Master Degree in InnovativeTechnologies in Energy Efficient Buildings for Russian & Armenian Universities and Stakeholders

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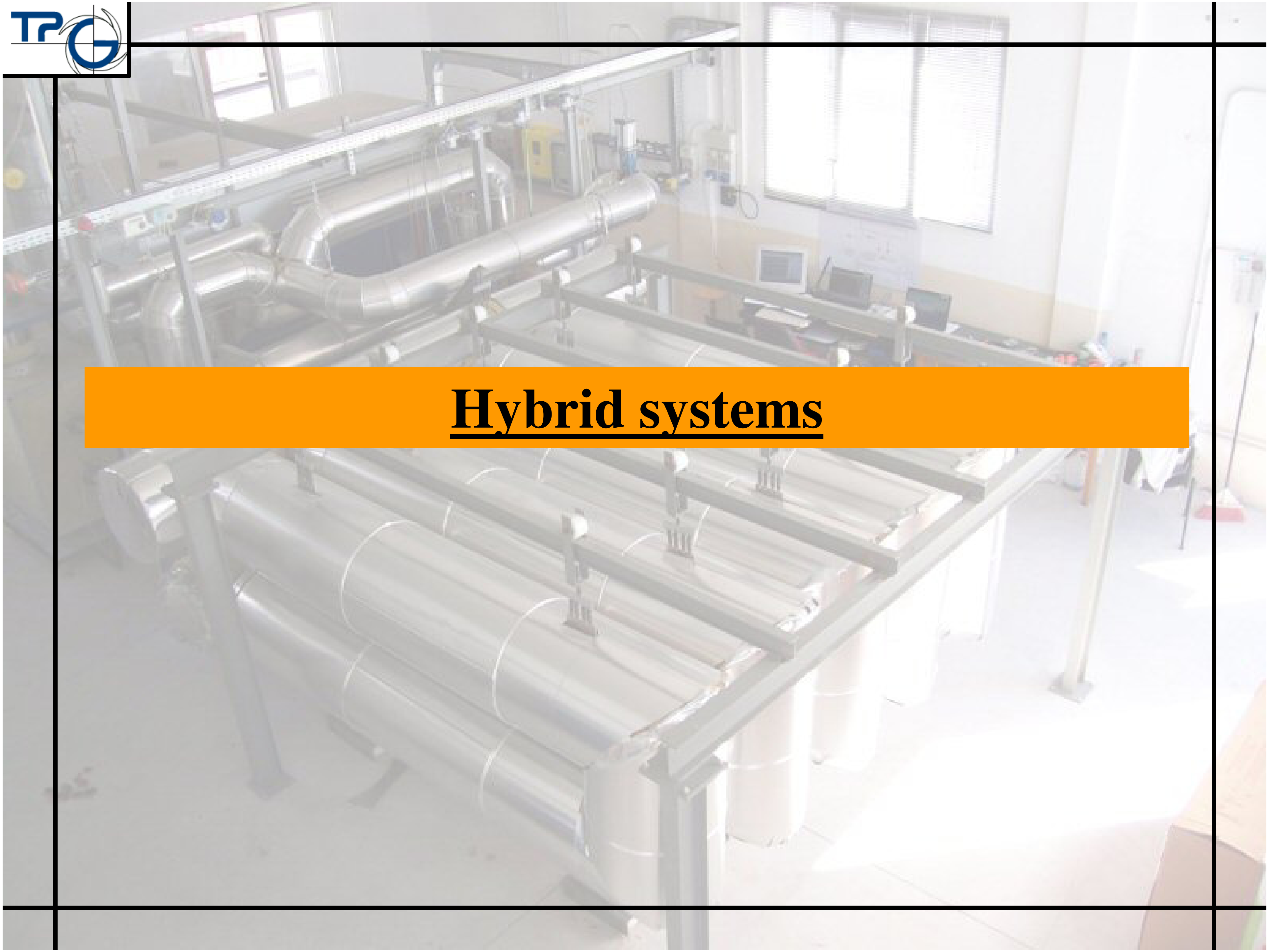
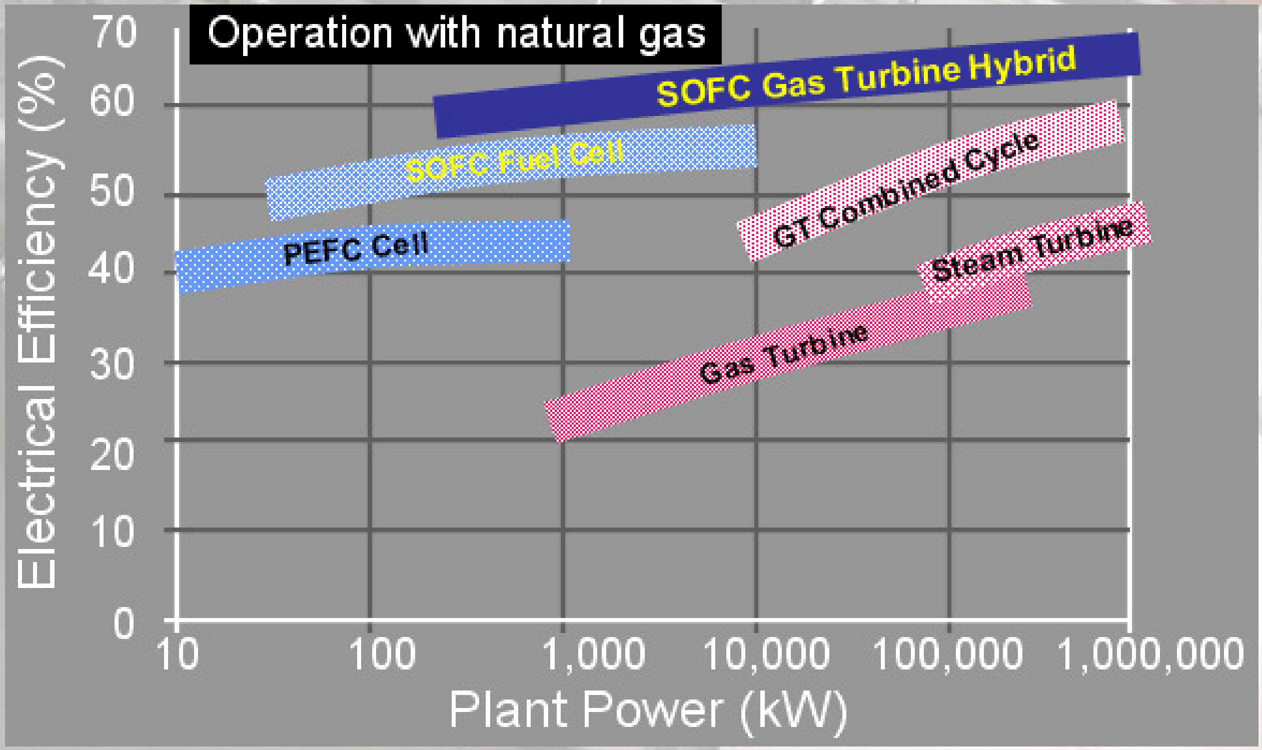


Hybrid systems

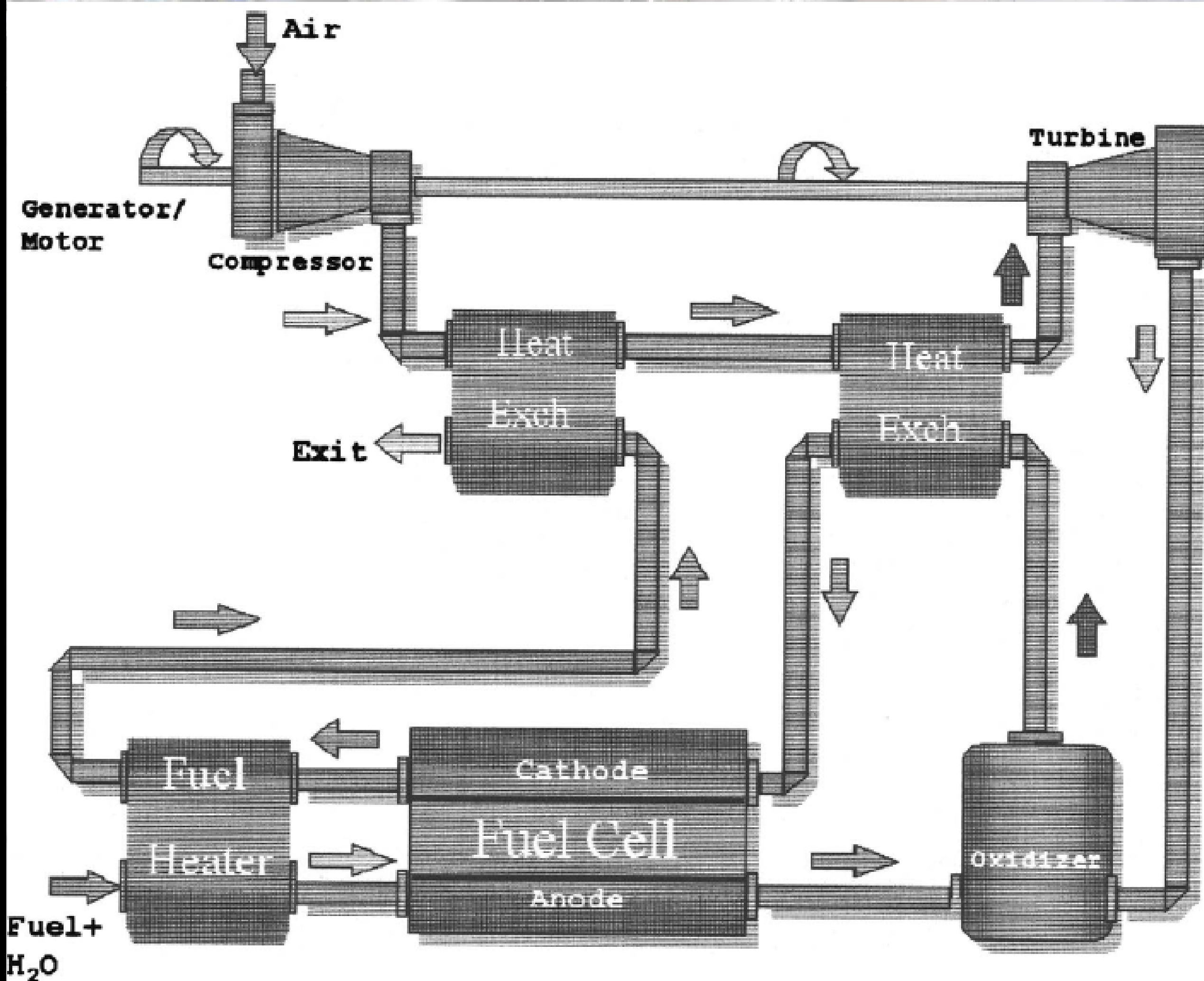
Hybrid System Aspects

- ✓Fuel cells generate high temperature exhausts.
- ✓Especially high temperature fuel cells generate exhausts at high exergy content (exhaust temperature: ~650°C for MCFC, up to 1000°C for SOFC).
- ✓Gas turbine highest temperature (expander inlet): 900°C-1450°C.
- ✓Steam plant highest temperature (expander inlet): 500°C-600°C.
- ✓System efficiency increase possible with power system coupling.



MCFC Hybrid Systems (1/15)

Athmospheric MCFC based Hybrid system (1/2)



Plant theoretically analyzed by National Fuel Cell Research Center (**NFCRC**) and National Energy Technology Laboratory (**NETL**)

CB: Catalytic Burner

MCFC Hybrid Systems (2/15)

Athmospheric MCFC based Hybrid system (2/2)

Fuel cell parameters

Parameter	Unit	Value
Number of Channels		216
Cell Active Area	m^2	1.08
	Anode Specification	
Inlet Temperature	K	923
Inlet Pressure	Pa	104,425.2
Exit Pressure	Pa	104,425.2
Channel Width	m	0.0031
Channel Height	m	0.0013
Inlet CH_4	mole frac	0.2798
Inlet CO	mole frac	0.005
Inlet CO_2	mole frac	0.0346
Inlet H_2	mole frac	0.1168
Inlet H_2O	mole frac	0.5662
	Cathode Specification	
Inlet Temperature	K	923
Inlet Pressure	Pa	104,425.2
Exit Pressure	Pa	104,425.2
Inlet CO_2	mole frac	0.1553
Inlet H_2O	mole frac	0.1553
Inlet N_2	mole frac	0.559
Inlet O_2	mole frac	0.1294
Channel Width	m	0.0031
Channel Height	m	0.0032
Exchange Current Density	amp/m^2	50
Diffusion Limiting Current Density	amp/m^2	4000
Transfer Coefficient		0.75
	Cell Specification	
Thickness	m	0.01
Heat Capacity	J/kg K	800
Density	kg/m^3	1500
Net Resistance	ohm m^2	$-6.667\times10^{-7}(T-273)+4.7833\times10^{-4}/Acell$
	Separator Specification	
Thickness	m	0.001
Heat Capacity	J/kg K	611
Density	kg/m^3	7900

Gas turbine parameters

Design Spec	Value
Design Mass Flow Rate (kg/s)	1.33
Design Turbine Inlet Pressure for NFCRC (kPa)	304
Design Turbine Inlet Pressure for NETL (kPa)	405
Design Turbine Inlet Temperature (K)	1050
Design Compressor Inlet Pressure (kPa)	101.325
Compressor Impeller Radius (m)	0.055
Design Compressor Inlet Temperature (K)	298
Design Speed (RPM)	65,000
Diffuser Expansion Ratio	1.4
Plenum Volume (NFCRC only) (m^3)	0.8

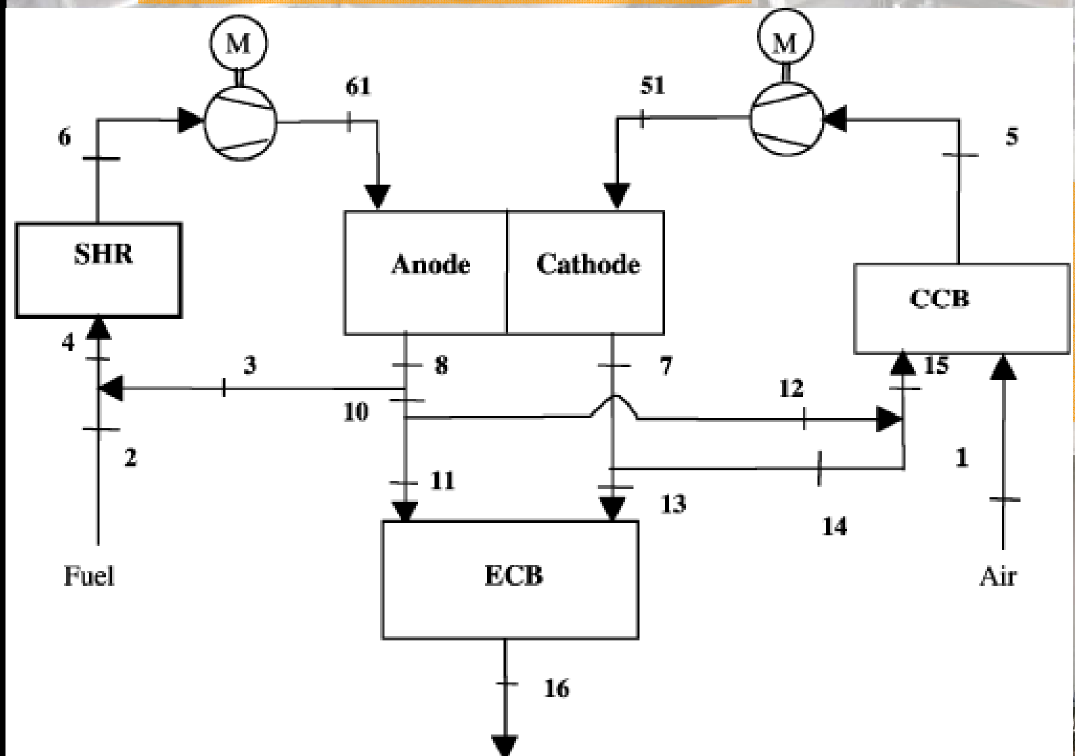
On design performance

Description	NFCRC	NETL
Catalytic Exhaust Temp (K)	1129.44	1106.724
Cathode Inlet Temp (K)	856.45	847.77
Gas Turbine Power (kW)	136.35	127.32
Fuel Cell Power (kW)	856.95	869.287
Efficiency	56.20%	56.50%
Current (single cell) (A)	1025.06	1039
Voltage (single cell) (V)	0.76	0.76

