Investigation of thermal protection systems for hybrid rocket motors

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15 December 2021 Padova

Outline

1. **Introduction**
   - Hybrid rocket motors
   - Thermal protection systems
2. **Experimental tests**
   - Experimental set-up
   - Combustion chamber
   - Nozzle zone
   - Materials selection
3. **Post-processing tools**
   - X-ray tomographies
   - SEM analyses
   - 1D ablation code

1. **Experimental results**
   - Test matrix
   - Graphite screening tests
   - Best graphites in-depth study
   - Throat inserts
   - Carbon & silica/phenolic
   - Backup liners
   - Convergent inserts
2. **Conclusions**

Extra

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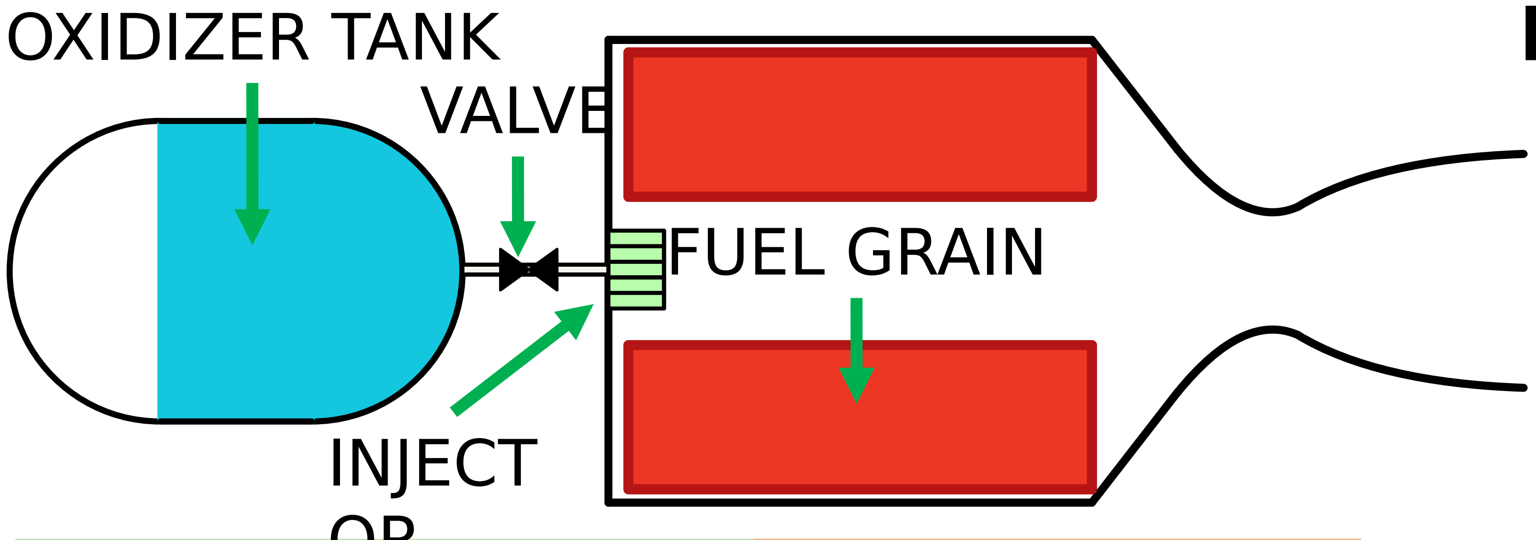
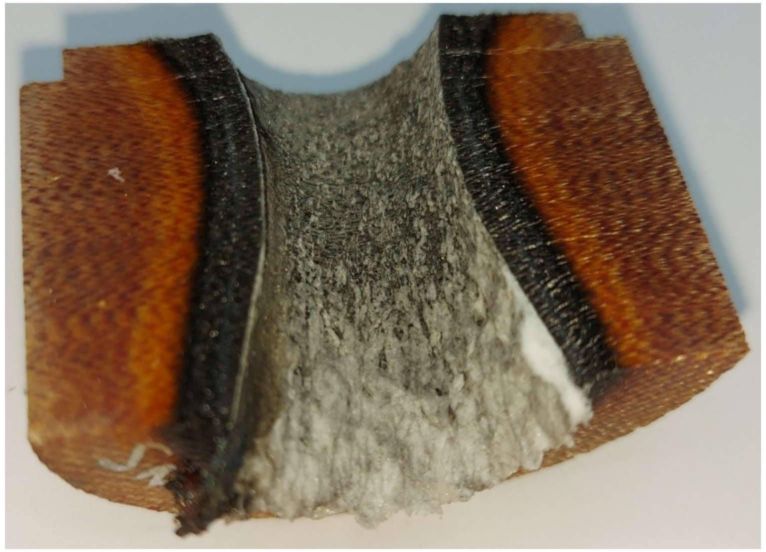
ybrid Rocket Motors

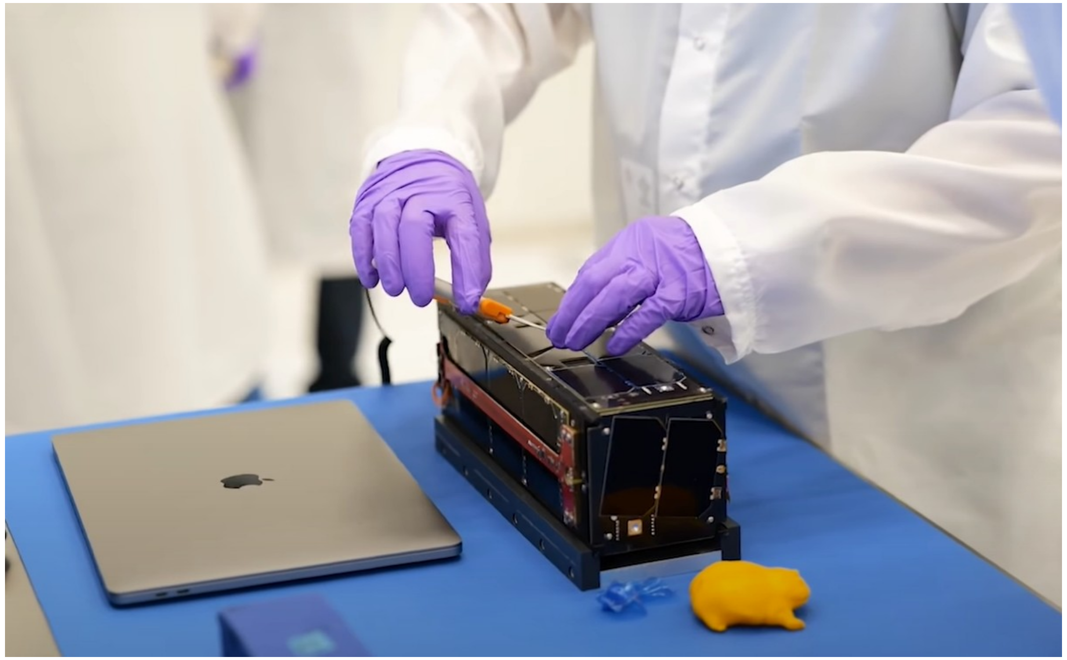


Passive cooling systems



Advantages	Disadvantages
➢ Safety ➢ **<u>Low costs</u>** ➢ **<u>Simplicity</u>** ➢ Green propellants ➢ Oxidizer flow control ➢ Mission abort and **<u>throttlability</u>**	➢ Low regression rates ➢ Low volumetric efficiency ➢ Combustion efficiency ➢ **<u>High oxygen content</u>**

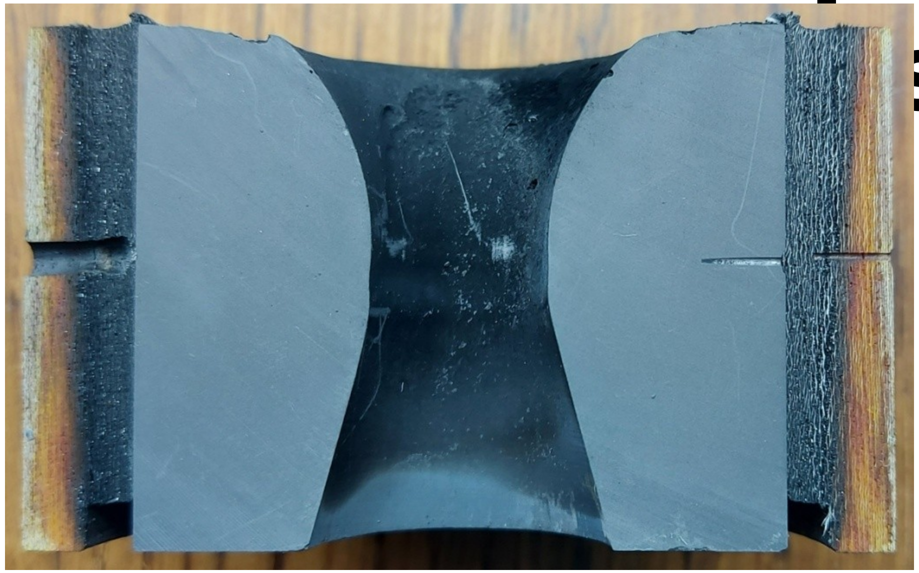
New space economy



TECHNOLOGY FOR PROPULSION AND INNOVATION

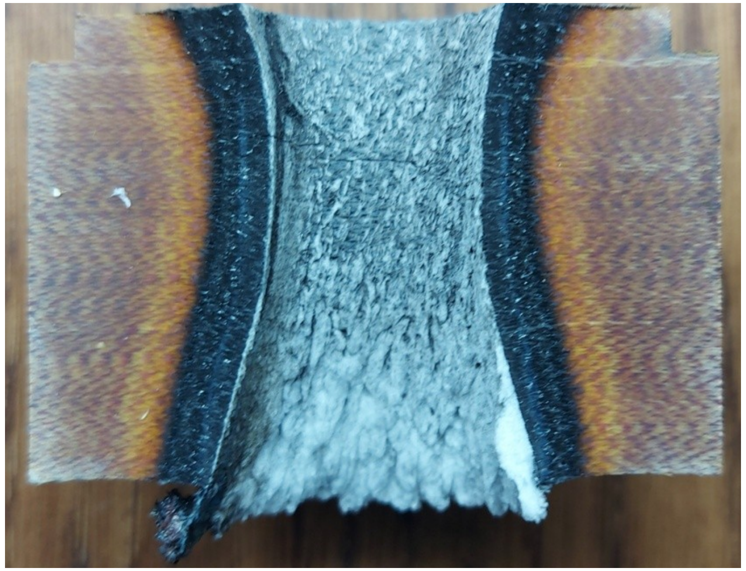
A University of Padua Spin-Off

Non-decomposing s



- Ceramics
- Metals with high melting point
- Polycristalline graphite
- Pyrolitic graphite
- Carbon/carbon composites

Decomposing materia



- Cotton/ phenolic
- Glass/phenolic
- Silica/phenolic
- Carbon/ phenolic

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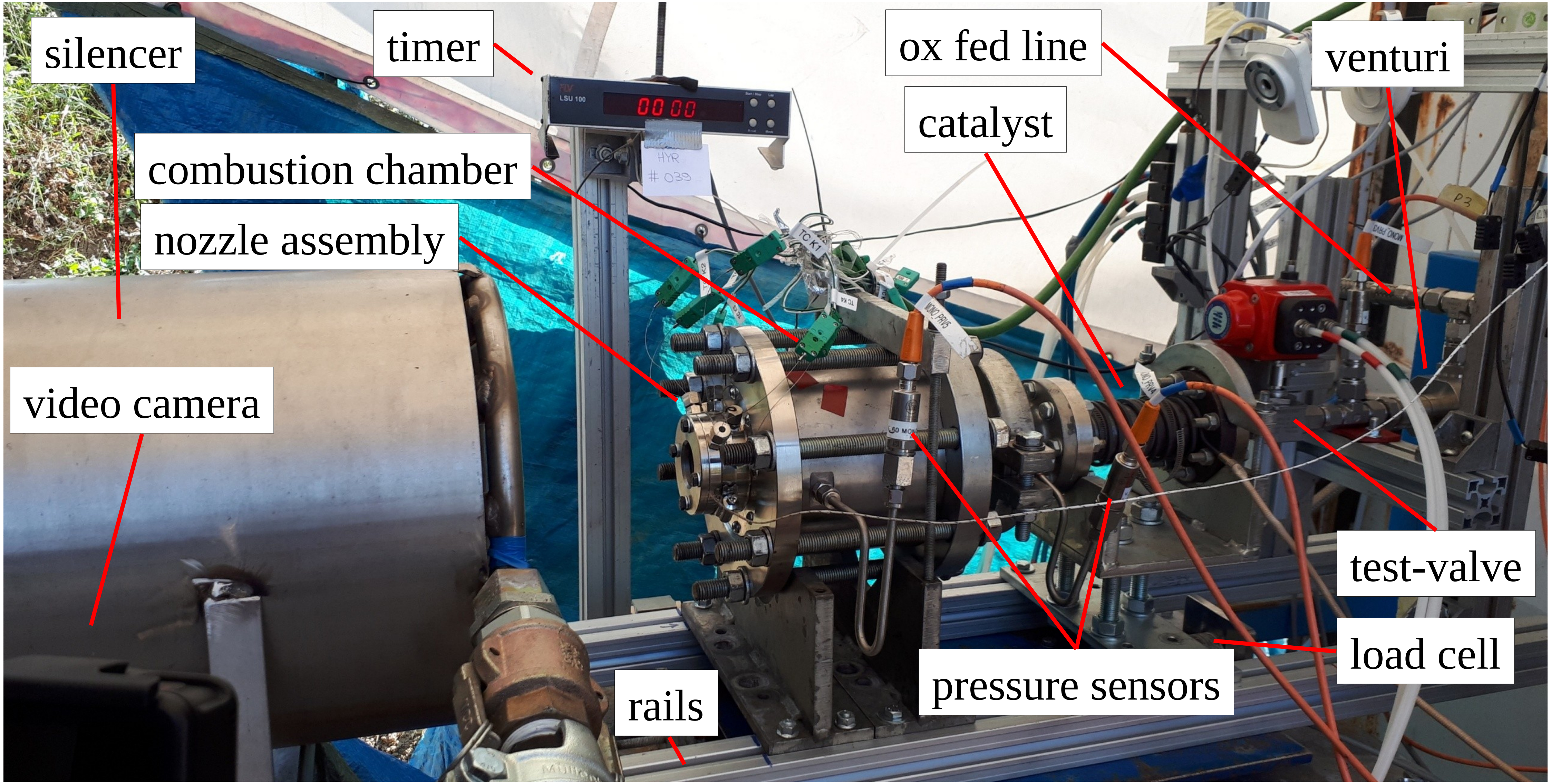
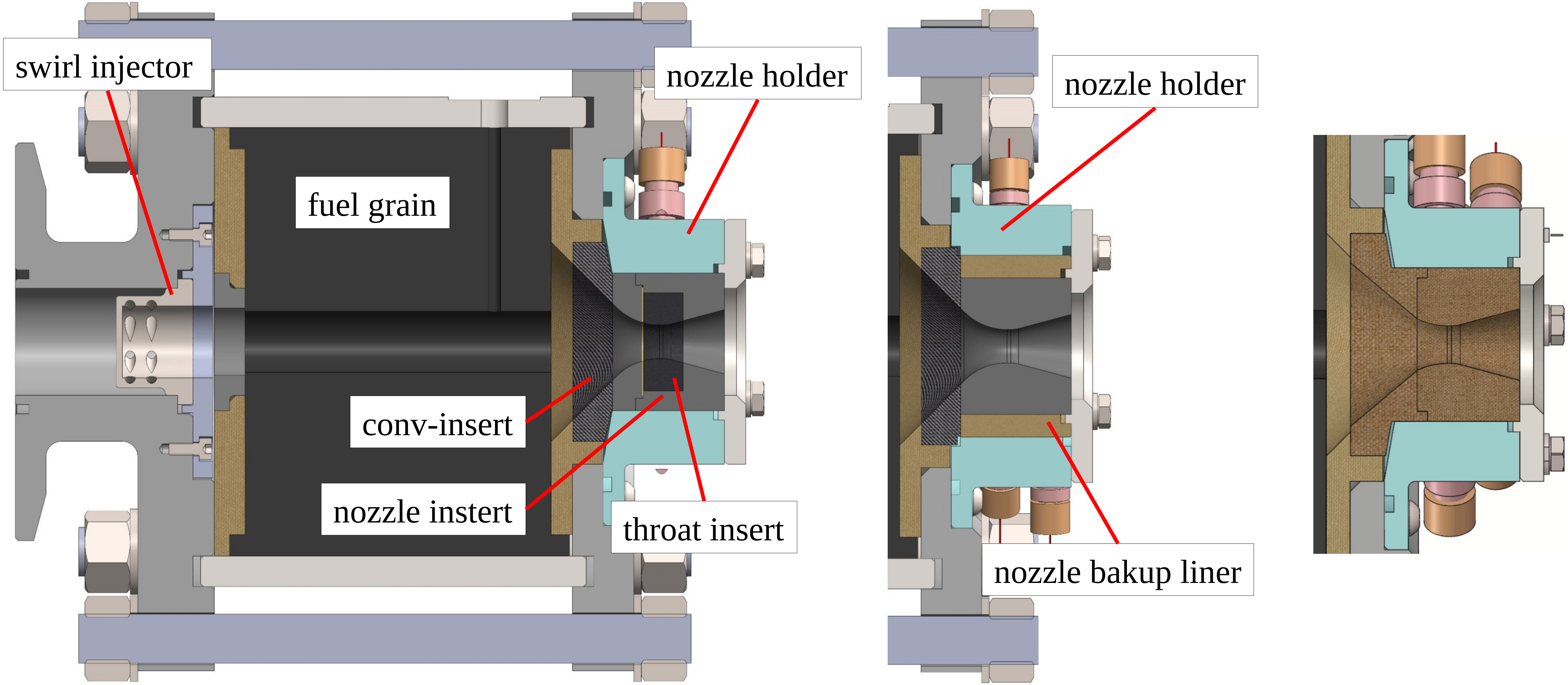
Experimental set-up

