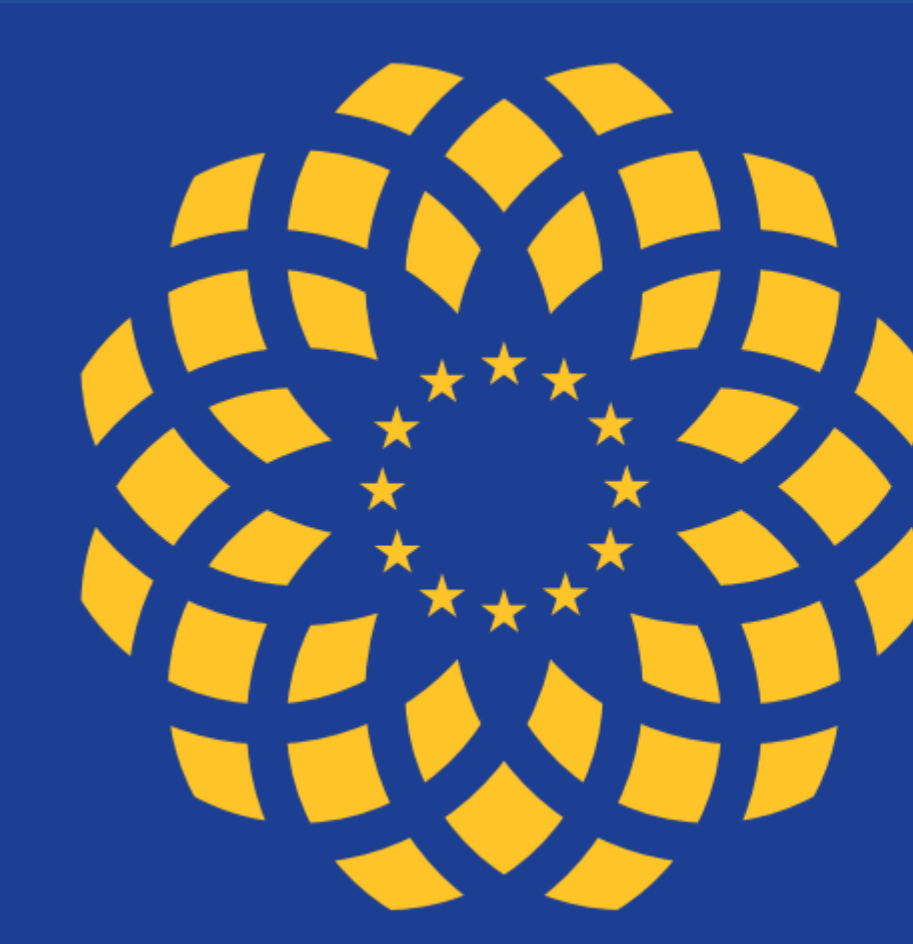


# F4E Procurement of the Pre-Compression Rings made of pultruded composite material (September 2019)



**FUSION FOR ENERGY**

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**Abstract** — The highly innovative process, proposed by CNIM and chosen by F4E, is based on a pultrusion technique that involves the manufacture of profiles of epoxy S2-glass. Each Pre-Compression Ring (PCR) is manufactured by winding the flat pultruded profile (2mm thick and about 2800 m long) and utilizing an adhesive tape (0,12 mm thick) between layers to freeze the geometry. After the curing cycle, the PCR is machined to reach the required geometry tolerances. Each PCR will have a diameter of approximately 5 m, a cross-section of 332 mm x 288 mm and will weigh approximately 3 tons. The PCRs will finally be proof tested at 600MPa in hoop stress that corresponds to 1.5 time the operational hoop stress. An extensive qualification phase has been released to prove that both materials and manufacturing technology can procure the 9 PCRs according to requirements. The manufacturing processes, the results of the qualification phase and the status of the production is presented.