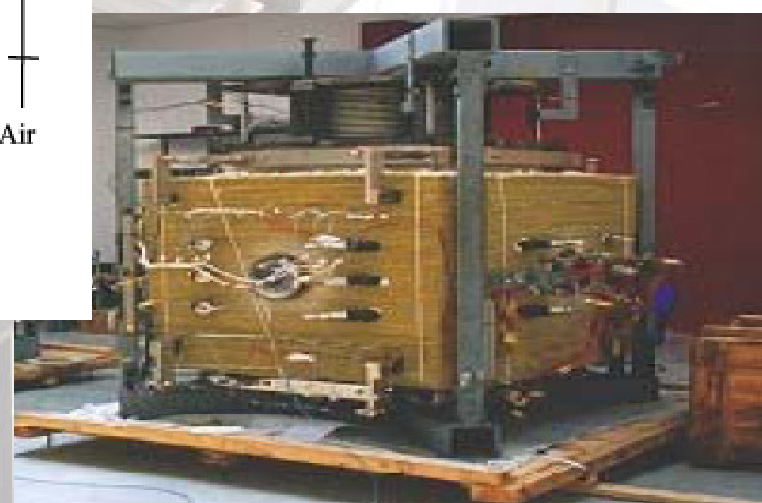
MCFC Hybrid Systems (3/15)

Pressurised MCFC based Hybrid system by ANSALDO Fuel Cells (1/9)

Fuel cell layout (1/2)



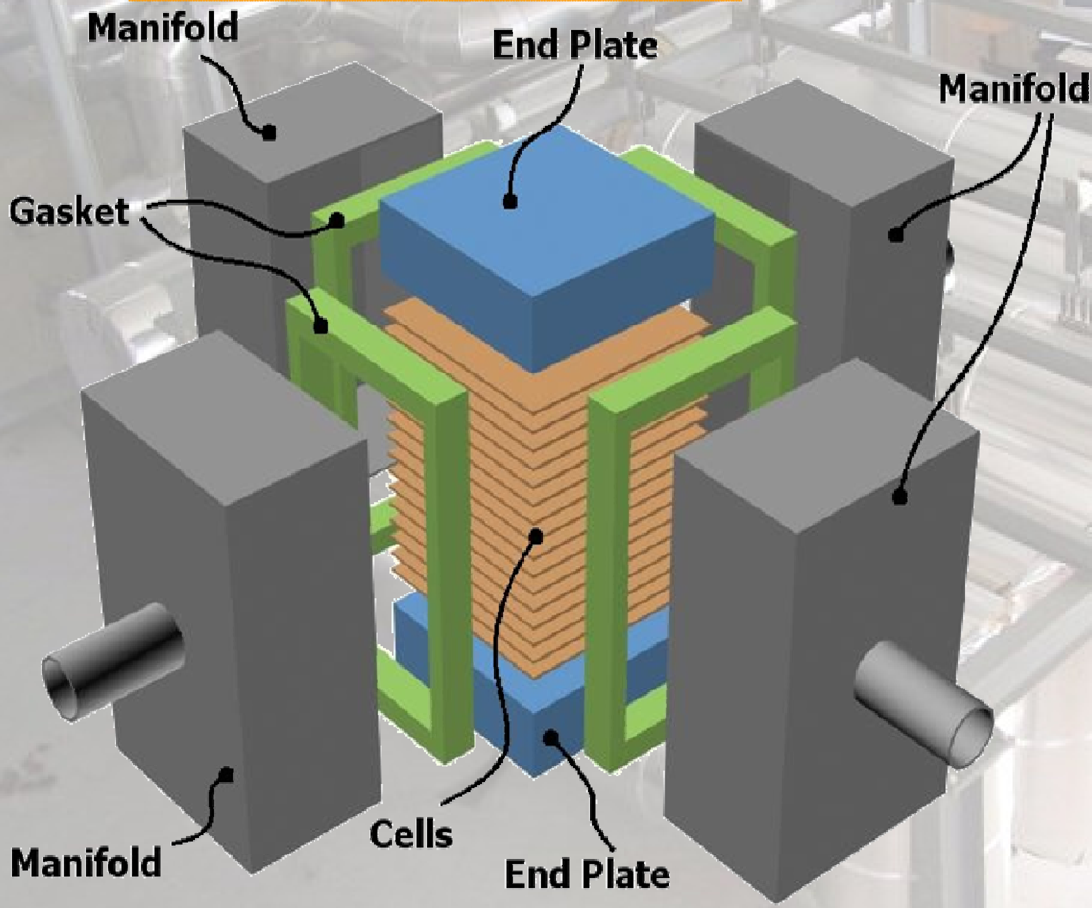
SHR: sensible heat reformer
ECB: exhaust catalytic burner
CCB: cathode catalytic burner

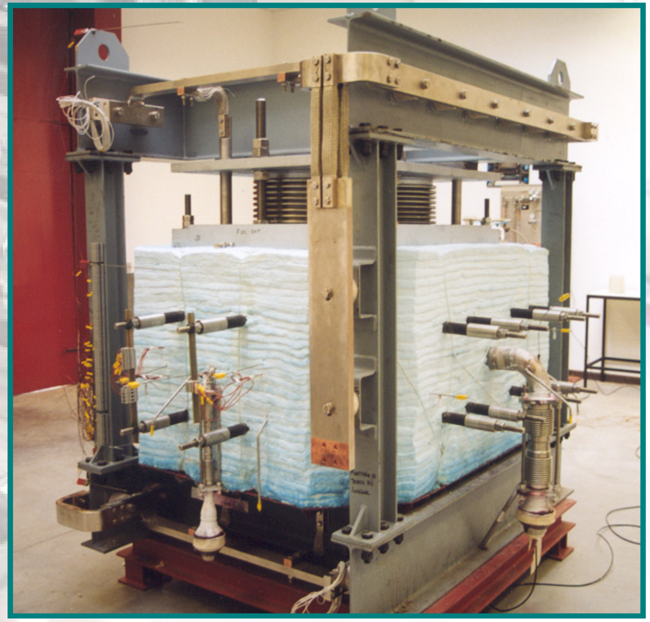


MCFC Hybrid Systems (4/15)

Pressurised MCFC based Hybrid system by ANSALDO Fuel Cells (2/9)

Fuel cell layout (2/2)





MCFC Hybrid Systems (5/15)

Pressurised MCFC based Hybrid system by ANSALDO Fuel Cells (3/9)

Fuel cell data

FCS design point performance (these values do not take into account the power necessary for the stack pressurisation)

Efficiency (%)	Power (kW)	Cell voltage (V)	Stack temperature (K)	Electricity to heat ratio	Fuel utilisation rate	
50.13	100.4	0.6528	922	0.9933	0.4068 (Single pass)	0.9377 (Total)

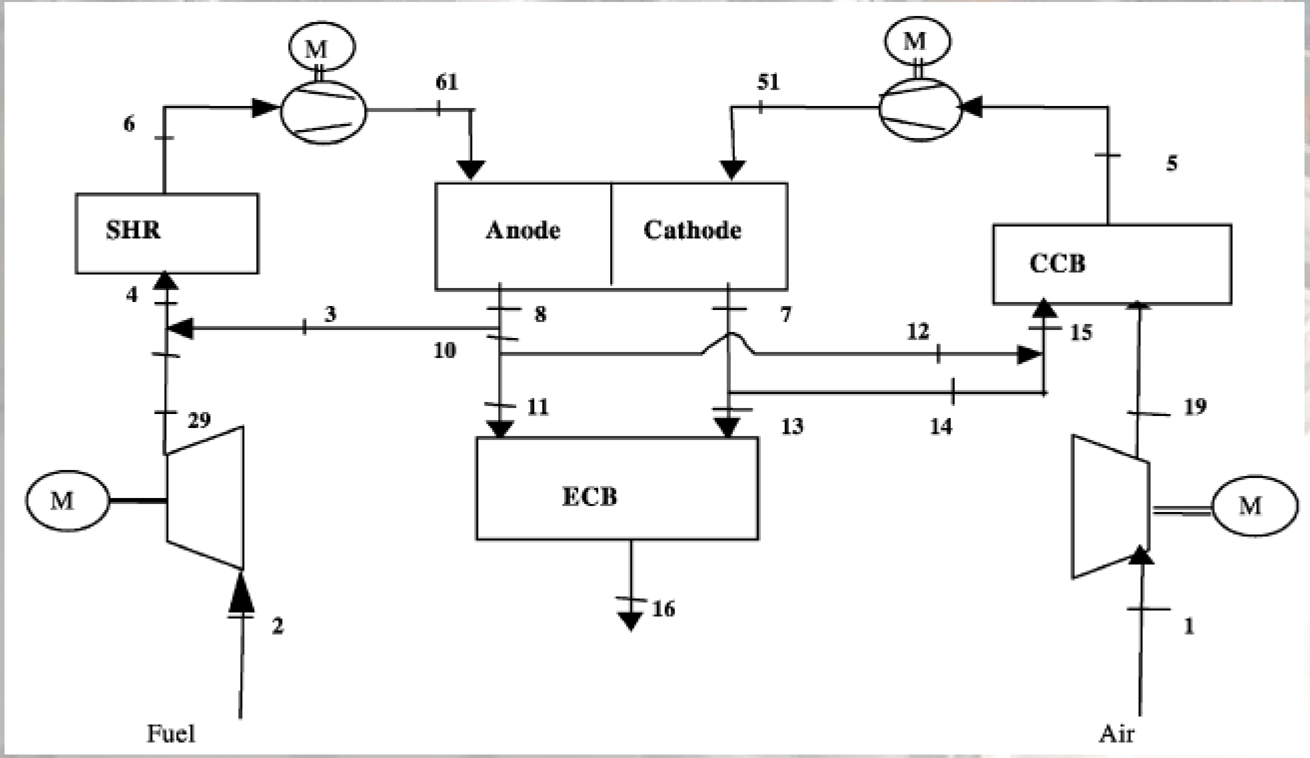
Temperature and composition at design point

System point[a]	*T* (K)	Molar fraction rate (%)						
		H_2	CH_4	CO	CO_2	H_2O	O_2	N_2
4 (reformer inlet)	948	4.136	2.584	4.254	61.85	27.17	0	0
61 (anode inlet)	856	8.37	0.743	6.729	58.81	25.34	0	0
8 (anode outlet)	967	4.092	0.7001	4.346	63.19	27.67	0	0
51 (cathode inlet)	904	0	0	0	8.175	9.087	11.1	71.6
7 (cathode outlet)	962	0	0	0	3.855	9.758	9.461	76.89
15 (CCB inlet)	959	0.464	0.110	0.493	10.58	11.79	8.388	68.17
16 (exhaust)	976	0	0	0	4.806	10.16	9.184	75.85

MCFC Hybrid Systems (6/15)

Pressurised MCFC based Hybrid system by ANSALDO Fuel Cells (4/9)

Pressurization by auxiliary compressors

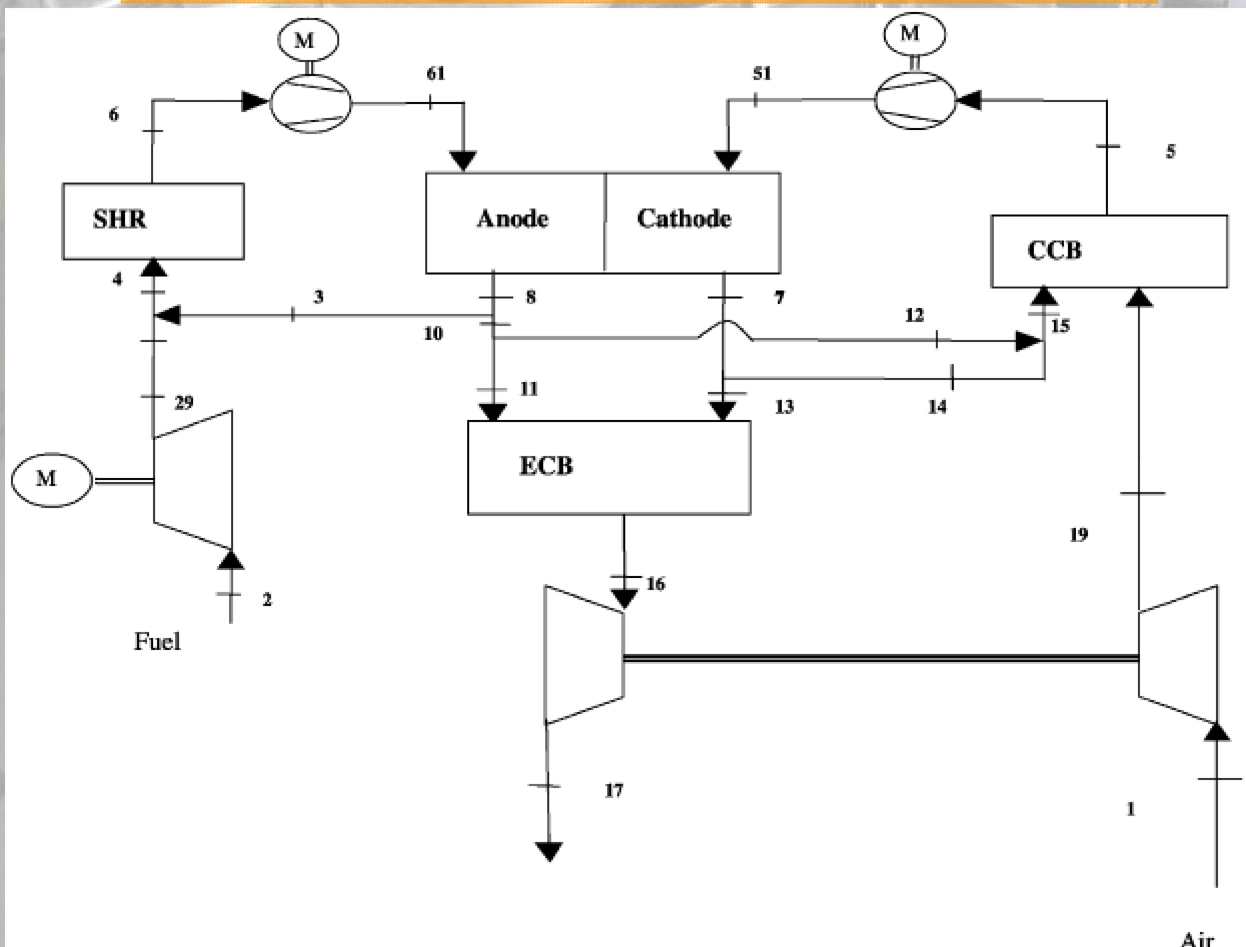


•Taking into account the power for the two auxiliary compressors the stack system efficiency is reduced to 40.1%