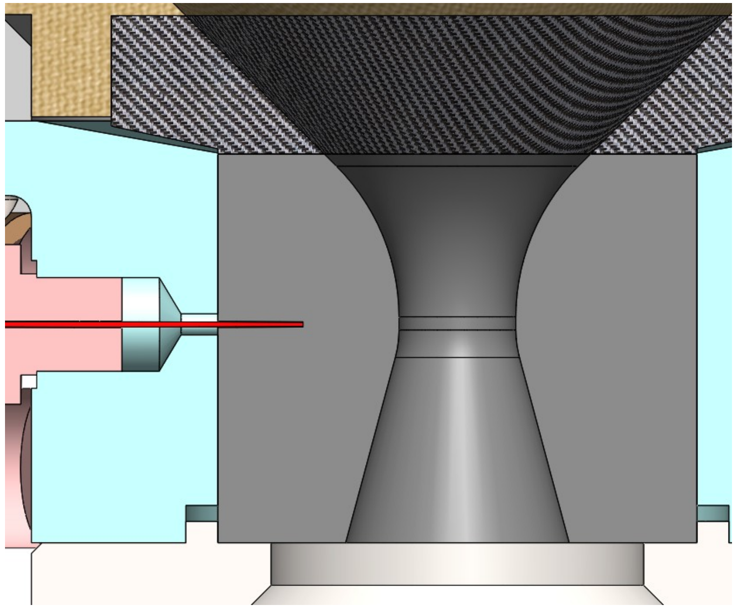


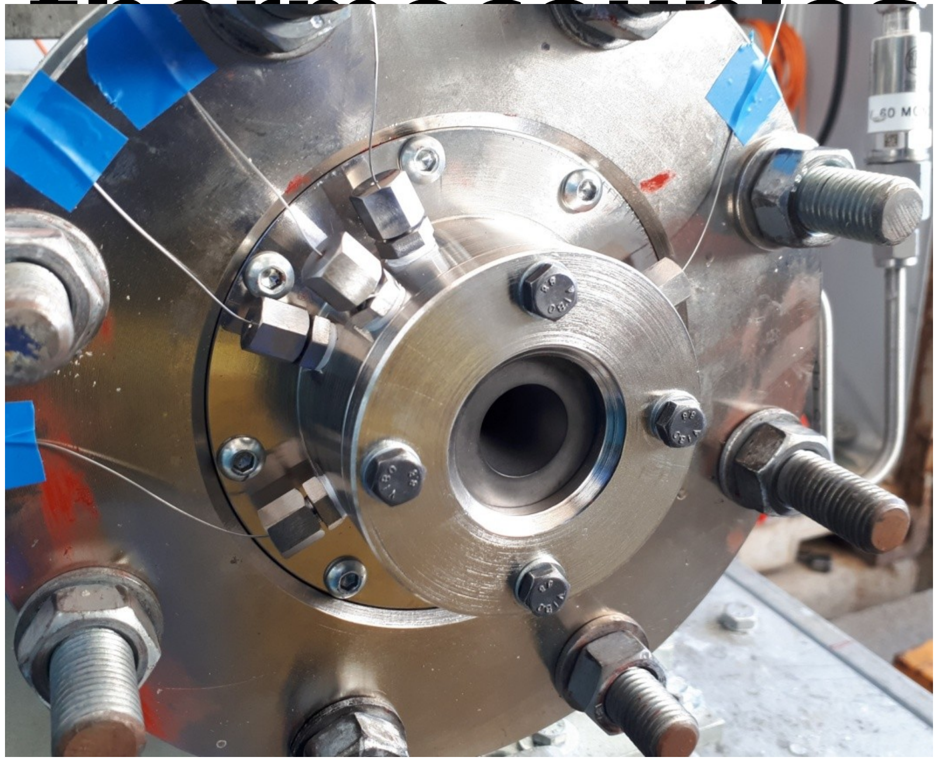
Combustion chamber

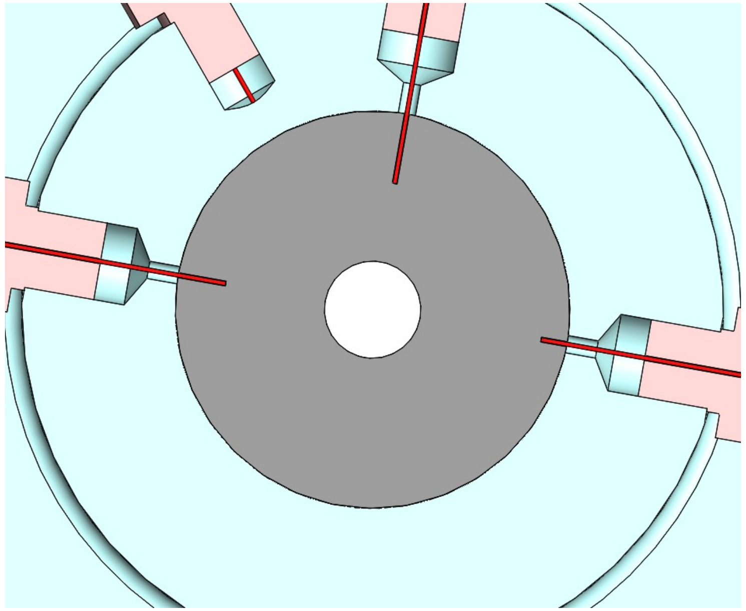


Nozzle zone

Disposition of the thermocouples

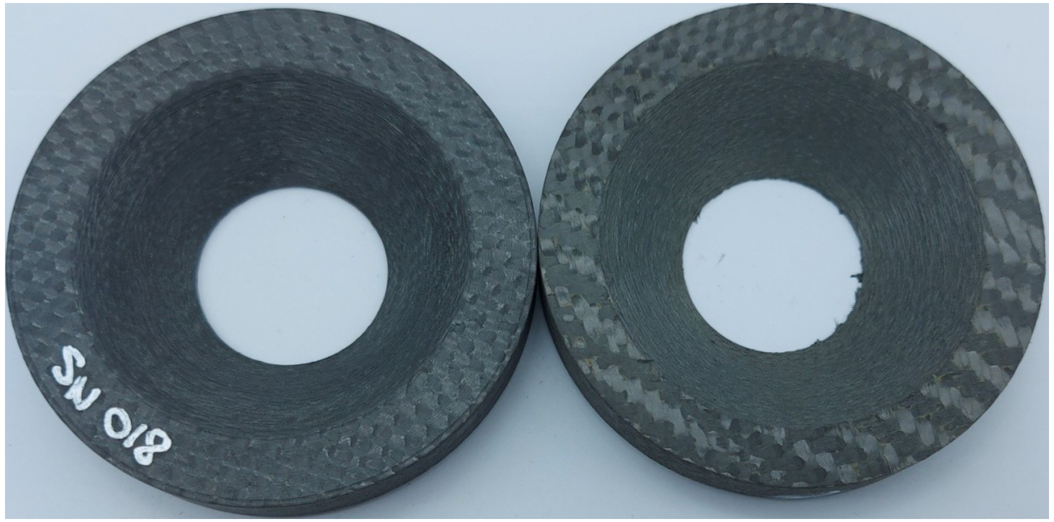






Materials selection

2 types of carbon/phenolic



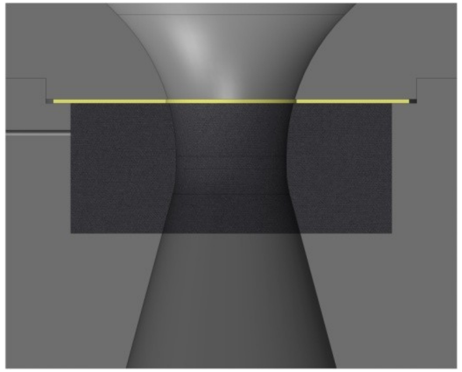
7 graphite grades

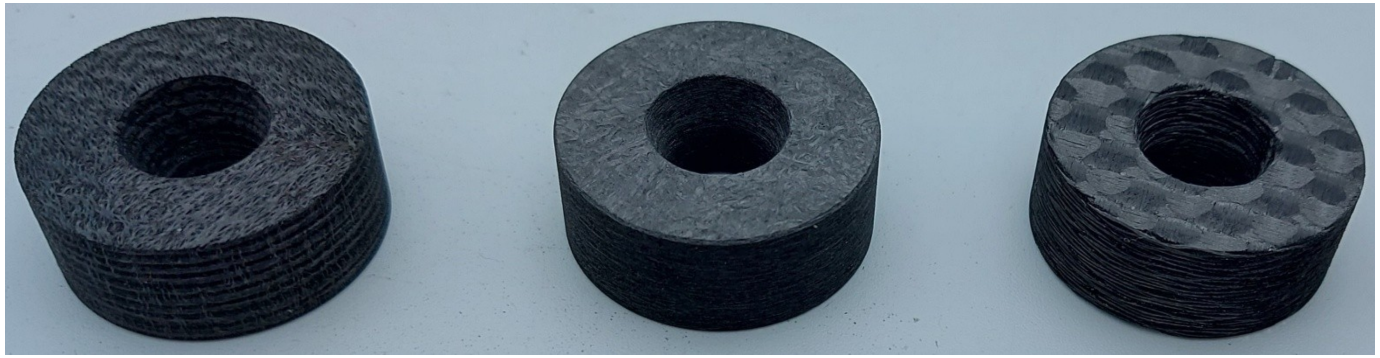
Silica/phenolic

Cotton/phenolic Glass/phenolic Silica

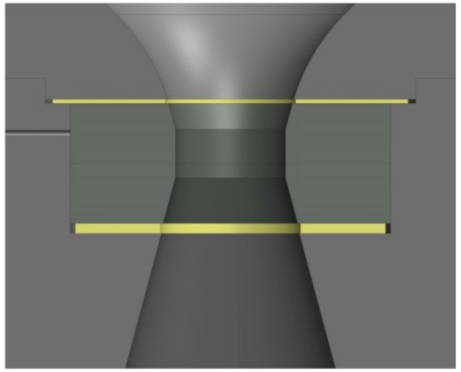
Materials selection

3 types of carbon-carbon

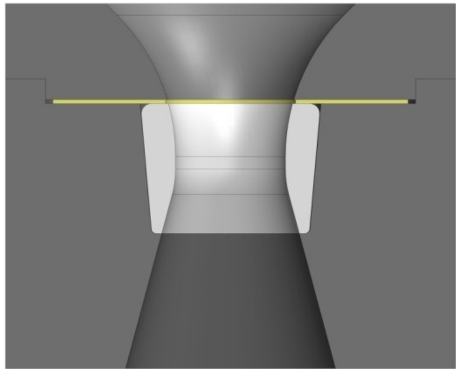




Glassy-carbon



Tungsten



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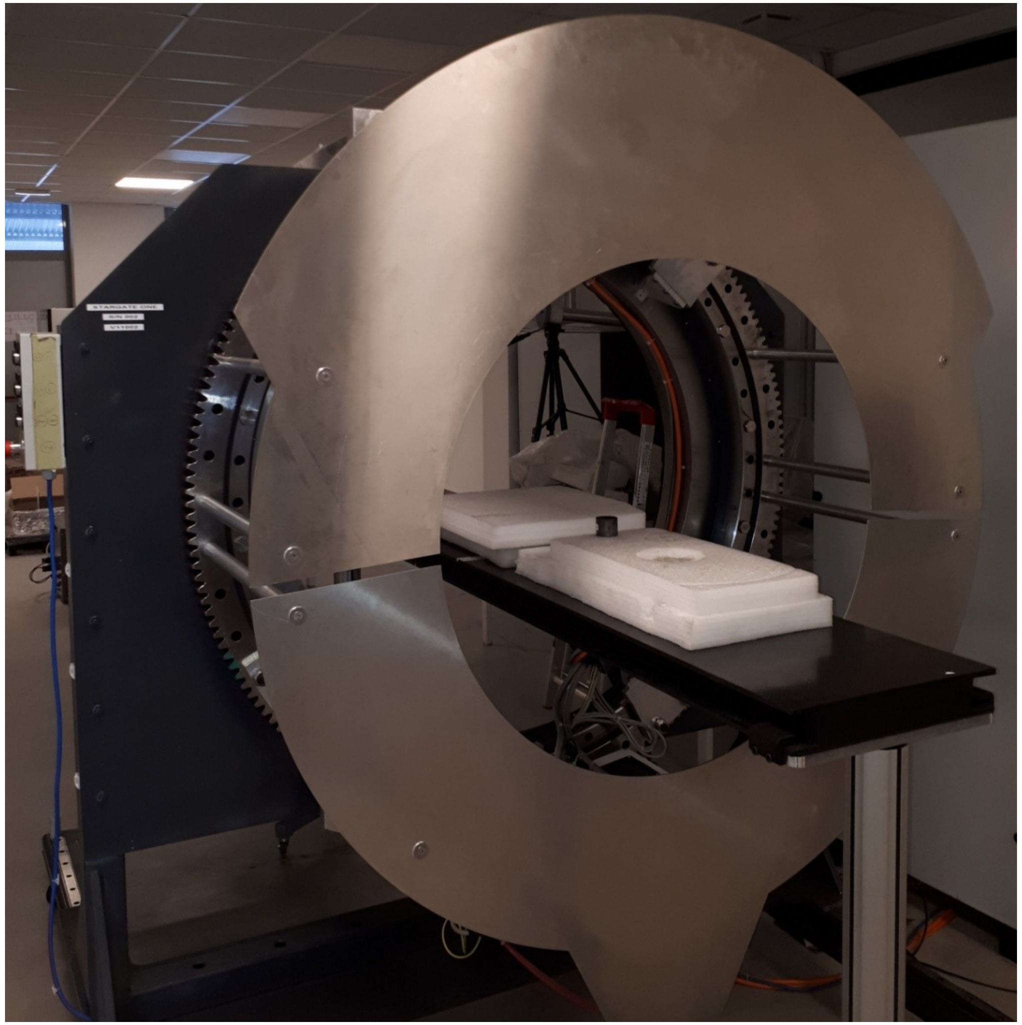
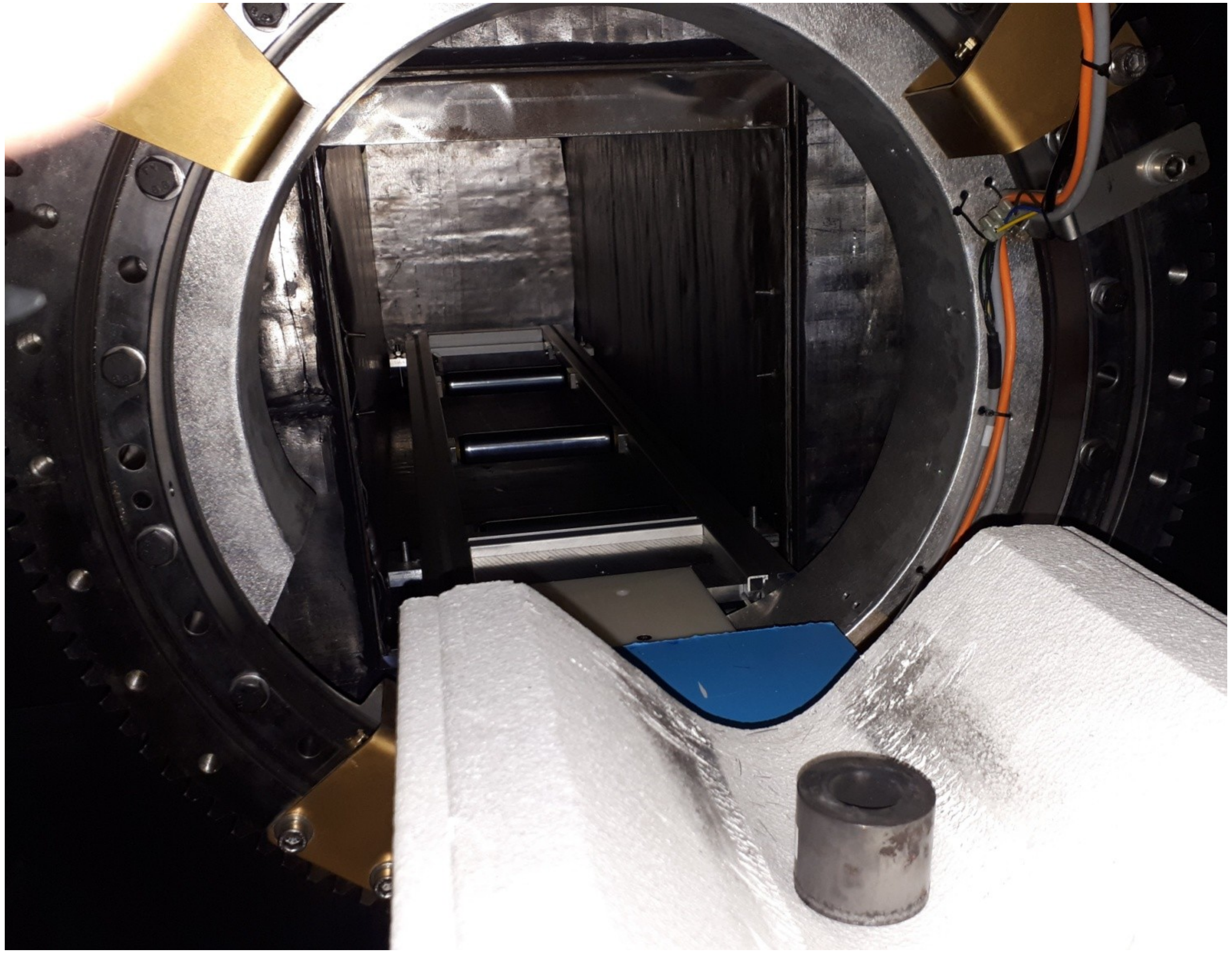
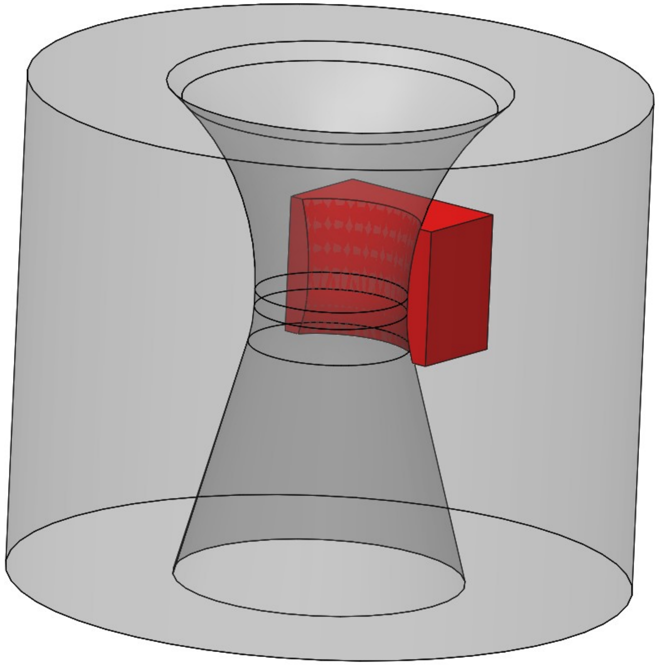
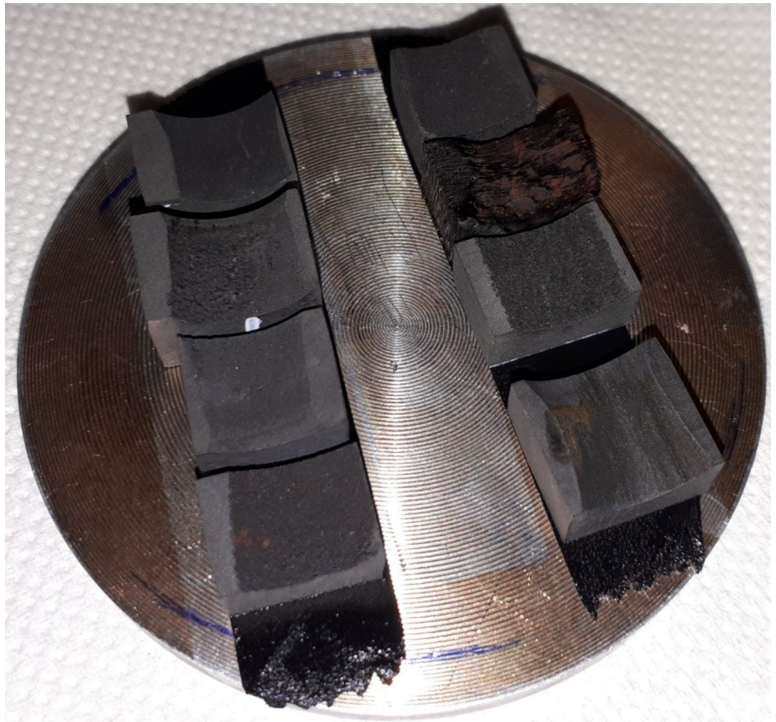
-ray tomographies



