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Fatigue Cyclic Testing of the ITER CS Inlets

Nicolai Martovetsky¹, Robert Walsh², Kevin Freudenberg¹, Wayne Reiersen¹, David Everitt¹, Dustin McRae³, Leonard Myatt⁴, Kristine Cochran⁴, and Cornelis Jong⁵

¹Oak Ridge National Laboratory, 1055 Commerce Park Drive, Oak Ridge, TN 37831, USA (NM is on assignment from Lawrence Livermore National Laboratory, WR is on assignment from Princeton Plasma Physics Laboratory)

²1800 E. Paul Dirac Drive, Tallahassee, FL 32310-3706, USA

³University of Colorado at Boulder, Boulder, CO 80309, USA

⁴Myatt Consulting, Inc., 8 Eric Road, Norfolk, MA 02056, USA

⁵ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St Paul Lez Durance, France

Abstract. ITER Central Solenoid (CS) is cooled by injecting supercritical helium at the inner diameter (ID), an area with the highest stress. The jacket near the helium inlet is the weakest structural element of the ITER CS due to the high stress concentration. To verify adequate mechanical performance of the inlets, we made six full-scale specimens and subjected them to relevant cycling loading in liquid nitrogen to assess the operational margin of the inlets.

To increase fatigue life of the inlets, we used a treatment called ultrasonic peening (UP). This treatment allows for the creation of a compressive residual stress at the surface of the jacket with the highest stress, which significantly delays initiation of the fatigue crack. For comparison purposes, one of the samples was intentionally not UP treated. Test results showed significant advantages of the UP treatment and demonstrated sufficient life to support the ITER CS mission.

1. ITER CS INLET DEVELOPMENT, FABRICATION, AND TESTING

The helium inlet design was selected because significant optimization work found it to be a good compromise for the highest reliability and lowest production cost [1]. The photo of the inlet is shown in Figure 1. The hole in the jacket is machined by drilling three overlapping holes, and the remaining “scallops” are not removed. The helium inlets are evaluated and qualified in accordance with the ITER design criteria as described in [1]. The analysis identifies two peak stress areas, shown in Figure 2 [2]. The first one is in the base metal near the weld toe. The second one is located in the middle of the holes adjacent to the cable space.





Figure 1. Helium inlet after welding.

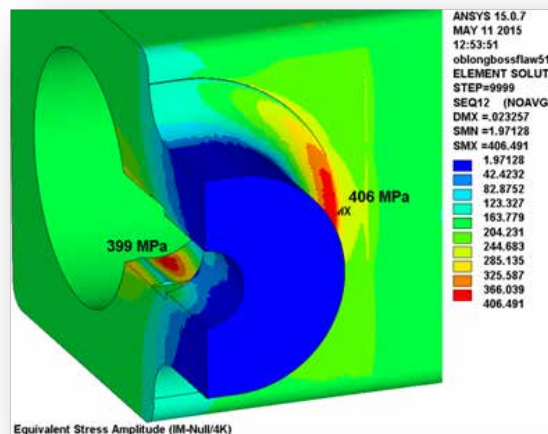


Figure 2. The alternating equivalent stress in the inlet.

However, the S-N fatigue life is approaching 1.0, even assuming the recommended 50 MPa residual stresses in the jacket. Independent analysis and measurements showed that the residual stresses may achieve up to 200–250 MPa in peak stresses. To ensure compressive forces in the weld toe, the project team decided to use a particular treatment in that area—weld ultrasonic peening (UP)—to achieve detectable flaw size.

1.1 Ultrasonic treatment of the inlet welds.

Ultrasonic peening—also called ultrasonic impact treatment—is a relatively new development in metal treatment [3]. The essence of ultrasonic peening is to create compressive residual stress in the areas that initiate the crack. This treatment was shown to be effective for both the weld and the base metal, extending the life of the part by an order of magnitude. Unfortunately, the only critical area accessible by the UP tooling is the toe of the weld; the inner hole is not accessible.