### PCR Winding Process

**PCR winding mandrel** | **Pultruded alignment system**

**164 turns in total** | **2800 m long**

**PCR just after winding** | **Bonding tape winding** | **Control system** | **Pultruded length**

### PCR Curing-Machining & Inspection Process

**PCR coming into to curing oven** | **Machining of the top surface and inner diameter** | **Flipping the PCR**

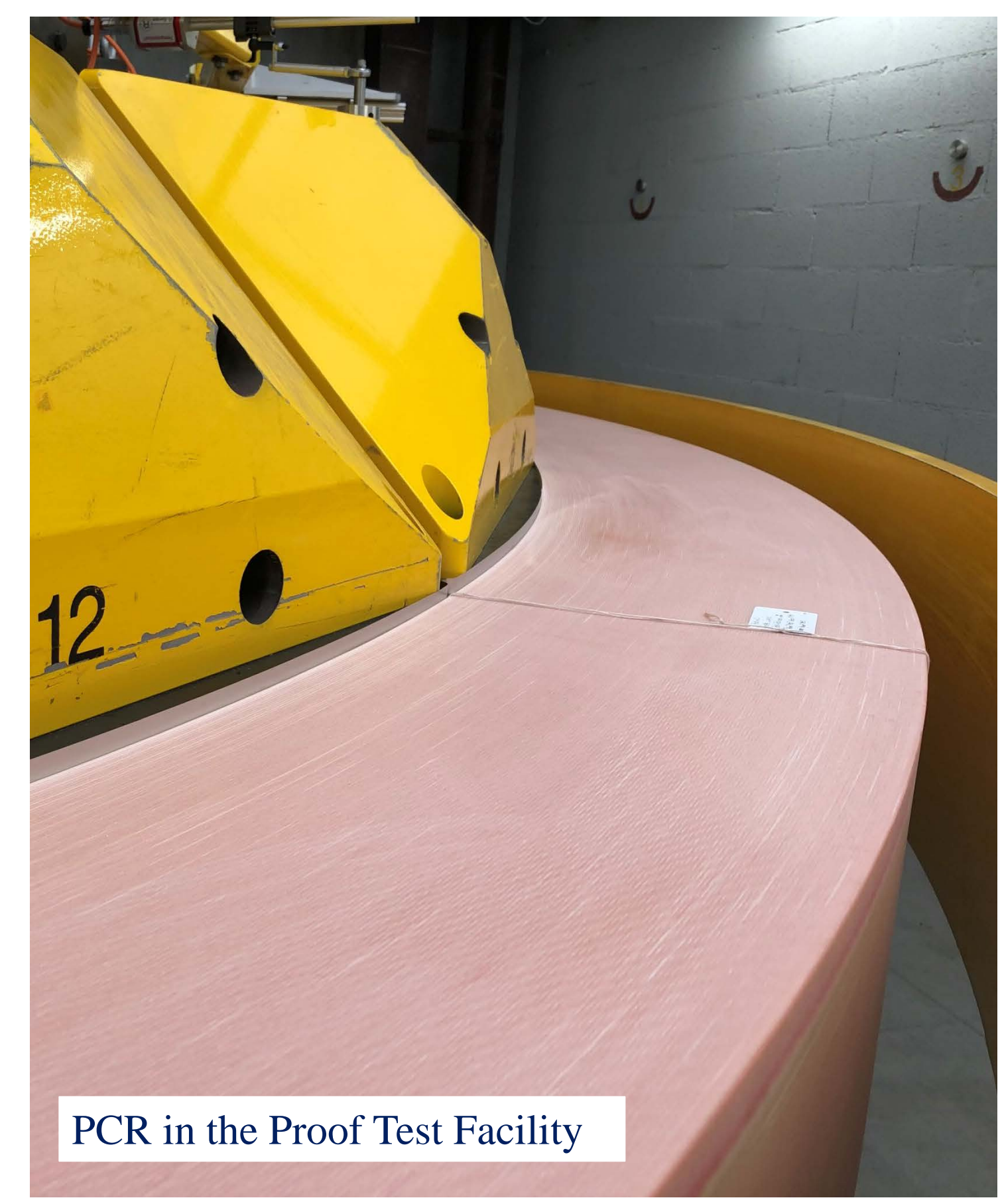
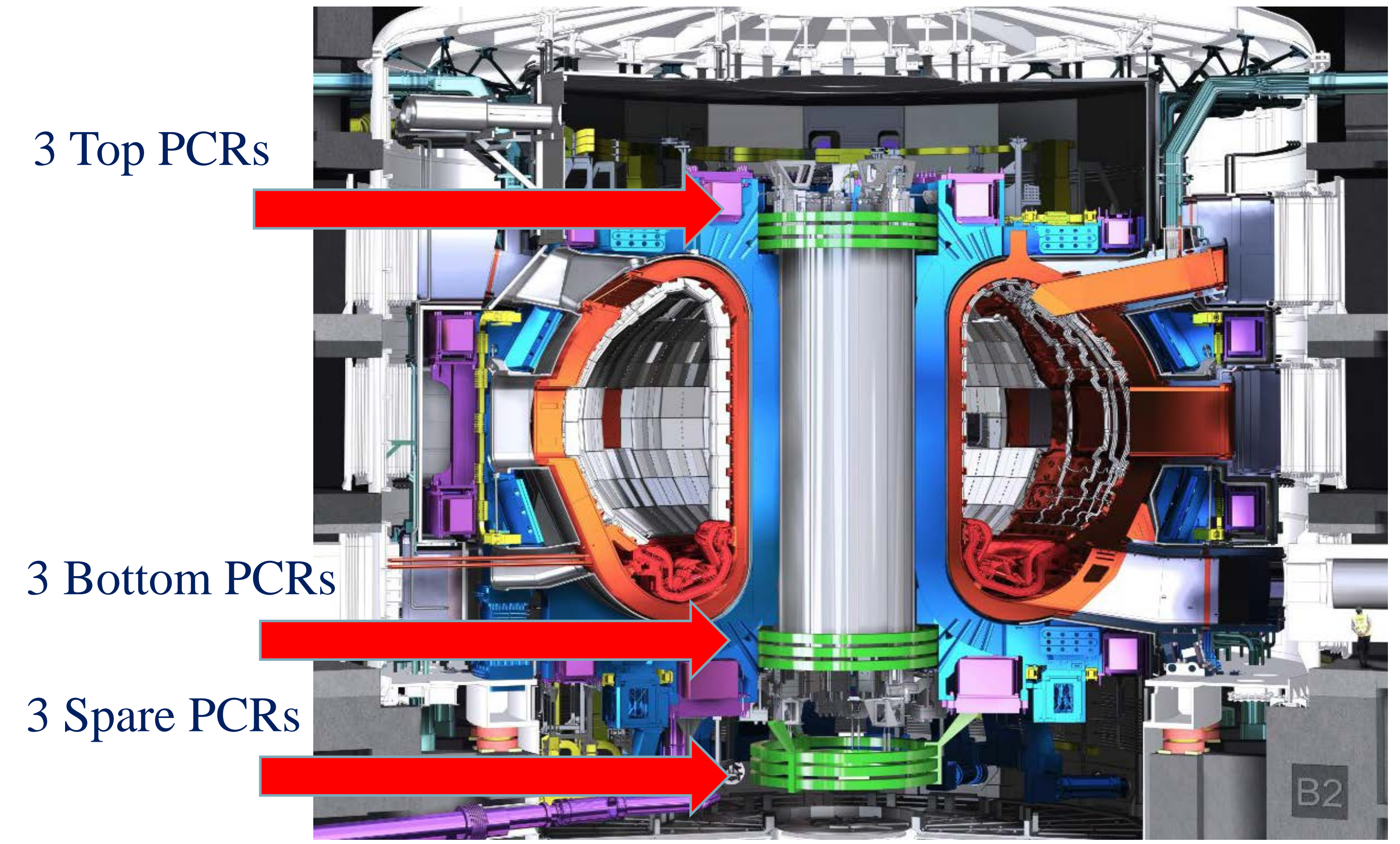
Outer clamping system to machine top surface ( $\Delta$  4 mm) and inner diameter ( $\phi$  4975 mm,  $\Delta$  1 mm)

