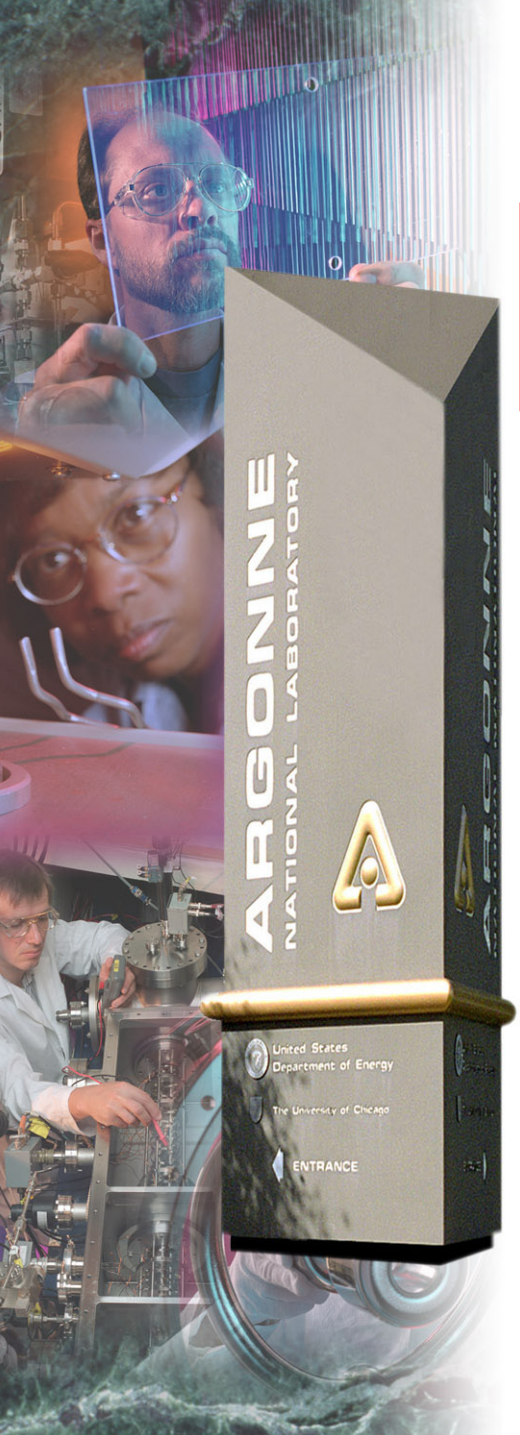

Startup of PEFC Stacks From Sub-Freezing Temperatures

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Start-up Time and Energy Consumption

Start-up Time: Time to place the FCS in a state where it is capable of producing rated power on demand.

- Achieving rated efficiency at rated power not a criterion
- Time may depend on the start-up event

Start-up Energy Consumption: Fuel energy consumed by the FCS in excess of the energy consumed if the FCS was at normal operating temperatures.

- Includes energy consumed when the vehicle is parked
- If energy stored in battery is used during or prior to the start-up event it must be translated into fuel energy.