The UP treatment effectively puts the surface layer of the weld and the parent material near the UP treatment into compression [4]. The depth is significantly greater than what is achievable by a regular

hammer peening. The toe of the weld is treated by the UP equipment, which significantly increases life of the weld.

A photo of the UP-treated inlet sample is shown in Figure 3. The UP treatment was performed by Applied Ultrasonics, now part of the Caterpillar company.



Figure 3. An inlet treated with ultrasonic peening.

1.2 Effect of UP treatment on superconducting properties of the CS conductor.

The UP treatment can be applied before or after the superconductor heat treatment (HT) to create a compressive residual stress on the surface layers of the weld. The CS conductor must go to the reaction HT to obtain superconducting filaments in the strands. The UP treatment generates acceleration of the strikers of up to 40,000 g. The Nb₃Sn filaments are brittle. It is safe to UP-treat the conductor before HT, when the strands are not superconducting. But after a long HT at elevated temperatures up to 650°C, part of the residual stress will be relieved. Effects of UP on the superconducting properties were not known. From the standpoint of residual compressive stresses, the UP treatment is more effective after HT, but there is a risk of damaging the superconducting filaments.

To study the effect of UP treatment after HT, we contracted Applied Ultrasonics to perform a UP on the CS conductor CSJA7 at the SULTAN facility. This conductor includes the relevant cable to be used by US ITER for fabrication of the central solenoid module. After completion of the mandatory test program, the sample was extracted from the test well and warmed; next, the UP treatment was performed on both sides of the conductor: the one exposed to the peak field and the opposite side. The Applied Ultrasonics engineer performed UP in a shape of three strips on each side in the middle of the high field area, as shown in Figure 4, on one of the legs of the CSJA7 sample for comparison.



Figure 4. A general view (top) and a closeup view (bottom) of the UP-treated conductor CSJA7.

After UP treatment, retesting of the CSJA7 showed no degradation, it even showed a slight growth that could be attributed to a relaxation of the residual stress in the cable. The Tcs (current sharing temperature) measurement history of the CSJA7 is shown in Figure 5 [5]. Fig. 5 shows the full history of the CSJA7 testing with electromagnetic (EM) cycles and Warm Up-Cool Down cycles (WUCD), which both can cause degradation of the properties (Tcs reduction). The sequence of EM and WUCD cycles is specified by ITER project. The effect of the UP treatment (a slight Tcs growth) is shown on the left (L) leg after 10000 cycles.

This test showed that it is acceptable and most efficient to apply UP treatment after HT.

