High Efficiency Approaches to Coal Syngas Use in Fuel Cell Systems with CO_2 Isolation

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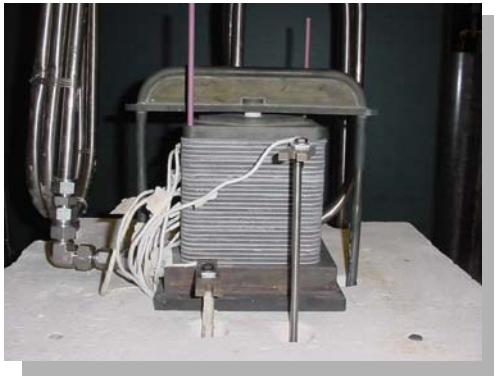
Background

- **SOFC fuel cells generate electricity and "high-grade" heat.**

- **SOFCs can *<u>inherently</u>* separate CO_2 using anode isolation.**

- **The separate anode/cathode flows have unique opportunities to use rejected heat:**
  - Is there a way to use the high-grade heat to assist the CO_2 compression for sequestration?
  - Can the heat be used to recycle the anode gas?



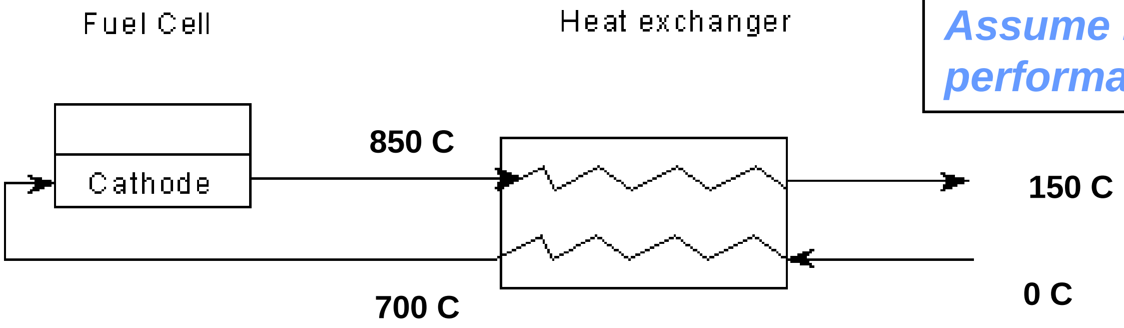
Basics of SOFC cycle

- **Cathode exit used to preheat cathode inlet**
- **Rejected heat at the exit of the heat exchanger is low grade.**

In this introduction…..