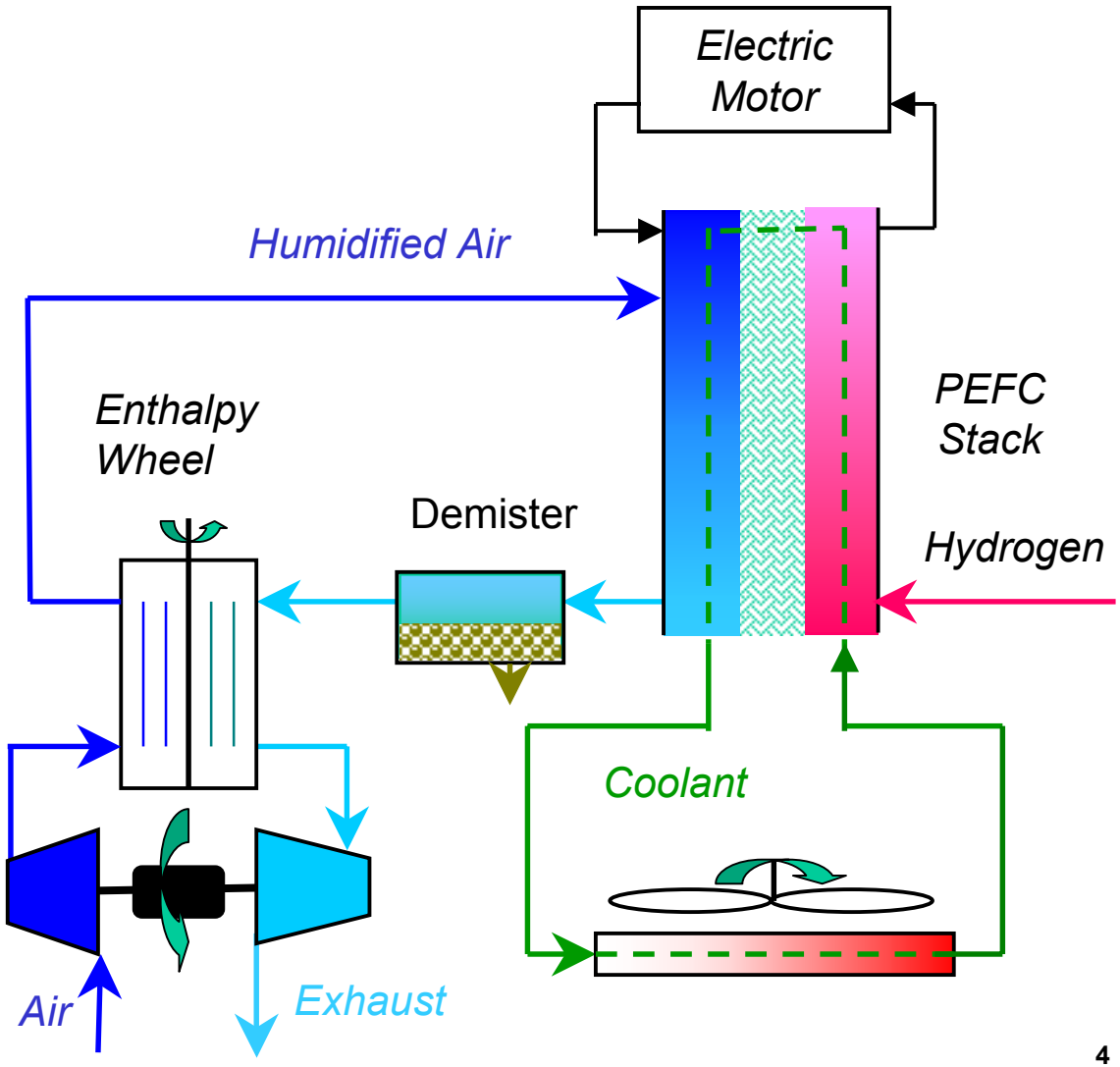
Start-up Methods

1. Self (IR) heating of stacks
2. Internal oxidation of hydrogen on MEA catalyst
3. External combustion of hydrogen
4. Insulated stack with electrical heating
5. Insulated coolant tank with electrical heating

Pressurized FCS with Enthalpy Wheel Humidifier

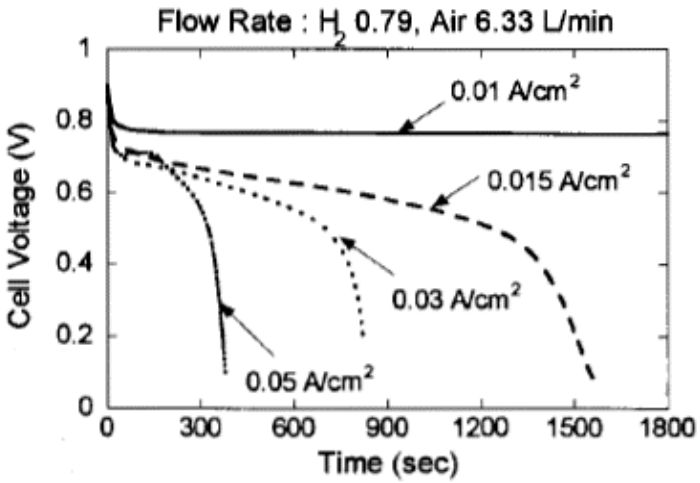
FCS for hybrid family sedan
- 80 kW FCS + 40 kW ESS
- 50% FCS efficiency at rated power
- 50% O_2 utilization
- 0.7 V at design point
- 1000 W/L energy density
- 1000 W/kg specific power