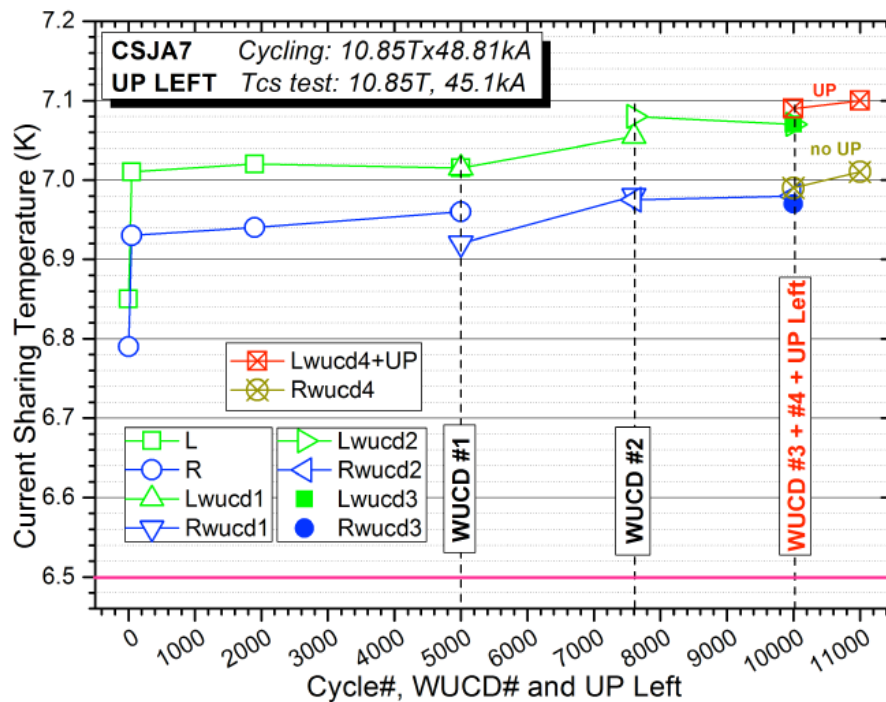


Figure 5. CSJA7 Current sharing temperature evolution, showing no negative effect after UP treatment.

2. DETERMINATION OF FATIGUE TEST PARAMETERS

During design verification, the US ITER Project Office proposed a prototypic fatigue test. The test plan was prepared [6] with the critical parameters given below.

2.1 Applied force.

The plan called for a nominal level of the equivalent stress defined by finite element analysis (FEA) with an extended number of cycles. Testing of the samples on the full-scale cross-section requires up to 61 metric tons of force in liquid nitrogen to reproduce the operating loads.

2.2 Number of samples.

To increase statistics of the tests and preserve the stress symmetry, we decided to put two inlets in opposite sides of the conductor. Most of the codes require a different number of cycles, depending on the number of specimens tested.

Such an arrangement effectively doubles the number of test specimens, and the assessment remains on the conservative side, recording only the weakest inlets. The project team decided to use five samples with UP treatment and one as welded for comparison to see the effectiveness of the UP treatment. With two inlets per sample, the effective number of specimens is 10.

2.3 Number of cycles.

A code determines the number of cycles for the acceptance criteria. The design number of cycles is 60,000. We were able to find three codes that specify the number of cycles versus the load and the number of specimens [7-9]. These codes have different requirements and definitions of failure. The ASME code—Sec. VIII, Division 2, Annex 5.F and Division 3, Article KD-12—prescribes the procedure to determine the number of cycles based on the designed fatigue curve.

The fatigue curve was taken from the test data; with a safety factor of two, it has the following relationship [1]:

$$N = \left[\frac{11831}{S_{eq}} \right]^{3.36}$$

Using the relationship and procedure described in the ASME code [7] for 10 specimens and conservative assumptions, we obtain the recommended number of test cycles of 157,000. This code defines failure as propagation of the crack all the way through the wall that will produce a measurable leak. This condition is called “leak before break.” Unfortunately, the ASME code edition recently introduced a condition that states the following: the procedure for establishing the required number of cycles for fatigue acceptance by testing shall not be used if the designed number of cycles exceeds 50,000. With our case having 60,000 cycles, we formally shall not use this assessment. Thus, the ASME code is not strictly applicable to our case as it stands now; however, the code does not address what to do with our situation.

The British standard design [8] recommends 3.5 times design cycles for 10 samples and standard deviation (SD) of 2, which gives $60,000 \times 3.5 = 210,000$ cycles before break if the level of loading is nominal. There is no discussion on leak before break in the code. Thus, failure is the rupture of the sample. The European Union standard EN 13445 [9] prescribes the number of cycles at the design level of the strain range to be the designed number of cycles times F value taken from Table 18-6 of that code [9]. For our selected number of samples, the F factor is 9. That number is also insignificantly different from two samples with two inlets. At 60,000 design cycles, the code EN 13445 results in 540,000 test cycles. The code is not specific regarding the definition of failure, so we shall assume it is a rupture of the sample. The EN 13455 has SD of 3 for the fatigue curve, also required by ITER. It is a more conservative approach than the British code one.

