Testing of DLR C/C-SiC for HIFiRE 8 Scramjet Combustor

David E. Glass and Diego P. Capriotti
NASA Langley Research Center
Hampton, VA USA

Thomas Reimer and Marius Kütemeyer
German Aerospace Center
Stuttgart, Germany

and

Michael Smart
University of Queensland
Brisbane, Australia

Outline

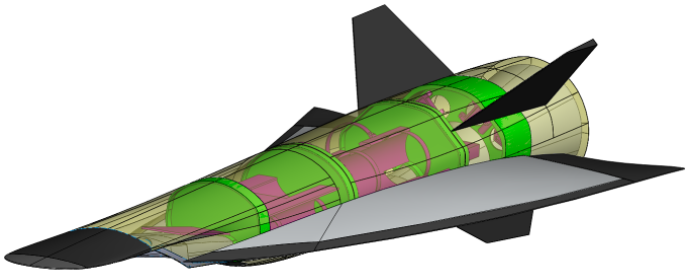
- **Introduction**
  - HiFIRE 8
  - DCR
- **Test**
- **Post-test SEM investigations**
- **Concluding remarks**

HIFiRE Program

Australian Government
Department of Defence
Defence Science and Technology Organisation

"The main goal of the HIFiRE Program is to develop the technology for sustained flight at Mach 8"

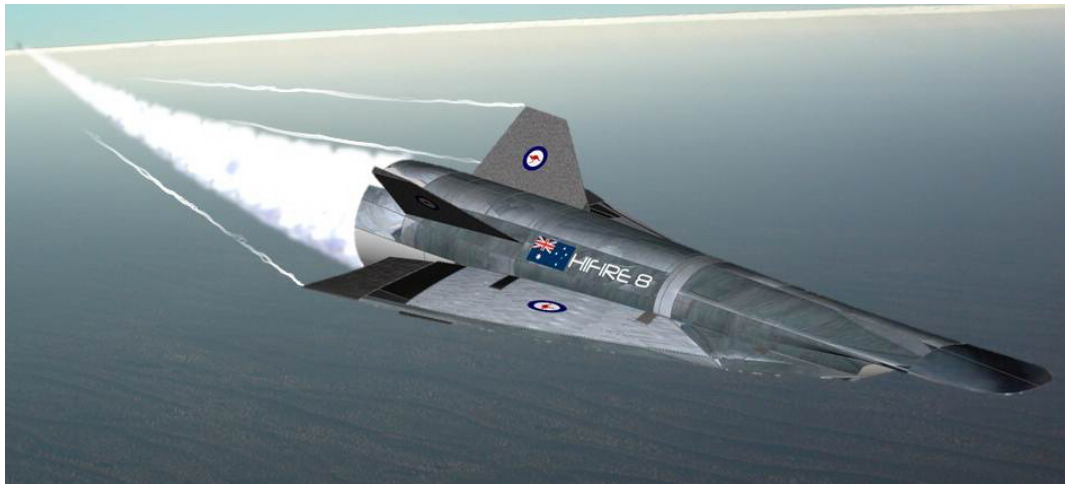
- **Jointly run by DSTO and the US Air Force**
- **Sounding rocket based launch**
- **9 flights over 5 years (first flight was in March 2009 – HIFiRE 0)**
- **Combination of fundamental hypersonic flow experiments and scramjet flights**
- ***Culminating in a sustained flight (30 second engine operation) of an autonomous vehicle - HIFiRE 8.***



HIFiRE 8

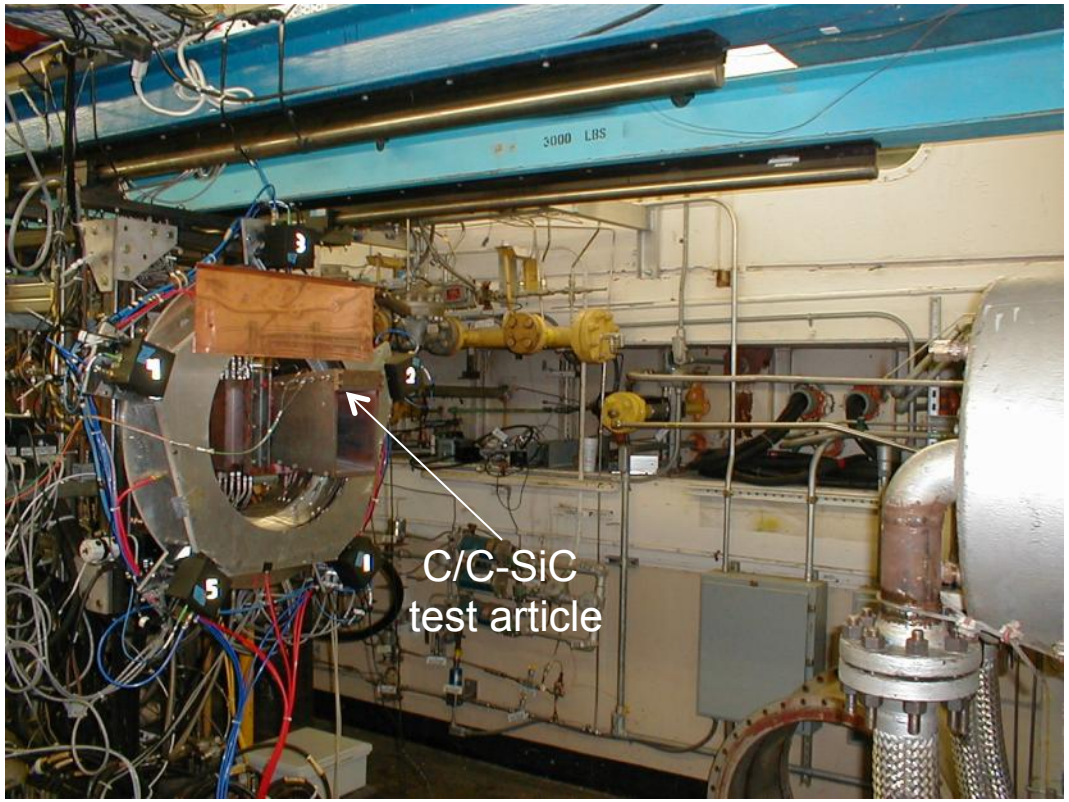
Motivation for CMC Panel Test

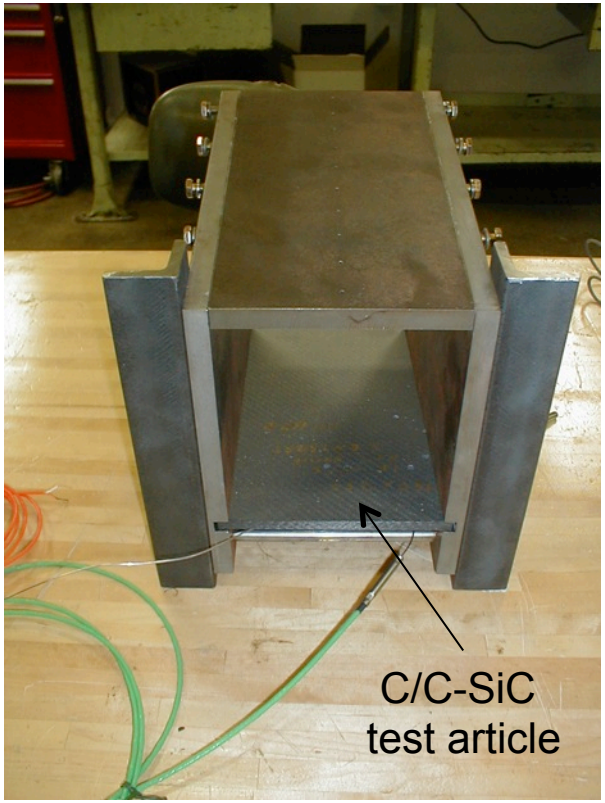
- **HIFiRE 8 Objective is to demonstrate 30 seconds of horizontal scramjet powered flight at Mach 7 and 1000 psf (55 kPa) dynamic pressure.**
- **Desire to avoid the complexity, weight, and cost of an actively cooled combustor.**
- **Decision made to examine the possibility of un-cooled CMC combustor.**
- **DLR C/C-SiC fins flying on other HIFiRE flights.**
- ***Decided to evaluate the performance of the DLR C/C-SiC (also C/C) at scramjet combustor conditions.***



