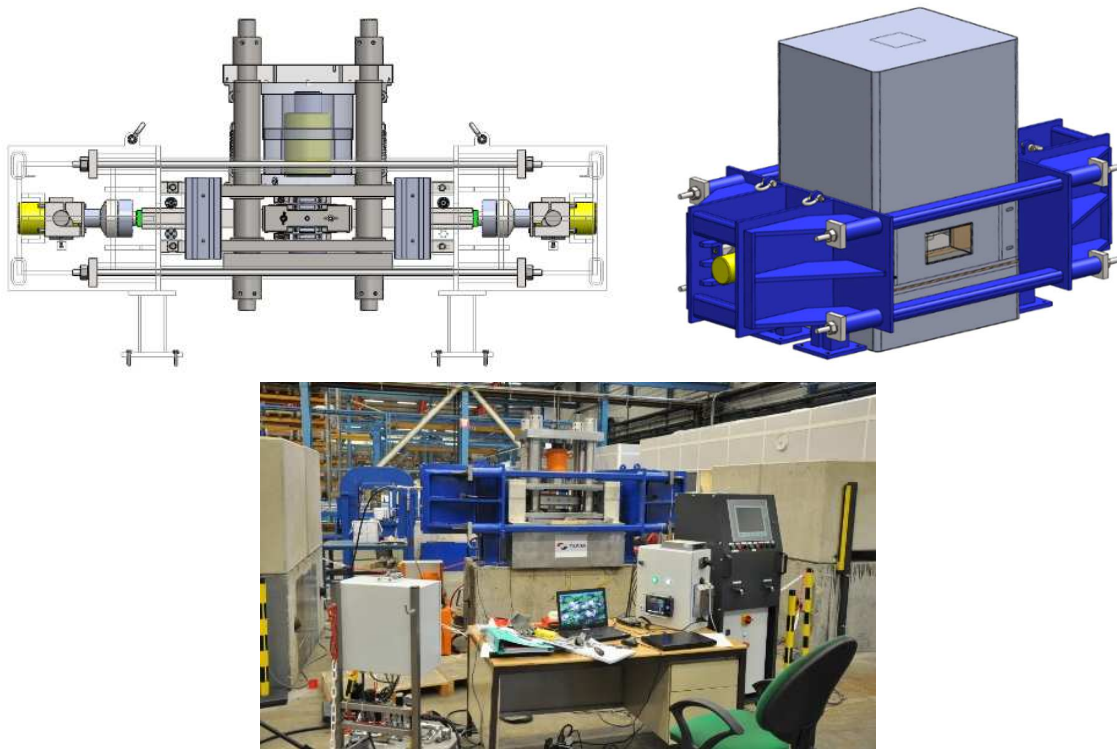


Figure 6. Purpose-designed tribometer for the Sliding material selection & qualification

This process led to the selection of a dry-component sliding complex, which passed successfully the different tests and was, best of all, 100% relevant in relation to the sliding complex qualified for Wendelstein 7-X reactor (Lingertat et al. (2009)). The qualification process went to the point of qualifying the supply-chain of the components itself. Ageing simulation and radiation exposure were defined in relation with the chemical-behaviour of the selected sliding complex.

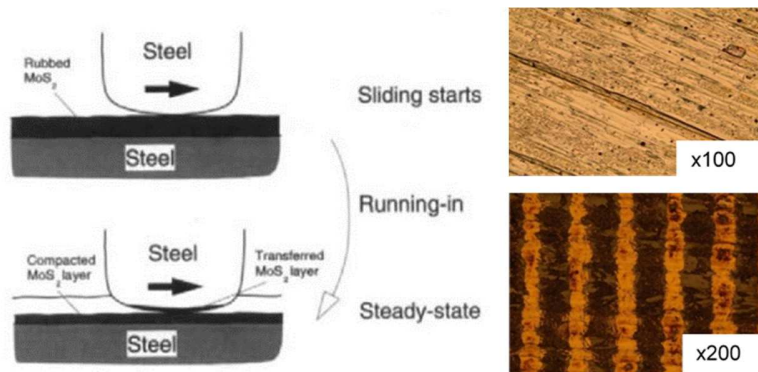


Figure 7. Dry sprayed coating mechanism as per Holmberg et al. (207) – Micrographic view without (top) and with (bottom) dry lubricant

From the tribological point of view, it was found that using dry coating at the sliding interface helps materials to slide against each other. The static friction coefficient is thus decreased and wear during long-term test is reduced. Dry sprayed coatings appear to have two periods during the life cycling:

- In the running period, under normal load and shear force, the coating becomes compacted to a fraction of its original thickness and a part is transferred on the counter face
- After some cycling, the reduction of the coating thickness stops. The useful layer of the coating only remains on top of the substratum. A steady-state period then starts with a smooth cycling and low wear.