Numeric values used just for an example

Assume ideal component performance



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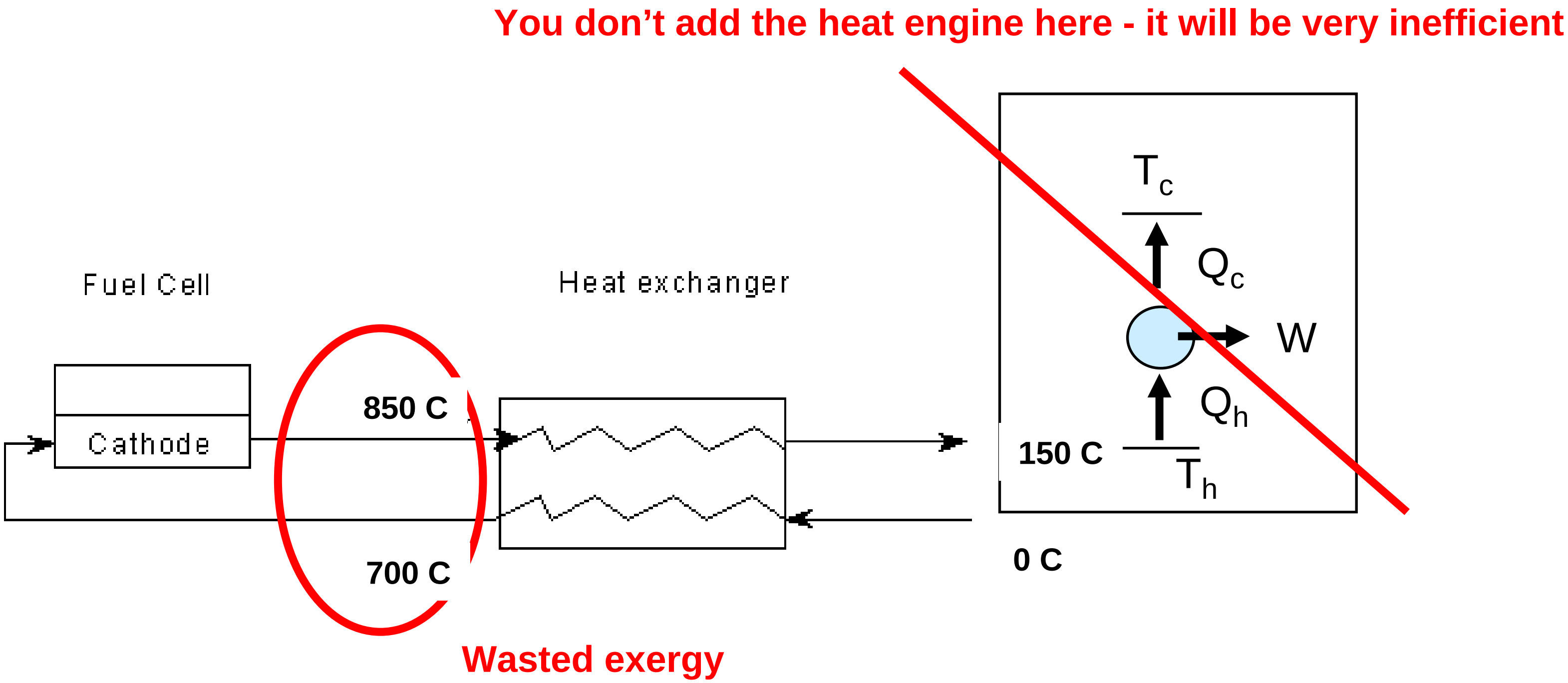


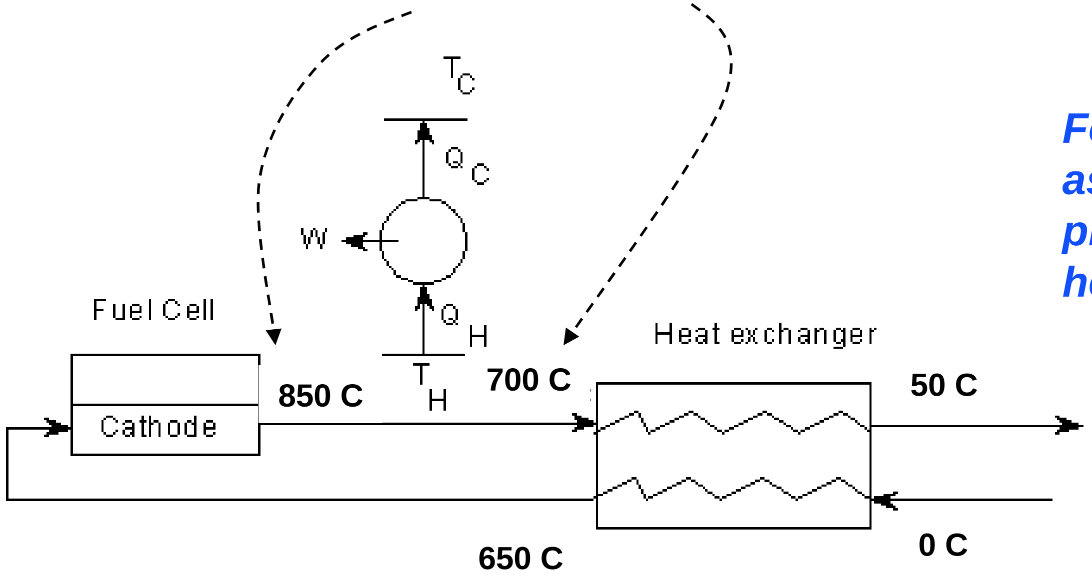
You don't add the heat engine here - it will be very inefficient

Wasted exergy

Basics of SOFC cycle

- **Ideally desired to capitalize on heat engine using the highest grade heat possible.**
- **The heat engine "uses" just the temperature rise across the fuel cell**

(i.e., in this example, 850 C to 700C)