MCFC Hybrid Systems (7/15)

Pressurised MCFC based Hybrid system by ANSALDO Fuel Cells (5/9)

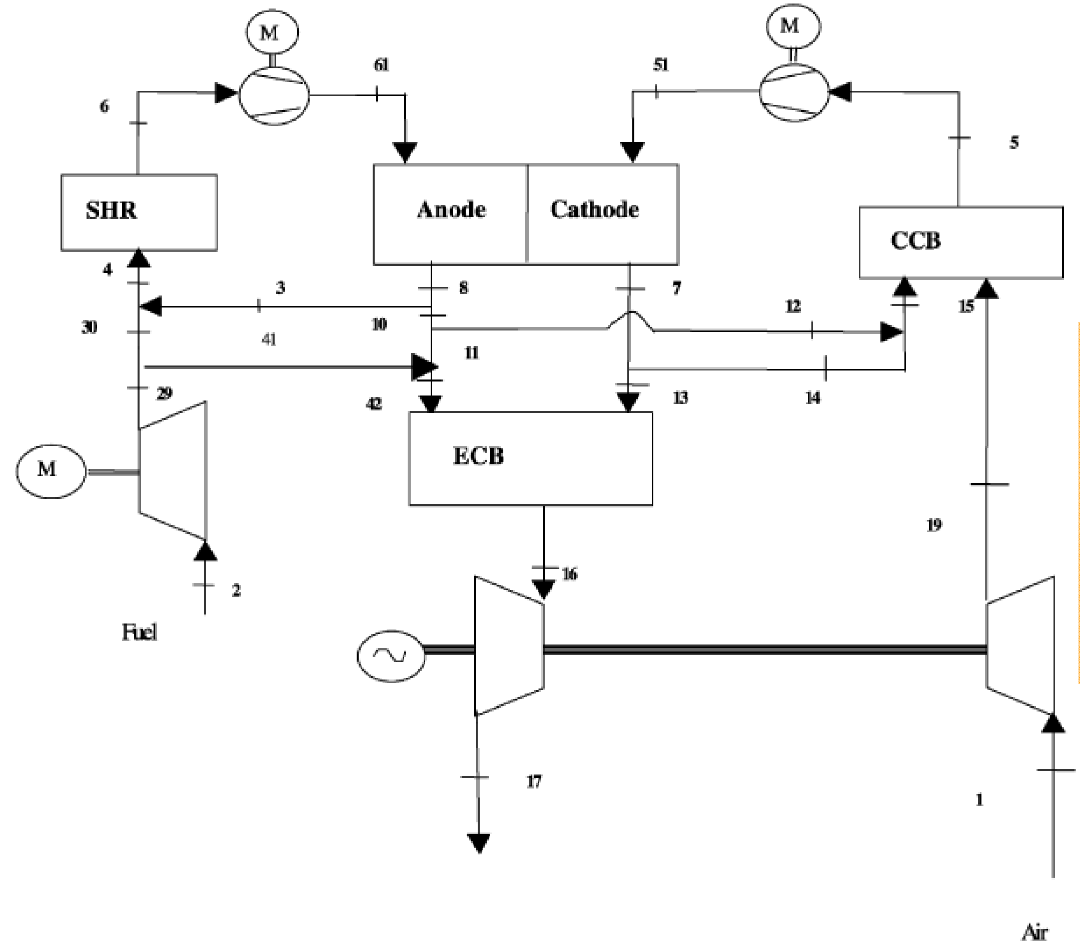
Pressurization by turbocharger



MCFC Hybrid Systems (8/15)

Pressurised MCFC based Hybrid system by ANSALDO Fuel Cells (6/9)

MCFC-mGT hybrid system (using a simple cycle gas turbine)

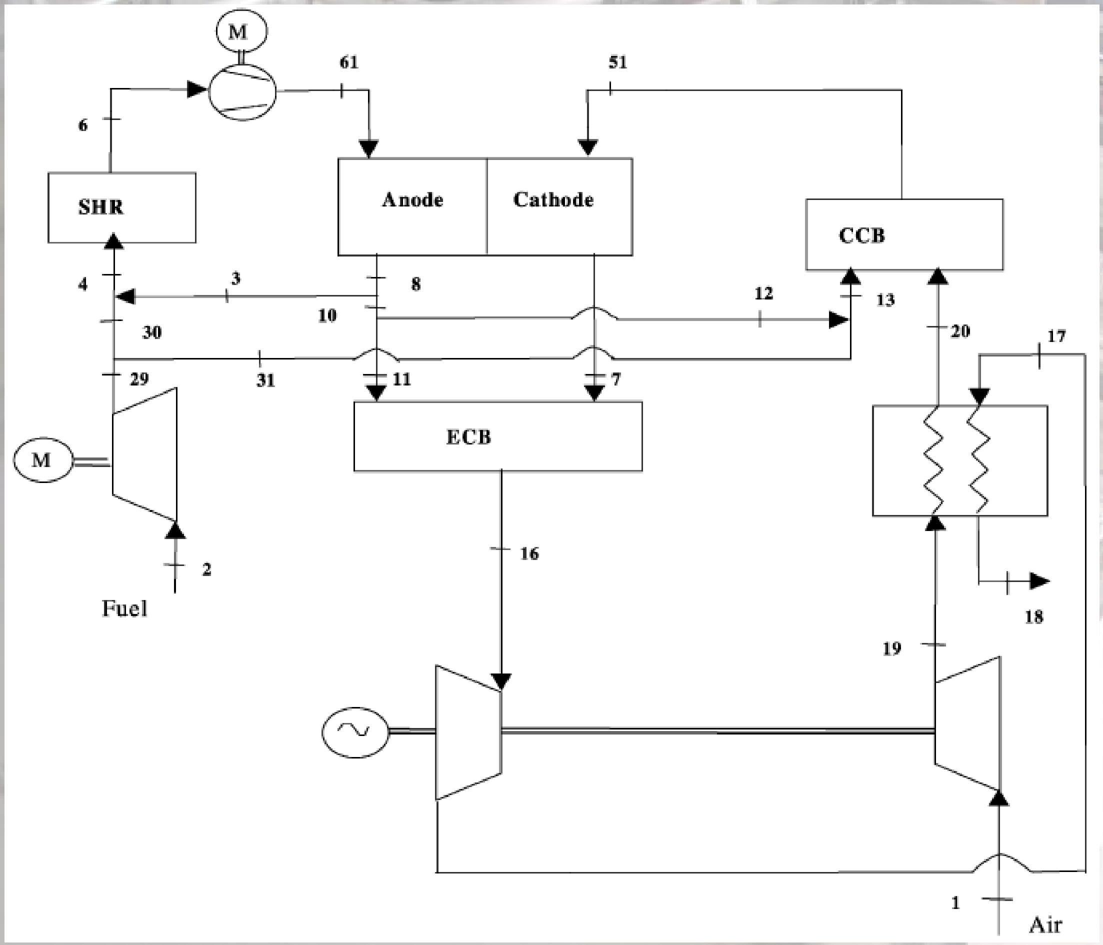


- Cell exhaust gas enters the gas turbine expander at about 3.5 bar and 700°C.
- Possibility of post-combustion in the ECB.

MCFC Hybrid Systems (9/15)

Pressurised MCFC based Hybrid system by ANSALDO Fuel Cells (7/9)

CFC-mGT hybrid system (using a regenerated cycle gas turbine) – Scheme 1

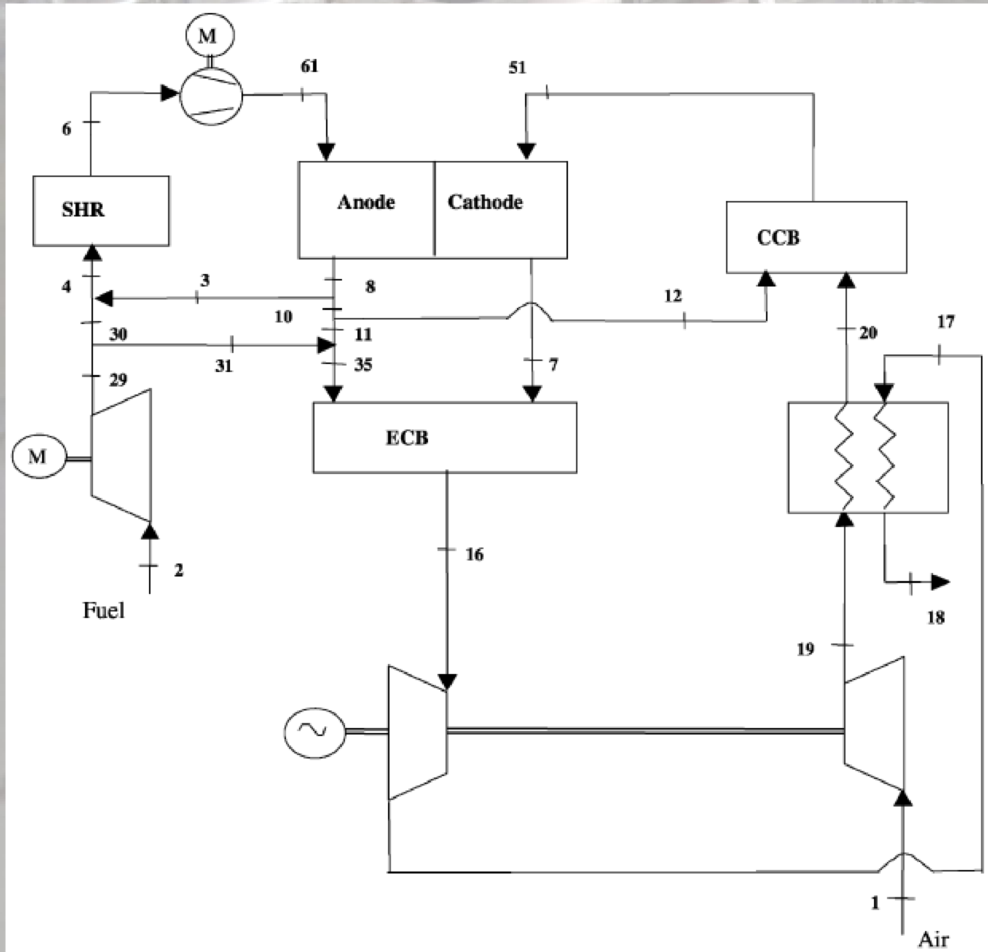


- Elimination of cathodic recycle.
- CCB outlet temperature is obtained with additional fuel (18% of the total fuel flow).

MCFC Hybrid Systems (10/15)

Pressurised MCFC based Hybrid system by ANSALDO Fuel Cells (8/9)

CFC-mGT hybrid system (using a regenerated cycle gas turbine) – Scheme 2

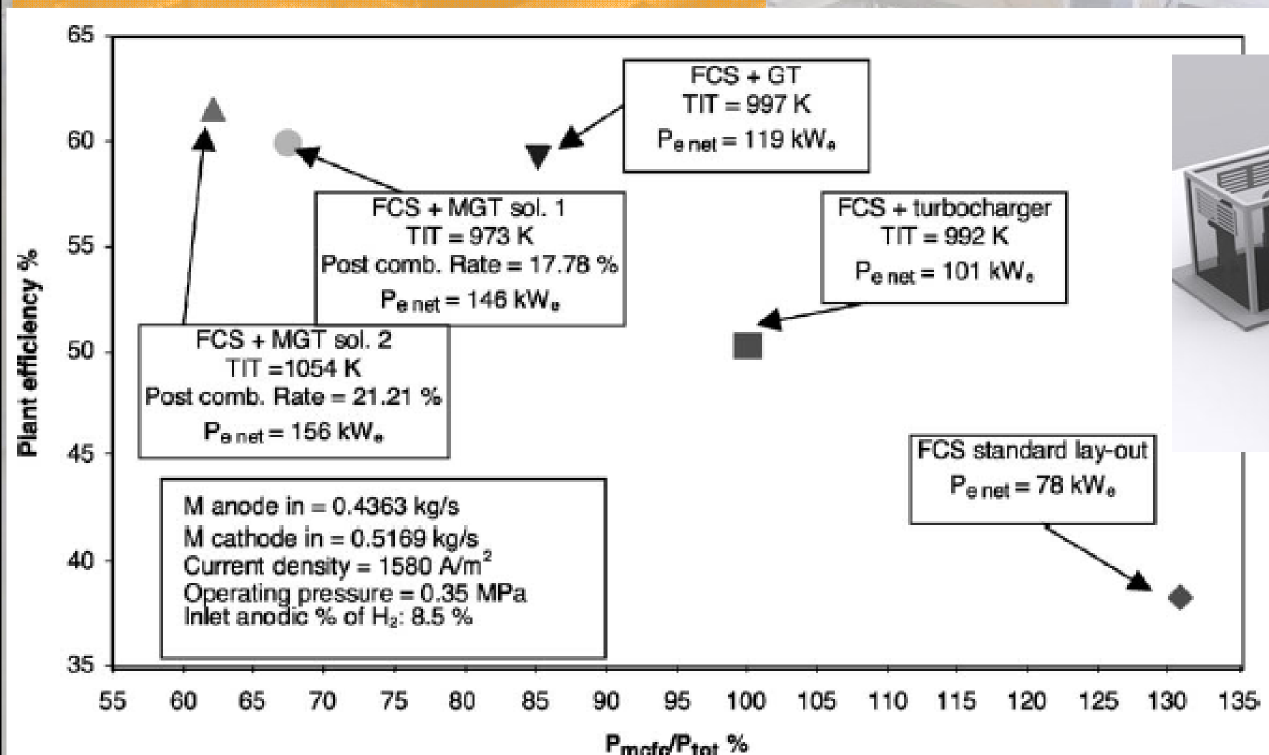


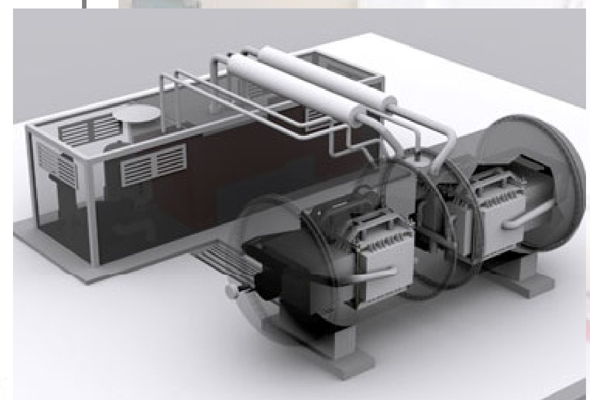
- Elimination of cathodic recycle.
- Elimination of fuel injection in the CCB.
- CCB outlet temperature is obtained with additional fuel in the ECB (21% of the total fuel flow).
- With this approach machine efficiency is increased.