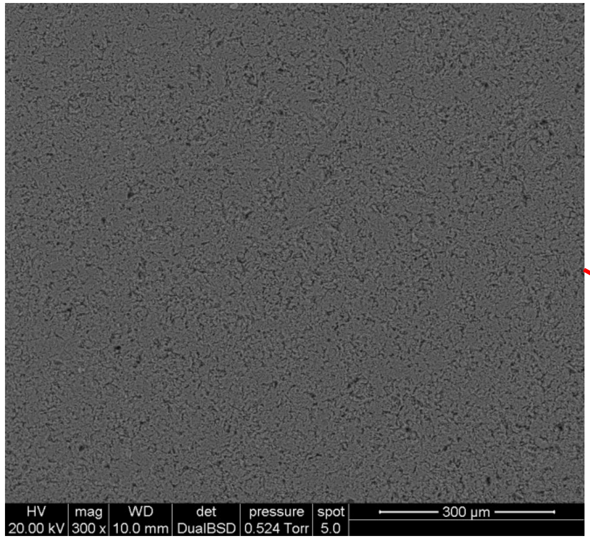


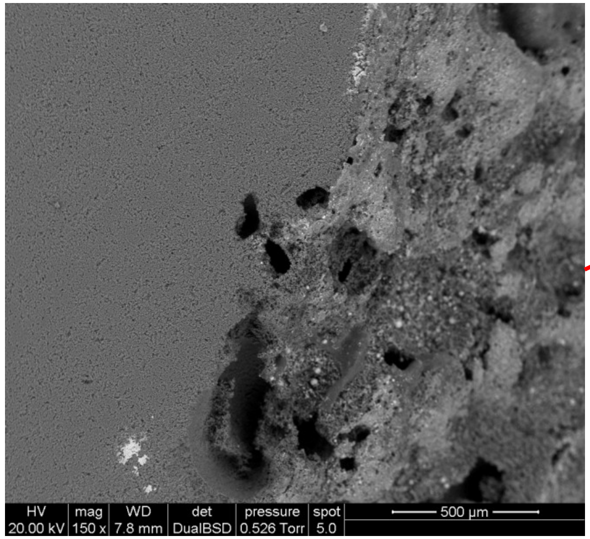
SEM analyses

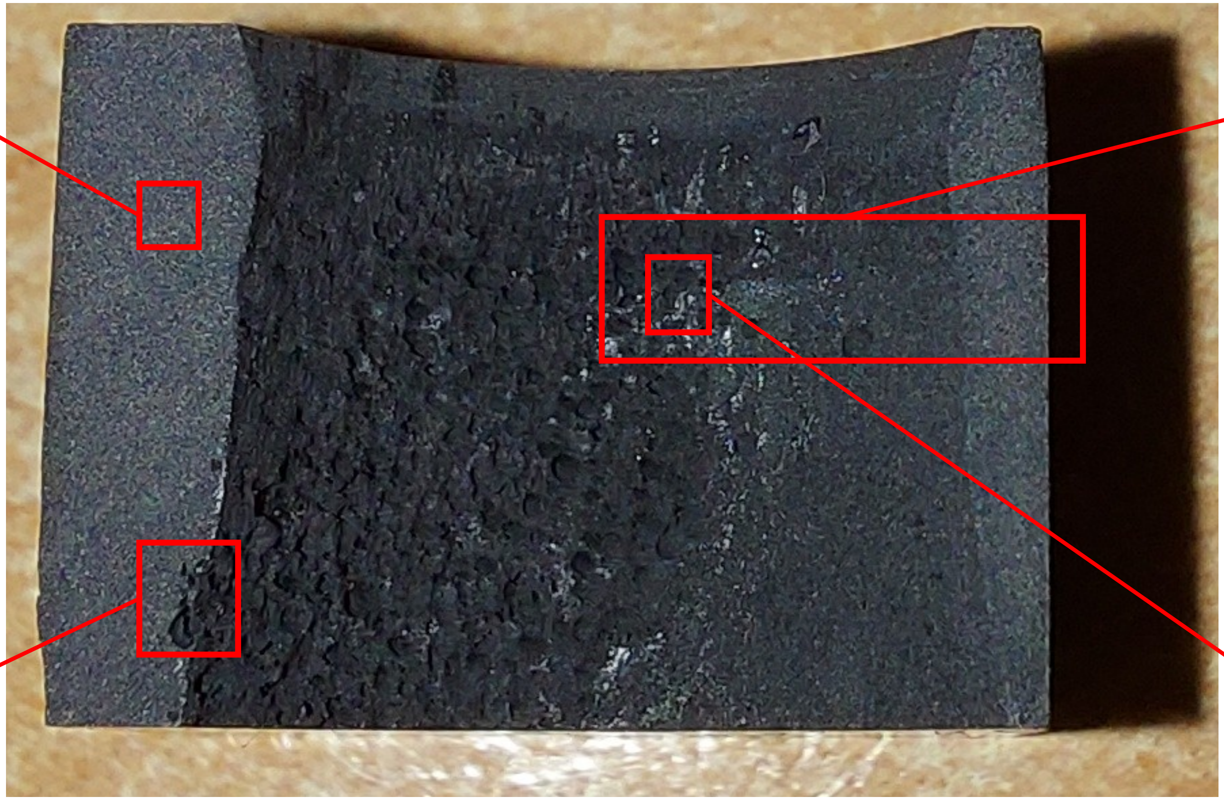


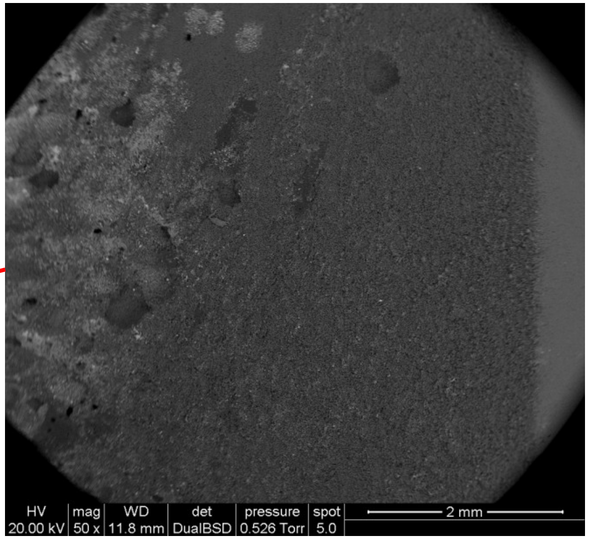


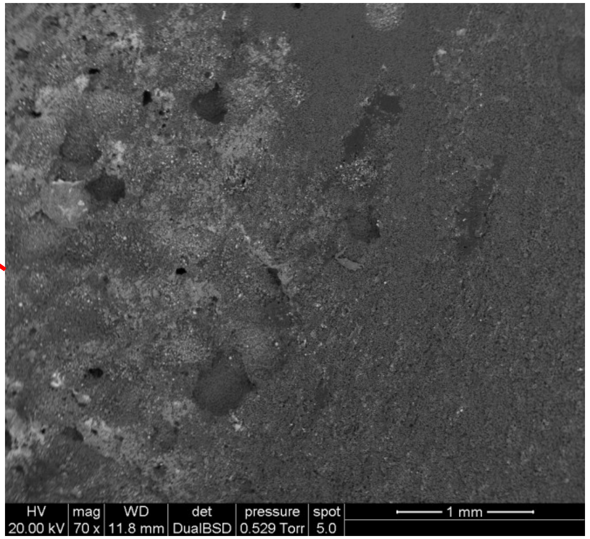
SEM analyses

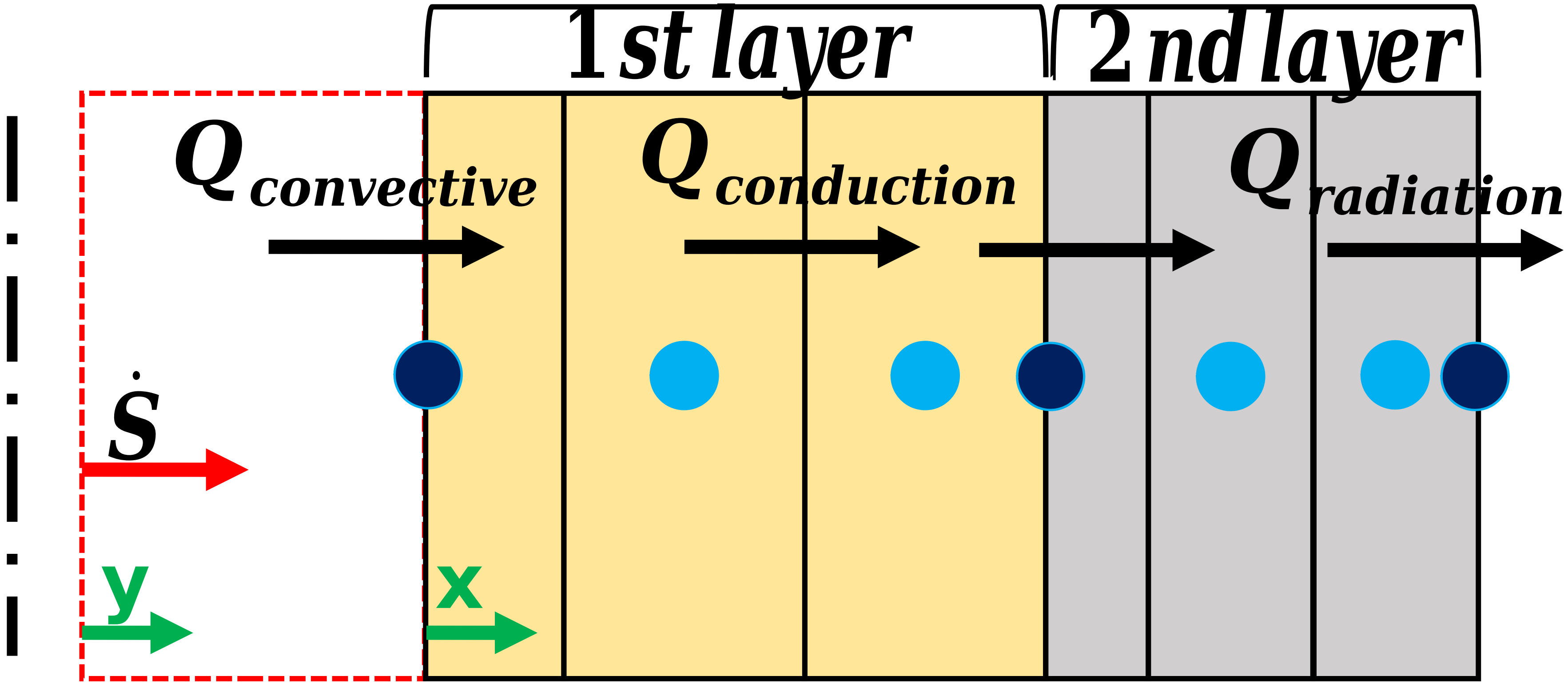






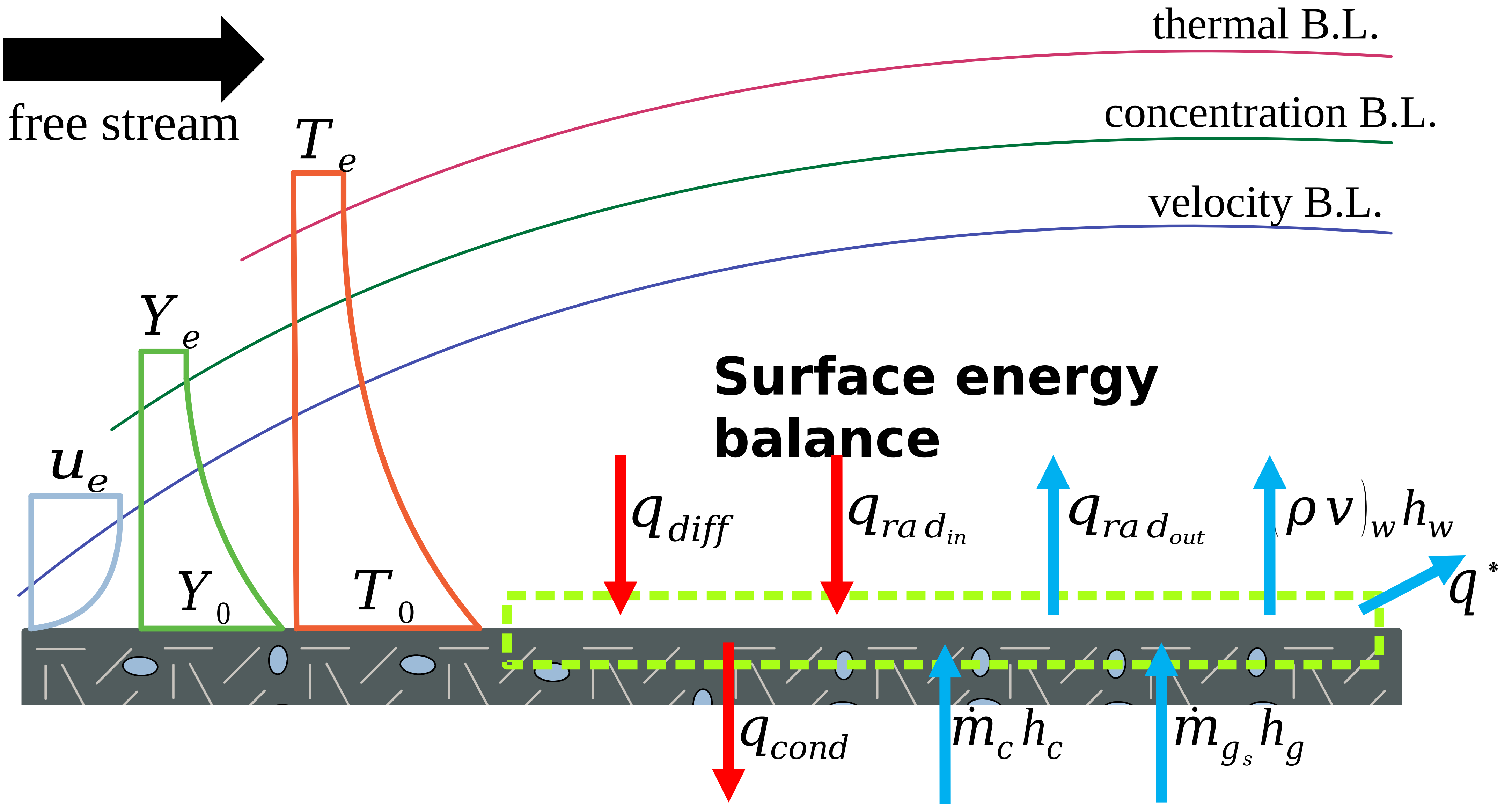






$$\rho c_p \left.\frac{\partial T}{\partial t}\right)_x = \frac{1}{A}\frac{\partial}{\partial x}\left(kA \left.\frac{\partial T}{\partial x}\right)_t\right. + \left(h_g - \bar{h}\right)\left.\frac{\partial \rho}{\partial t}\right)_y + \dot{S}\rho c_p \left.\frac{\partial T}{\partial x}\right)_t + \frac{\dot{m}_g}{A}\left.\frac{\partial h_g}{\partial x}\right)_t$$

D ablation model



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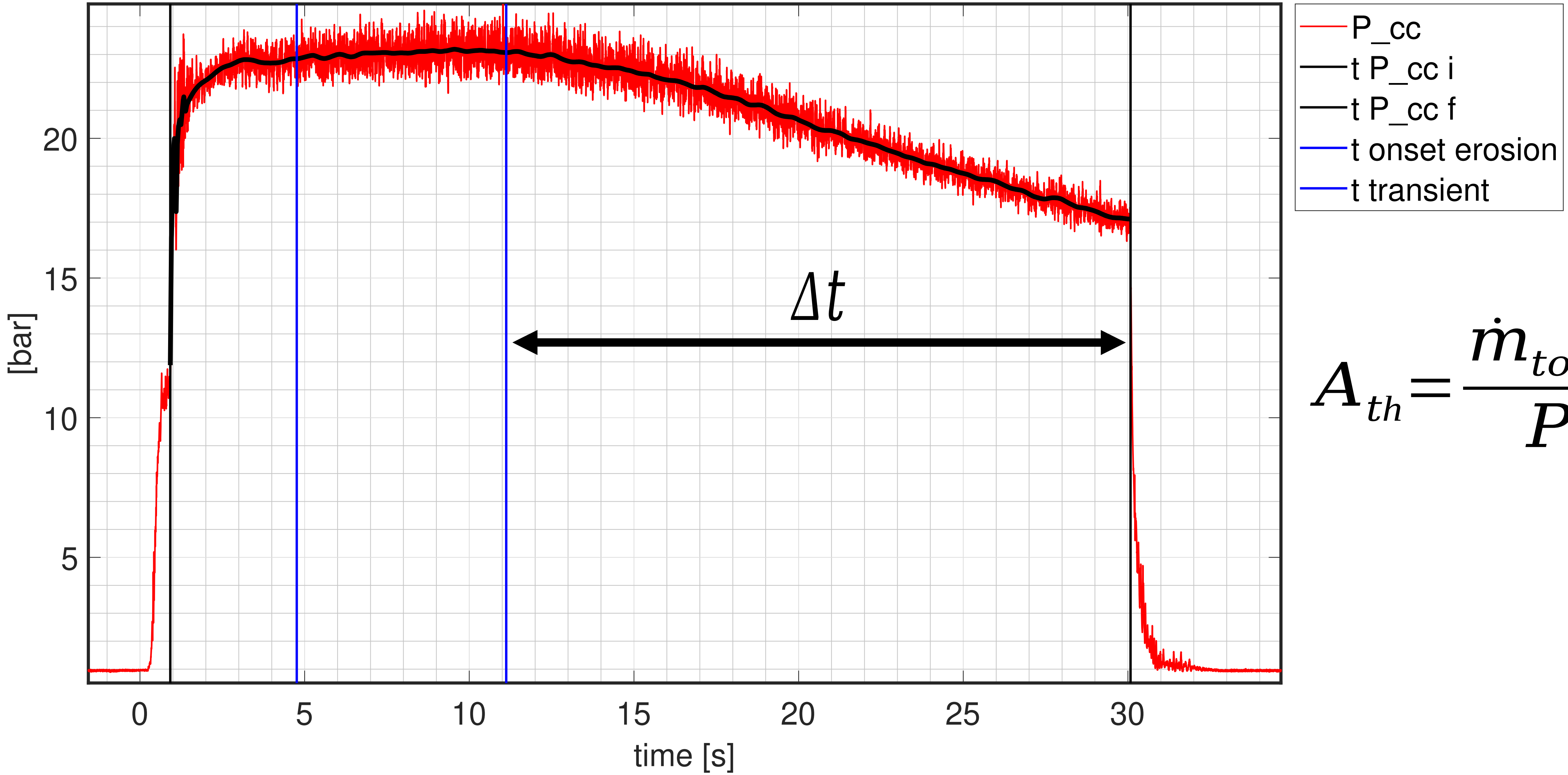
Test matrix

- Screening tests on graphite grades
- Phenolic-based materials
- Further tests on the best graphites
- Screening tests on carbon/carbons
- Glassy-carbon
- Backup nozzle liners
- Tungsten

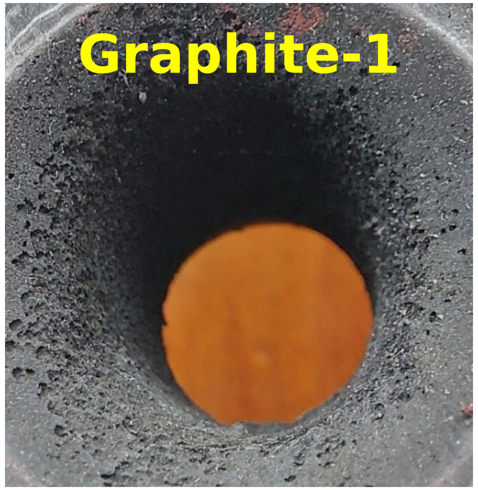
	Burning time	Catalyst bed	Pre-flange	Inj-insert	Grain length	Post-flange	Conv-insert	Nozzle insert	Throat insert	Nozzle backup liner
001	≈15 s	1	1: cotton/ph	-	100 mm	1: cotton/ph	-	graphite-1	-	-
002	≈30 s	1	1: cotton/ph	-	100 mm	1: cotton/ph	-	graphite-1	-	-
003	≈30 s	1	1: cotton/ph	-	100 mm	1: cotton/ph	-	carbon/ph -1	-	-
004	≈30 s	1	1: cotton/ph	-	100 mm	1: cotton/ph	-	graphite-2	-	-
005	≈30 s	1	1: cotton/ph	-	100 mm	1: cotton/ph	-	graphite-3	-	-
006	≈30 s	1	1: cotton/ph	-	100 mm	1: cotton/ph	-	graphite-4	-	-
007	≈30 s	1	1: cotton/ph	-	100 mm	1: cotton/ph	-	graphite-4	-	-