850 C

700 C

50 C

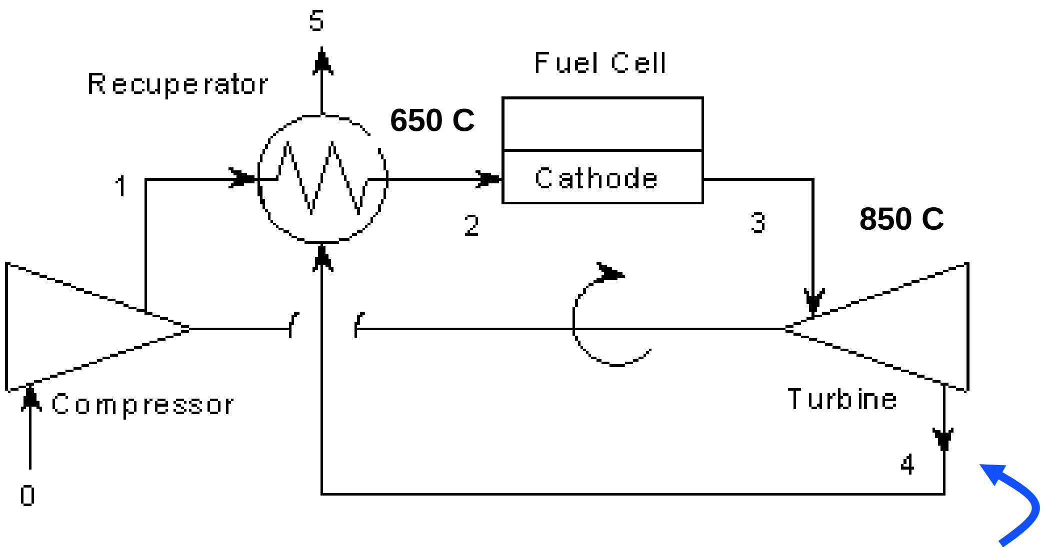
650 C

0 C

For discussion, assume 50 C pinch point on heat exchangers

Brayton Cycle Example

- **The turbine is a recuperated cycle.**
- **Note: for a recuperated cycle the efficiency is *highest* at *lower* pressure ratios.**
- **In this example – to isolate the anode – there is no combustor temperature rise.**



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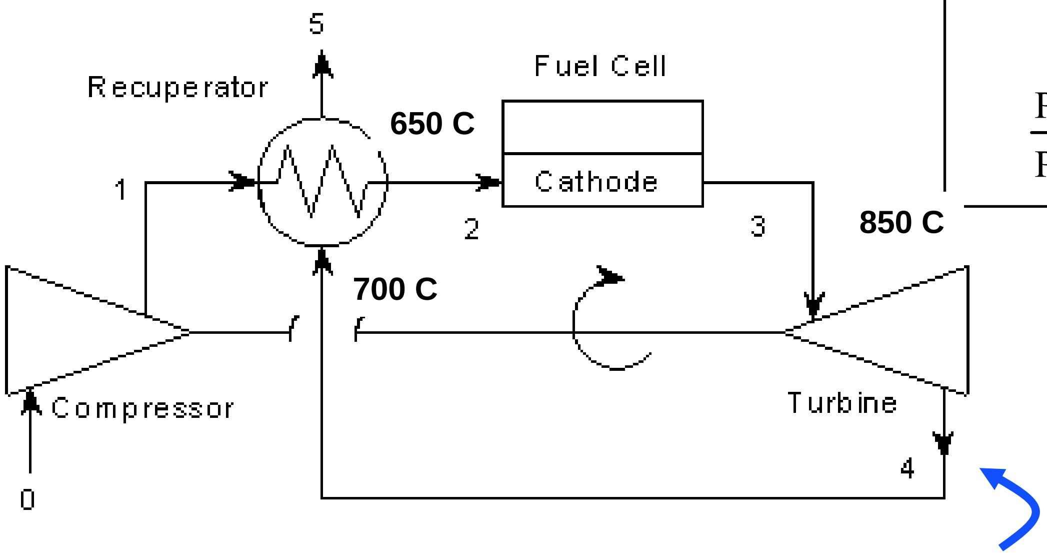
What temperature do you expand to right here?

Brayton Cycle Example

- The turbine is a recuperated cycle.
- Note: for a recuperated cycle the efficiency is ***highest*** at ***lower*** pressure ratios.
- In this example – to isolate the anode – there is no combustor temperature rise.

