Table 1: DLR consortium – approach to manufacturing, for various functional layers in the m-SOFC (MSC)

Functional Layer	Composition	Thickness (micron)	Fabrication route
Substrate	Fe-26Cr-Mn, Mo, Ti, Y_2O_3	950-1050	Powder Metallurgy
DBL	$La_{0.6}Sr_{0.2}Ca_{0.2}CrO_3$, LSM	10-30, 2-3 respectively	Air Plasma Spray (APS); PVD
Anode	NiO-YSZ (1:1 Vol ratio)	40-60	Air Plasma Spray (APS)
Electrolyte	8-YSZ	35-50	VPS, LPPS (vacuum PS, low pressure PS)
Cathode	LSM, LSCF	20-30	APS, Suspension PS, Colloidal Spray

Table 2: Comparison of current densities (at 0.7 V) of single cells – ASC and MSCs, under similar conditions

Temperature	Standard ASC (A/cm^2)	ASC under MSC conditions (A/cm^2)	MSC (A/cm^2)
800° C	1.95 ± 0.19	1.19 ± 0.07	0.76
750° C	1.56 ± 0.13	1.04 ± 0.04	0.68
700° C	1.08 ± 0.09	0.79 ± 0.01	0.63
650° C	0.63 ± 0.07	0.55 ± 0.02	0.48

Table 3[6]: Metal Support Options
Summary of candidate support metals

Metal	CTE (ppm/K)	Cost ($/kg, 2009)	Relative Oxidation Resistance
NiCrAlY	15-16	63	Excellent
Hastelloy-X	15.5-16	22	Excellent
Ni	16.5	18	None[a]
Ni-Fe (1:1)	13.7	9	None[a]
300-Series SS	18-20	2	Poor
400-Series SS	10-12	2	Very Good

Note that CTE of electrolytes (YSZ, CGO, LSGM) are 10-12 ppm/K
[a], Readily oxidizes in air or during cooling in fuel

Table 4: Composition and Properties of Crofer®22 H[28]
Summary – specially designed steel Crofer® **22H**

○ **23% Cr for**	Good Oxidation Resistance
	Low CTE
○ **0.5% Mn addition for**	Limitation of Cr evaporation
	Low contact resistance
○ **0.1% La for improved**	Oxide scale adherence
	Oxide resistance
○ **≤ 0.05% Al for**	Low oxidation rates
○ **0.5% Nb for**	High creep strength
○ **2% W for**	High creep strength
	Low CTE
○ **0.2% Si for**	Low oxidation rates together with Nb
	High creep strength
+ good workability → Ideally suited construction materials for ICs in SOFC systems	

Table 5: Crofer®22 H in comparison to other alloys[28]

	Cr	C	N	Mn	Si	Al	W	Nb	Ti	La
Crofer® 22 APU	23	0.004	0.004	0.45	<0.05	<0.05	-	-	0.06	0.1
Crofer® 22H*	23	0.007	0.02	0.45	0.25	<0.05	2	0.5	0.06	0.1
Fe 22Cr 2W 0.5Nb 0.2Si**	23	0.002	0.007	0.43	0.24	<0.05	2	0.5	0.06	0.1
In wt. - %, Fe balance, S ≤ 0.002										
*, typical values of commercial melts										
**, analysis of a 10 kg laboratory melt										

Table 6: Data compiled by Molin et al.[39] regarding CTE of 3 systems studied

Chemical composition (weight %) and thermal expansion coefficient (ppm/K) of materials used in this study.

	Structure	TEC (CTE)	Cr	Ni	Mn	Mo	Si	Fe
317[a]	**Austenitic**	19.0	18.27	11.87	0.12	3.04	0.85	balance
430L[b]	**Ferritic**	11.5	16-18	-	<1.0	<0.5	<1.0	balance
PI 600[a]	**Austenitic**	13.3	15.56	74.12	0.05	-	0.84	9.11
[a], Specified by the manufacturer – AMETEK Specialty Metal products								
[b], Typical range of compositions								

Table 7: Composition Ranges of IN625 alloy (Inconel 625) [42]