Finally, underpinning the relevance of the sliding complex for the CSB application demands to deal with potential failing mode of the complex itself. Two physical failing modes are possible for this type of sliding complex.

First, scales may appear during the movement if the coating is removed from the sliding surface. When the bare sliding material is directly in contact with the mating surface, the wear of the sliding material is substantial. As there is plastic deformation of the material during the movement, sliding movement cannot be pure Coulomb principle: here, there is no pure point-contacts as there is also plastic deformation of the matter (creation of scales). In this configuration, this plastic deformation needs to be overcome and then this phenomenon increases the static friction coefficient. The qualification campaign thus focused specifically on the definition of the proper surface states, products and application conditions for which no scales would appear.

Then, the sliding interface could be subjected to “stick-slip” phenomenon. The “stick-slip” phenomenon is the spontaneous shaking/jerking motion which can occur when two objects are sliding over each other. The stick-slip can be described as two surfaces which alternate between sticking to each other and sliding over each other. This phenomenon depends on many factors such as the material in contact, their Young modulus, the applied compression, temperature... The use of dry sprayed lubricant decreases the influence of this phenomenon in decreasing the gap between static and dynamic friction coefficient.

### ***Contribution of scaled-prototypes tests***

The next steps focused on (small-)scaled prototypes of the final CSB. Homothetic factor  $\lambda$  was applied to the dimensions,  $\lambda = 1/4, 1/2$  and, eventually, 1, meaning a factor  $\lambda^2$  was applied on the load. This scaling gives the opportunity to test the smaller prototypes on the full-scale working ranges (ranges of loads and range of temperature), given that a specific testing bed is designed for this purpose.

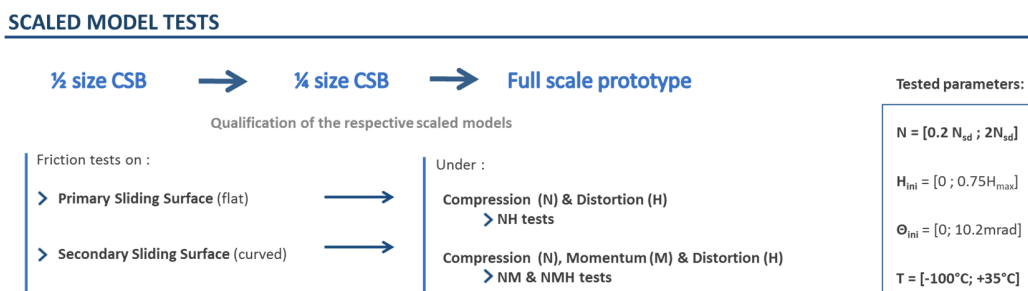


Figure 6. Synthetic prototypes testing program

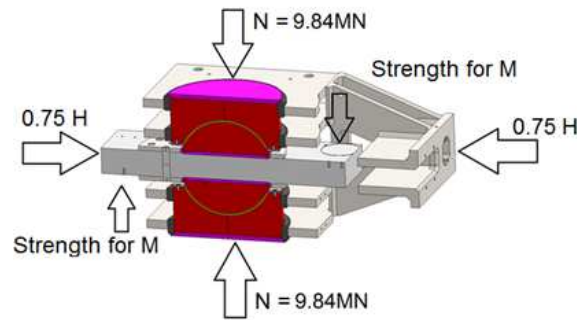


Figure 8. Combined load combinations for scaled-prototype tests.

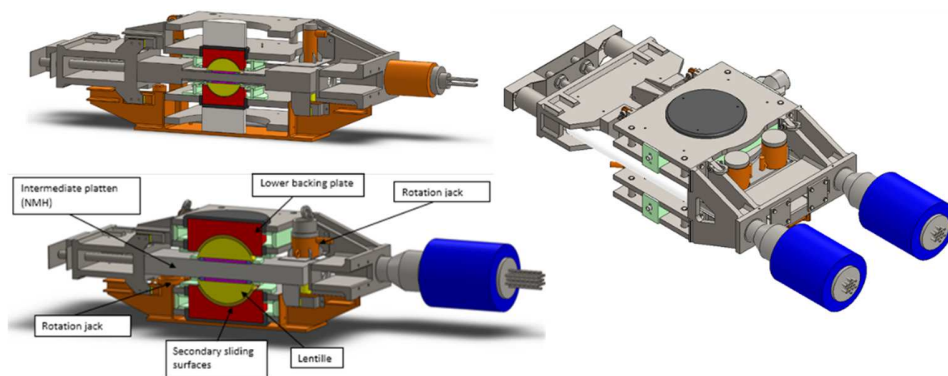


Figure 9. Testing bed apparatus purpose-designed to applied combined N-H-M load to the scaled-prototypes

In the midst of the scaled-models testing campaign, the capacity of the CSB is checked under extreme vertical load (until 6 times the nominal vertical load), thus demonstrating plastic stability of the system. In addition to this extreme vertical load test, a serviceability test demonstrates that the sliding behaviour of the CSB is unchanged after application of 4 times the vertical nominal load. Eventually, the scaled prototype is tested in real dynamic conditions. Some microscopic inspections of the matter are performed to check that no micro-cracks or failure were initiated by this extreme load. The design of the Cryostat Support Bearing is thus granted for robust and safe.