MCFC Hybrid Systems (11/15)

Pressurised MCFC based Hybrid system by ANSALDO Fuel Cells (9/9)

Performance comparison





MCFC Hybrid Systems (12/15)

Pressurised MCFC based Hybrid system by TOYOTA (1/4)

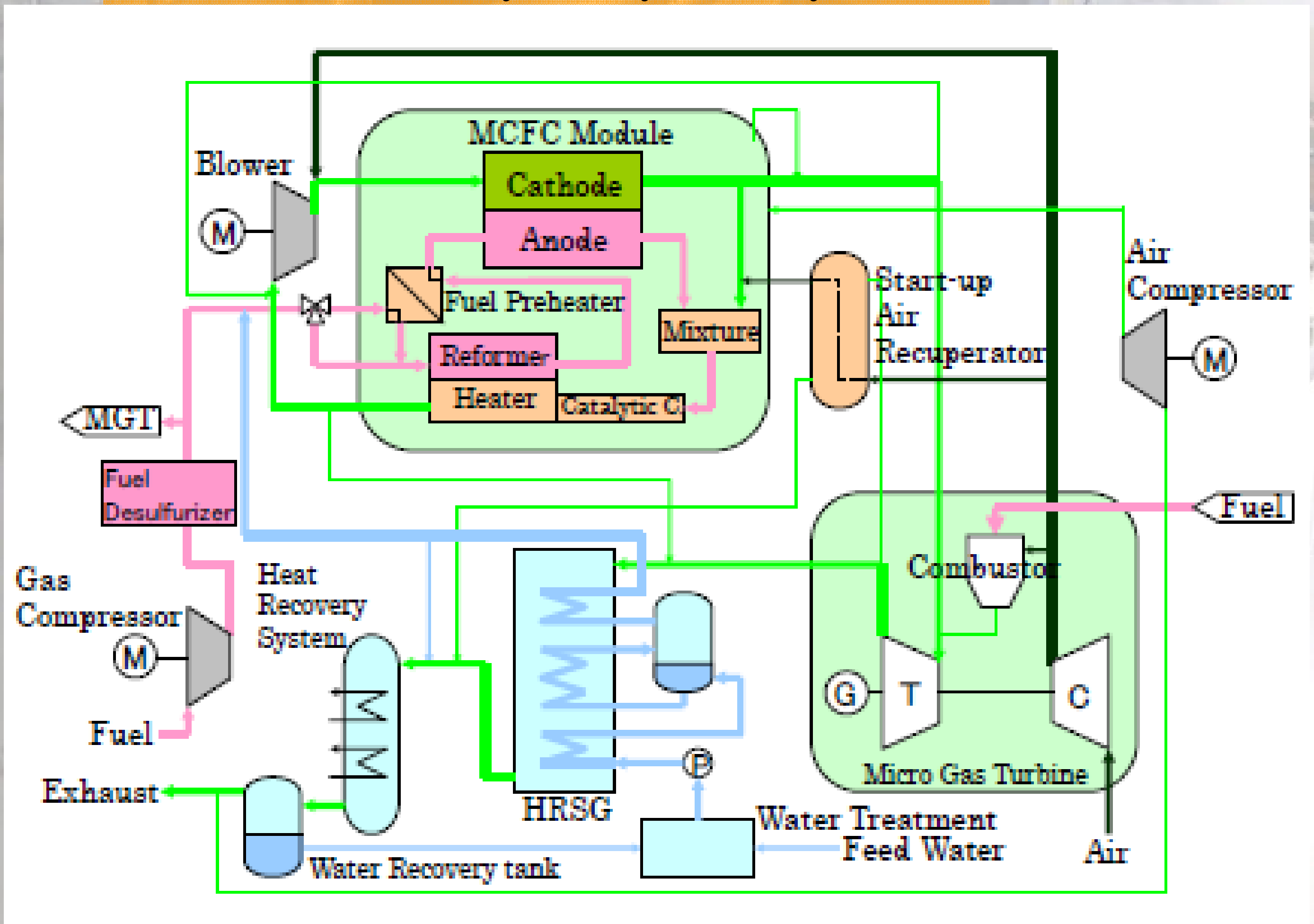
Fuel cell data

Stack structure :	Intermediate gas holder type
Manifold type :	Internally manifolded type
Gas supply method :	Co-flow
Composition :	Li/Na
Number of cells :	140cells
Electrode area :	1.015m2

MCFC Hybrid Systems (13/15)

Pressurised MCFC based Hybrid system by TOYOTA (2/4)

MCFC/mGT hybrid system layout



MCFC Hybrid Systems (14/15)

Pressurised MCFC based Hybrid system by TOYOTA (3/4)

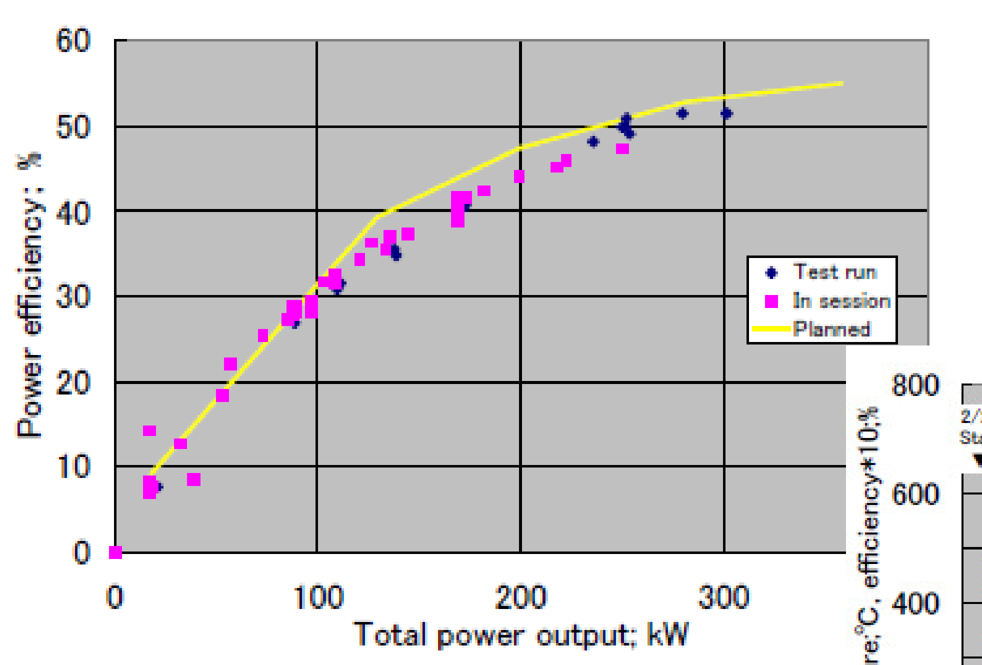
MCFC/mGT hybrid system: performance estimation

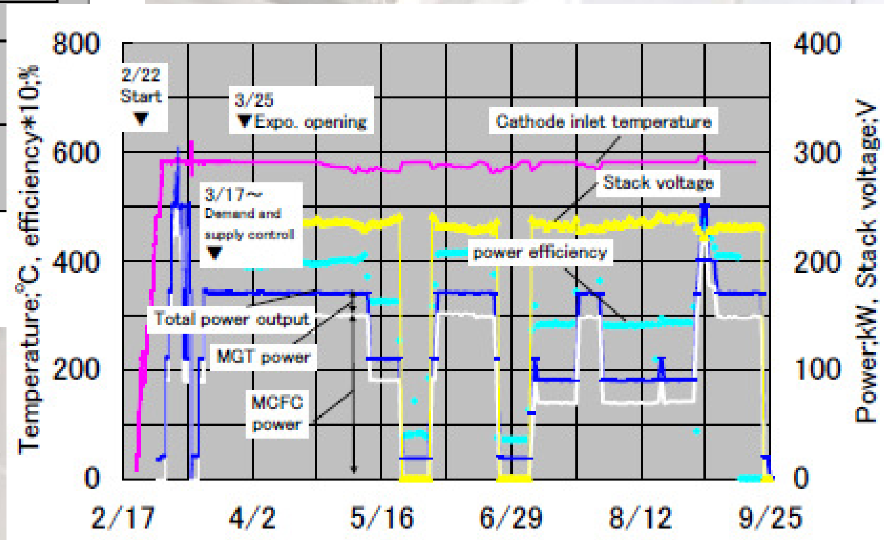
	EXPO	MOTOMACHI
MCFC Stack	2stack	1stack
Operating Pressure (MPaG)	0.335	0.15
Cell Voltage (V)	0.726	0.757
Current Density (mA/cm2)	158	182
Stack Temperature (℃)	580/670	580/642
MCFC AC Power (kW)	310	187
MGT AC Power (kW)	48	16
System AC Power (kW)	358	203
Efficiency (%:Gross AC/LHV)	55	44.3

MCFC Hybrid Systems (15/15)

Pressurised MCFC based Hybrid system by TOYOTA (4/4)

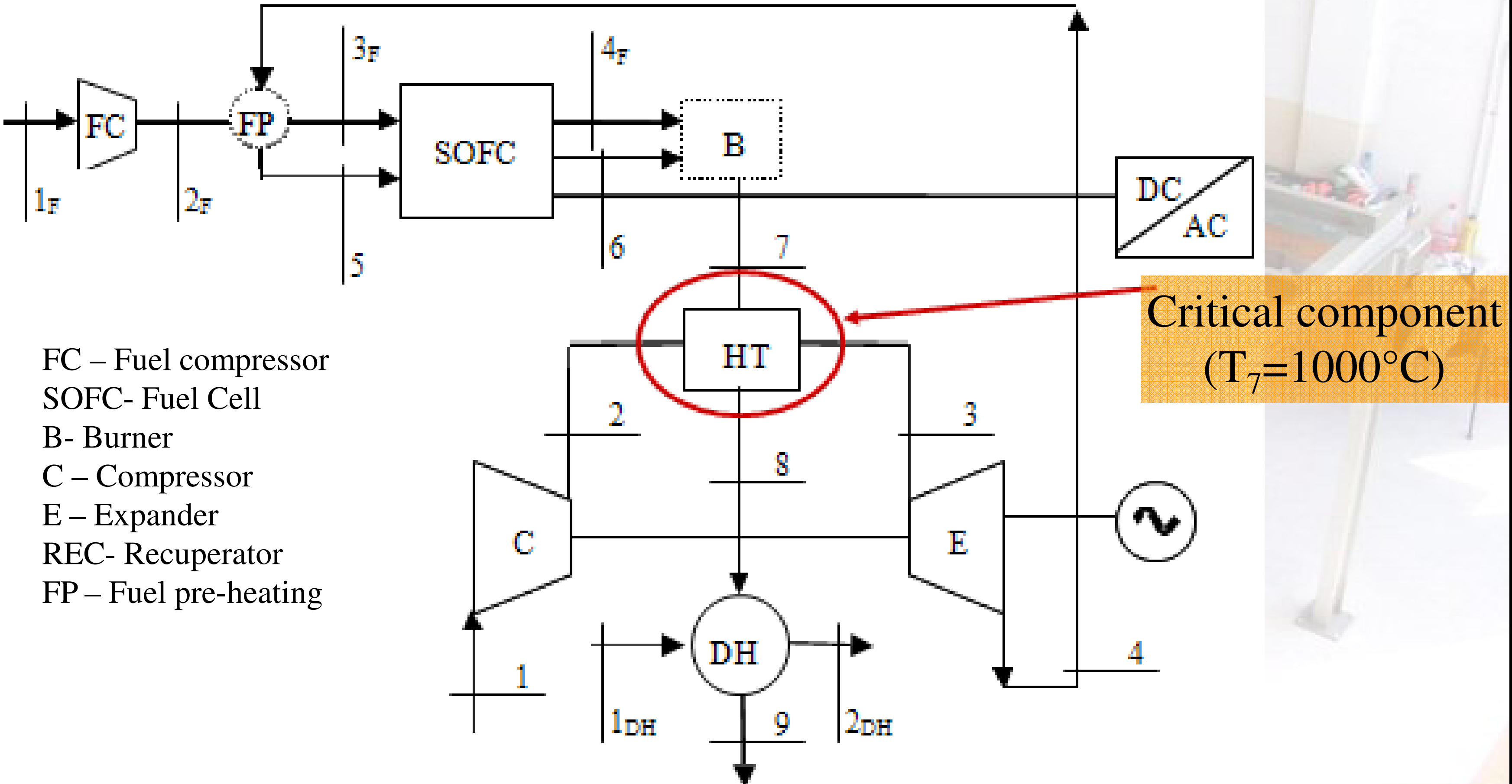
MCFC/mGT hybrid system: 2005 World EXPO test results





SOFC Hybrid Systems (1/7)

Athmospheric SOFC based Hybrid system

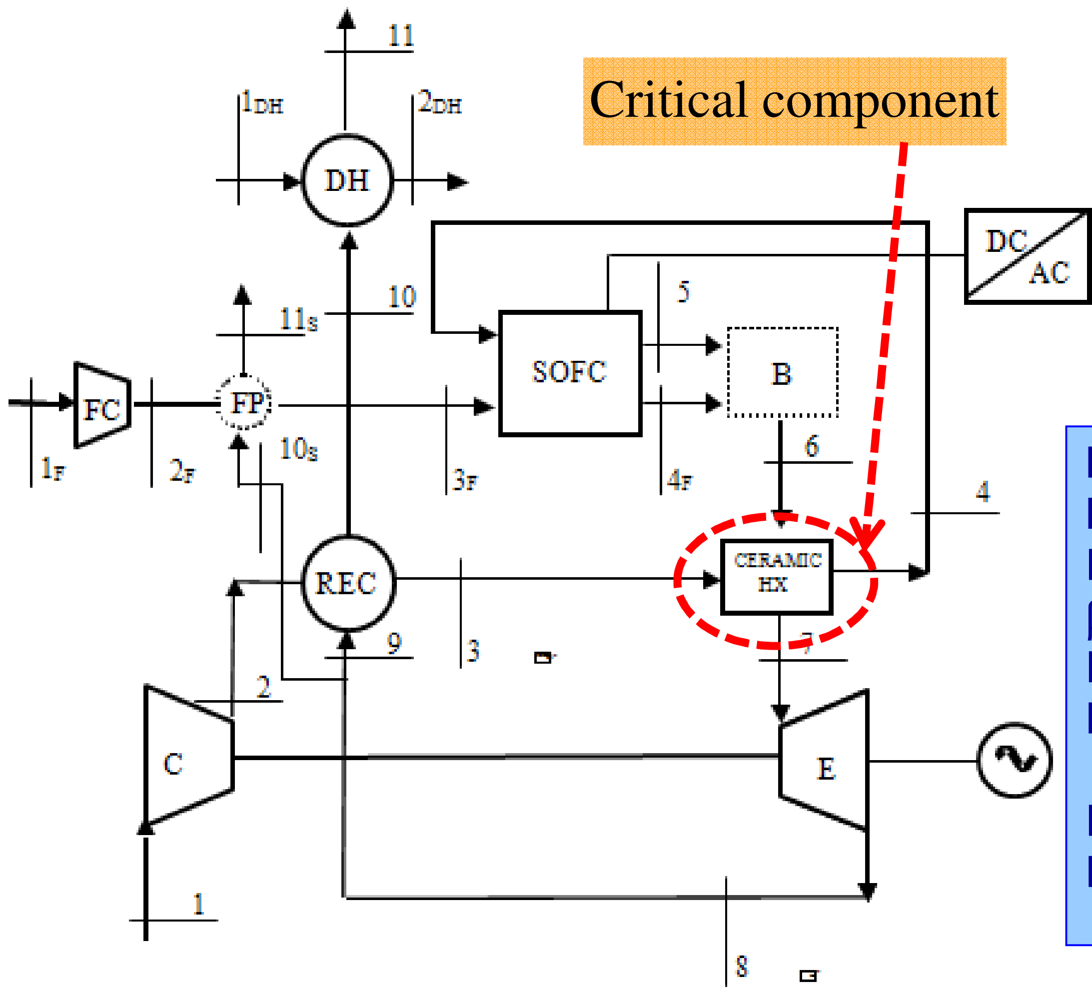


FC – Fuel compressor
SOFC- Fuel Cell
B- Burner
C – Compressor
E – Expander
REC- Recuperator
FP – Fuel pre-heating