CEM
- 2.5 atm at rated power
- 91 g/s rated flow
- Motor can be overloaded for 30 s
- 120% of design flow possible

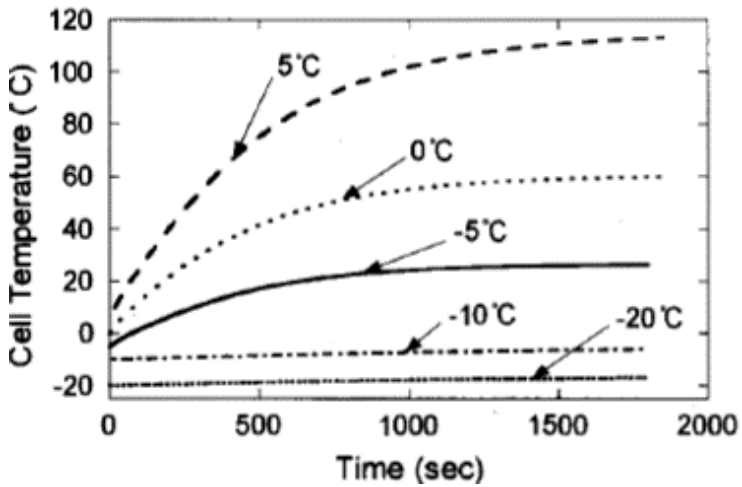


Self-Heating From Sub-Freezing Temperatures

- Japanese study* on single cell, 104-cm^2 MEA, 1-2 atm
- At -3 to -25^{o}C, cell performance decreases at higher current density and pressure and lower temperature.
- Self heating is feasible above -5^{o}C (Threshold T_1): Balance between heat generated by cell reaction, heat convected with flowing gases and loss of ECSA due to ice formation



Cell voltage at -10°C



Start-up at various temperatures

* Y. Hishinuma, T. Chikahisa, F. Kagami and T. Ogawa, "The Design and Performance of a PEFC at a Temperature Below Freezing", JSME International Journal, 47, 2004, p235~241.

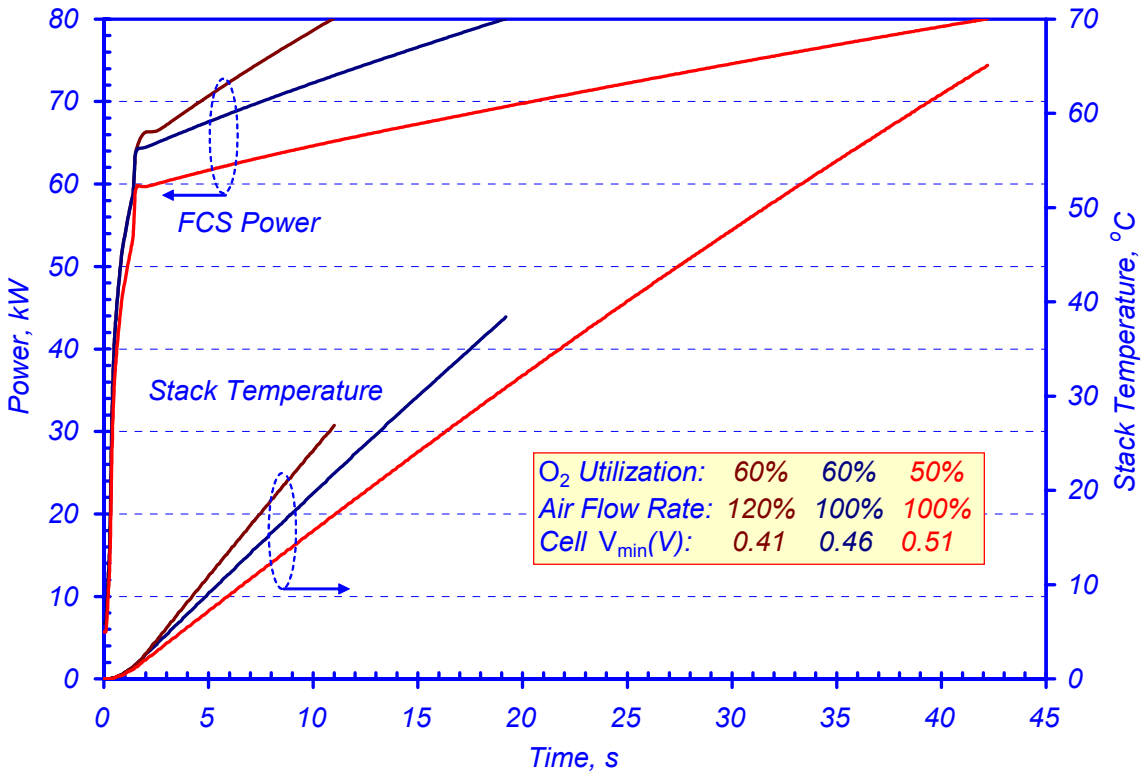
Self-Heating Above Freezing Temperatures