Required pressure ratio?

$$\frac{P3}{P4} = \left(\frac{T3}{T4}\right)^{\frac{\gamma}{\gamma-1}} = 1.7$$

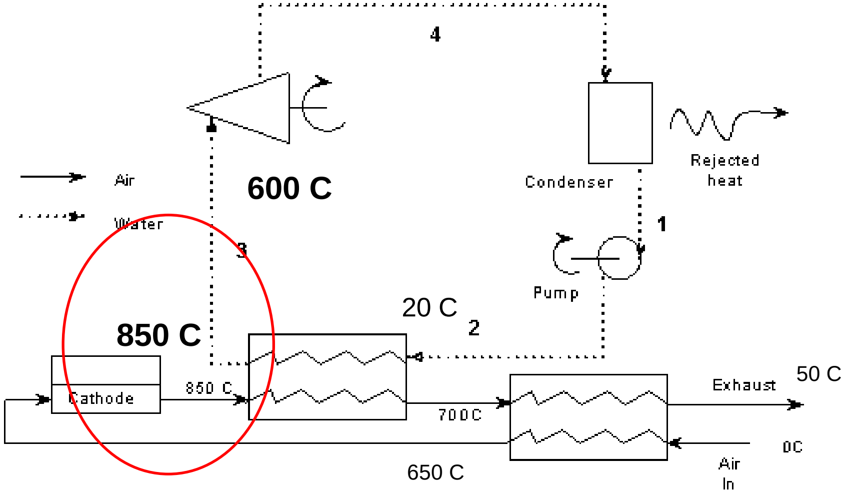


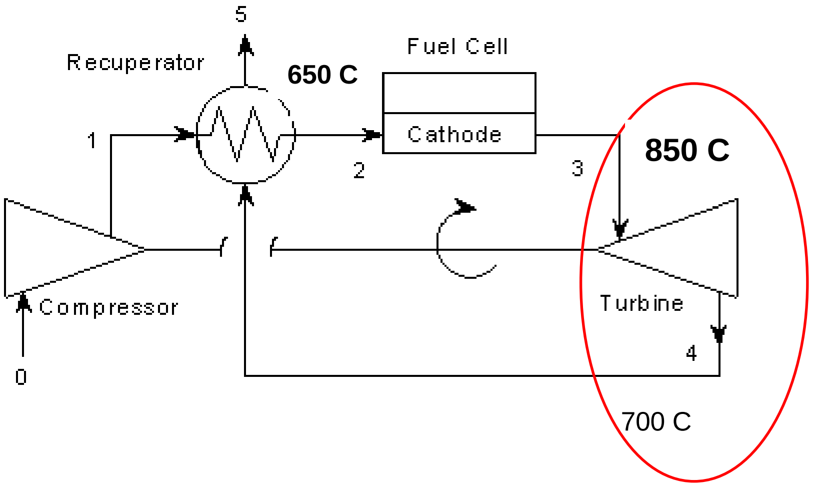
Answer:
700 C

What temperature do you expand to right here?

Comparing the bottoming cycles

- **Higher efficiency is produced by using the FC rejected heat at the full thermodynamic potential (hottest condition)**





The heat engine peak temperature Is set by the steam cycle (600 C supercritical)

The availability of the 850 C stream is reduced.