008	≈30 s	1	1: cotton/ph	-	100 mm	1: cotton/ph	-	graphite-5	-	-
009	≈30 s	2	2: cotton/ph	2: graphite-1	110 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	-	-
010	≈30 s	2	1: cotton/ph	-	110 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	C/C-2	-
011	≈30 s	2	1: cotton/ph	-	110 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	C/C-3	-
012	≈30 s	2	1: cotton/ph	-	110 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	C/C-1	-
013	≈30 s	2	1: cotton/ph	-	100 mm	1: cotton/ph	-	graphite-6	-	-
014	≈30 s	2	1: cotton/ph	-	110 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	glassy carbon	-
015	≈30 s	2	1: cotton/ph	-	93 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	-	-
016	≈30 s	2	1: cotton/ph	-	93 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	-	-
017	≈30 s	2	1: cotton/ph	-	140 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	-	-
018	≈30 s	2	1: cotton/ph	-	140 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	-	-
019	≈30 s	2	3: cotton/ph	3: graphite-1	105 mm	2: cotton/ph	2: carbon/ph-2	graphite-7	-	-
020	≈30 s	2	3: cotton/ph	-	140 mm	3: cotton/ph	3: carbon/ph-1	graphite-4	-	cotton/ph
021	≈30 s	2	3: cotton/ph	-	140 mm	3: cotton/ph	3: carbon/ph-1	graphite-4	-	glass/ph
022	≈15 s	2	2: cotton/ph	2: graphite-1	110 mm	4: cotton/ph	4: Silica/ph	Silica/ph	-	-
023	≈15 s	2	1: cotton/ph	-	100 mm	cotton/ph	-	carbon/ph -2	-	-
024	≈30 s	2	4: cotton/ph	4: graphite-1	105 mm	3: cotton/ph	3: carbon/ph-1	graphite-4	-	Silica/ph
025	≈30 s	2	4: cotton/ph	4: graphite-1	105 mm	2: cotton/ph	2: carbon/ph-1	graphite-4	Tungsten	-
026	≈30 s	2	1: cotton/ph	-	93 mm	2: cotton/ph	2: carbon/ph-1	graphite-7	-	-