β= 4; $P_{FC\ ac}$=1198 kW; $P_{GT\ ac}$=422 kW; P_{HS}=1550 kW; η_{FC}=0.44; η_{HS}=0.55

SOFC Hybrid Systems (2/7)

Pressurised SOFC based Hybrid system (1/6)



FC – Fuel compressor
SOFC- Fuel Cell
B- Burner
C – Compressor
E – Expander
REC- Recuperator
FP – Fuel pre-heating

M_fuel = 0.018 kg/s
M_air =1.05 kg/s
P_{FC}/P_{HS} = 83%
β = 4
Fuel Cell Power = 474.8 kW
Hybrid System Power =565.8 kW

Fuel Cell Efficiency = 0.53
Hybrid System Efficiency =0.62

SOFC Hybrid Systems (3/7)

Pressurised SOFC based Hybrid system (2/6)

Theory of Pressurisation 1

- Ideal cell voltage is a function of pressure (Nernst Equation)

Cathode O_2 partial pressure

$$E_{ideal} = -\frac{\Delta G^0}{n_e \cdot F} + \frac{R \cdot T_S}{n_e \cdot F} \ln\left(\frac{\left(p_{O_2}\right)^{1/2} \cdot p_{H_2}}{p_{H_2O}} \right)$$

Anode partial pressure ratio remains constant

Ideal cell voltage increases with increasing pressure

SOFC Hybrid Systems (4/7)

Pressurised SOFC based Hybrid system (3/6)

Theory of Pressurisation 2

- Cell voltage = Ideal voltage - Losses

$$E_{cell} = E_{ideal} - \eta_{activation} - \eta_{ohmic} - \eta_{diffusion}$$

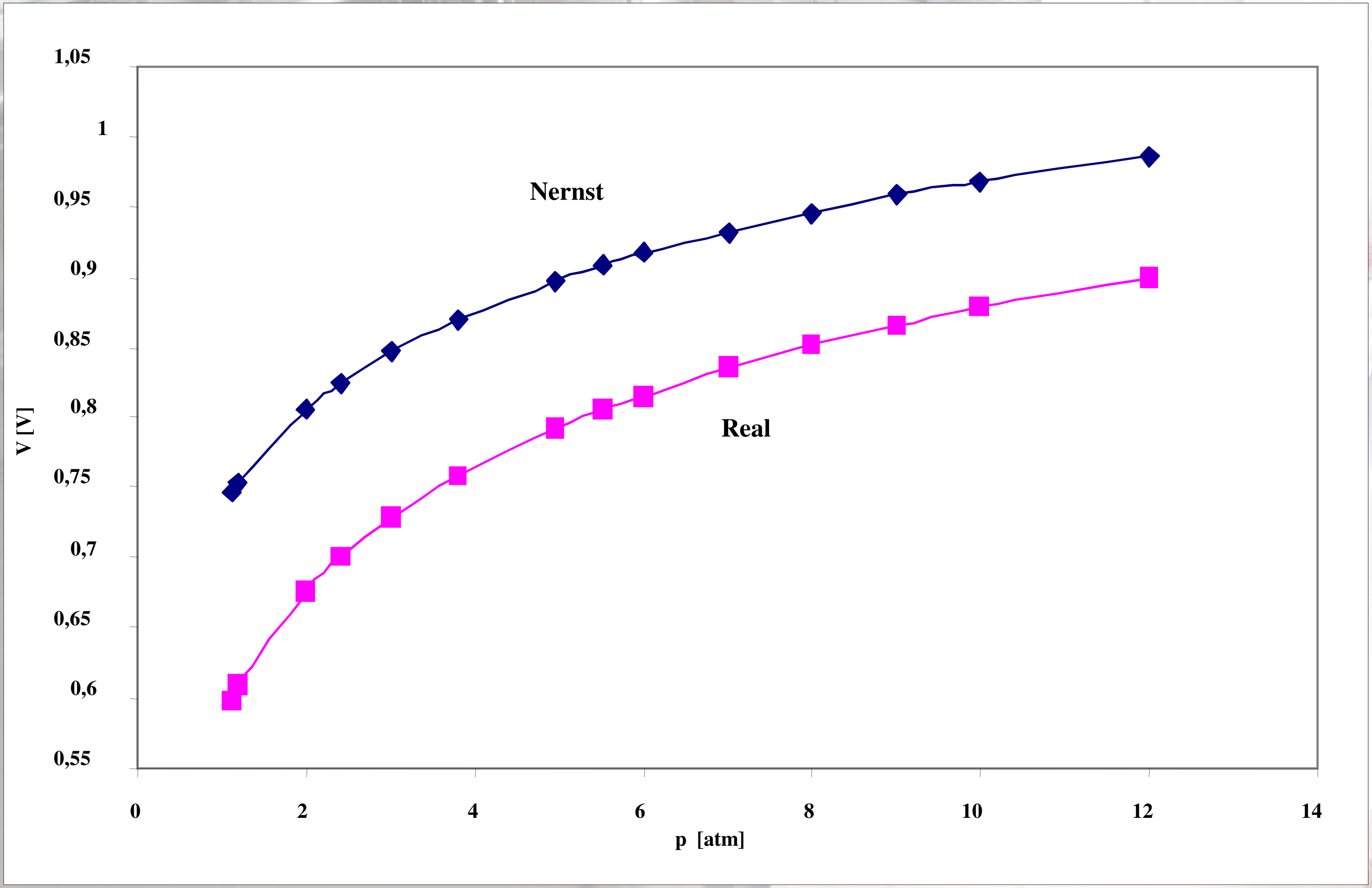
Electrode process losses reduce with increasing pressure

Mass transport losses reduce with increasing pressure

At constant current, cell voltage and hence power increase with pressure

SOFC Hybrid Systems (5/7)

Pressurised SOFC based Hybrid system (4/6)



SOFC Hybrid Systems (6/7)

Pressurised SOFC based Hybrid system (5/6)

DIRECT BENEFITS OF PRESSURE

- Pressurisation reduces pressure drops caused by flows
- Pressurisation reduces pumping work required to overcome pressure drops: **allows greater power density through reduction in passage size; reduction in stack volume big driver for overall system cost.**
- Reduces area and cost of heat exchangers
- Increases cell performance: **50% stack efficiency; translates to €/kW.**

Direct effect of pressure on key parameters	
Pressure drops	1/ P
Pump work	1/ P^2
Heat exchanger area (based on U_{press}/U_{amb})	$1/P^{0.5}$ – $1/P^{0.8}$
Cell performance ΔV mV	59 log Pr

SOFC Hybrid Systems (7/7)

Pressurised SOFC based Hybrid system (6/6)

Pressurised and atmospheric HS compared

Identical stack in pressurised and atmospheric configurations

- **Near term SOFC stack**
- **Underlying stack efficiency 50%**
- **System efficiency exceeds stack efficiency for pressurised case**
- **Atmospheric recuperator must be done with exotic material**
- **Pressurised recuperator can be stainless steel**

	Atm	Press'd
Efficiency Net AC LHV	44%	67%
Net power kW	684	1051
Recuperator hot inlet temp °C	871	576

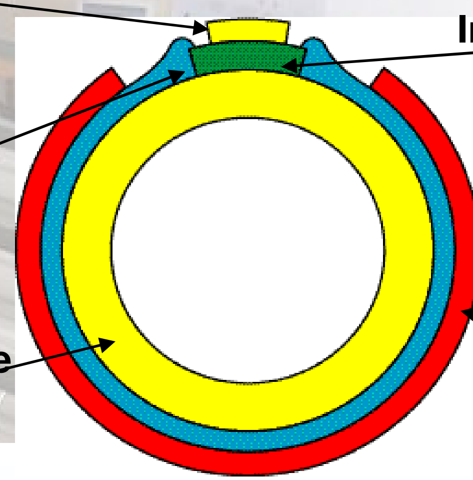
SOFC HS Based on Tubular Cells (1/7)

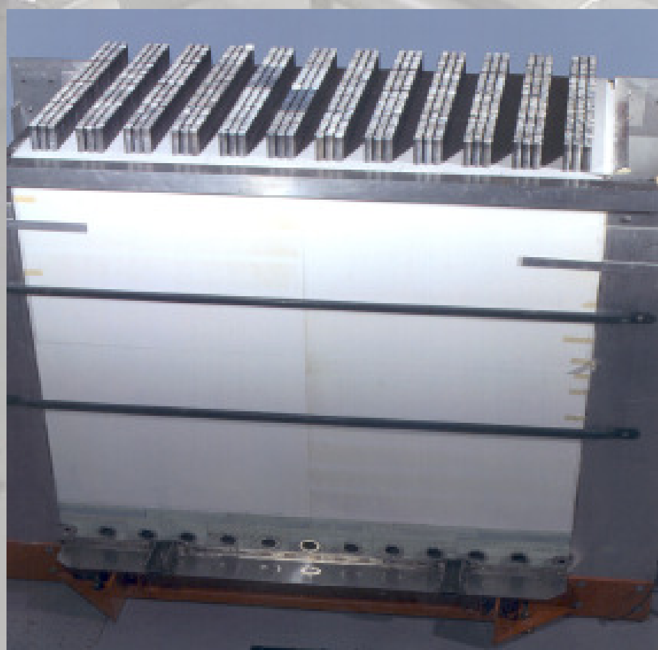
✓Cell details (1/3)

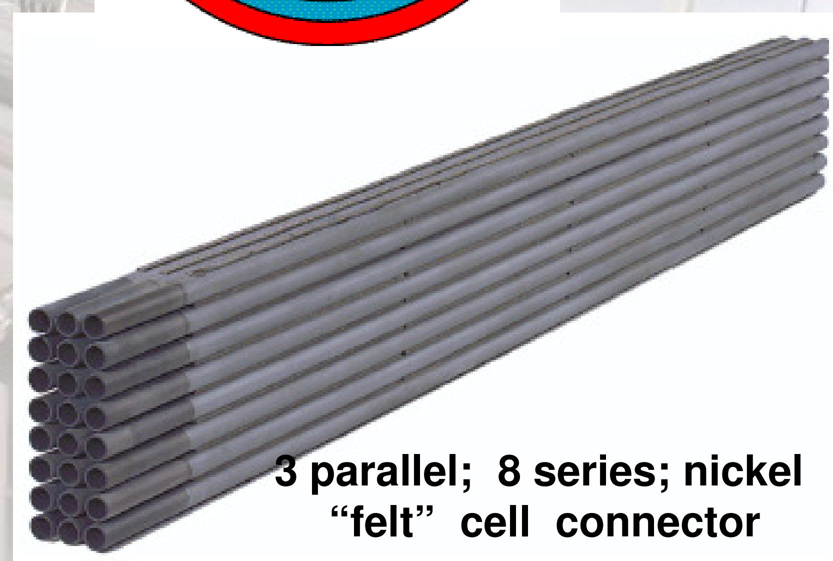
Air Electrode Supported Tubular SOFC

130 kWe DC @ 1 atm

180 kWe DC @ 3.8 atm

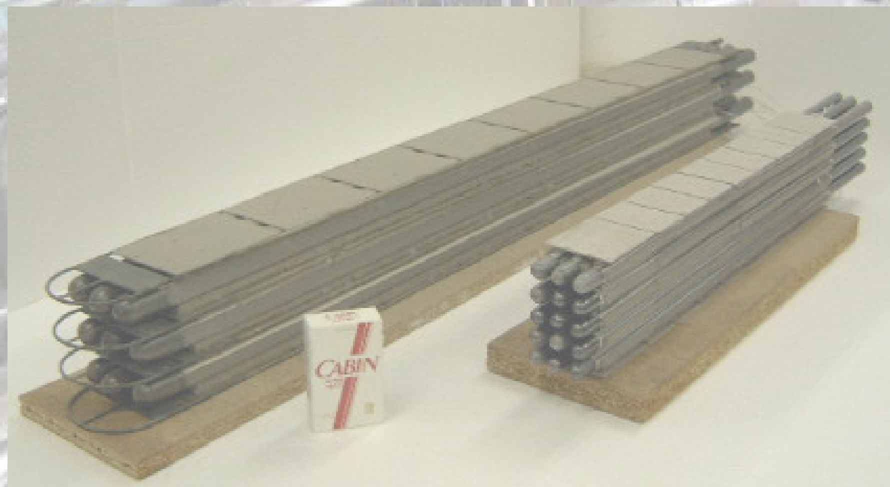






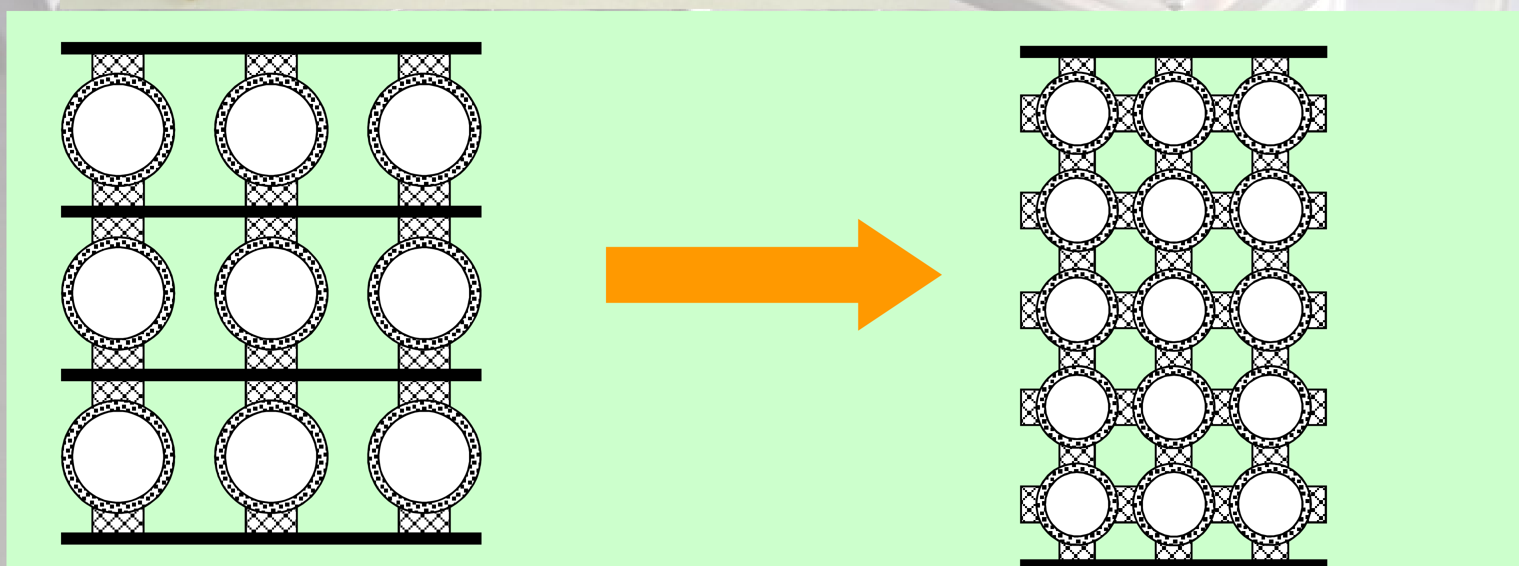
SOFC HS Based on Tubular Cells (2/7)