Oven Heating Ramp Rate from 25°C to 68°C: 4 hours (about 10°C/h);  
Temperature distribution on PCR: 80 hours (0 / +10h);  
Curing duration at 65°C  $\pm$  3°C: 20 hours ( $\pm$  1h);  
Natural cool down till room temperature

Inner clamping system to machine bottom surface ( $\Delta$  4 mm) and outer diameter ( $\phi$  5639 mm,  $\Delta$  4 mm)

Bonding layers inspected: No defects encountered | Roughness <50  $\mu$ m

**Machining bottom surface and outer diameter** | **UT inspection** | **Final surface**



### Results

QUALIFICATION MATERIAL TEST RESULTS	Qualification results at RT	Qualification results at 4K
Fibre content (% volume)	0.72	
Void content (% volume)	0.013	
Tg (°C)	197.8	
Mean UTS – longitudinal direction (MPa)	1845	1715.6
Mean tension stiffness – longitudinal direction (GPa)	61	53.3
Mean Radial compression strength (MPa)	185.2	385.6
Mean Radial compression stiffness (GPa)	23.5	28.7
Creep in tension	Achieved	
Creep in radial compression	Achieved	
Mean Radial shear strength (MPa)	61.3	102.2
Mean radial shear stiffness (GPa)	4.91 average 5.45 max	
Mean Double Lap shear strength (MPa)	30.7	13.6
Mean Combined compression (40 MPa) - Shear strength (MPa)	45.5	
Combined Compression (118, 135.4MPa) Shear test, 25°	59	
Combined Compression (272.1 MPa, 302.1 MPa) Shear test, 15°	77	122
Combined Compression (270, 254.2 MPa) Shear test, 25°		91
Combined Compression (344, 356.3, 317.5 MPa) Shear test, 15°		

### MAXIMUM STRESSES AND MINIMUM STRENGTH RATIOS FOR PCRS AT RT AND 4K PRELOAD

Stress condition	RT strength		RT preload		4K strength		4K preload	
	B basis Strength	Max Stress	B basis Strength	Max Stress	B basis Strength	Max Stress	B basis Strength	Max Stress
Circumferential stress, $\sigma_1$	1784	494	3.61	1533	420	3.65		
Radial stress, $\sigma_2$	-183	-78	2.35	-342	-72	4.75		
Vertical stress, $\sigma_3$	53	24	2.21	52	24	2.17		
Radial Shear Stress, $\sigma_{12}$	57	12	4.75	94	10	9.40		
Vertical Shear Stress, $\sigma_{13}$	57	3	>10	94	3	>10		
Adhesive Shear Stress, $\sigma_{23}$	30	13.3	2.26	36	13.4	2.69		
Minimum 3D Tsai Hill	All dir'ns	All dir'n	1.60	All dir'ns	All dir'n	1.91		
Min 1st ply 3D Tsai Hill	All dir'ns	All dir'n	2.01	All dir'ns	All dir'n	2.25		



- 1/5 Mock-ups UTS: 1286 MPa & 1372.2 MPa hoop stress.
  - 1/5 Mock-up Stress Relaxation: 820 MPa, 1340 hours.
  - 1/3 Thickness Slice UTS: 1140 MPa, 1067 MPa, both 47 radial elongation.
- PCR 1, 2, 3 SUCCESSFULLY PASSED THE PROOF TEST (600 MPa in Hoop)**  
**Radial displacement 28 mm**

DIMENSIONAL MEASUREMENTS	PCR Nominal dimensions	PCR 1	PCR 2	PCR 3
External Diameter	5639 mm ( $\Delta$ 4 mm)	5639.42 (2.32)	5639.45 (1.82)	5639.9 (2.00)
Internal Diameter	4975 mm ( $\Delta$ 1 mm)	4975.3 (0.94)	4975.06 (1.26)	4974.9 (1)
Height	288 mm $\pm$ 1 mm	287.97	287.64	287.53
Thickness	(332) mm	332.01	332.18	332.21
Shape top face	4 mm	1	1,56	1,4
Shape bottom face	4 mm	0,48	0,9	1,36