Test results

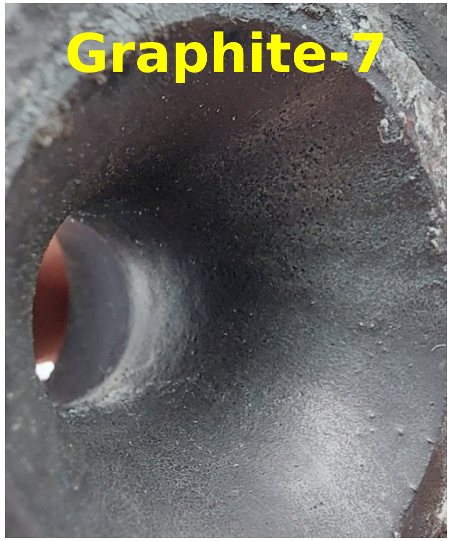


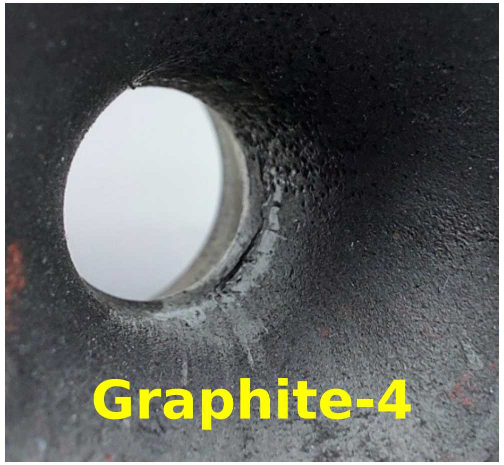
$$A_{th} = \frac{\dot{m}_{tot}\, c^*}{P_{cc}}$$

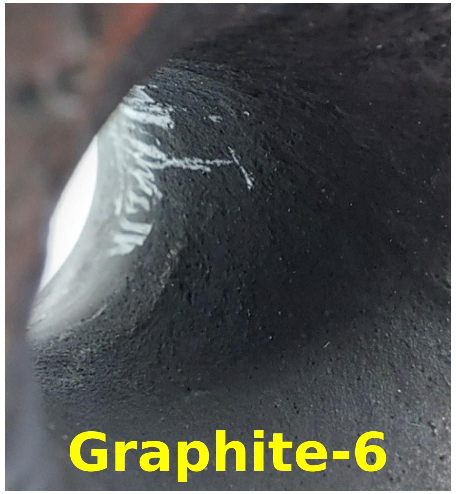
raphite screening tests



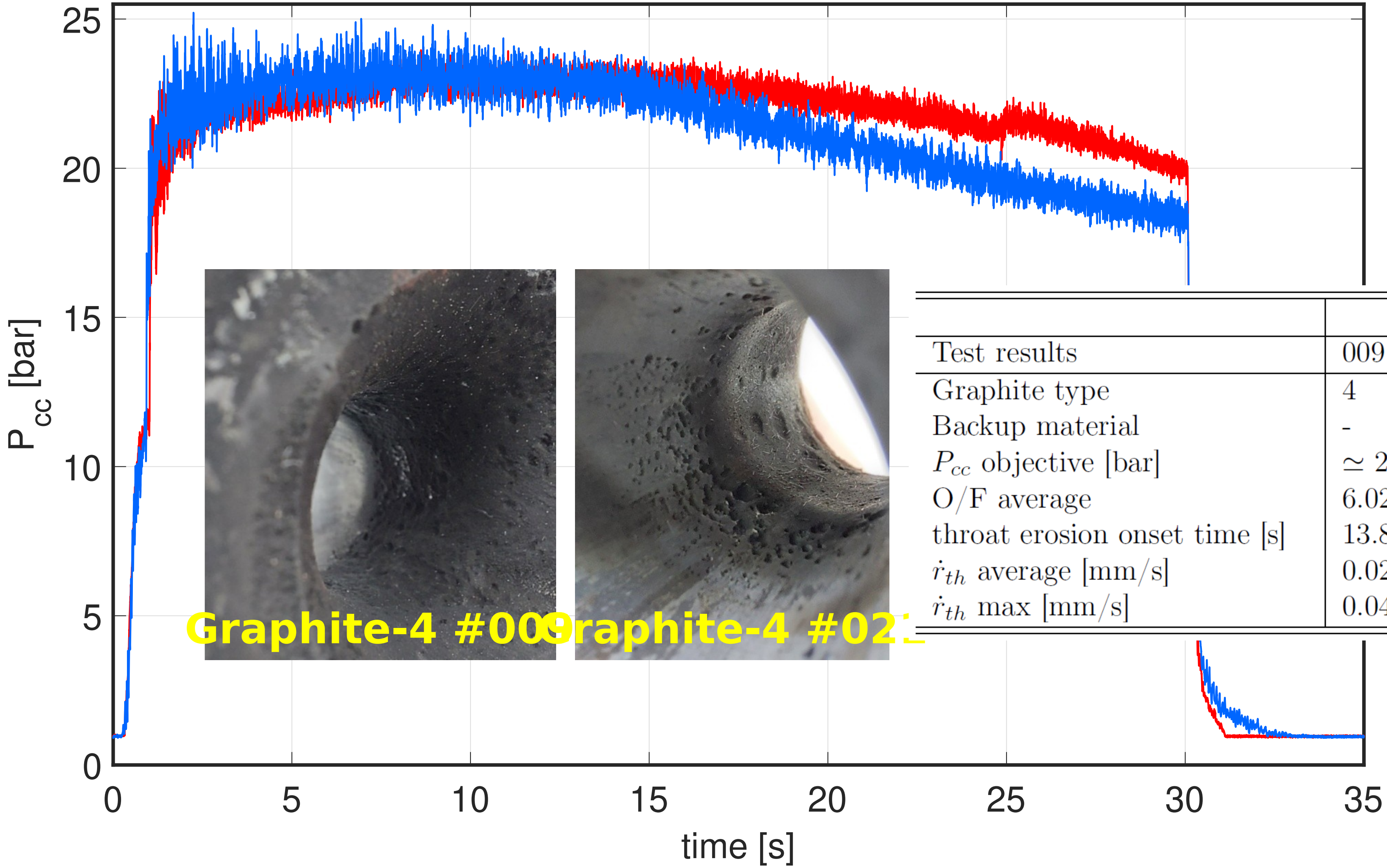
	Test ID from the test matrix							
Test results	001	002	004	005	006	007	008	013
Graphite type	1	1	2	3	4	4	5	6
P_{cc} objective [bar]	$\simeq 20$	$\simeq 20$	$\simeq 20$	$\simeq 20$	$\simeq 20$	$\simeq 20$	$\simeq 20$	$\simeq 20$
O/F average	6.63	6.80	6.55	7.00	5.99	6.24	6.21	6.70
throat erosion onset time [s]	12.84	12.78	11.42	10.00	13.20	13.30	9.19	10.23
$\dot{r}_{th}$ average [mm/s]	0.1099	0.1015	0.0827	0.423	0.0225	0.0212	0.1422	0.0584
$\dot{r}_{th}$ max [mm/s]	-	0.124	0.1165	0.830	0.0375	0.0363	0.163	0.0745





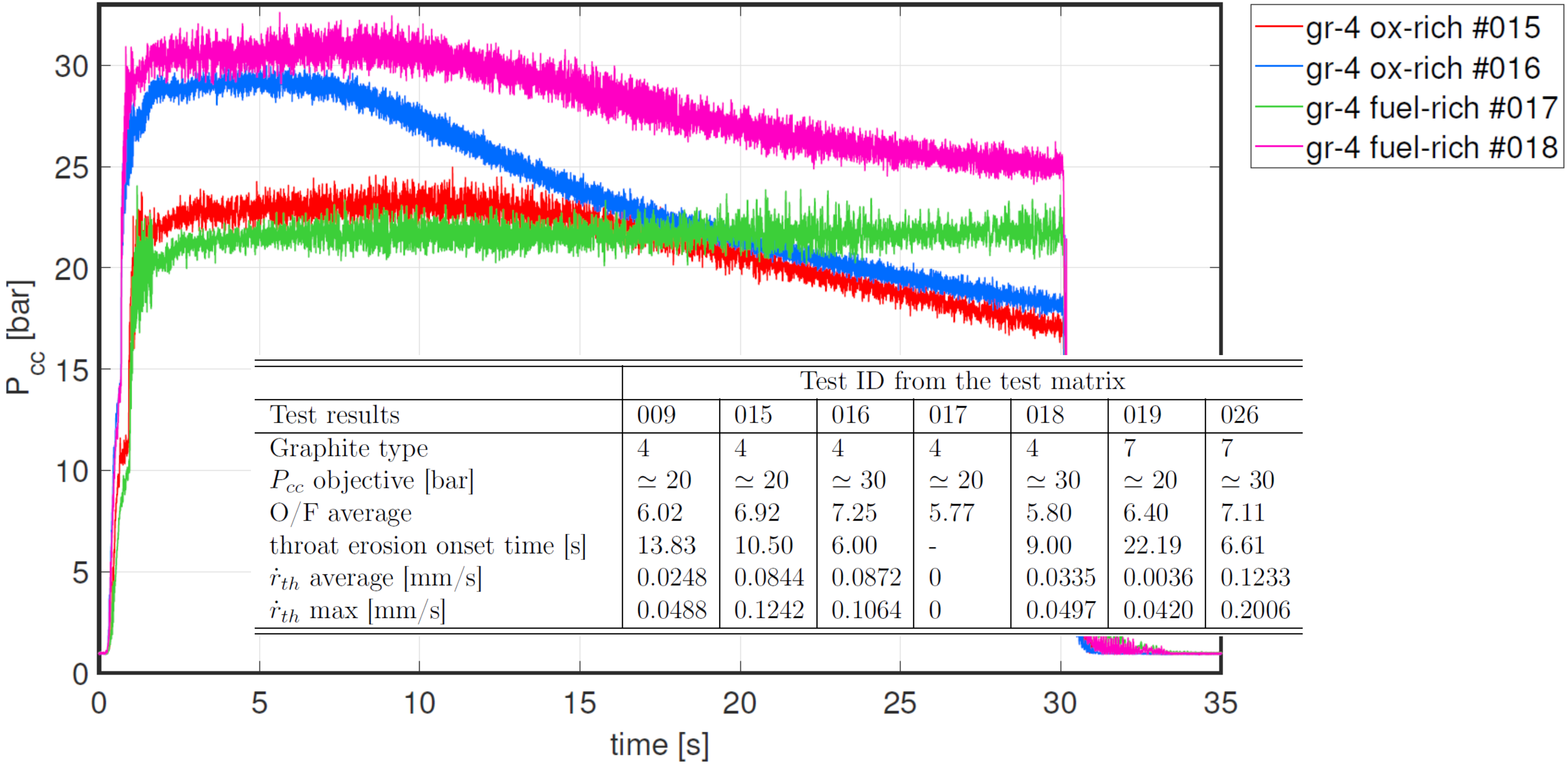


raphites in-depth study



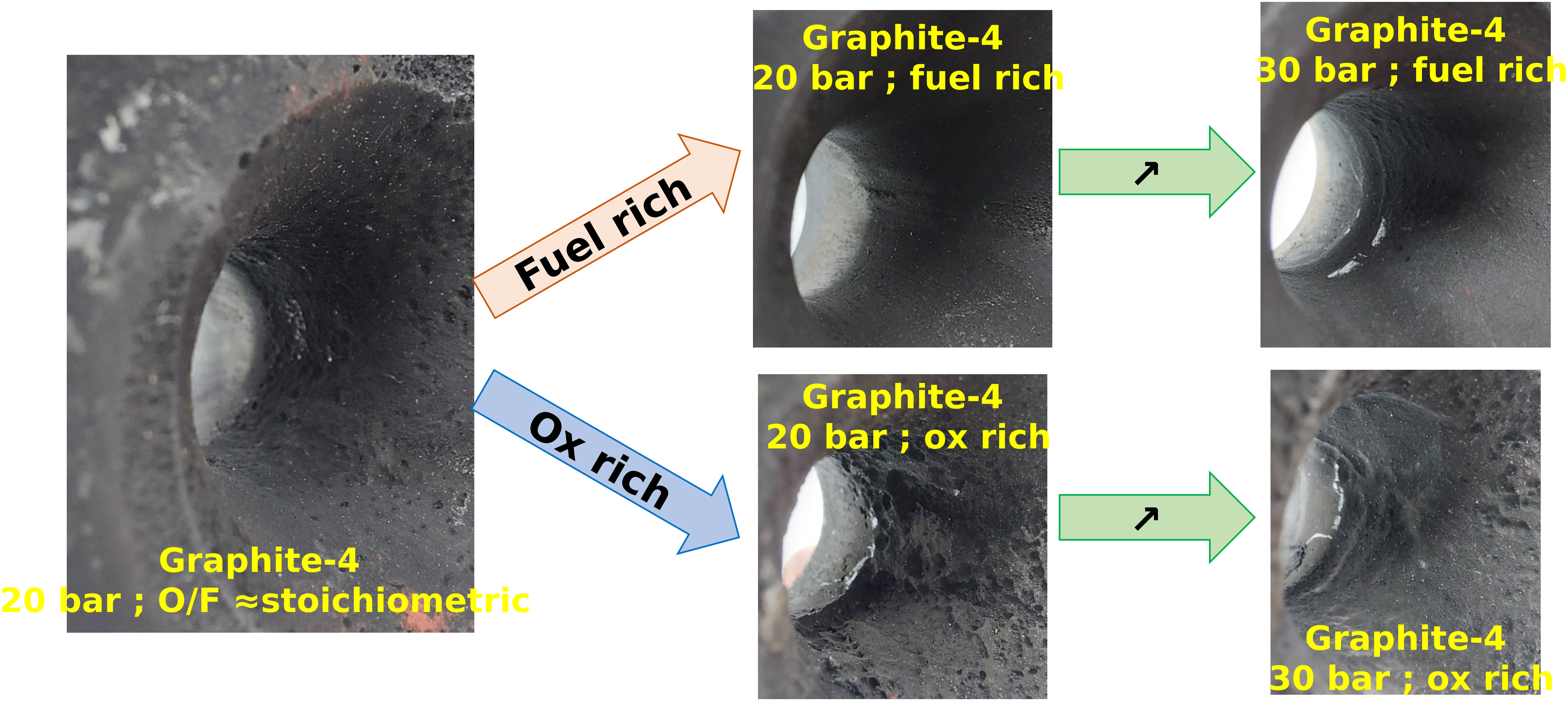
	Test ID from the test matrix			
Test results	009	020	021	024
Graphite type	4	4	4	4
Backup material	-	cotton/ph.	glass/ph.	silica/ph.
P_{cc} objective [bar]	$\simeq$ 20	$\simeq$ 20	$\simeq$ 20	$\simeq$ 20
O/F average	6.02	6.27	6.54	6.63
throat erosion onset time [s]	13.83	8.71	11.82	10.56
$\dot{r}_{th}$ average [mm/s]	0.0248	0.0471	0.0300	0.0409
$\dot{r}_{th}$ max [mm/s]	0.0488	-	-	-