Durable Combustor Rig (DCR)

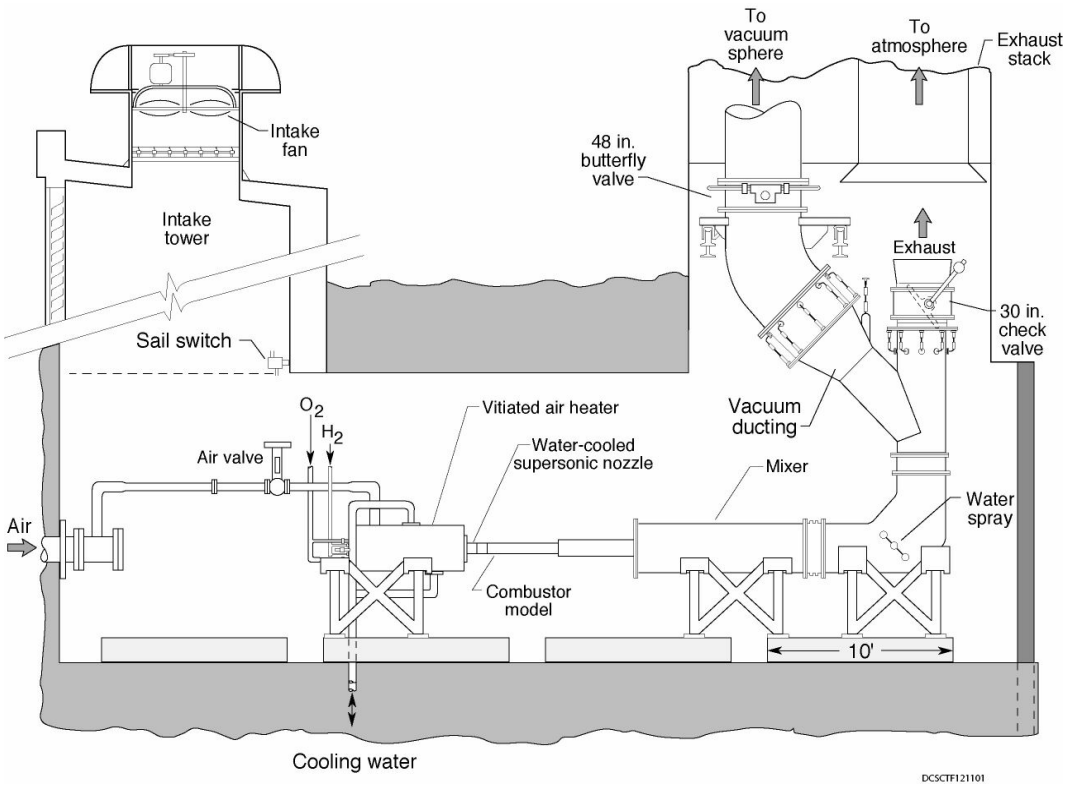
- **Simulated Mach 6 conditions**
  - Actual flow velocity ~ Mach 2
- **q = 1000 psf (479 hPa)**
- **H = 793 Btu/lb (1.846 MJ/kg)**
- **Hydrogen fuel**





Direct Connect Supersonic Combustion Test Facility (DCSCTF)

- **Simple, older facility used for basic testing of scramjet combustors**
  - Mixing of a combusting fuel stream with the hot test gas
- **H_2/Air/O_2 combustion heated, wet (contains water) test gas**
- **M_∞ = 3.5 to 7.5 by varying H_2/Air/O_2**
- **Match total enthalpy, test gas O_2 content, $P_{isolator}$**
- **16 x 16 x 52-foot ventilated test cell (4.87 x 4.87 x 15.85 m)**

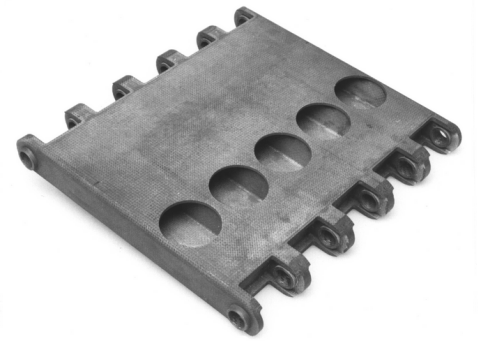


Simulated Flight Mach Number (at 1000 psf 478 hPa)	Facility Total Pressure (psia)	Facility Total Temperature (°R)	Facility Total Enthalpy (BTU/lb_m)	Facility Nozzle Exit Mach number	Facility Nozzle Exit Pressure (psia)	Facility Mass Flow Rate (lb_m/s)	Test gas water mole fraction
5	94.8 (6.53 bar)	2103 (895°C)	574 (1.34 MJ/kg)	2.12	10.0 (690 hPa)	8.08 (3.7 kg/s)	12.7
6	91.4 (6.3 bar)	2721 (1238°C)	793 (1.85 MJ/kg)	2.10	10.0 (690 hPa)	6.73 (3.1 kg/s)	18.5

Outline

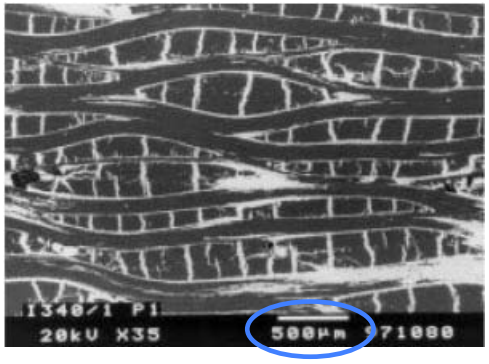
- Introduction
- Test
- Post-test SEM investigations
- Concluding remarks

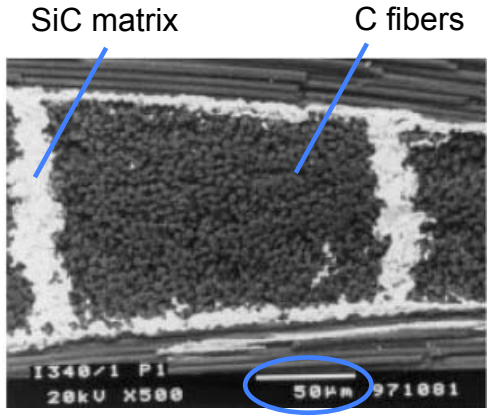
DLR C/C-SiC



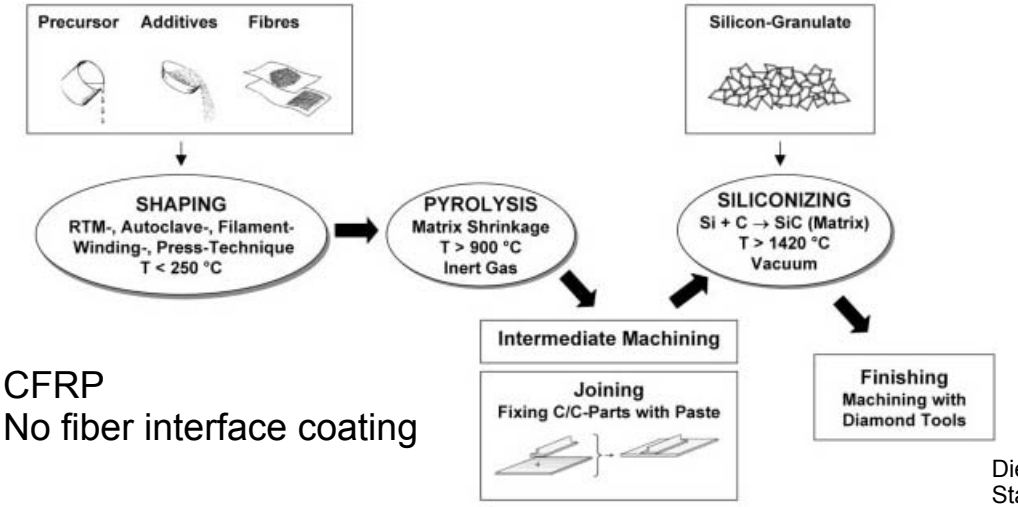
- **Under development since the 1980's**