3. MODIFICATION OF SAMPLE DURING THE TEST CAMPAIGN

The six test specimens began as full cross-section specimens with respect to the conduit cross-section (round hole in square, nominal area = 1,568 mm²). Only one full cross-section specimen (2-P) was successfully tested to completion, and two other full cross-section specimen tests (1-P and 1-AW) were started but prematurely interrupted after < 50,000 cycles because of fatigue failures of the pull rods. Following multiple failures, the project team decided to modify the specimens to reduce the required pull load but leave the stress field unchanged in the critical areas. These two specimens and the remaining three others were modified by removing 3 mm on two sides to reduce their nominal cross-sectional area from 1,568 mm² to 1,285 mm². The smaller cross-section enabled reduction of the maximum fatigue load from 607 kN to 434 kN. The stress state at the CS helium inlet regions of interest (the weld toe and inside hole surfaces) on the modified specimens (with the modified load) was maintained. The load reduction was a little higher than the reduction of the cross-section area. The reason for this as follows.

In the original full-scale design, the helium inlet testing load was underestimating the stress at the toe; therefore, to get it to match the ITER helium inlet results, the load was increased to 607 kN. At the time, we thought this mismatch was real and was the difference between axial testing and the real helium inlet stress field. When this error was discovered, the load was adjusted to match the stress in the sample to the operating equivalent stress.

4. TEST PROCEDURE

The fatigue tests are conducted on a 500 kN servo-hydraulic test machine equipped with a cryostat to enable testing at 77 K with the sample and fixture immersed in liquid nitrogen. Originally it was thought that, with some modifications, the NHMFL 500 kN MTS could be used to perform the full cross-section specimen fatigue test ($P_{max} = 607$ kN, $P_{min} = 61$ kN). The modifications were executed, and the machine met the requirements, but there were problems with fatigue failures of the pull rods. After the successful completion of one full cross-section specimen, we modified the full cross-section specimen that reduced the fatigue maximum load from 607 kN to 434 kN. The tests are conducted in

force control with a sine wave function at a frequency from 0.5 Hz to 2.5 Hz. The fatigue test parameters for the full size and the reduced size tests are given in Table 1.

Table 1. Loads for CS Inlet Testing

Full Scale Tests	Reduced Scale Tests
R (ratio of P_{\min}/P_{\max}) = 0.1	R (ratio of P_{\min}/P_{\max}) = 0.1
Frequency = 0.5 Hz	Frequency = 2.5 Hz
P_{\max} = 607 kN	P_{\max} = 434 kN
P_{\min} = 60.7 kN	P_{\min} = 43.4 kN

The sample is thread-connected to the test machine pull rods, and a spherical nut is used at the bottom connection for alignment purposes (Figure 6). Once the sample is installed, the test fixture is lowered into a vacuum-insulated bucket dewar and slowly cooled to 77 K with liquid nitrogen. The dewar hold time before refill becomes necessary is approximately 12 hours.

Some of the samples were equipped with strain gauges that confirmed expected strain and fully elastic behavior of the jackets.