raphites in-depth study

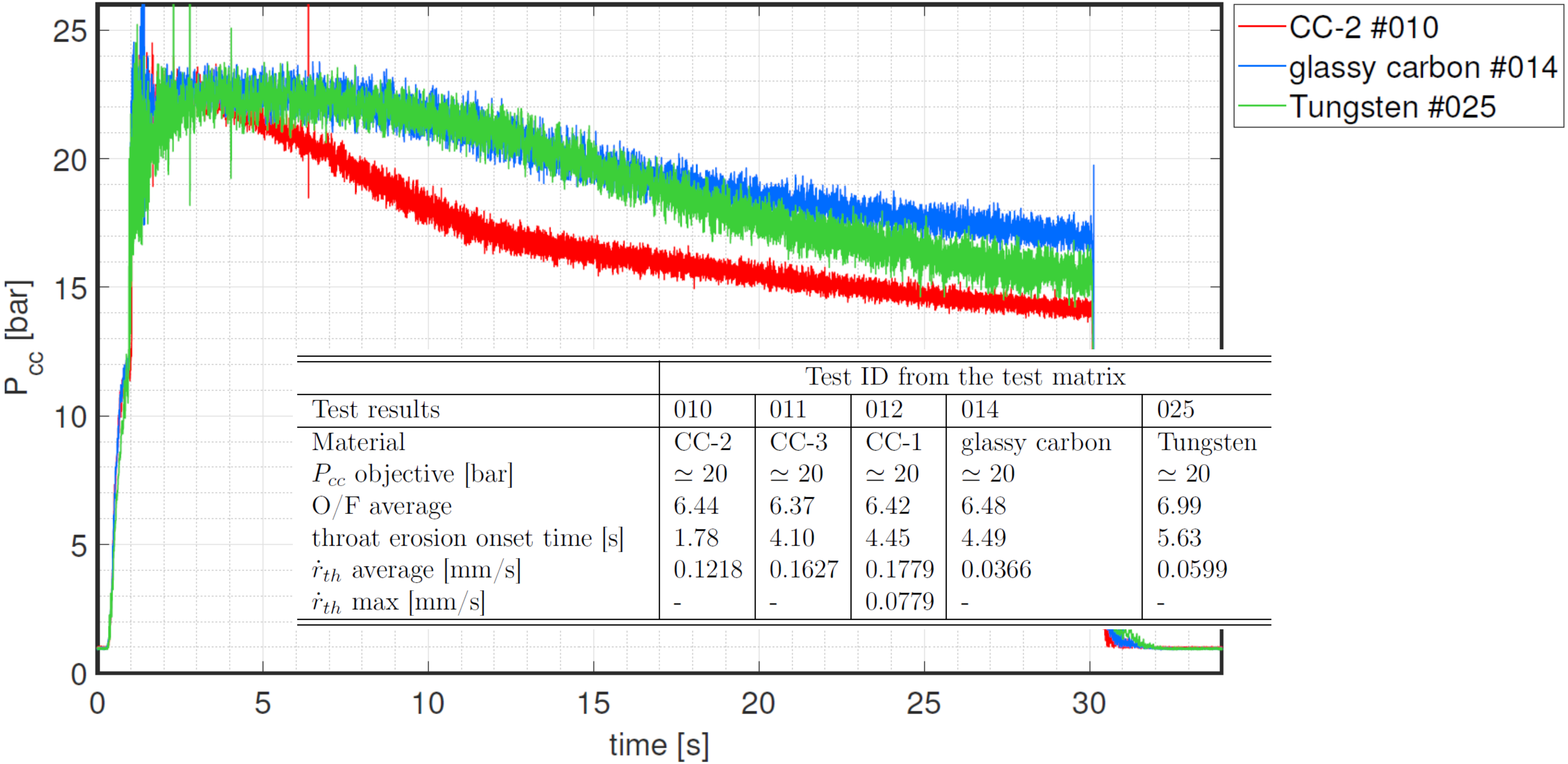


	Test ID from the test matrix						
Test results	009	015	016	017	018	019	026
Graphite type	4	4	4	4	4	7	7
P_{cc} objective [bar]	$\simeq 20$	$\simeq 20$	$\simeq 30$	$\simeq 20$	$\simeq 30$	$\simeq 20$	$\simeq 30$
O/F average	6.02	6.92	7.25	5.77	5.80	6.40	7.11
throat erosion onset time [s]	13.83	10.50	6.00	-	9.00	22.19	6.61
$\dot{r}_{th}$ average [mm/s]	0.0248	0.0844	0.0872	0	0.0335	0.0036	0.1233
$\dot{r}_{th}$ max [mm/s]	0.0488	0.1242	0.1064	0	0.0497	0.0420	0.2006

raphites in-depth study



Throat inserts

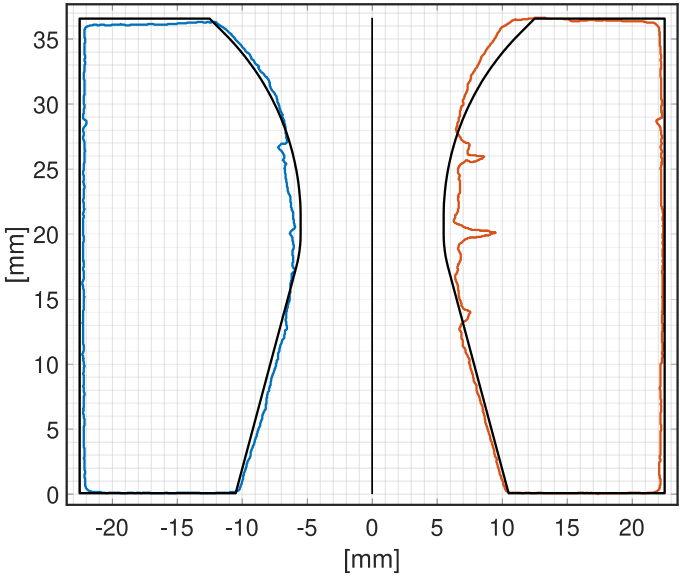


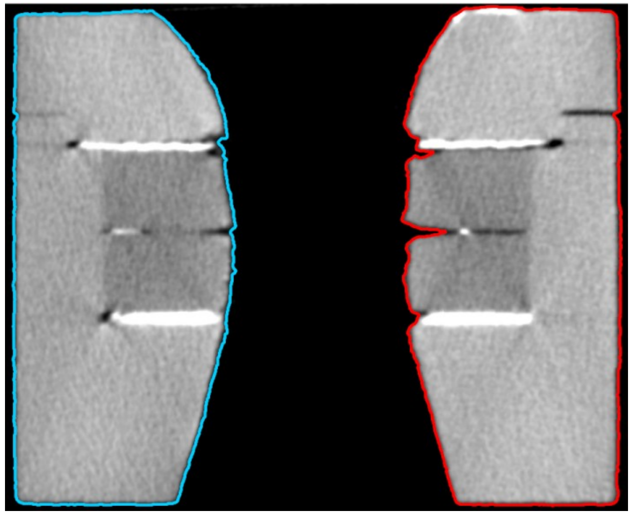
	Test ID from the test matrix				
Test results	010	011	012	014	025
Material	CC-2	CC-3	CC-1	glassy carbon	Tungsten
P_{cc} objective [bar]	$\simeq$ 20	$\simeq$ 20	$\simeq$ 20	$\simeq$ 20	$\simeq$ 20
O/F average	6.44	6.37	6.42	6.48	6.99
throat erosion onset time [s]	1.78	4.10	4.45	4.49	5.63
$\dot{r}_{th}$ average [mm/s]	0.1218	0.1627	0.1779	0.0366	0.0599
$\dot{r}_{th}$ max [mm/s]	-	-	0.0779	-	-