✓Cell details (2/3)



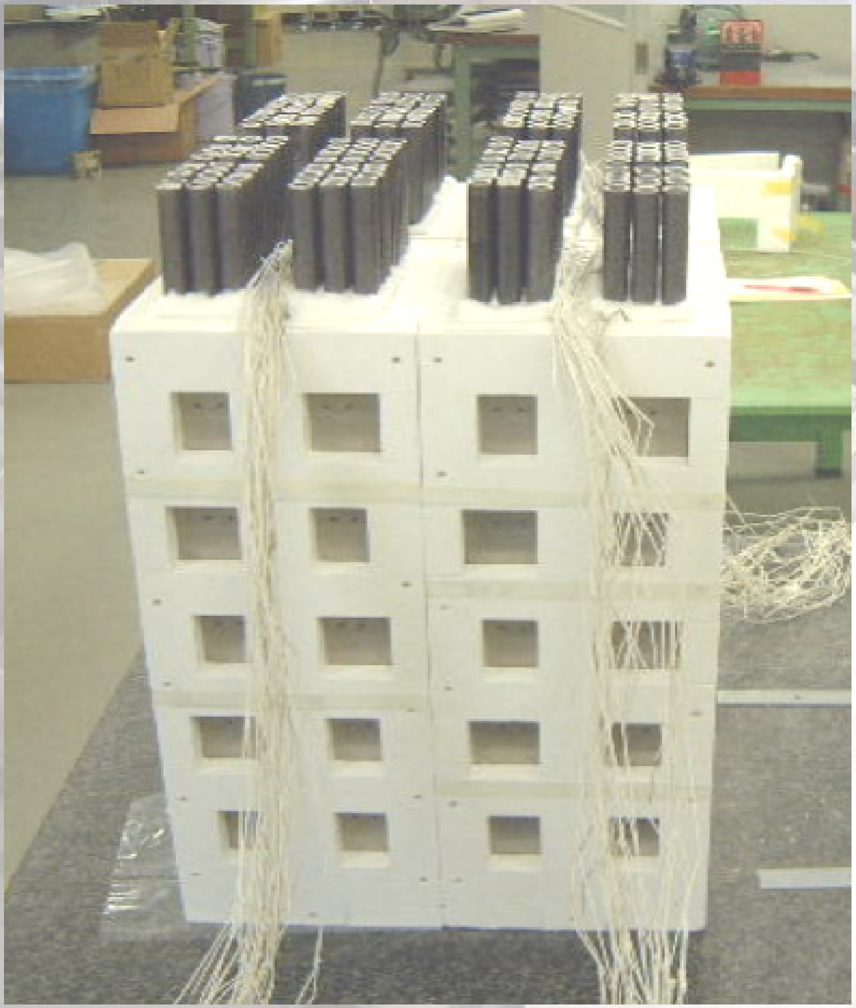
NEW BUNDLE

5 Series ∗ 3 Parallel



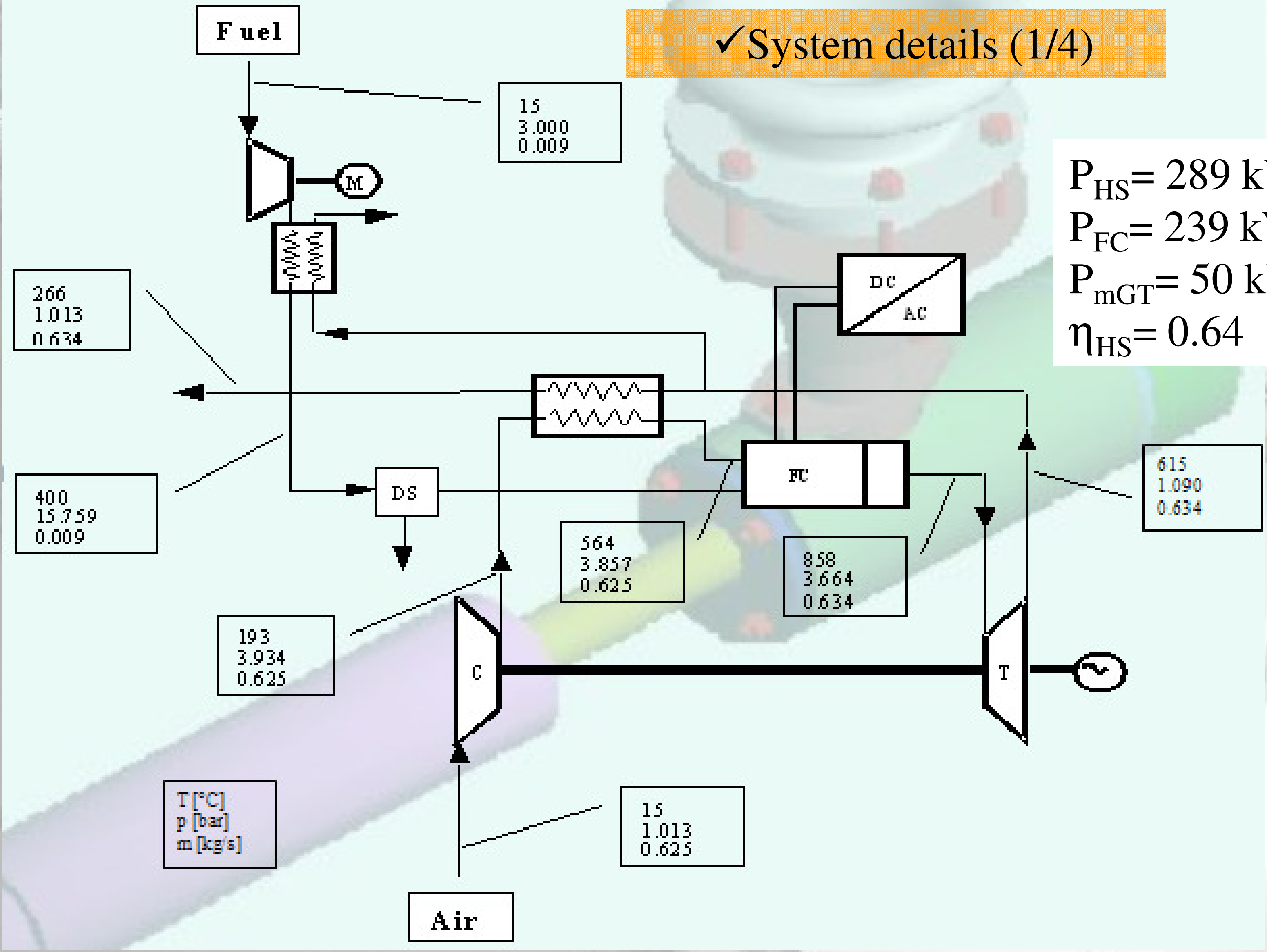
SOFC HS Based on Tubular Cells (3/7)

✓Cell details (3/3)



SOFC HS Based on Tubular Cells (4/7)

✓System details (1/4)



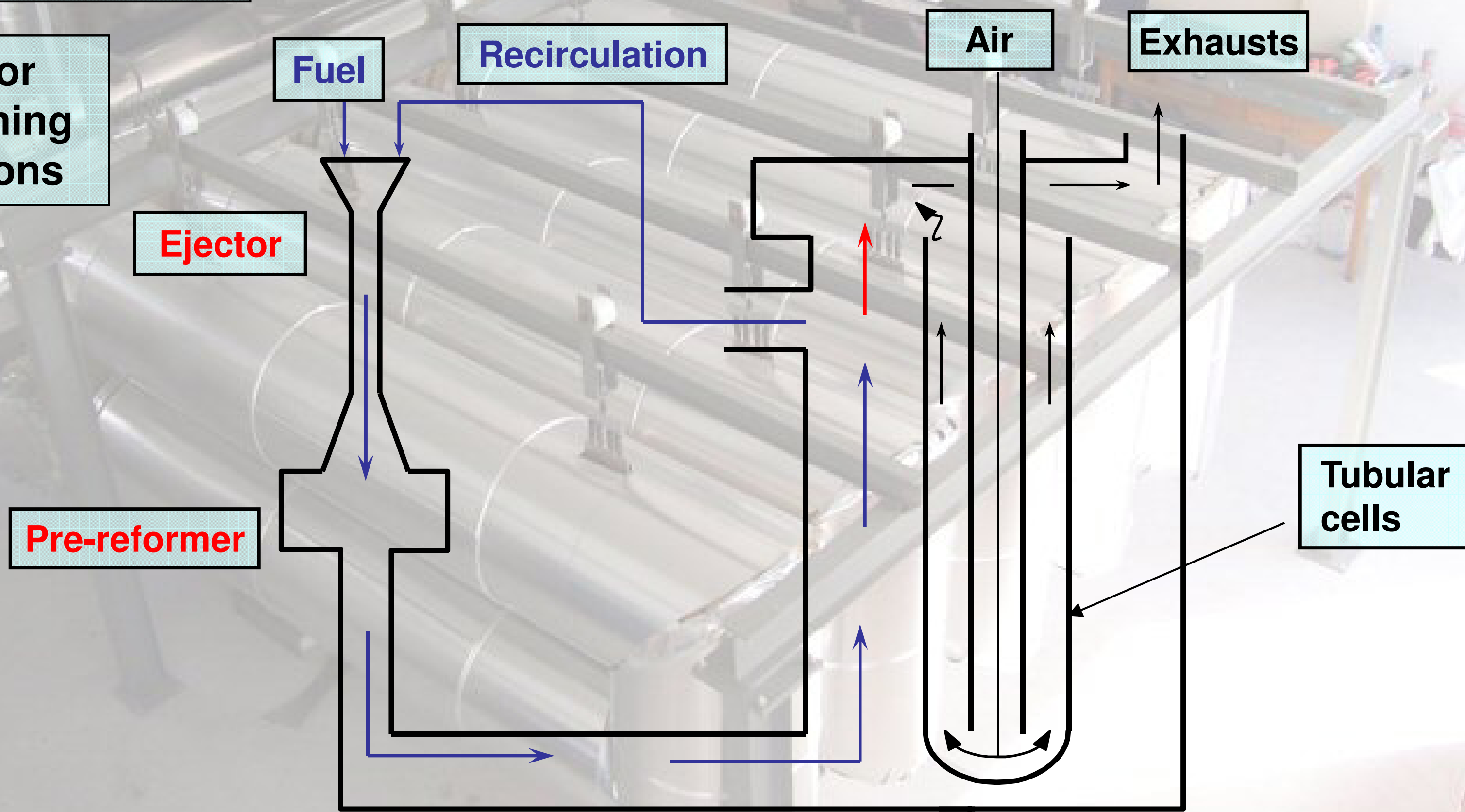
P_{HS}= 289 kW
P_{FC}= 239 kW
P_{mGT}= 50 kW
η_{HS}= 0.64

SOFC HS Based on Tubular Cells (5/7)

✓System details (2/4)

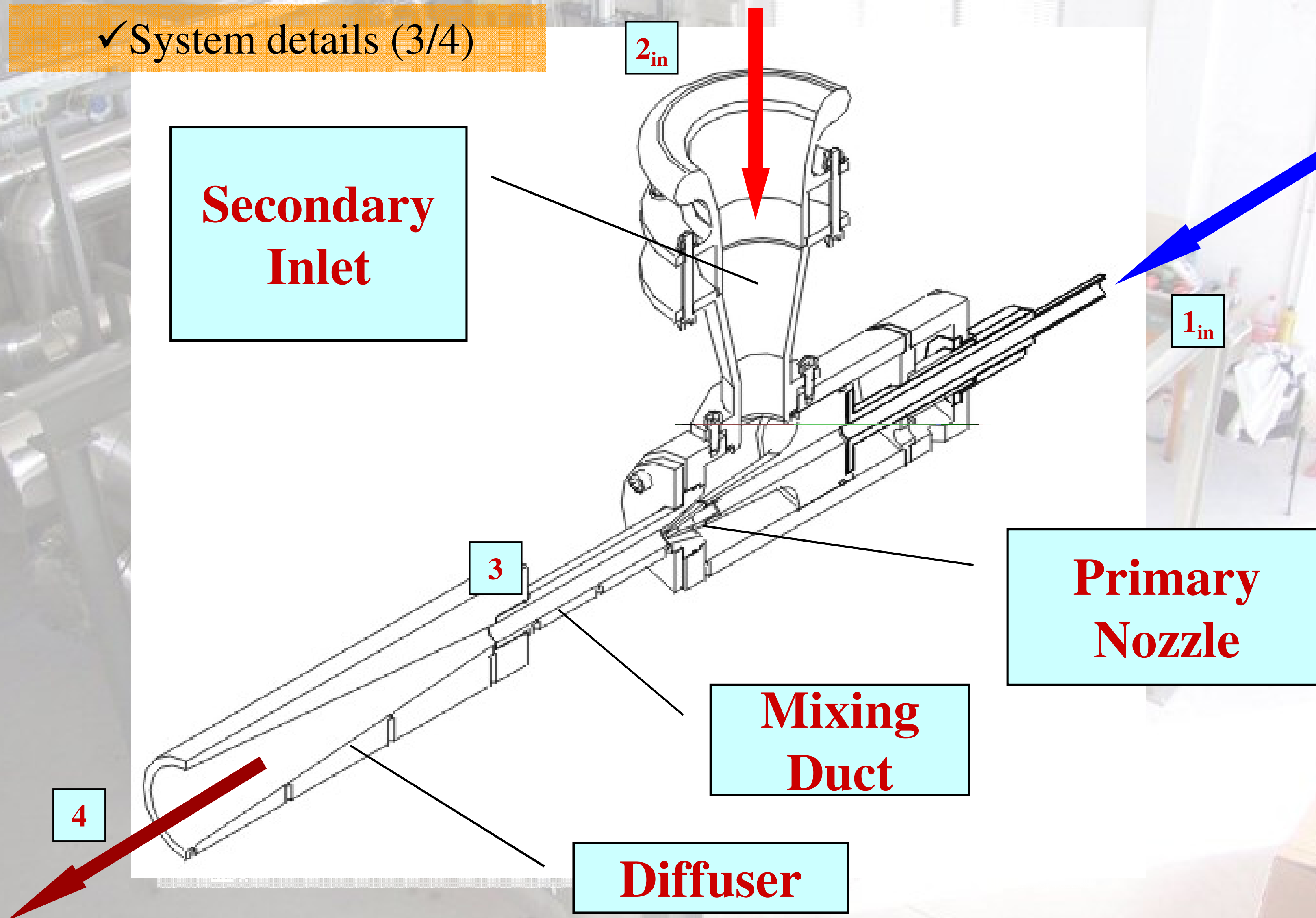
$$STCR = \frac{nH_2O}{nCO + nCH_4}$$

Heat for reforming reactions



SOFC HS Based on Tubular Cells (6/7)