HYTEX	National hypersonic technology program. Development of a C/C-SiC intake ramp
CETEX	Manufacture of a C/C-SiC thermal protection system for the reentry capsule Express
Hot structures	Technology program for the development of joining technologies for fibre reinforced ceramics
FESTIP	Development of a C/C-SiC thermal protection system for a single-stage space vehicle
TETRA	Development of a thermally extremely loaded (T_{max} = 3272°F, 1800°C) C/C-SiC nose cap for the NASA experimental space craft X-38
FOTON	Development and reentry test of a new concept of a C/C-SiC thermal protection system for spacecraft
SHEFEX	Development of an extremely loaded (T_{max} = 3452°F, 1900°C), cost efficient thermal protection system on the basis of flat C/C-SiC panels
EXPERT	Development of a C/C-SiC nose cap (current project)





SEM of 3002°F (1650°C) heat treatment C/C-SiC



- CFRP
- No fiber interface coating

LSI (liquid silicon infiltration) process for C/C-SiC

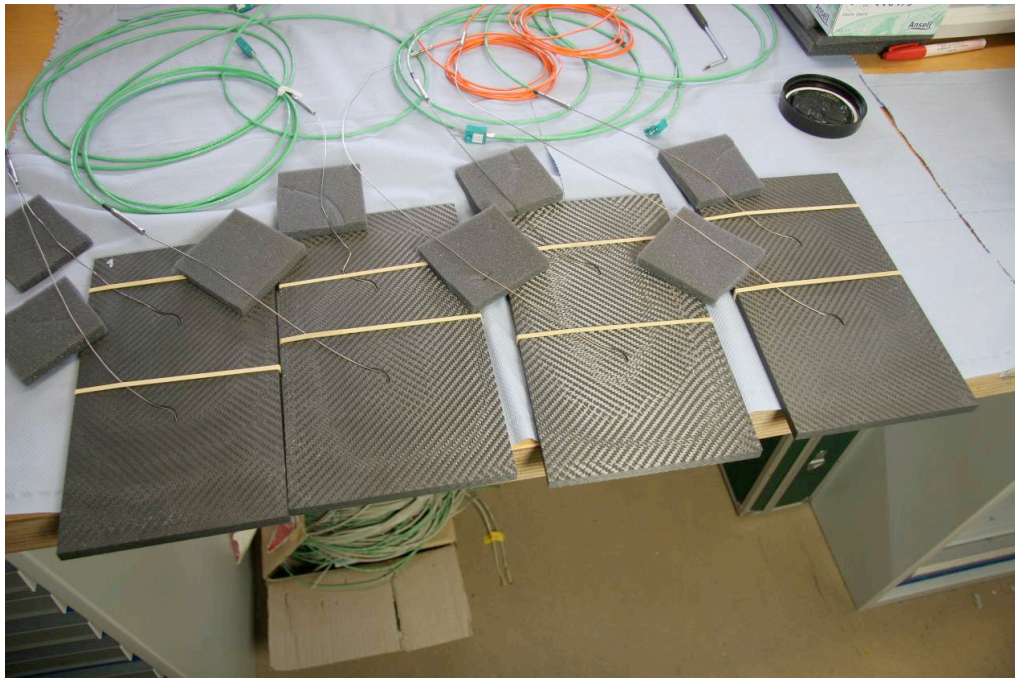
Dieter Jacob, editor, et al., "Basic Research and Technologies for Two-Stage-To-Orbit Vehicles", Final Report of the Collaborative Research Centres 253, 255, and 259, Wiley-VCH Verlag GmbH & Co. KGaA, 2005.

Test Panels

- **Size: 254 mm x 145 mm x 8 mm**
- **Mass: ~ 550 g**
- **Instrumentation**
  - Embedded TC's
  - 2 mm below the cool surface (6 mm below hot surface)

Panel No.	Type K	Type S	Test load level
1	1	1	medium/ high
2	2	0	low
3	1	1	medium/high
4	1	1	spare