oat inserts - Tuungsten & glassy-car

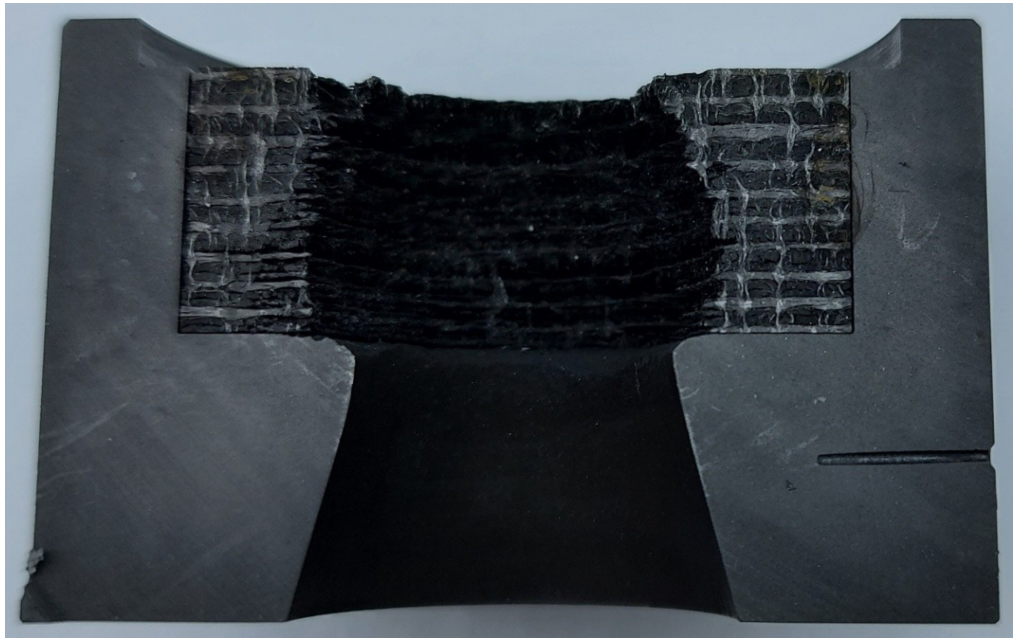
Tungsten

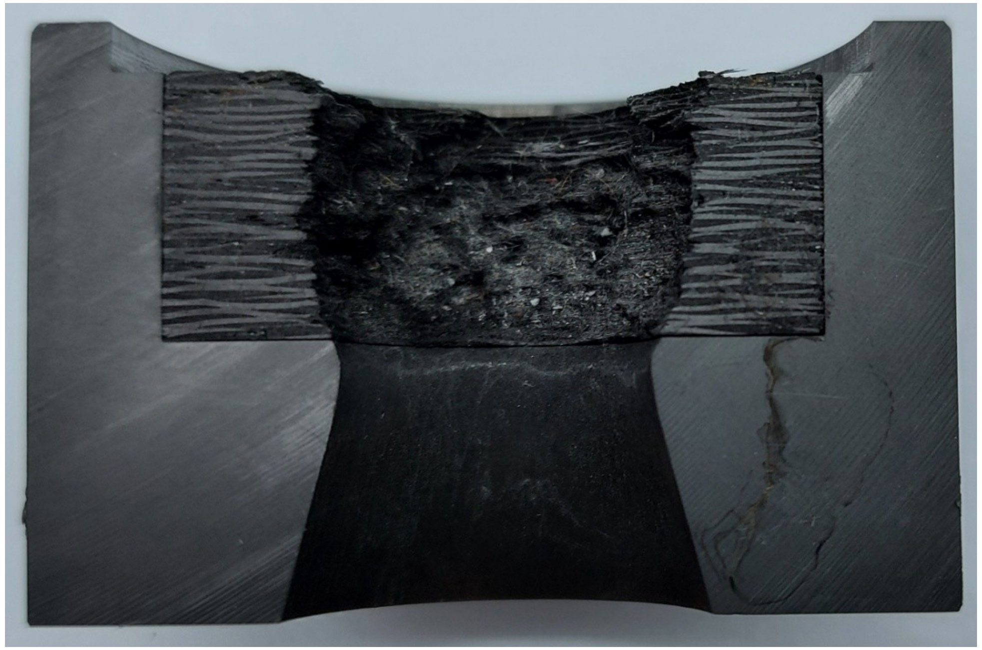
Glassy-carbon

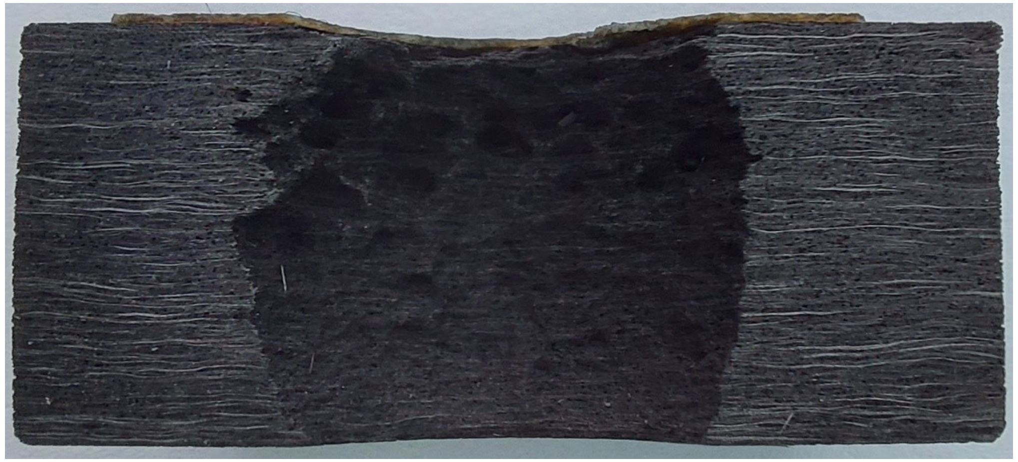




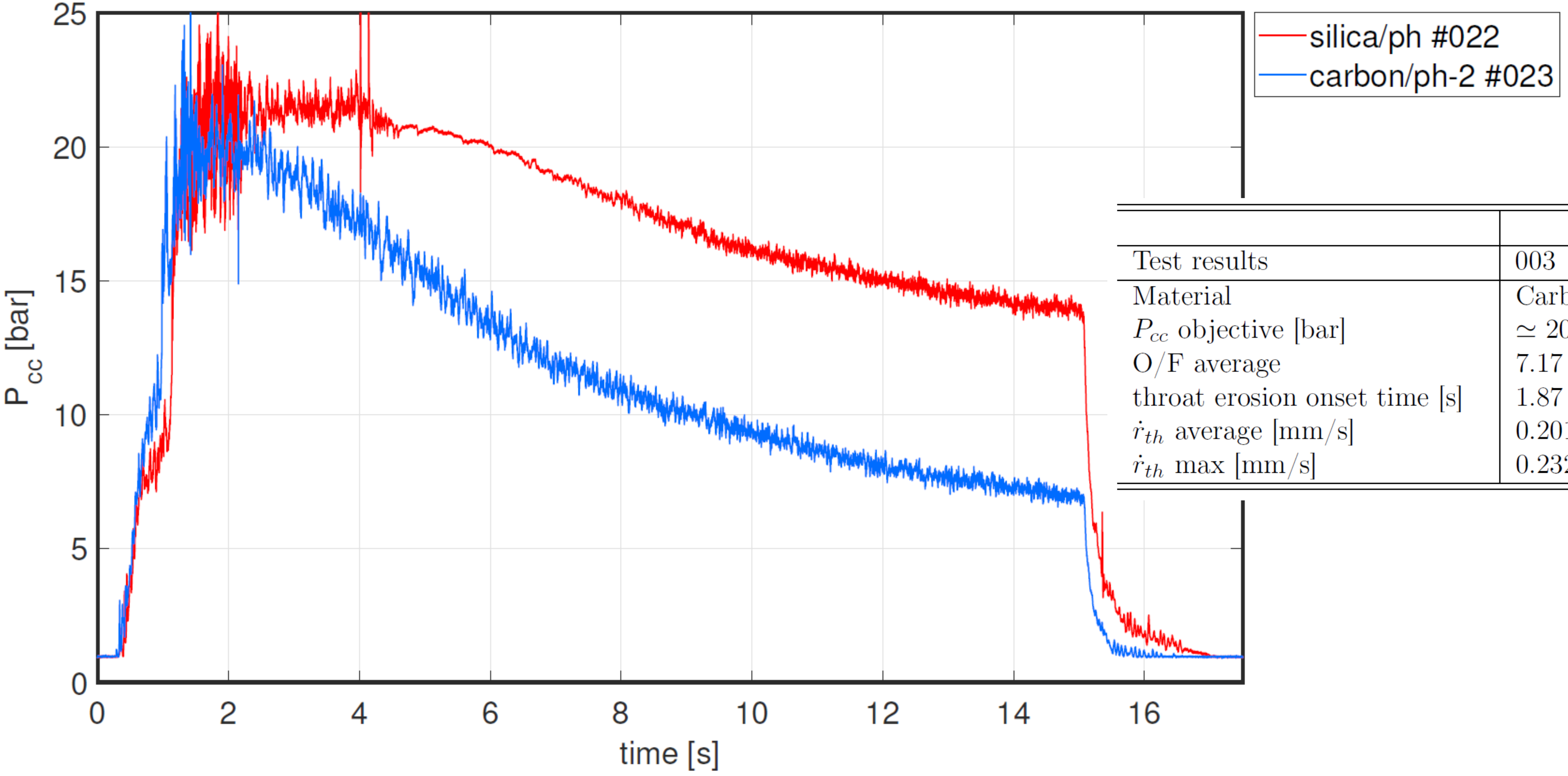
roat inserts - carbon/carbon



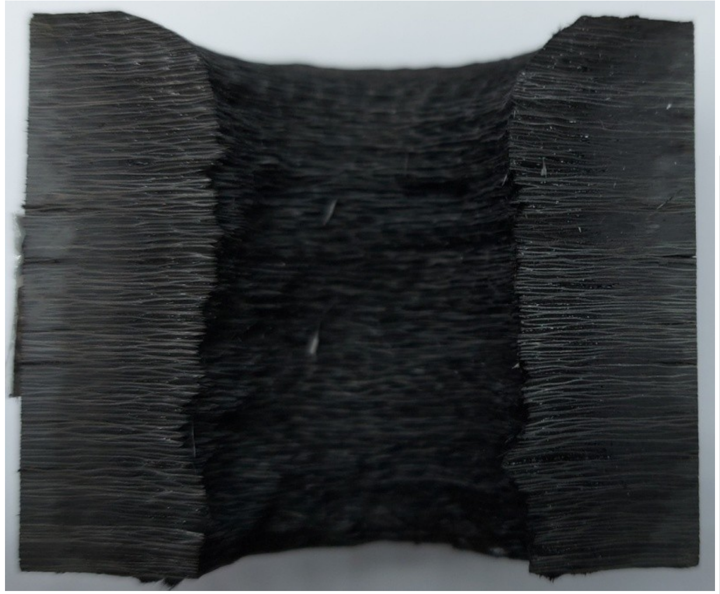




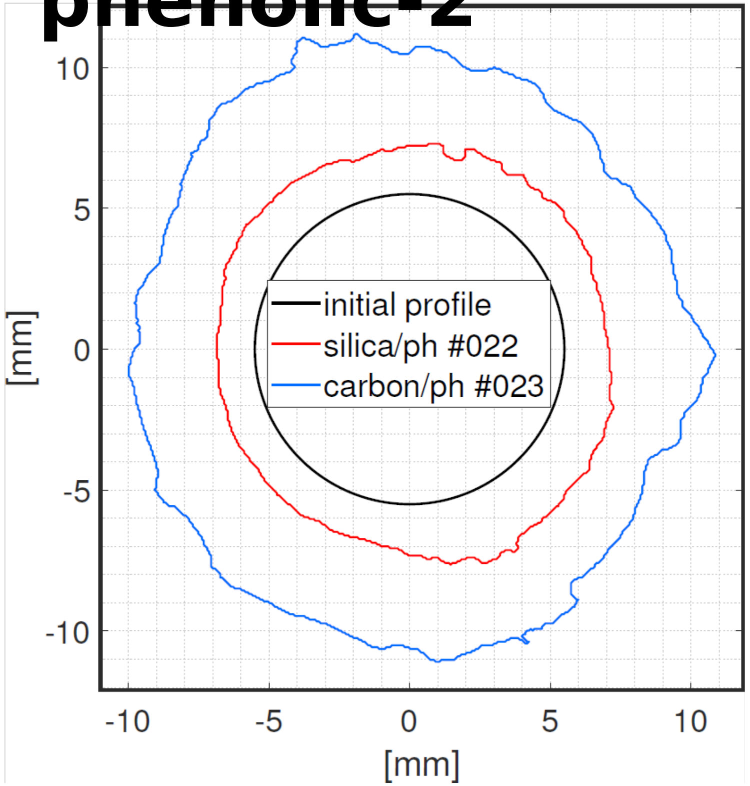
arbon & silica/phenolic

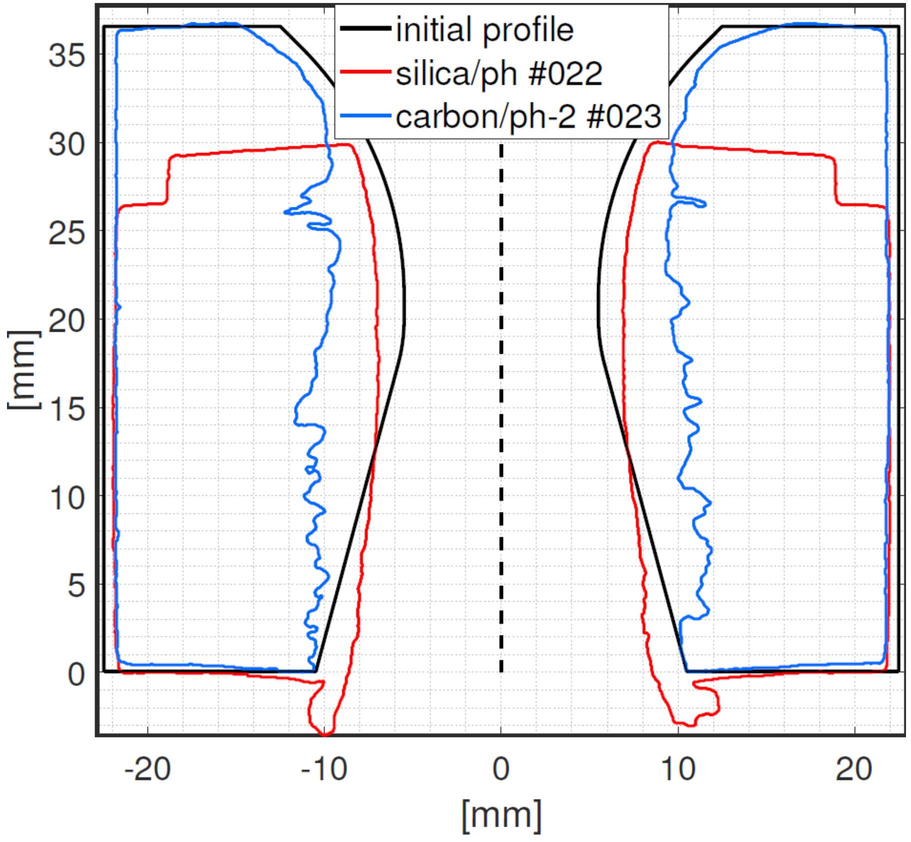


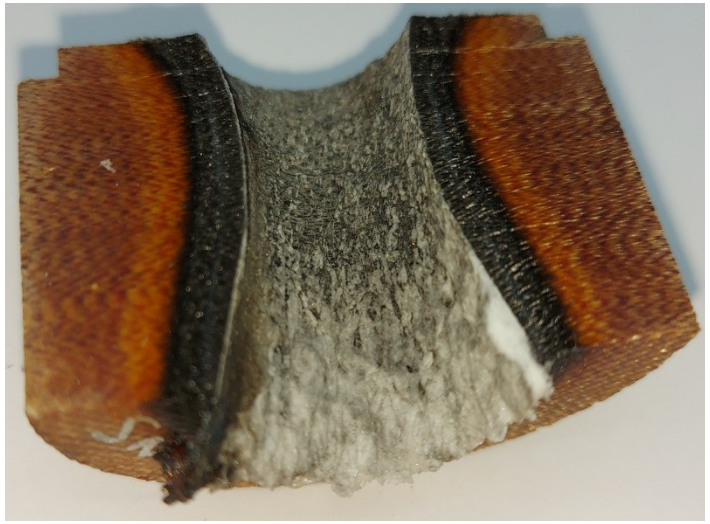
	Test ID from the test matrix		
Test results	003	023	022
Material	Carbon/ph-1	Carbon/ph-2	Silica/ph
P_{cc} objective [bar]	$\simeq 20$	$\simeq 20$	$\simeq 20$
O/F average	7.17	8.08	7.95
throat erosion onset time [s]	1.87	0.73	3.91
$\dot{r}_{th}$ average [mm/s]	0.2010	0.3377	0.1576
$\dot{r}_{th}$ max [mm/s]	0.2326	0.4488	0.2407