GCtool simulations to determine the stack temperature (T_2) at which the FCS can produce rated power at higher than design-point O_2 utilization

Stack Temperature	O_2 Utilization	Air Flow Rate	Cell Voltage	FCS Efficiency
80°C	50%	100%	0.70 V	50%
40°C	60%	100%	0.55 V	40%
28°C	60%	120%	0.48 V	35%

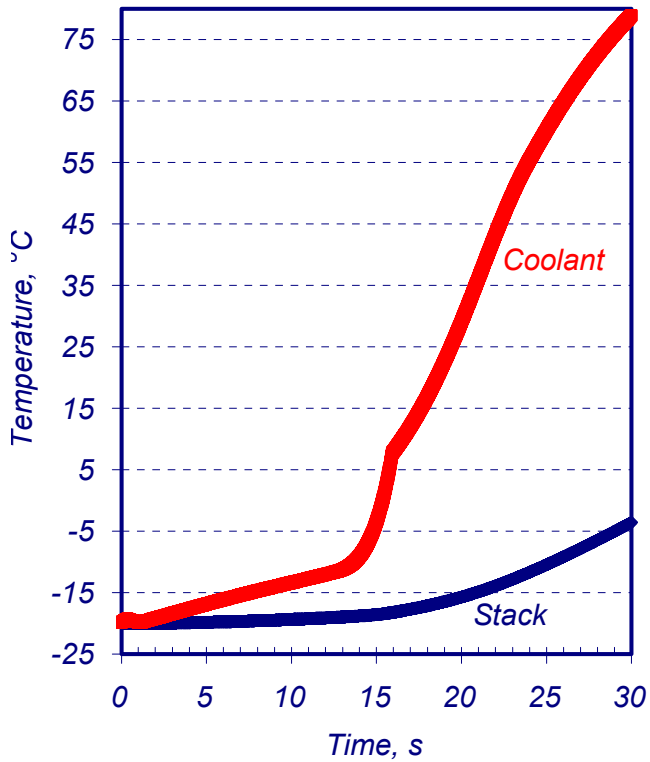
Start-Up Time For Self-Heating Above Threshold Temperature (0°C)