Not tested



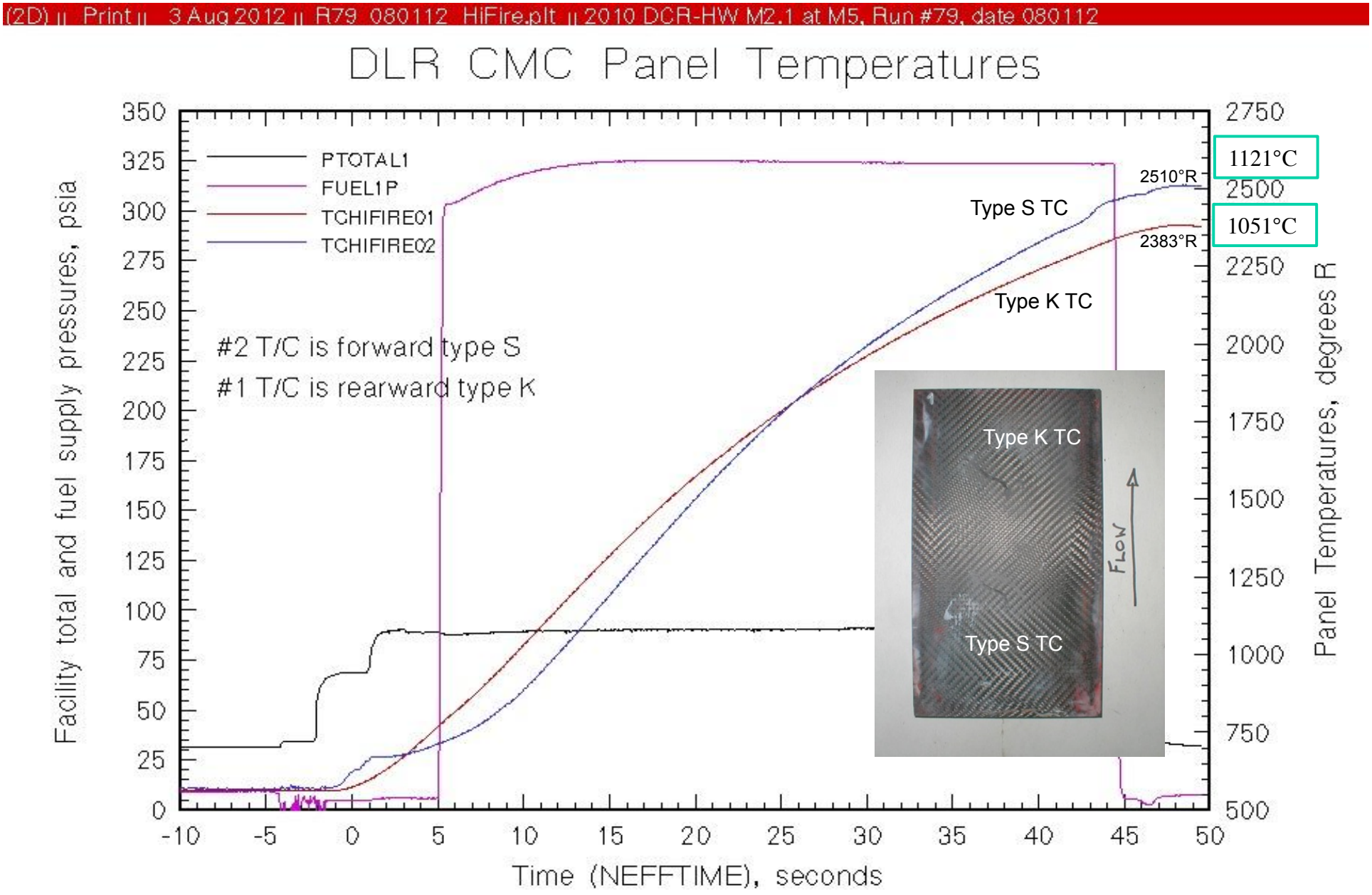
Test Matrix

Panel	Run No.	Simulated Flight Mach No.	Temperature at end of Test, °R		P_0	T_0	ER	ER	Fuel-on Time [sec]	Total Test Duration [sec]
			Type K	Type S	[psia]	[°R]	(ramp + film)	(S3)		
C/C HP635-7	68	5	859	858	96.1	2131			n/a	20
	69	5	1507	1450	96.1	2117	0.556		35	40
	70	5	1611	1548	95.9	2130	0.741		35	40
	71	6	1002	1031	89.4	2546			n/a	20
	72	6	1878	1796	91.8	2611	0.986		40	45
	73	6	1026	1015	88.8	2558			n/a	20
	74	6	1987	1800	91.6	2594	1.003		39	44
	75	6	2051	1835	90.8	2626	1.023		39	44
C/C-SiC #4	52	5	1005	972	92	1939			n/a	20
	53	5	1248	1193	91.6	1957			n/a	40
	54	5	997	971	91.8	1989			n/a	20
	55	5	1214	1329	92.6	2020	0.53		14	20
	56	5	1044	1062	94.2	2035			n/a	20
	57	5	1737	1834	94.5	2070	0.58		32.5	38.5
	58	5	1076	1087	94.2	2070			n/a	20
	59	5	1319	1421	93.7	2073	0.53	0.36	13/5*	20
	60	5	1010	999	94.6	2059			n/a	20
	61	5	2126	2142	95.3	2063	0.52	0.32	29.5/19.5*	39.5
C/C-SiC #3	62	6	1281	1291	90.6	2624			n/a	20
	63	6	1295	1319	90.7	2647			n/a	20
	64	6	2025	2206	90.6	2648	1.01		30	40
C/C-SiC #1	76	6	1382	1317	89.6	2591			n/a	20
	77	6	2352	2515	91.9	2599	1.009		39	44
	78	6	2342	2504	91.2	2639	1.039		39.5	44.5
	79	6	2336	2462	91.9	2654	1.047		39.5	44.5

C/C-SiC Panel #1, Tests 76-79

- **Insulation added to back surface to increase hot-surface temperature**
  - Zirconia felt, type ZYF-100, 4 layers, 0.1” each
  - ~350°F higher TC reading than with no insulation
  - No significant erosion from the 3 fueled tests (3 x 44 sec)
- **Mach 6**
  - Enthalpy, H_{t0} = 793 Btu/lb_m
  - Dynamic pressure, q = 1000 psf
  - Fuel injectors 24” upstream of C/C-SiC leading edge
- **RTV used to seal panel**
  - High temperature silicone sealant
  - T_{max} ~ 650°F
  - Overheated and burned

Panel Temperatures (Run 79)



Carbon Steel Fixture After Panel #1 Tests

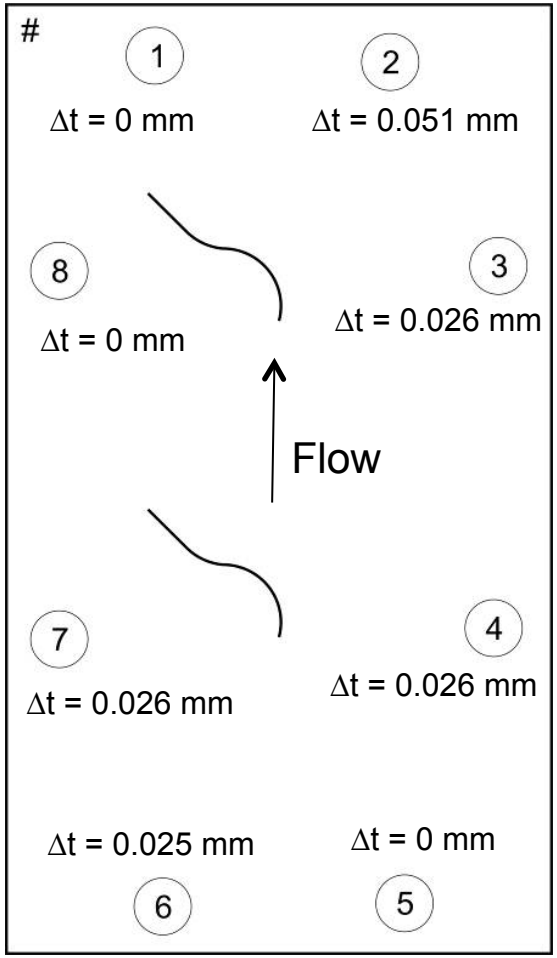
- **Steel sidewalls melted and metal can be seen exiting the duct during video**

Fixture with panel removed

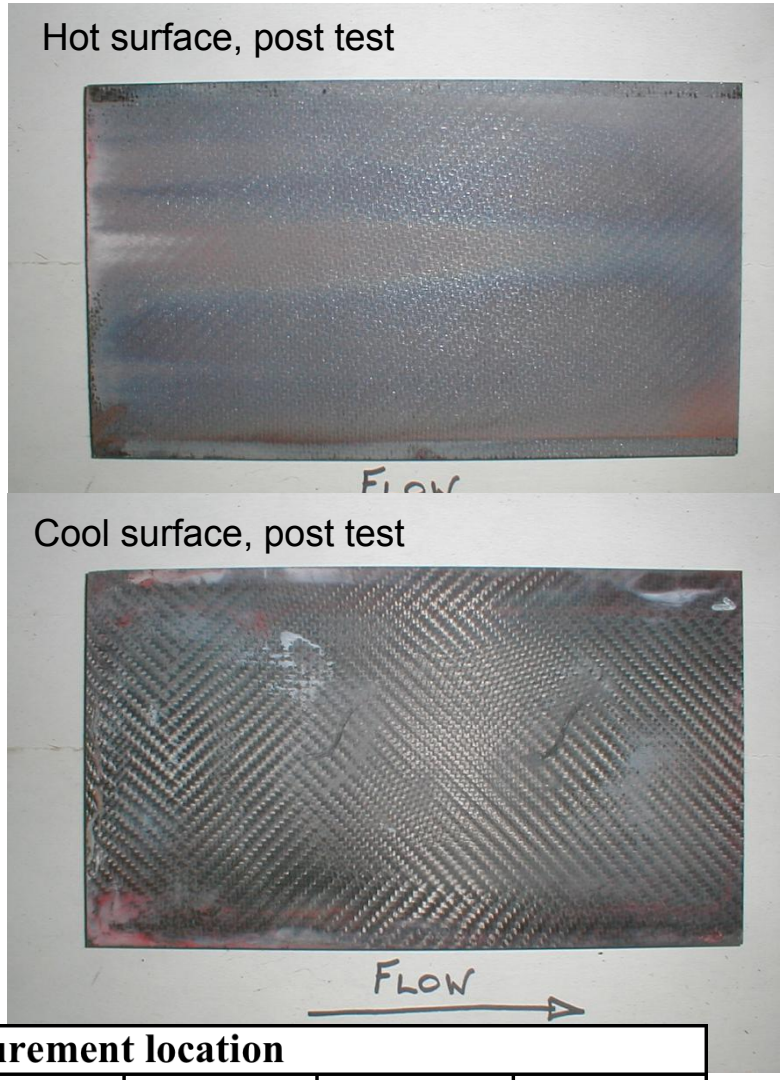
Melted carbon steel sidewalls. Slot for panel shown.