Element	Ni	Cr	Fe	Mo	Nb	Mn	Si	Al	Ti	Co
Amount by specification (wt %)	>58	20-23	<5	8-10	3.15-4.15	<0.5	<0.5	<0.4	<0.4	<1
Determined by EDS (wt%)	64.4	20.1	2.4	8.1	3	0.6	0.5	-	-	-

Table 8: Comparative Study of PLD vs Suspension Plasma Spray (Thermal Spray)[46]

Summary of materials, structures, and processing methods for Cell #1 and Cell #2

Components	Substrate	Anode	Electrolyte	Cathode
Cell #1				
Material	SS430	NiO-SDC	ScSZ/ SDC	SSCo-SDC
Processing		Screen Printing	PLD[a]	Screen Printing
Thickness		90 micron	2/20 micron	25 micron
Cell #2				
Material	Hastelloy X	Ni-SDC	SDC	SSCo-SDC
Processing		SPS[b]	SPS	Screen Printing
Thickness		30 micron	30 micron	45 micron

Table 9: Typical Plasma Spray process conditions used by Kesler et al.[55]

Plasma spraying parameter values

Parameter	Cathode	Electrolyte	Anode
Feedstock	48.2%wt LSM/ YSZ bal.	23.7 wt% YSZ aq. suspension	46% wt NiO/ 38% wt YSZ/ 16 wt% Carbon black powder
Particle Size (micron)	32-45/ 25-32	D50 = 1.6	250
Plasma Gas flow rate (slpm)	250	220	250
Plasma Gas Composition	23.3 % N_2, 76.6 % Ar	80% N_2, 20% H_2	23.3 % N_2, 76.7 % Ar
Torch current (A per cathode)	183	250	183
Nozzle size (mm)	9.5	12.7	12.7
Number of passes	60	25, **50**, 100[a]	80
Preheat Temp (°C)	300	20, **325**, 450[a]	300
Standoff distance (mm)	100	70, **80**, 90[a]	100

[a],values in bold were held fixed during variation of other parameters.

Table 10: Plasma processing parameters for electrolyte deposition (suspension plasma spray) [56]

Electrolyte Suspension Plasma Processing Parameters

Parameter	High Flow Rate	Medium Flow Rate	Low Flow Rate
Plasma gas flow rate (slpm)	275	250	230
Plasma gas composition (%)	70% N_2, 25% Ar, 5% H_2	80 % N_2, 15 % Ar, 5 %H_2	87% N_2, 13% Ar
Current (A per cathode)	250	250	250
Nozzle (mm)	9.5	9.5	9.5
Preheat Temperature (°C)	300-350	300-350	300-350
Standoff Distance (mm)	90	80	80

Table 11: Summary of key performances in laboratory scale, using different manufacturing process, and materials.