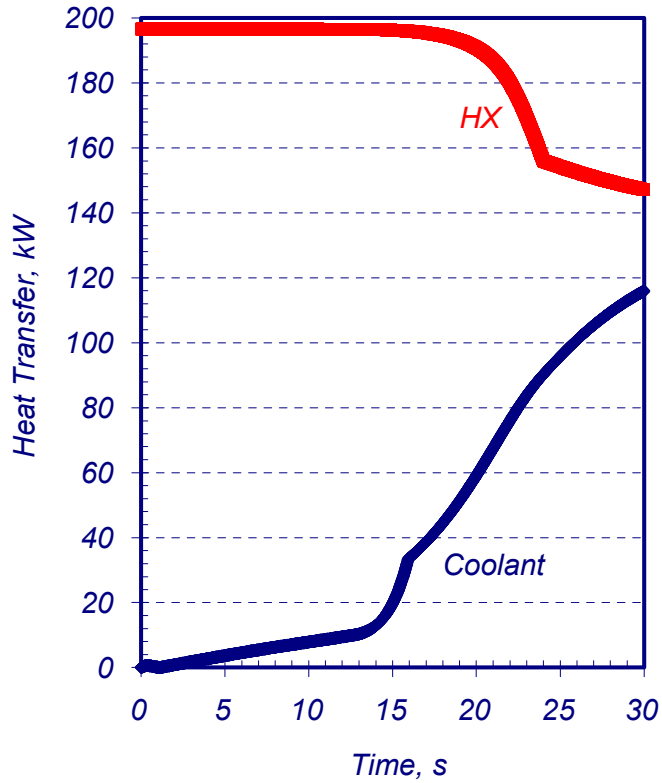
- ~2 s for CEM to reach 97.5 krpm, ~3 s for 110 krpm.
- Minimum start-up time: 40 s at 50% O_2 utilization & 100% air flow; 20 s at 60% O_2 utilization; 10 s at 120% air flow
- Fuel energy consumed in heating stack from T_1 to T_2: 1-1.3 MJ



Stack Heating to Threshold Temperature External H_2 Burner

- Need a compact HX, probably of microchannel design, 10 kg estimated mass
- 1.4 MJ required to heat the stack from -20°C to 0°C.
- Stack heat up is slow and ineffective (5.6 MJ of fuel energy)





Stack Heating to Threshold Temperature Internal Oxidation of H_2 on MEA Catalyst

- Maximum H_2 concentration in the cathode air ~0.5-3.5%
- Maximum O_2 concentration in the anode H_2 ~1-7%
- Peak turbine inlet temperature 250°C

Cathode		Anode		Stack
H_2 Volume %	Adiabatic Temperature	O_2 Volume %	Adiabatic Temperature	Heat-up Time
0.5	20°C			335 s
2.0	145°C			84 s
3.5	270°C			46 s
3.5	270°C	2	315°C	44 s
3.5	270°C	5	810°C	40 s
3.5	270°C	7	1130°C	35 s

Stack Heating to Threshold Temperature Insulated Stack with Electrical Heating

- 1” insulation, 0.05 W/m.K
- Stack cools from 80°C to 0°C in 13-25 h
- A 40-kW hybrid battery maintains stack at 0°C for 6-24 h

Ambient Temperature	Cool-Down Time to 0°C	Heat Loss at 0°C
-10°C	25 h	20 W
-20°C	19 h	40 W
-40°C	13 h	80 W

- Periodically operate FCS for ~4 min at 25% power
  - ✓ Recharge the battery (480 W.h)
  - ✓ Excess power (60%) to electrical heaters
  - ✓ Heat the stack from 0 to 80°C
  - ✓ 5.3 MJ/day fuel energy consumption at -20°C ambient

Stack Heating to Threshold Temperature Insulated Coolant Tank with Electrical Heating

- 1” insulation, k = 0.05 W/m.K
- A 5-gallon tank at 40°C heats stack to 0°C in 5-25 s
- Tank cools from 70°C to 40°C in 12-18 h
- A 40-kW hybrid battery maintains tank at 40°C for 11-18 h

Ambient Temperature	Time for Tank to Cool to 40°C	Heat Loss from Tank at 40°C	Time to Heat Stack to 0°C
-10°C	18 h	27 W	5 s
-20°C	16 h	32 W	10 s
-40°C	12 h	43 W	25 s

- Periodically operate FCS for ~6 min at 25% power
  - ✓ Recharge the battery (480 W.h)
  - ✓ Excess power (75%) to reheat the tank to 70°C
  - ✓ 9.1 MJ/day fuel energy consumption at -20°C ambient

Current Work

Modifying stack model to simulate transients

- Formation of ice
- Effect of ice on reaction kinetics

Need data to validate the stack model at sub-freezing temperatures

- Membrane conductivity
- Electrocatalyst activity
- Experimental polarization curves for single cells