C/C-SiC Panel #1 Post Test

- **4 tests**
- **M ~ 6 enthalpy**
- **20 sec tare (no fuel)**
- **3 x 44 sec fueled tests**

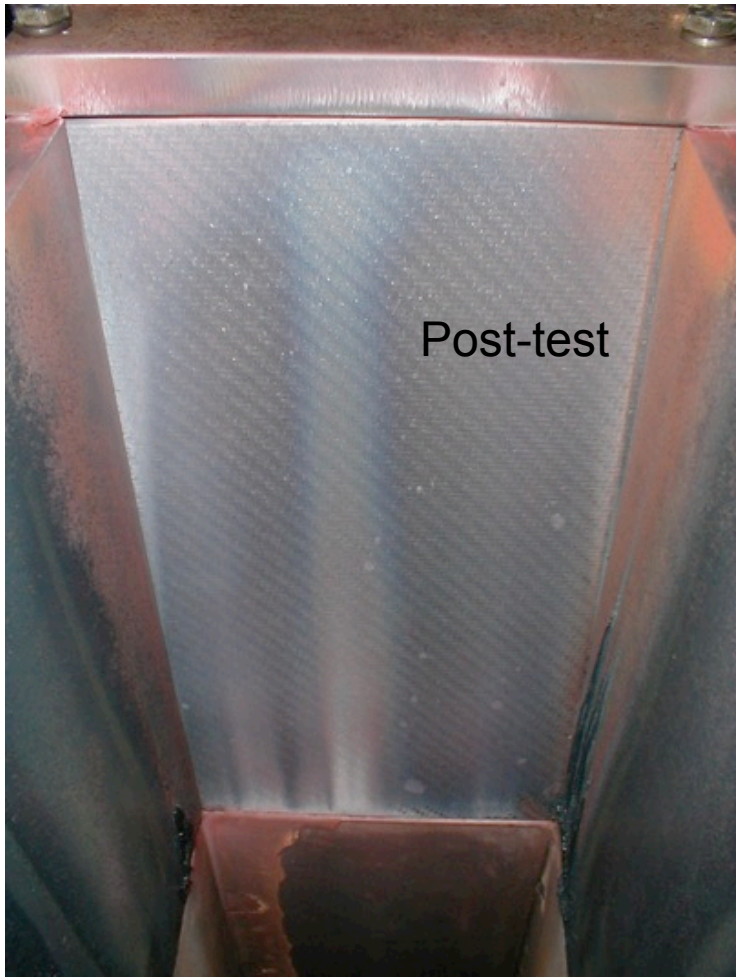


Locations for thickness measurements, ~ 0.003" uncertainty



	Thickness (mm) / Measurement location							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Pre-test	8.026	8.052	8.052	8.103	8.306	8.280	8.052	8.052
Post-test	8.026	8.001	8.026	8.077	8.306	8.255	8.026	8.052