S. No.	Fabrication Method	Materials for electrodes, electrolytes	Barrier Layers	References	Performance, degradation
1	Tape Casting and co-firing process; Screen Printing of Cathode, in-situ firing; co-firing of the oxide substrate can be done for Fe-Ni	Anode functional layer (Ni-YSZ, 30 micron), **electrolyte (YSZ, 15 micron)**, and cathode (LSCF, 30 micron); Thin metal support (Ni-Fe, 70 micron)	None	Kim et al.[49]	1.05 to 1.1 V of OCV and 1.4 W/cm^2 maximum power density at 800 C, initially; Huge degradation due to coarsening, cathodes and anodes (lack of barrier layers, possibly)
2	Tape casting, co-firing; Screen printing of cathodes with in-situ firing (1450 C, can be done for Fe-Ni Oxides, which can be reduced later	**GDC electrolyte (10 micron)**, Ni-GDC (CGO) anode; LSM with BSCF (Ba, Sr, Co, Fe Ox) as cathode	None	Yan e al. (2015)[50]	Peak power density of 1.04 W $/cm^2$ at 650ºC, OCV ~ 0.9 V; No degradation after 5 Redox Cycles; No long term degradation data
3	Tubular cells, support precursor oxides prepared by Phase-inversion and co-sintering (> 1400ºC), reduction in-situ	NiO-YSZ anode, **YSZ electrolyte**, LSM-YSZ with C-poreformer, cathode; Fe-Ni alloy tube as porous support	None	Han et al. (2016)[51]	0.26 W/cm^2 at 800º C, using moist hydrogen as fuel and ambient air as oxidant; no degradation data
4	Tape Casting, co-firing in air at 1400º C; Reduction in situ, final step	**YSZ electrolyte (10 micron thick)**, Ni-YSZ anode, Proprietary Cathode; Porous Ni as support	None	Kong et al. (2010)[52]	Power density, from 0.23 and 0.80 W/cm^2 in the temperature range of 650–800º C; no degradation data
5	2 Step firing process for anode and support; in-situ reduction, as final step	NiO-YSZ anode, **YSZ electrolyte**, LSM-YSZ, LSCF Cathodes; Porous Ni support substrate	None	Choi and co-workers (2011)[53], (2016)[61]	Power Density of 0.93 W/cm^2 at 800 °C [53]; no degradation data
6		30 micron -thick Ni-YSZ (yttria-stabilized zirconia) anode, and **~15 micron-thick YSZ electrolyte**, LSCF Cathode; ~120 micron-thick NiFe-support			Power Density of 0.43 W/cm^2, at 800 ºC[61]; no degradation data
10	APS on porous Ni support, with variation in permeability; Sequential deposition of 6 layers on top of the porous Ni; 15 cm^2 cell area (>> button cell)	LSCM (barrier)/ LDC-NiO (anode funct. Layer)/ LDC (interlayer prior to electrolyte)/ **LSGM Electrolyte**/ LSGM-LSCF (Cathode functional layer/LSCF (cathode current collection)	Interlayers on anode and Cathode side	Hwang et al. (2011)[40]	Very high power densities of 0.9 W/cm^2 at 0.7 Volt operating voltage, 800ºC obtained; Degradation rates of < 3% /kHr, in Hydrogen feed
11	Thermal Spray - Plasma (High Velocity Oxy-Fuel spray for anode and electrolyte; wet colloidal spray for cathode	SDC electrolyte, and NiO-SDC composite anode, LSCF cathode; SS430L substrate	None	Yoo et al. (2012)[41]	Power density of 165 mW cm^2 at 0.6 V and open circuit voltages around 0.88 V, were obtained at 600 C under 50% H_2 in Ar (3% H_2O)
12	Plasma Spray process - anode; Plasma Spray Thin Film (PSTF), modified for a v. low pressure operation; LSCF deposition by screen printing (final sintering of cathode not mentioned)	50-80 micron thick YSZ, Ni-YSZ anode, LSCF cathode; Ferritic SS porous substrate (procured from Hoganas)	None	Gupta et al. (2015)[55]	Power Density of about 0.6 W/cm^2 at 0.7 V (cell operating voltage) at 800º C (moist Hydrogen feed (5% moisture in feed); Degradation data and stabilization work, in progress
13	Axial Injection Suspension Plasma Spray for Anode functional layer and Cathode functional layer; Electrolyte and anode bridging layer by Powder Plasma	Ni-YSZ anode, YSZ electrolyte (20-25 micron), LSCF-SDC cathode functional layer; SS40L porous disk support	None	Kesler (2013)[74]	Power density of about 0.71 W/cm^2 at 750ºC ad 1.13 W/cm^2 at 850ºC in Hydrogen; low OCVs due to electrolyte imperfections
14	Solution Precursor Plasma Spray (SPPS) for Anodes; all others similar		None	Kesler (2014)[75]	Power density of about 0.45 W/cm^2, at 750 ºC, with OCV of about 1.05 V, in Hydrogen
15	Cathodes by Suspension Plasma	Cathodes modified by using Carbon black pore formers for better microstructure	None	Kesler (2016)[76]	0.06 $Ohm.cm^2$ ASR for cathodes, 744ºC
16	Tape casting, lamination, co-firing of half cell; cathodes by screen printing and in-situ firing	Ni-YSZ anode/ YSZ electrolyte/$(Bi_2O_3)_{0.7}(Er_2O_3)_{0.3}$-Ag cathode; SS430L porous support	None	Zhan (2013)[77]	Max power density of 568 mW/ cm^2 at 750º C, in Hydrogen; ASR of 0.09 Ohm. cm^2 obtained from symmetric cell data