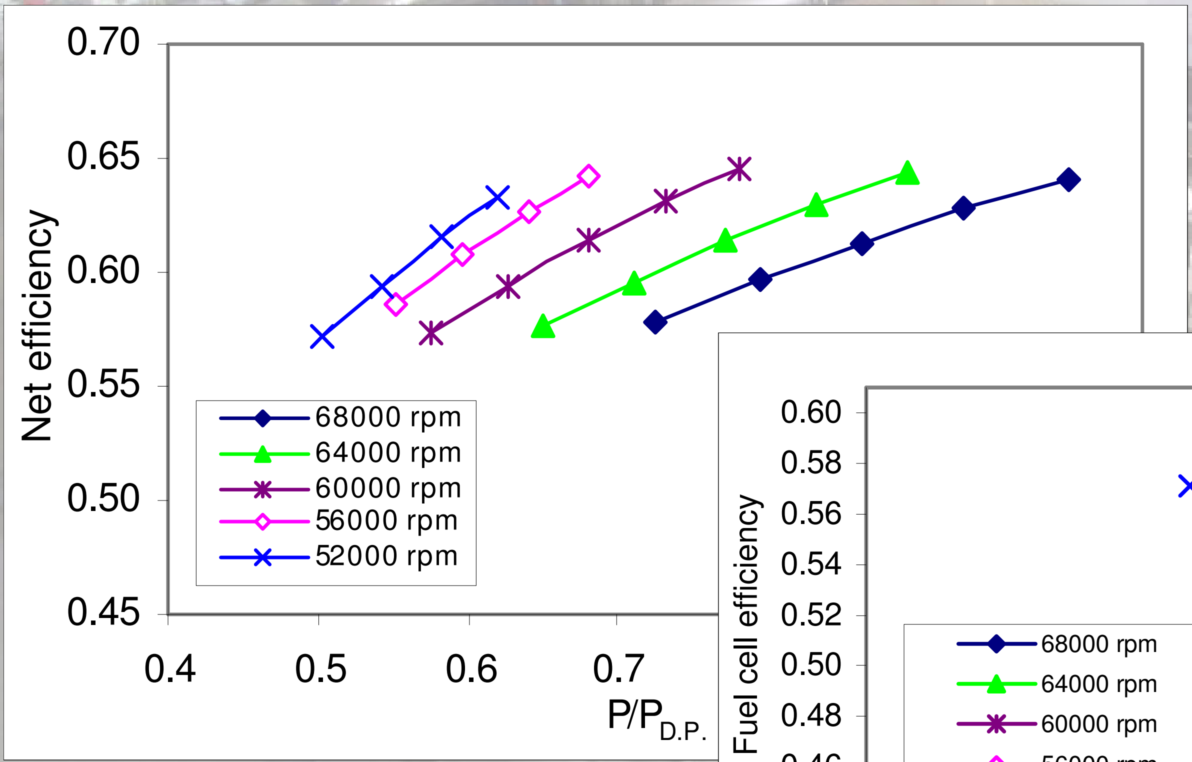
✓System details (3/4)



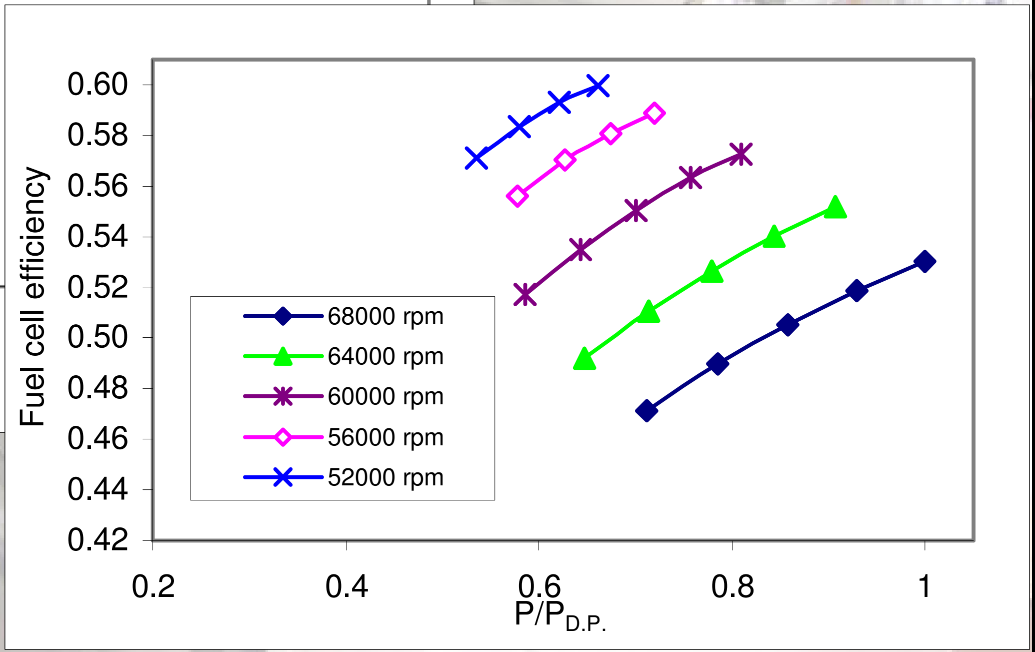
SOFC HS Based on Tubular Cells (7/7)

✓System details (4/4)

Part-Load analysis



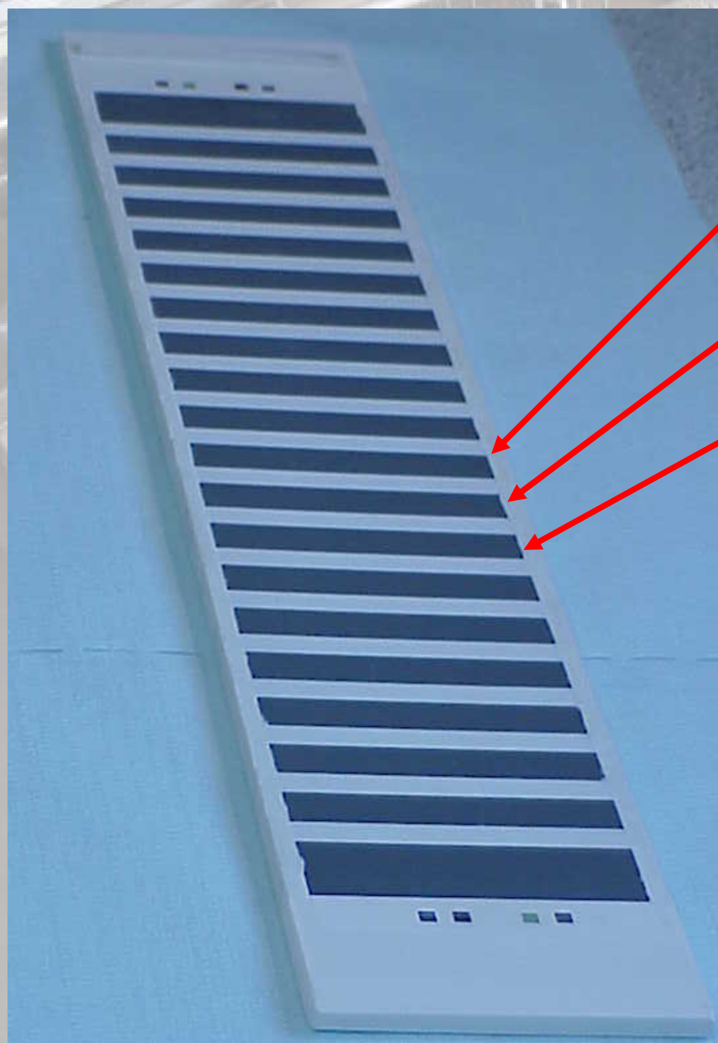
Plant Net Efficiency

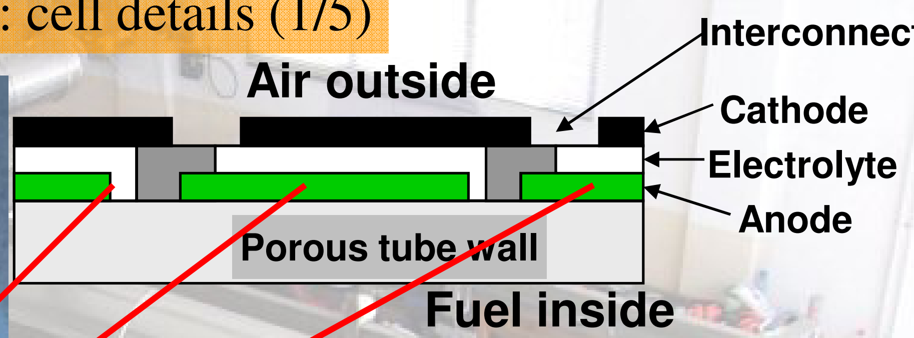


SOFC Efficiency

SOFC HS Based on Flattened Cells (1/8)

✓Rolls-Royce Fuel Cell Systems: cell details (1/5)



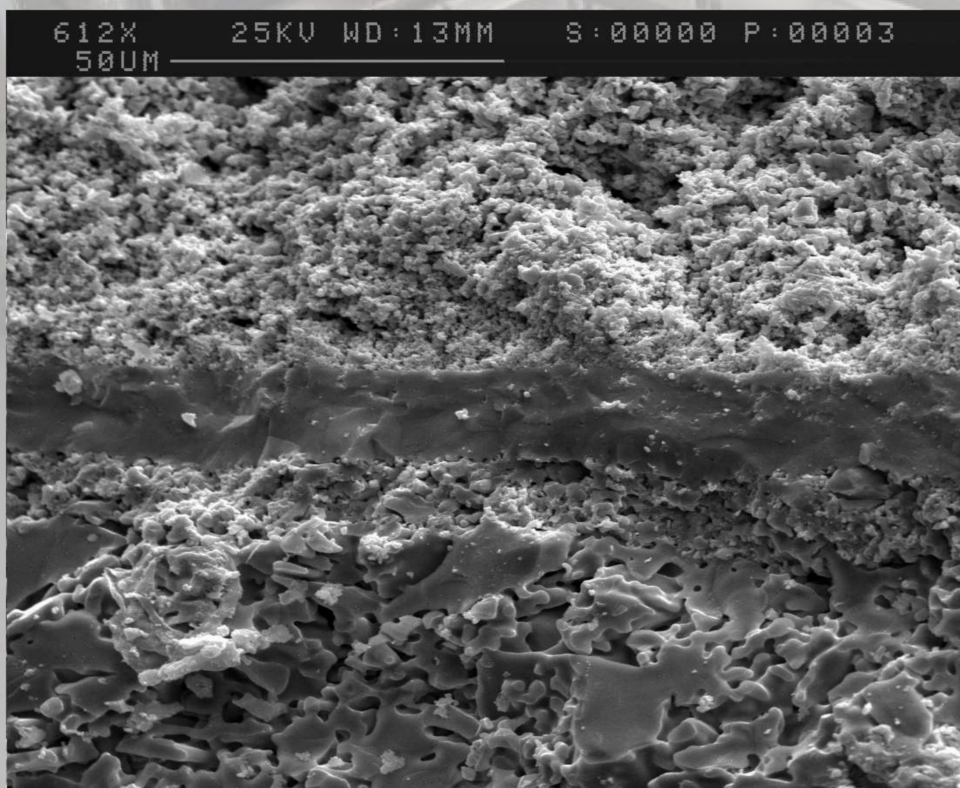


Section through one wall of tube

- Series connected cells
  - Give low currents and high voltages
  - Enable reduction in material used (cf HV distribution lines)
- Structural support is cheap inactive material
  - Avoids cost of high purity active material for bulk quantities
  - All active materials in thin layers

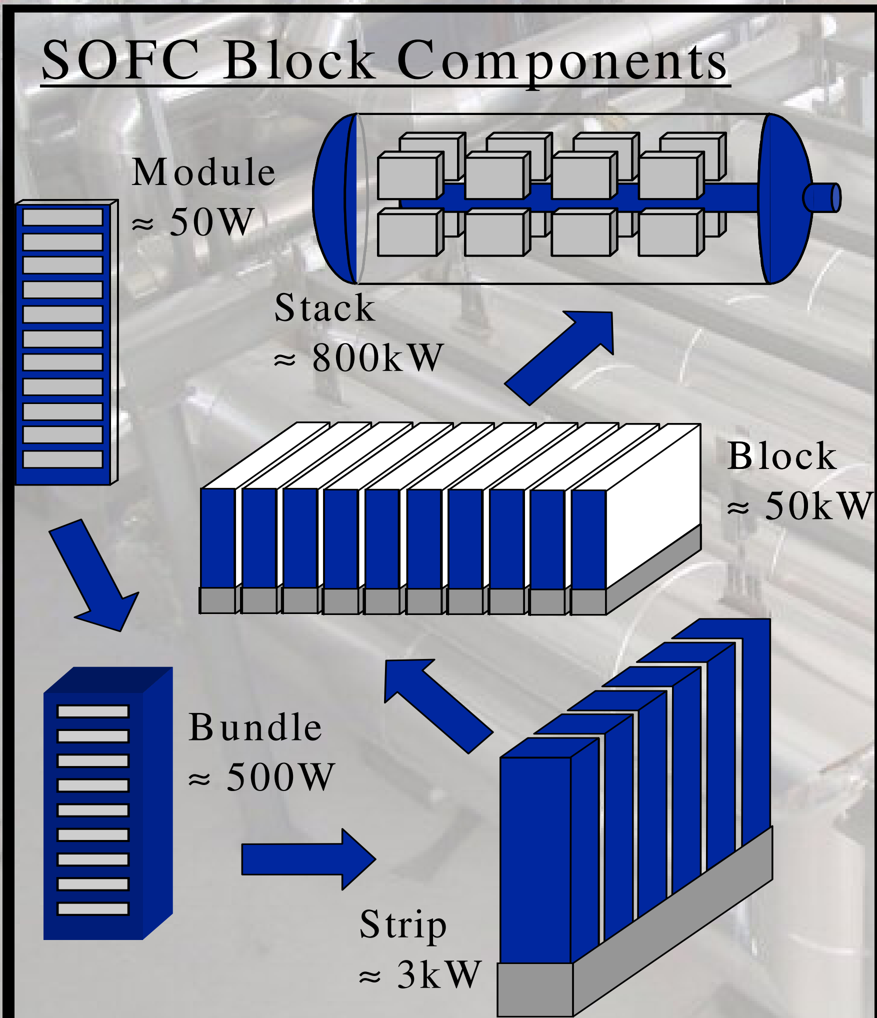
SOFC HS Based on Flattened Cells (2/8)

✓Rolls-Royce Fuel Cell Systems: cell details (2/5)



SOFC HS Based on Flattened Cells (3/8)