Pre- and Post-Test 79 Photographs



Discoloration due to melting
of carbon steel fixturing

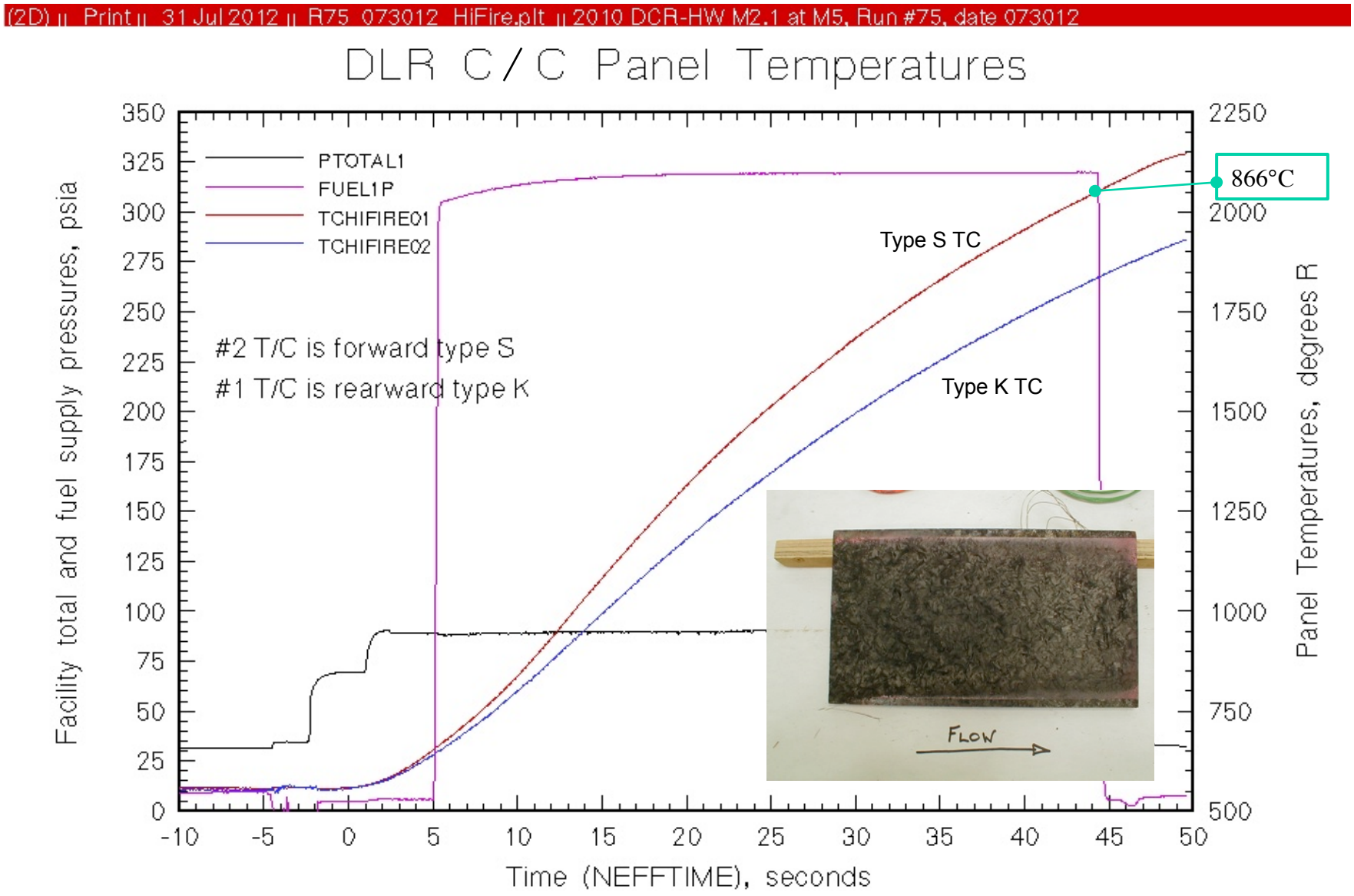
C/C-SiC Panel #1, Run 79

Insert movie here

Test Matrix

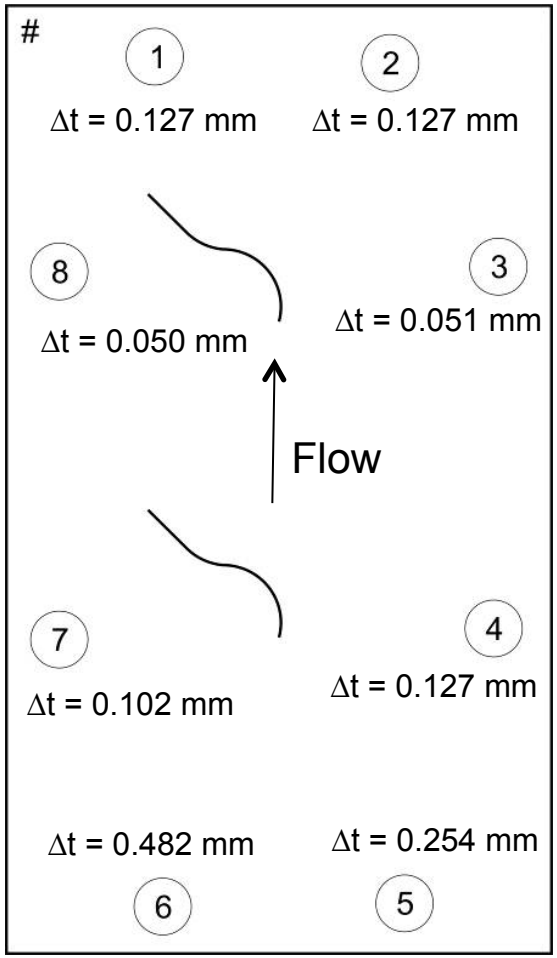
Panel	Run No.	Simulated Flight Mach No.	Temperature at end of Test, °R		P_0	T_0	ER	ER	Fuel-on Time [sec]	Total Test Duration [sec]
			Type K	Type S	[psia]	[°R]	(ramp + film)	(S3)		
C/C HP635-7	68	5	859	858	96.1	2131			n/a	20
	69	5	1507	1450	96.1	2117	0.556		35	40
	70	5	1611	1548	95.9	2130	0.741		35	40
	71	6	1002	1031	89.4	2546			n/a	20
	72	6	1878	1796	91.8	2611	0.986		40	45
	73	6	1026	1015	88.8	2558			n/a	20
	74	6	1987	1800	91.6	2594	1.003		39	44
	75	6	2051	1835	90.8	2626	1.023		39	44
C/C-SiC #4	52	5	1005	972	92	1939			n/a	20
	53	5	1248	1193	91.6	1957			n/a	40
	54	5	997	971	91.8	1989			n/a	20
	55	5	1214	1329	92.6	2020	0.53		14	20
	56	5	1044	1062	94.2	2035			n/a	20
	57	5	1737	1834	94.5	2070	0.58		32.5	38.5
	58	5	1076	1087	94.2	2070			n/a	20
	59	5	1319	1421	93.7	2073	0.53	0.36	13/5*	20
	60	5	1010	999	94.6	2059			n/a	20
	61	5	2126	2142	95.3	2063	0.52	0.32	29.5/19.5*	39.5
C/C-SiC #3	62	6	1281	1291	90.6	2624			n/a	20
	63	6	1295	1319	90.7	2647			n/a	20
	64	6	2025	2206	90.6	2648	1.01		30	40
C/C-SiC #1	76	6	1382	1317	89.6	2591			n/a	20
	77	6	2352	2515	91.9	2599	1.009		39	44
	78	6	2342	2504	91.2	2639	1.039		39.5	44.5
	79	6	2336	2462	91.9	2654	1.047		39.5	44.5

C/C Panel Temperatures, Run 75



C/C Panel Test Post Test

- 100 sec, M ~ 5 conditions
- 193 sec, M ~ 6 conditions



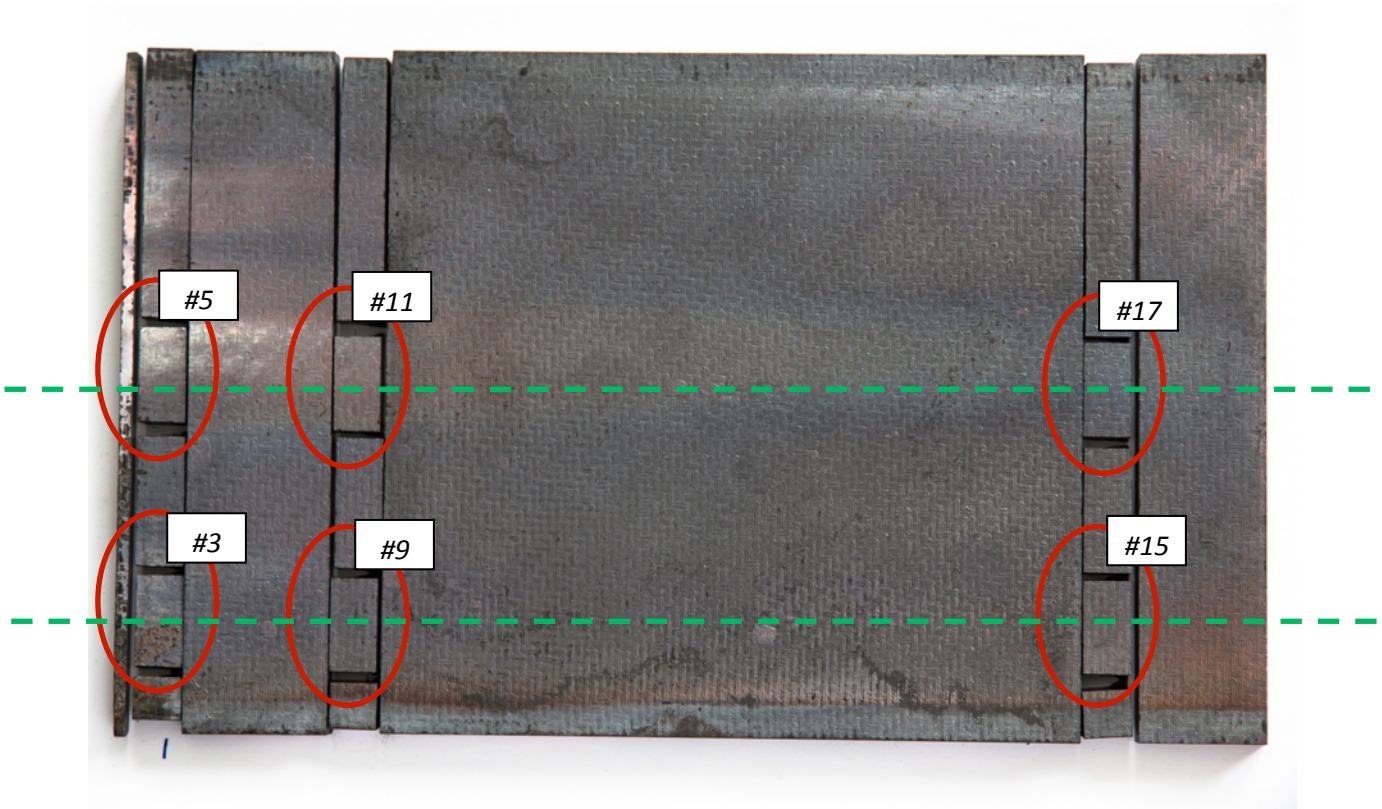
	Thickness (mm) / Measurement location							
	1	2	3	4	5	6	7	8
Pre-test	10.008	10.008	10.008	10.008	10.084	10.109	9.957	9.931
Post-test	9.881	9.881	9.957	9.881	9.830	9.627	9.855	9.881