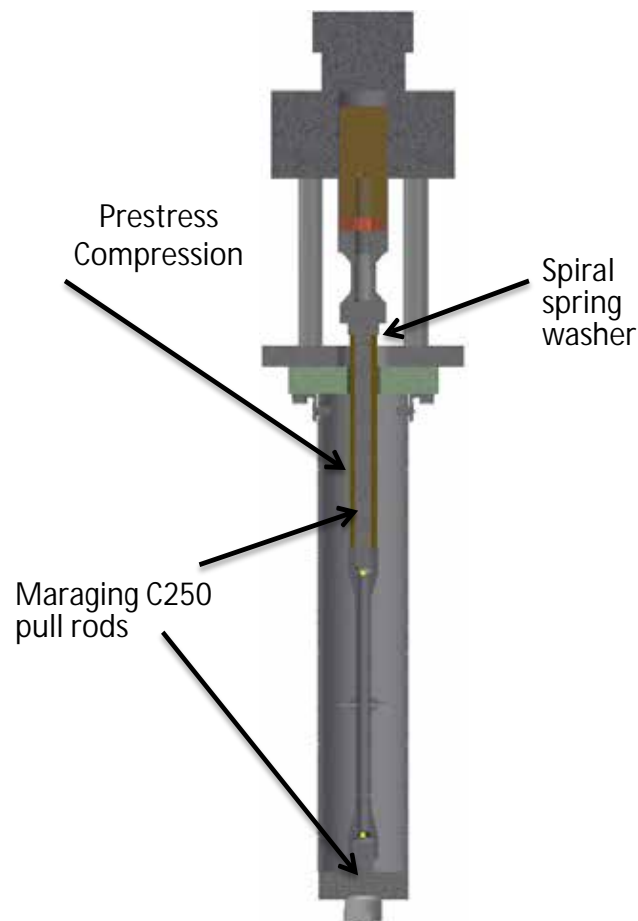


Figure 6. Schematic of the test specimen and reaction fixture without the LN2 dewar in place.

5. TEST RESULTS AND DISCUSSION

Table 2 shows the summary of the test results of the CS inlet testing.

Table 2. CS conduit with welded helium inlets—fatigue test results, T = 77 K, r-ratio = 0.1

Condition	Sample ID	Max force, kN	Max fatigue stress, MPa	Nominal fatigue stress range, MPa	Cycles to failure	Comments
As welded + HT	1-AW-RS	434	336	303	158,451	Crack originated at the weld toe
	1-P-RS	434	336	303	337,491	Crack originated at the hole in the jacket
	2-P	607	387	348	> 540,000	Did not fail and reached designed number of cycles
As welded + HT + UP	3-P-RS	434	336	303	> 850,660	The inlet did not fail, but the grip failed
	4-P-RS	434	336	303	723,317	Crack originated at the hole in the jacket
	5-P-RS	434	336	303	534,518	Crack originated at the hole in the jacket

Notes: HT = heat treated; UP = ultrasonic peened.

One of the six samples did not receive post-weld peening of the helium inlet weld toe before testing. It failed prematurely compared with the five peened samples, providing evidence that post-weld peening of the weld toe is effective at extending the CS conduit helium inlet fatigue life. The results for the five post-weld peened specimens are as follows: three specimens successfully satisfied the 77 K life requirement of > 540,000 cycles, and two samples failed at < 540,000 cycles.

The inside of the machined helium inlet port was initially identified to be the secondary high-stress region of interest before testing, whereas the weld toe region was the primary high-stress region. The peening of the weld toe effectively transfers the highest stress region from the weld toe to the inside of the helium inlet port.

The most severe relevant code [9] requires a geometric mean average (GMA) of 540,000 cycles. The five peened samples would have an GMA of 570,000 in the conservative evaluation if the samples that survived the cyclic tests broke the next cycle. The test results fulfill requirements of the code [9] and also meet the requirement of [8], which is to exceed 210 kcycles at the nominal load before break. Despite the code requirement of 50,000 cycles [7], we do not have an accurate number for the cycles before leak. Estimates of the propagation of the crack from the leak to catastrophic failure can be made roughly as 100 kcycles [10]. With that estimate, all inlets easily pass the requirement of 157,000 cycles, as required by the 2007 ASME BPV code Section VIII, Division 2.

6. CONCLUSIONS

The ITER CS inlets meet requirements for fatigue testing presented in national and international structural codes [7–9]. Ultrasonic peening is a necessary condition for fabrication of the inlets with sufficiently long life for the ITER CS. Ultrasonic peening extends life of the inlets significantly, by a factor of 3.5–5 or higher. All failures in the peened specimens were initiated in the second-highest stress location—the area where the cable space meets the drilled hole of the inlet. This agrees with the FEA and fracture mechanics predictions.

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The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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