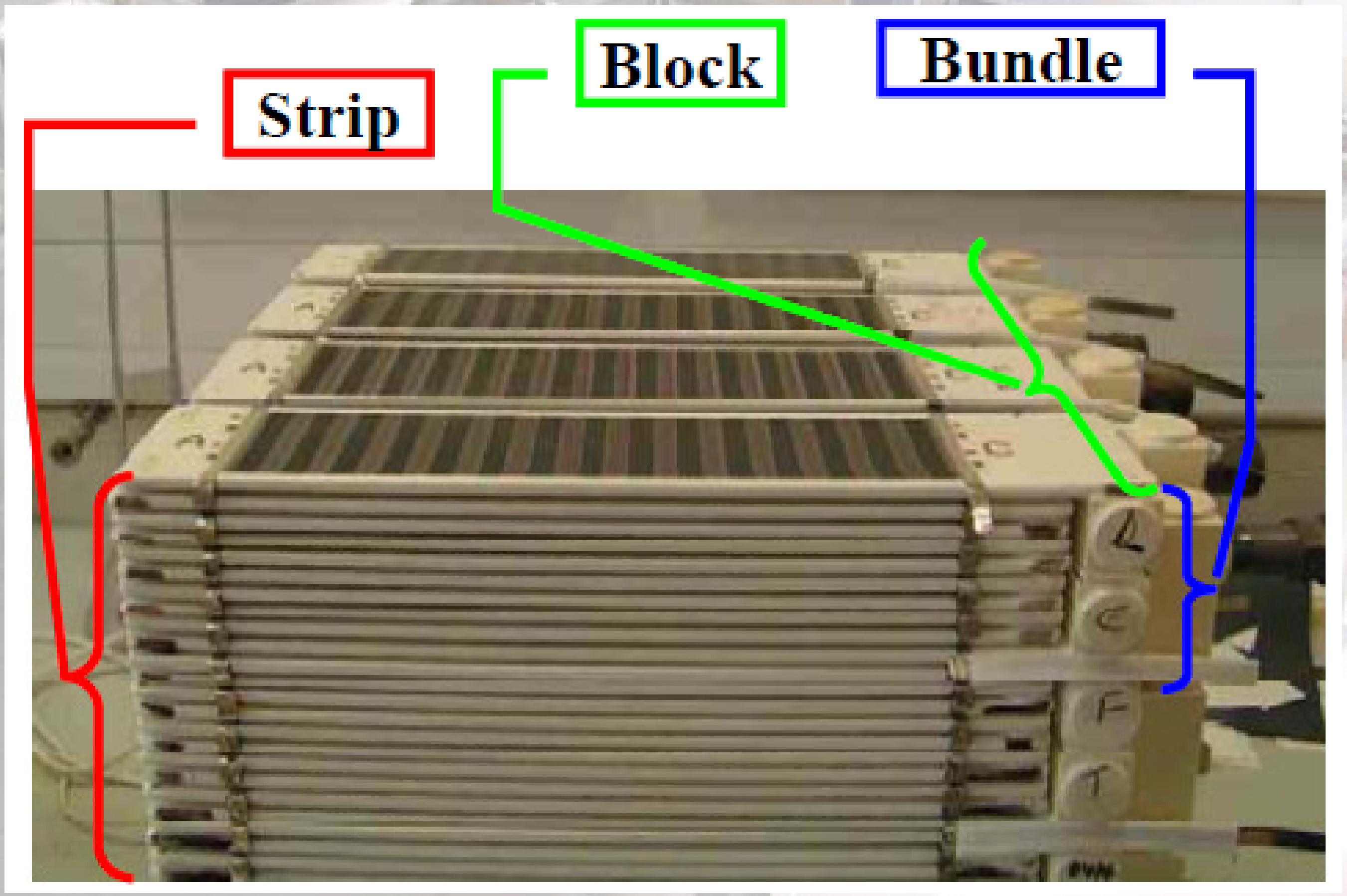
✓Rolls-Royce Fuel Cell Systems: cell details (3/5)



- **Module arrangement allows for thermal expansion compliance**
- **Modular stack design allows scale up to multi-megawatt range using the same basic building blocks**
- **Design allows for flexibility in fuel processing options**
- **The use of high temperature pressurised SOFC plays to Rolls-Royce technical strengths**

SOFC HS Based on Flattened Cells (4/8)

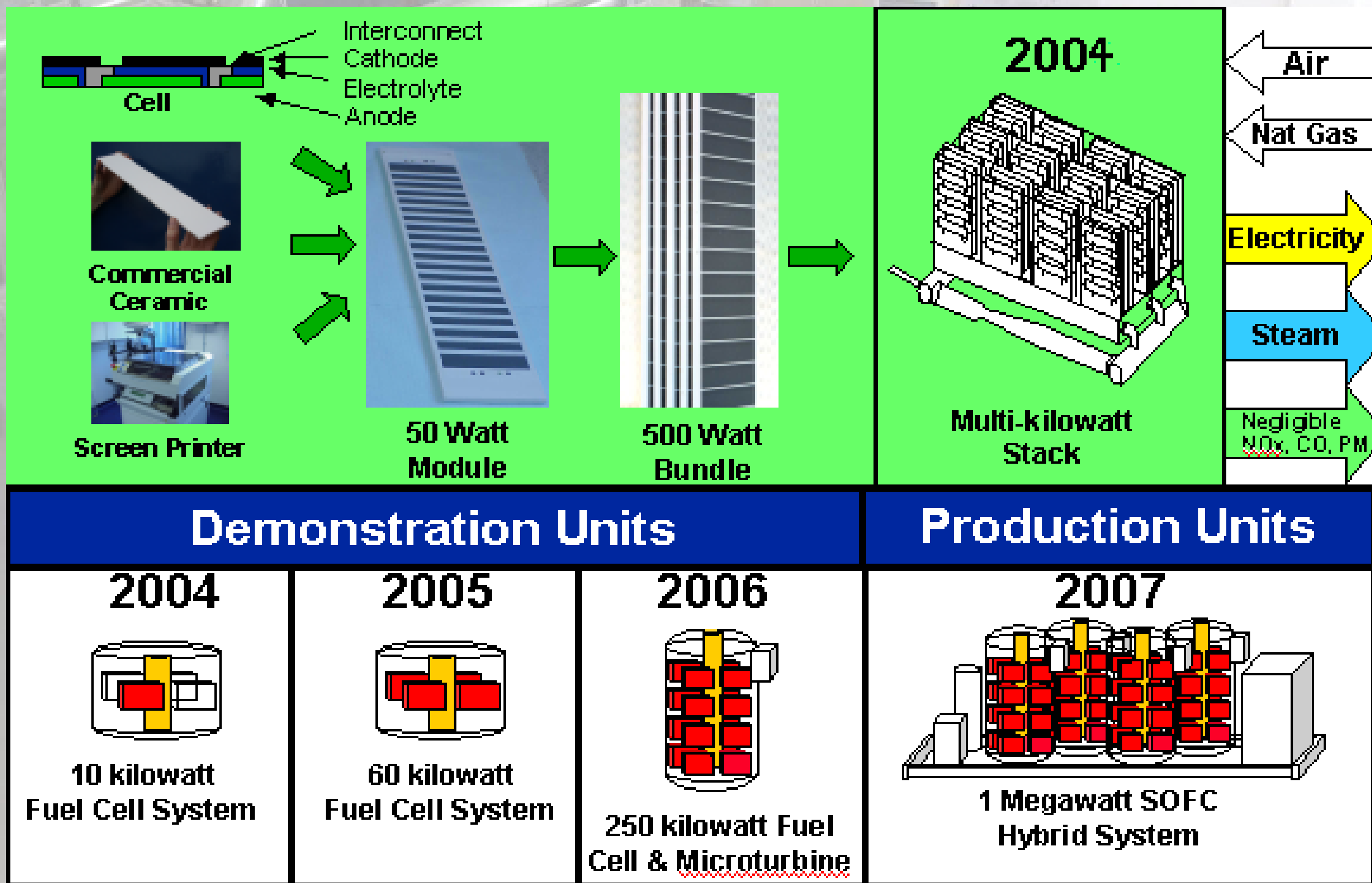
✓Rolls-Royce Fuel Cell Systems: cell details (4/5)



SOFC HS Based on Flattened Cells (5/8)

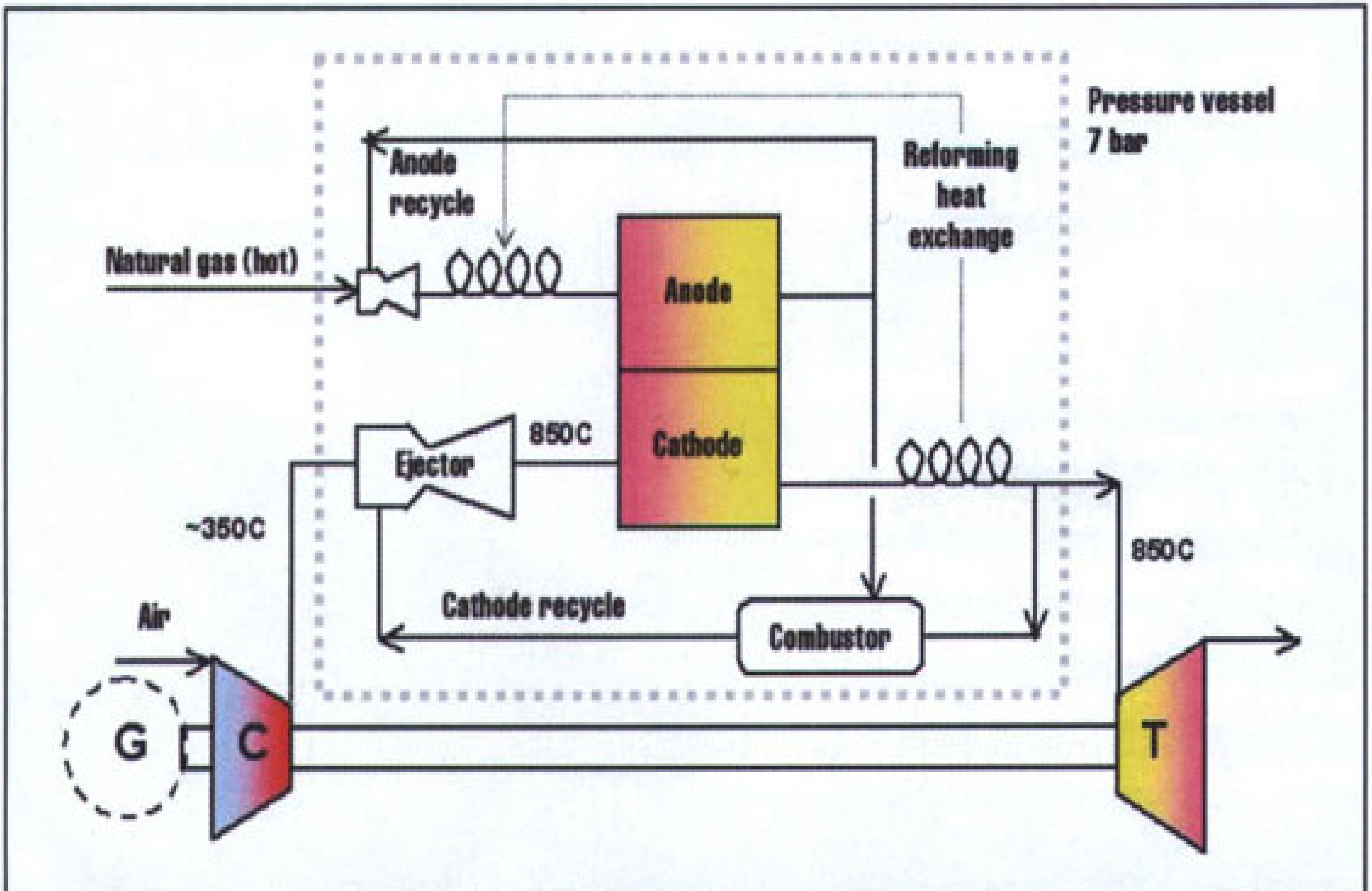
✓Rolls-Royce Fuel Cell Systems: cell details (5/5)

Development plan *(Integrated Planar SOFC)*



SOFC HS Based on Flattened Cells (6/8)

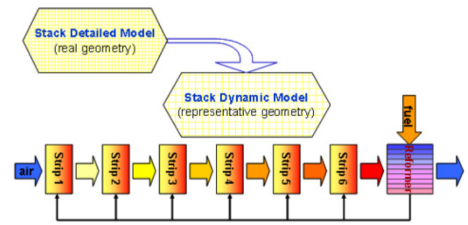
✓Rolls-Royce Fuel Cell Systems: plant details (1/3)

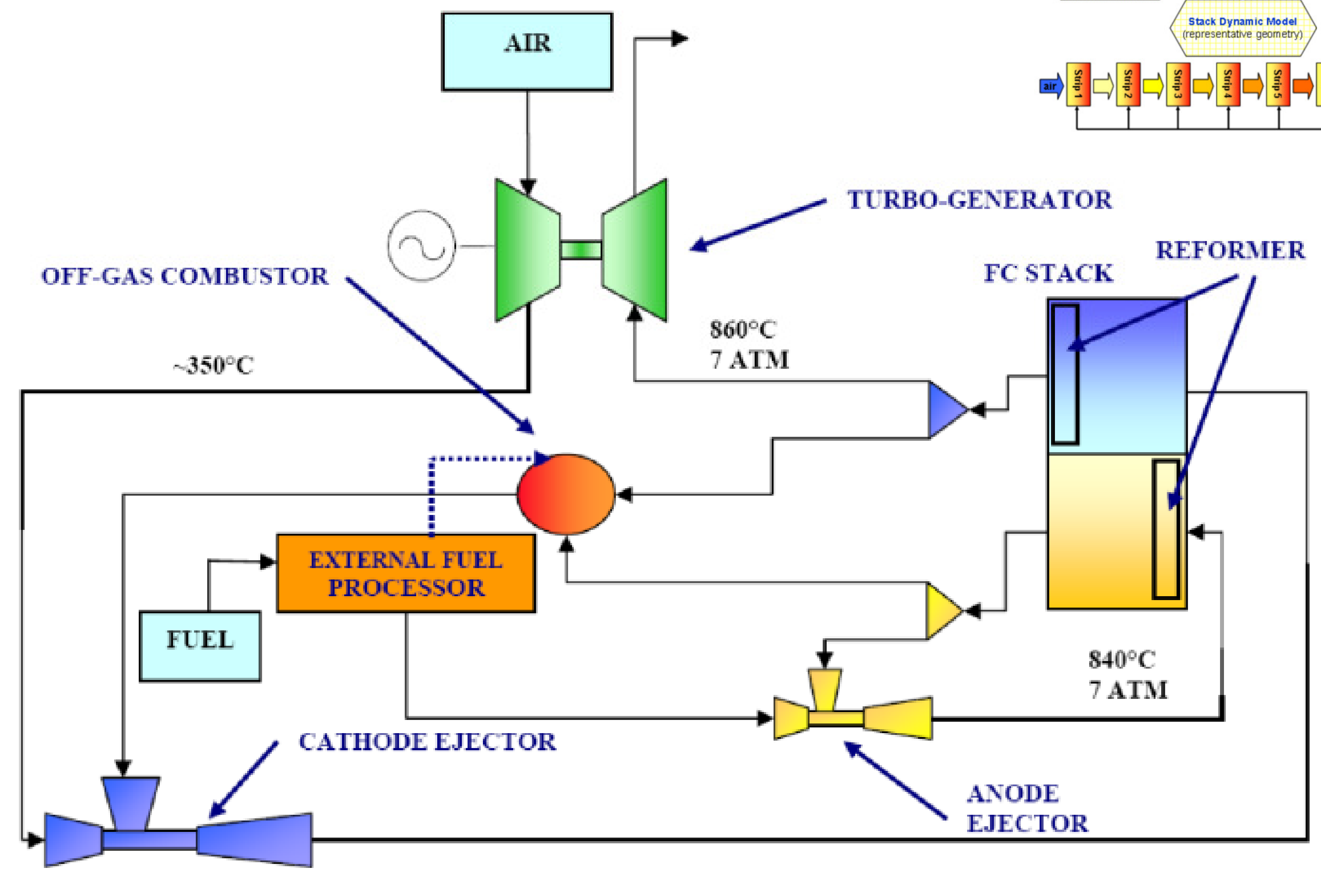


Rolls-Royce's novel solution: the heat-exchanger-less SOFC hybrid cycle. The system is pressurised to 7 bar

SOFC HS Based on Flattened Cells (7/8)

✓Rolls-Royce Fuel Cell Systems: plant details (2/3)





SOFC HS Based on Flattened Cells (8/8)

✓Rolls-Royce Fuel Cell Systems: plant details (3/3)