Outline

- Introduction
- Test
- Post-test SEM investigations
- Concluding remarks

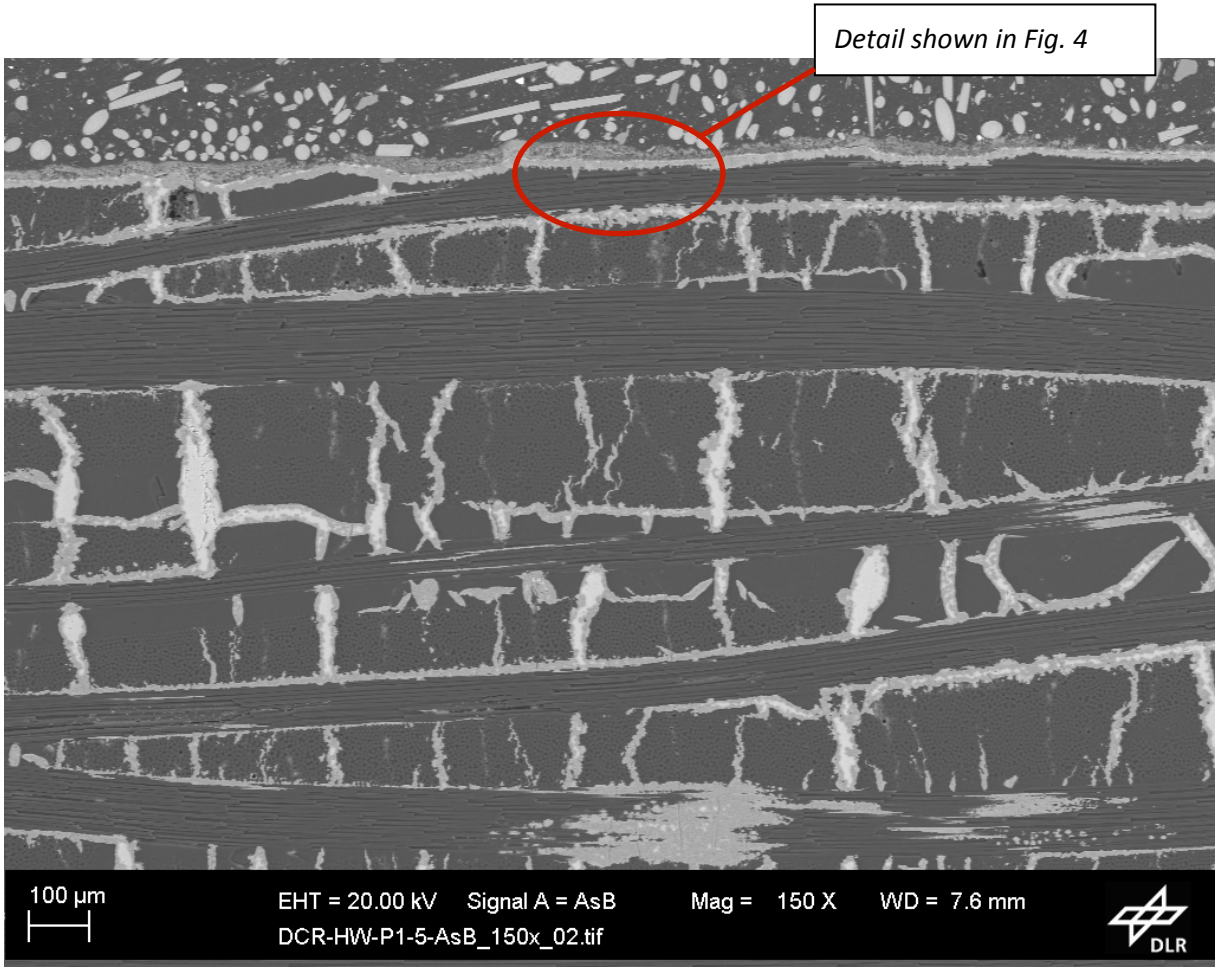
Post-Test SEM Investigations

- SEM investigations done at DLR with C/C-SiC panels
- Results shown for panel 1 centerline samples #5 and #17



Post-Test SEM Investigations

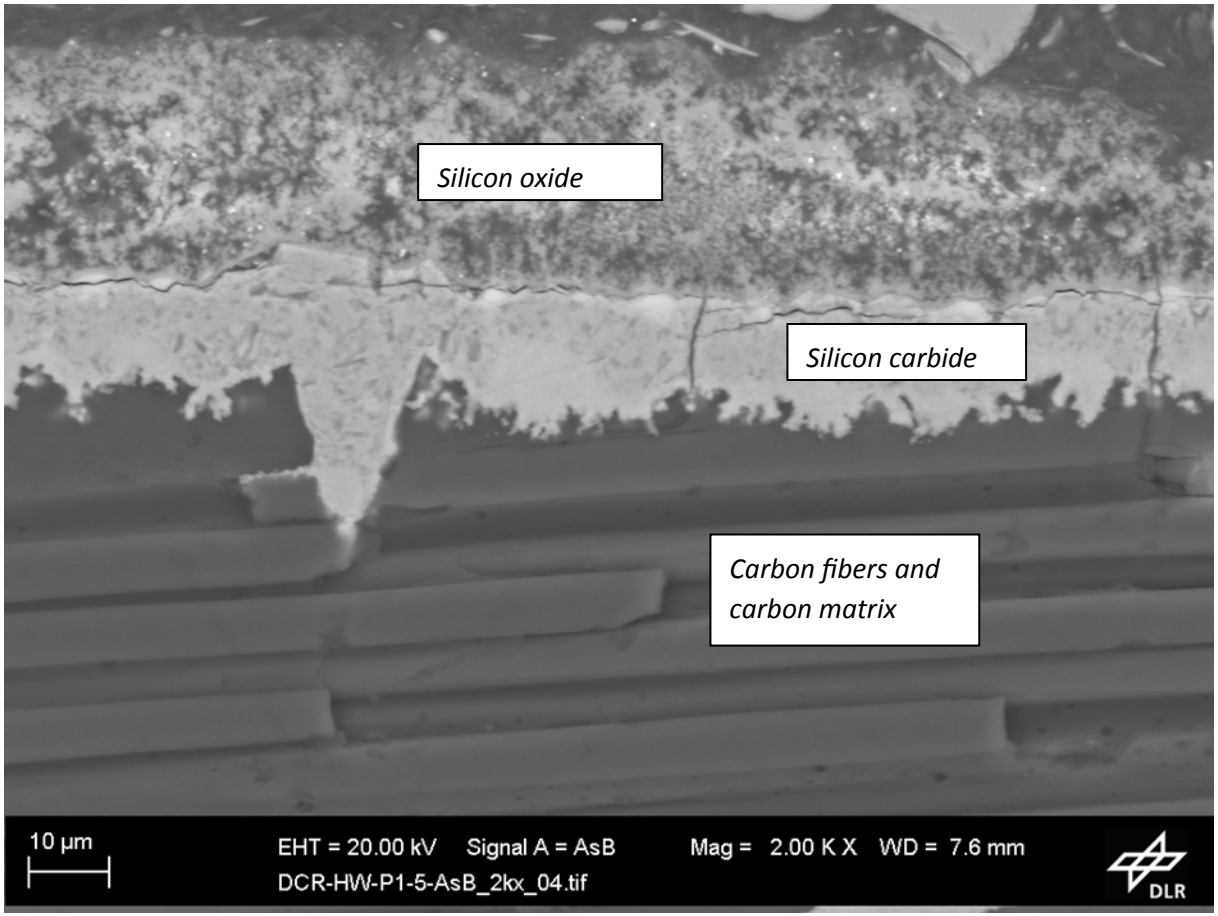
- SiO2 layer on top of the sample
- No other signs of oxidation or erosion