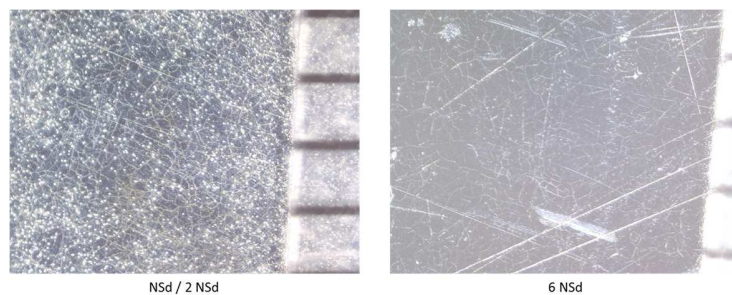


Figure 10. Micrographic inspection of the coating to detect any damages after ultimate load

Last but not least in the testing of scaled prototype, a purpose-designed 70MN testing bed was eventually built to test the scale-1 prototypes.



Figure 11. 70MN testing bed for the scale 1 prototype testing

However, the testing of the real CSB (scale 1) is industrially unfeasible under all the design working range and any type of load combinations, and the testing campaign was thus reduced to 2 DOF tests for the scale 1 CSB: vertical+horizontal or vertical+rotation. An additional strategy is thus needed to transfer from partial tests to the full behaviour of the bearing: the testing campaign is enhanced by the FEM calculations, to obtain the full behaviour law of the CSB in the 5 DOF.

#### ***Coupling with FEM, complementary approach***

A Finite-Elements Model is introduced in parallel, which is calibrated with:

- the results on the scaled prototypes;
- some strains monitoring performed on accessible parts of the bearings, during the tests.

The aim of the FEM is to deliver predictive resisting / sliding forces under the different loads combinations, whenever they cannot be physically tested. Correlation between FEM and strain monitoring increases the level of confidence of FEM results.

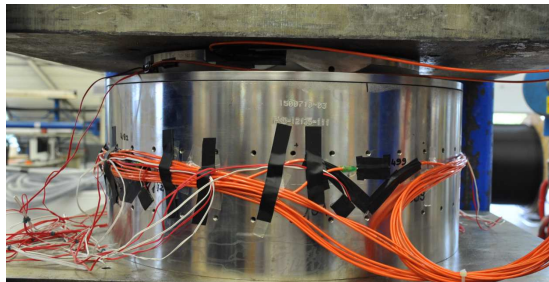


Figure 12. Optical & electrical gauges for strain monitoring & FEM calibration

Calibration and validation of the predictability of the FEM requires first a detailed modelling not only of the CSB system but also of the testing environment, as both systems are coupled during the tests.

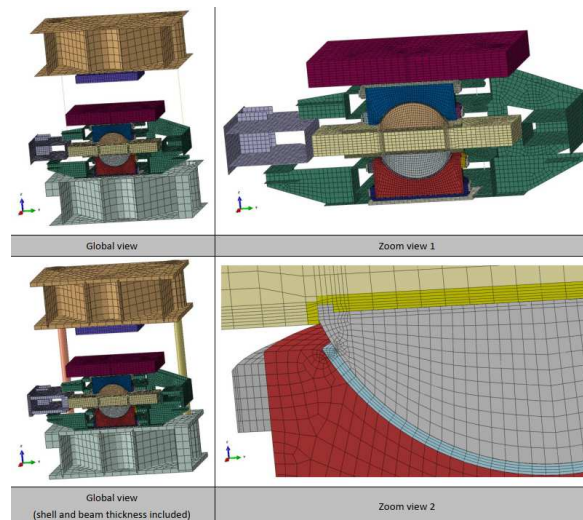


Figure 13. Abaqus FEM of a scaled-prototype & its testing environment

## CONCLUSION

Cryostat Support Bearings are uncommon spherical, metallic, sliding bearing system, working in a unique environment. The CSB ought to transfer the loads coming from the Tokamak machine down the Civil structure supporting it. The qualification process of such critical components is therefore a crucial step, in order to demonstrate that it fulfils adequately the Nuclear Safety requirements.

Given that no standard covers such unique bearing, the qualification strategy is, on the one hand, underpinned by standards-inspired analysis and, on the other hand, built on a dual approach which combines tests under working conditions on different scales of prototypes, tests monitoring and a calibrated predictive Finite Element Model. This strategy oriented fundamentally the design of the CSB at its early stage.

The successful completion of the qualification process is the cornerstone in the demonstration of the CSB compliance with Nuclear Safety requirements.

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