Carbon/ phenolic-2

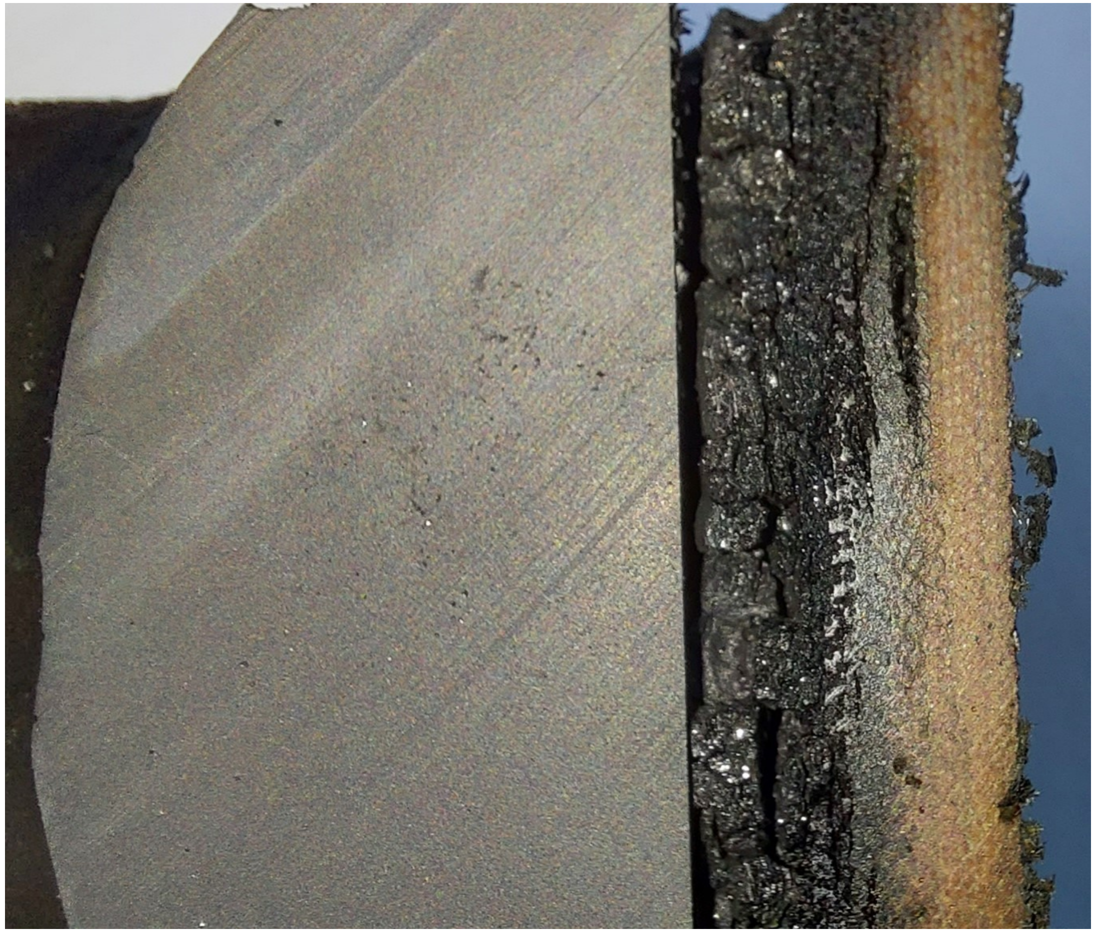




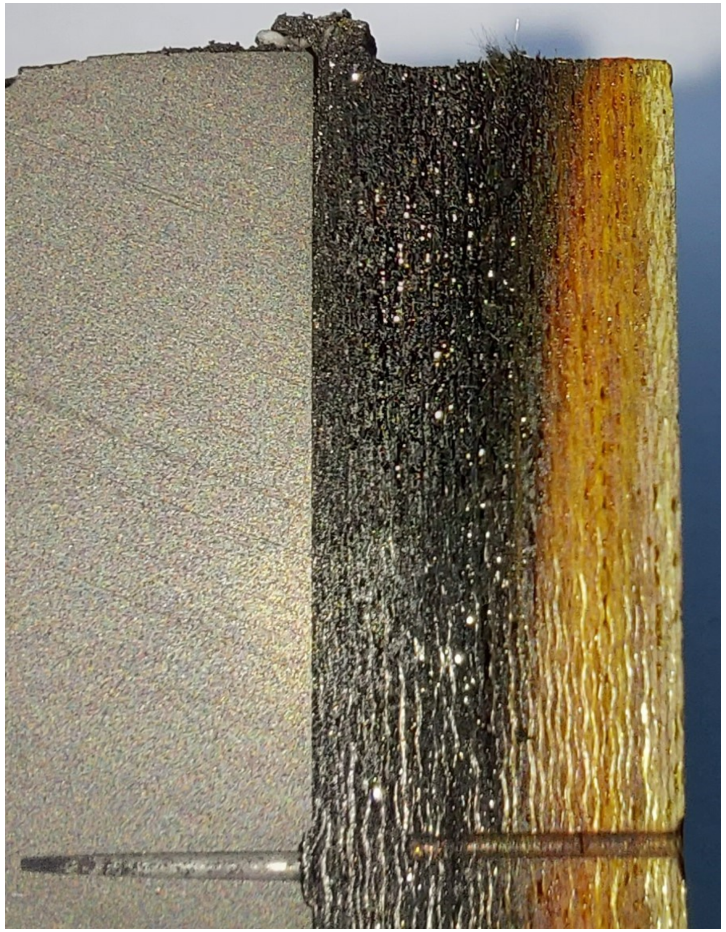


Silica/ phenolic-2

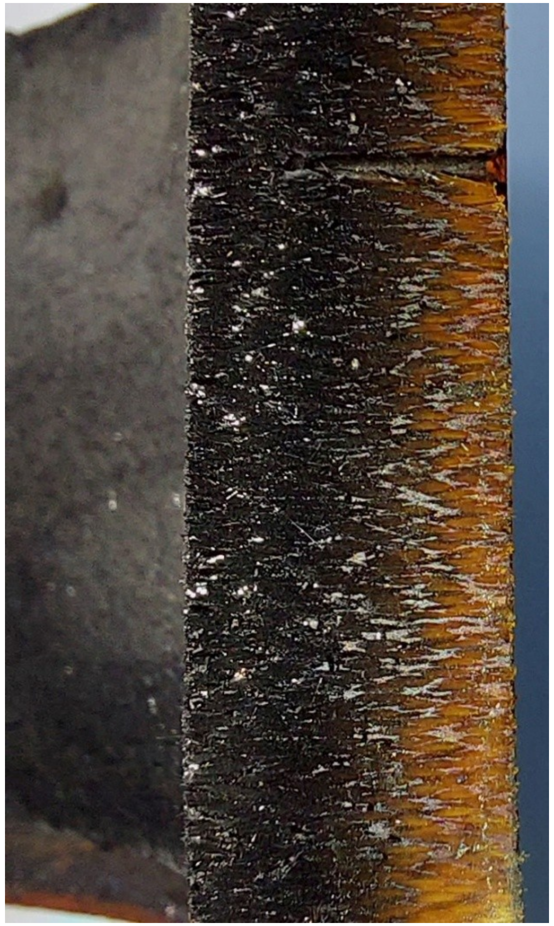
Backup liners



Cotton/phenolic

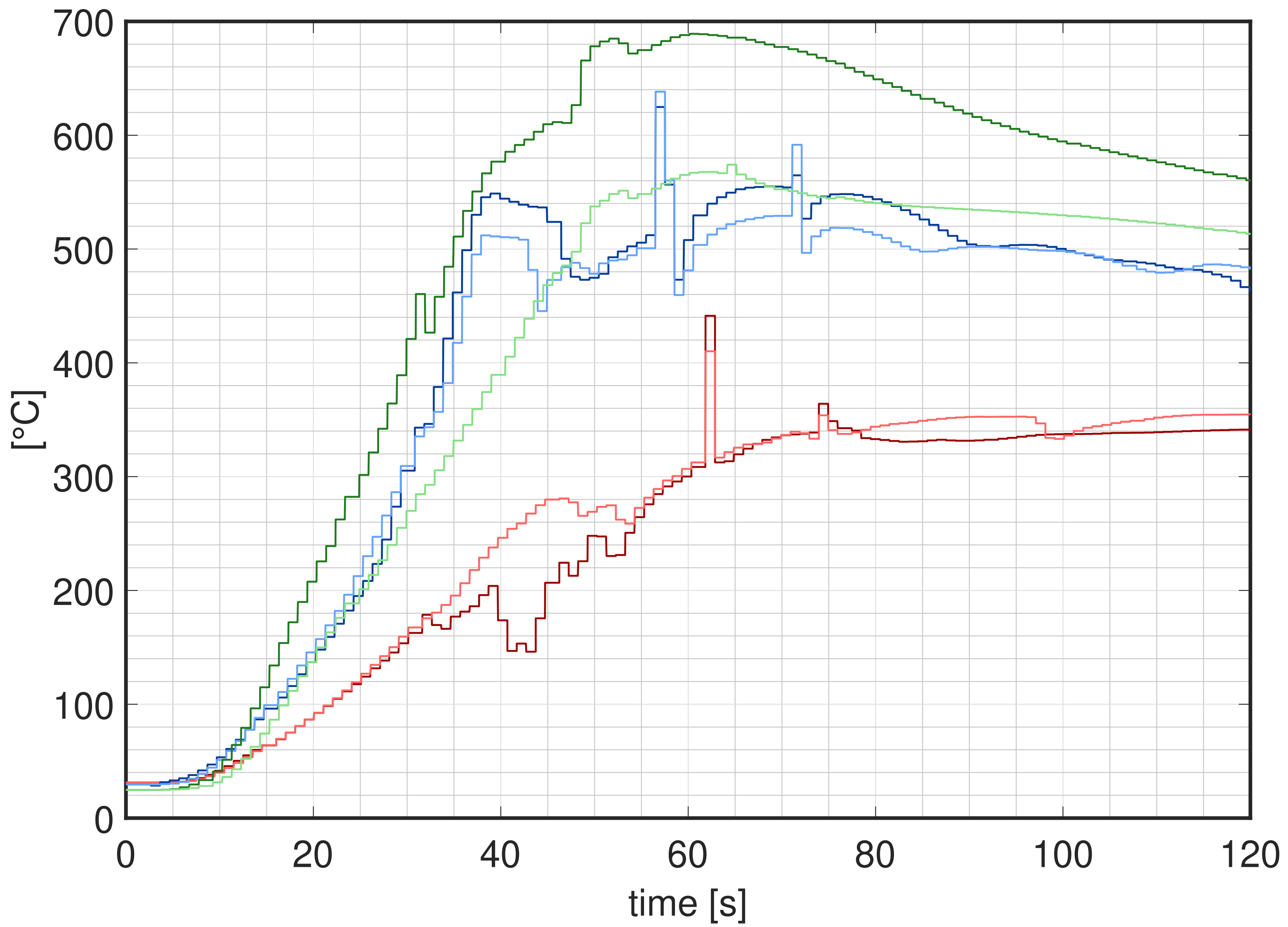


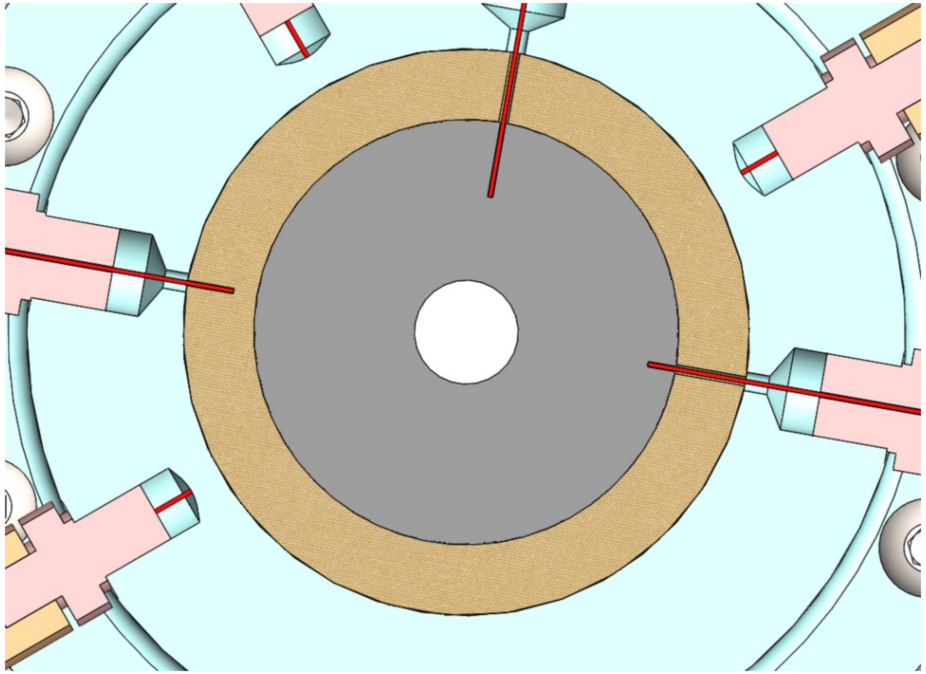
Glass/phenolic



Silica/phenolic

Backup liners



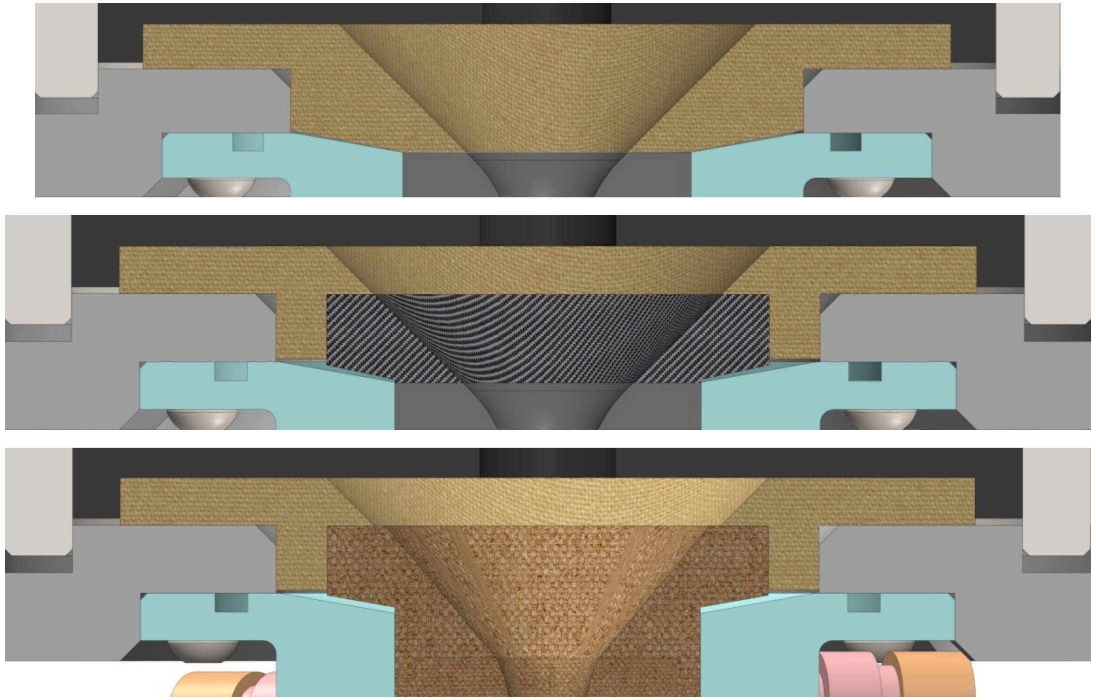


onvergent inserts

Cotton/ phenolic

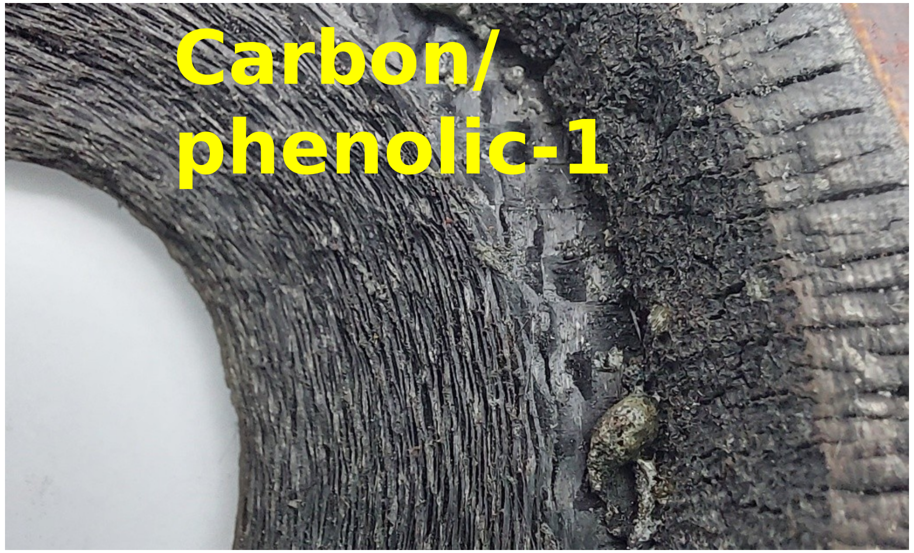
Carbon/ phenolic-1/2

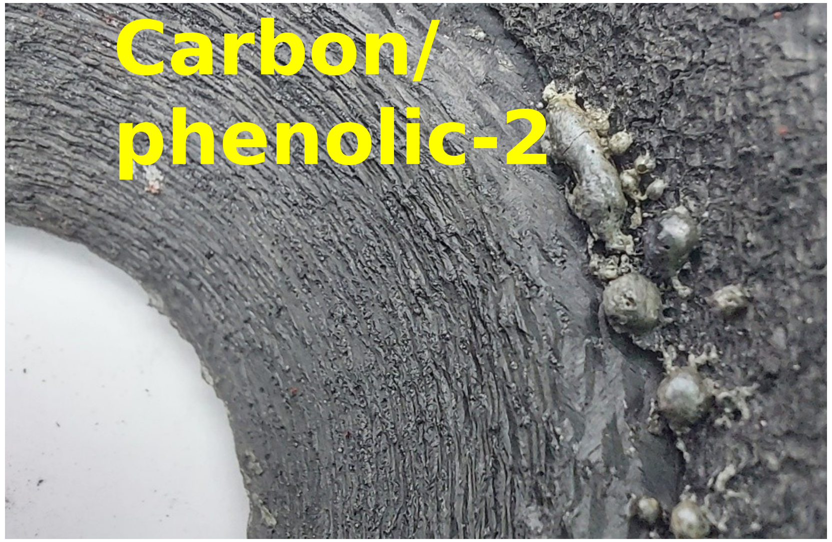
Silica/ phenolic



	Test ID from the test matrix			
Test results	-	-	019	024
Material type	Cotton/ph	Carbon/ph-1	Carbon/ph-2	Silica/ph
P_{cc} objective [bar]	$\simeq 20$	$\simeq 20$	$\simeq 20$	$\simeq 20$
O/F average	-	-	6.40	7.95
$\dot{r}_{th}$ average [mm/s]	0.34	0.12	0.079	0.075

onvergent inserts





Outline

Conclusions

- There could be large differences between the erosion performances of different graphite grades. The most important parameters that should be compared are the density, grain size, pore size, flexural strength, and thermal conductivity.
- Graphite has good performances considering also its low cost but are very sensitive to the mixture ratio of the engine. It could be more convenient to work with fuel rich mixtures because of the benefits on the erosion behavior of graphite.
- Commercial carbon/carbon materials exhibit low erosion performances so their use in the throat region should be avoided.
- Glassy-carbon and Tungsten have booth an acceptable erosion rate but have a much higher cost compared to graphite.
- Silica/phenolic is the best phenolic-based composite for the hybrid rocket motor environment. Its main cause of erosion are the shear stresses of the combustion gases so its use should be limited to the converging region or in general to areas with lower shear stresses.

Thank you for your time! Any questions?