Sample # 5

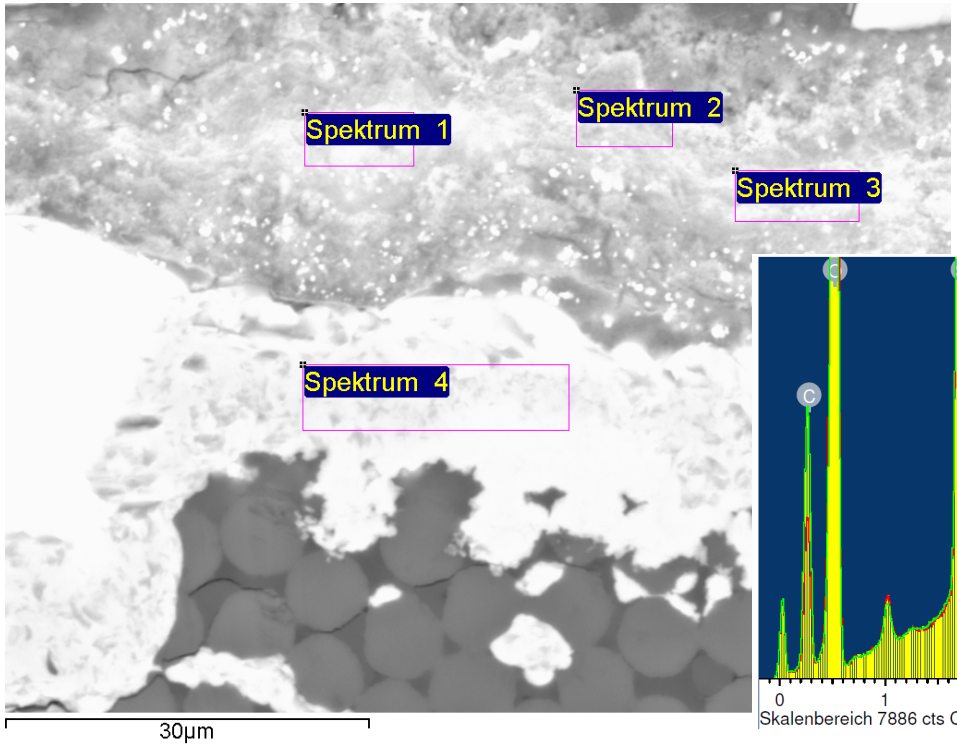
Post-Test SEM Investigations

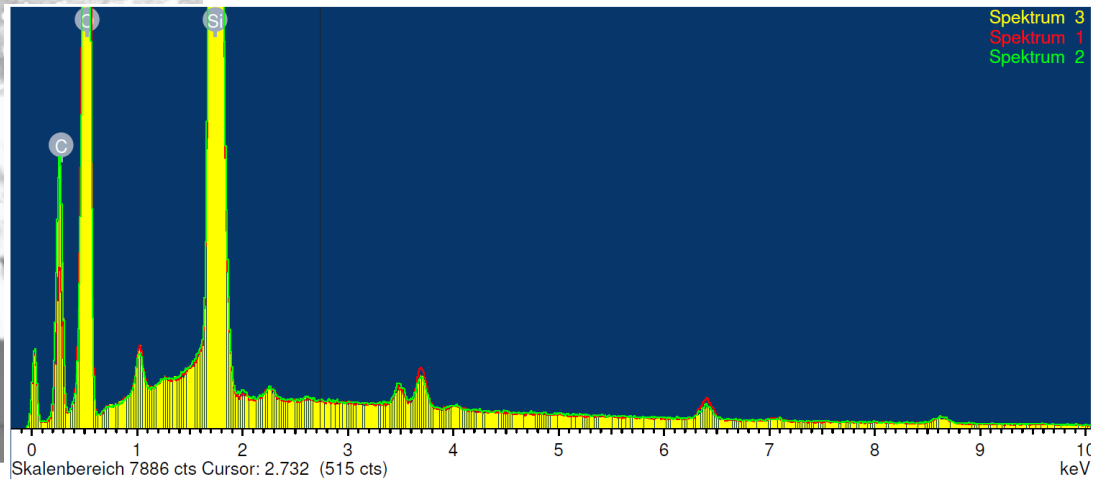
- **EDX analysis to confirm constitution of the top layer**



Post-Test SEM Investigations

- **EDX analysis to confirm constitution of the top layer**





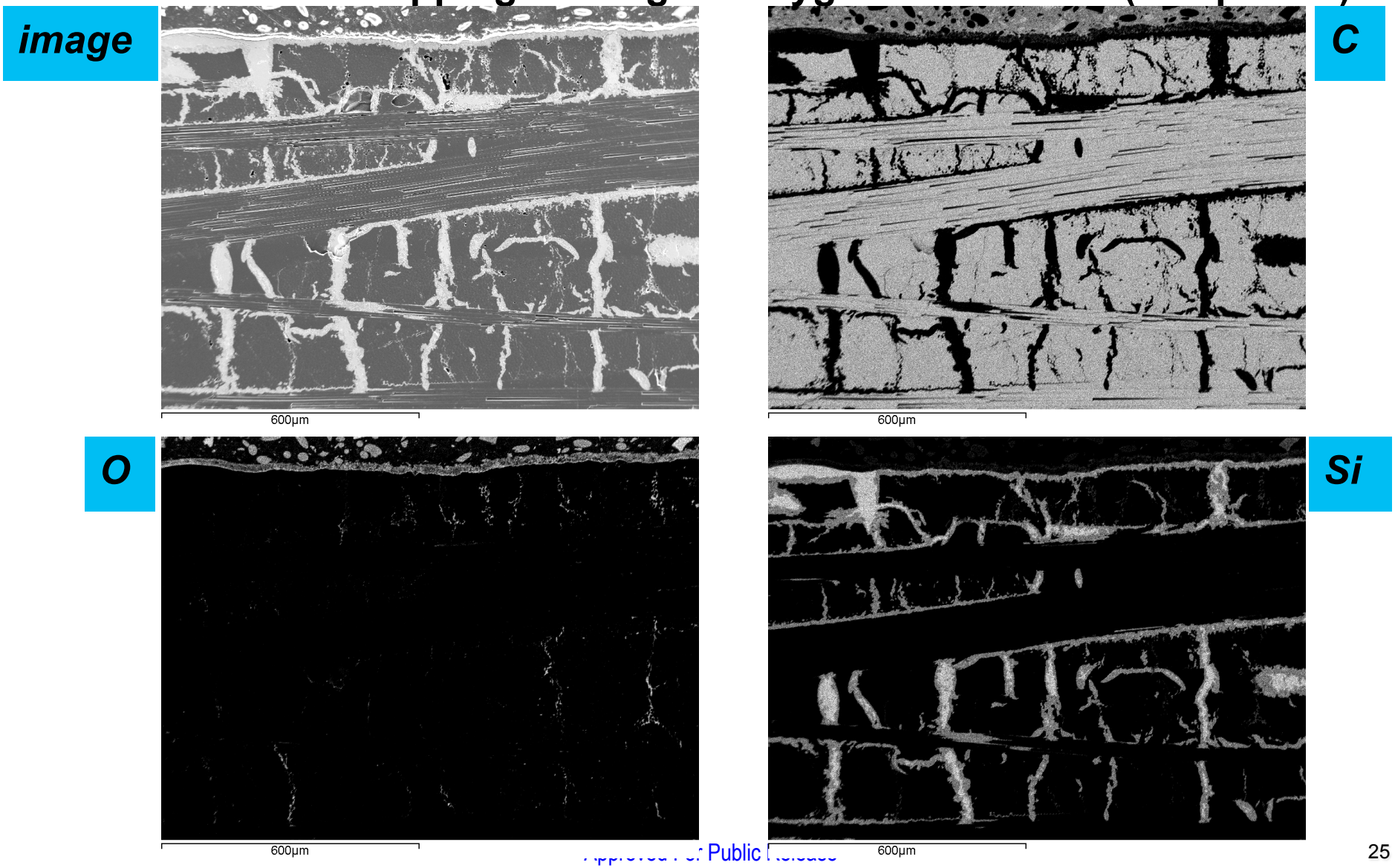
Prozessoption: Alle Elemente analysiert (Normalisiert)

Spektrum	In Stat...	C	O	Si	P	In	Sn
Spektrum 1	Ja	28.98	51.82	19.20			
Spektrum 2	Ja	39.13	43.54	17.34			
Spektrum 3	Ja	37.52	46.24	16.25			
Spektrum 4	Ja	50.40	0.88	48.10	0.10	0.18	0.35
Max.		50.40	51.82	48.10	0.10	0.18	0.35
Min.		28.98	0.88	16.25	0.10	0.18	0.35

Alle Resultate in Atom%

Post-Test SEM Investigations

- EDX element mapping looking for oxygen distribution (sample # 5)



Outline

- Introduction
- Test
- Post-test SEM investigations
- Concluding remarks

Concluding Remarks

- **DCR performed very well**
  - Has since been mothballed
- **DLR C/C-SiC**
  - Performed very well with very little erosion
  - Tested at M ~ 6 flight conditions for several minutes
  - Flight is M ~ 7, ~ 30 sec.
  - SEM investigations show little effect of oxidation
  - Mass loss and thickness reduction negligible
- **Overall Conclusion**
  - Under the given conditions the performance was excellent
  - Being considered for flight vehicle