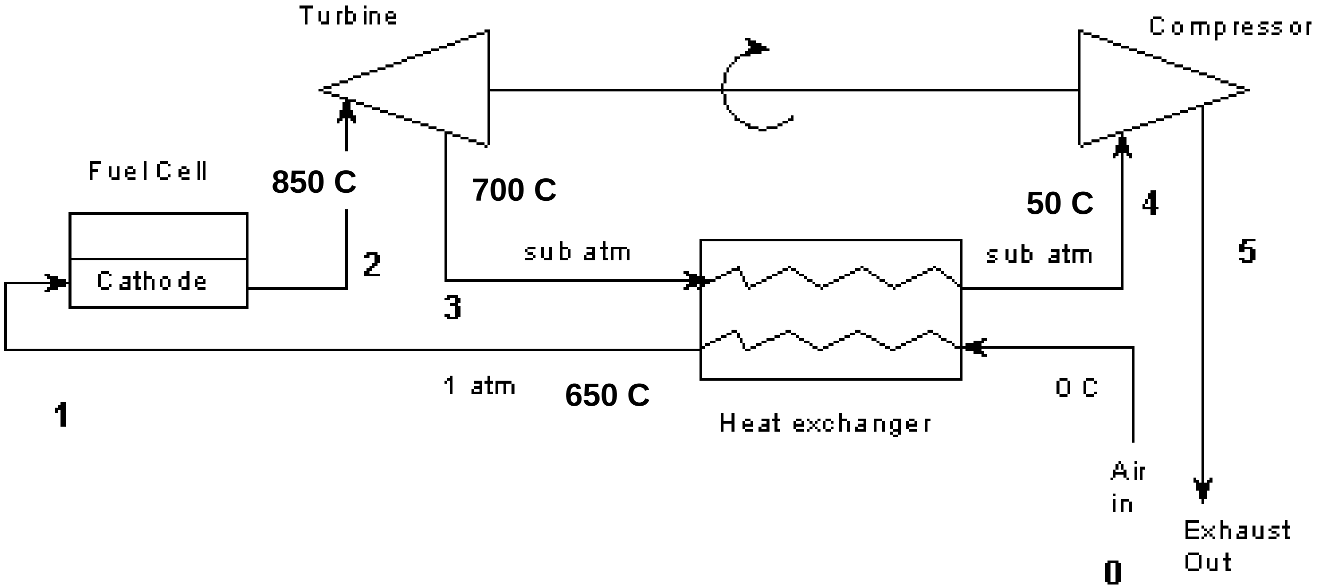
The heat engine uses the cathode Heat from 850 C to 700 C to produce work; i.e., at the full availability

850 C = 1561F, “easy” turbine condition

Brayton cycle + atmospheric pressure fuel cell

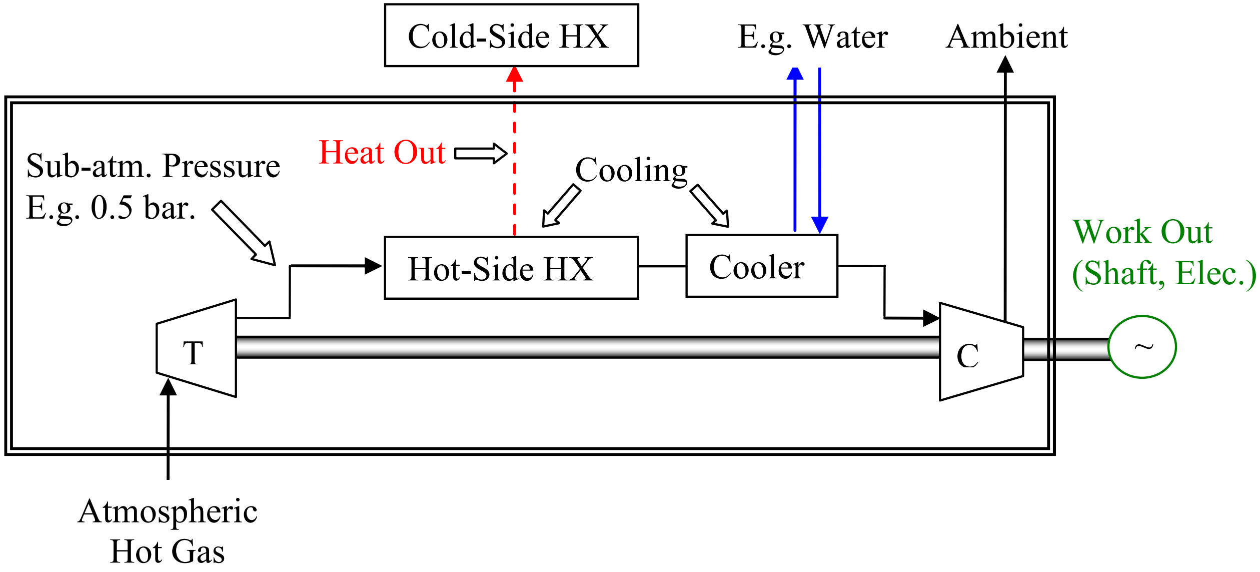
- **"Inverted" brayton cycle takes ambient pressure hot gas and expands to sub-atmospheric.**

- **IBC concept is old, but first operation very recent:**
  - **First analysis:** Hodge,J. **(1955)** "Cycles and Performance Estimation", Butterworths, London, pp. 172-174.
  - **Proposed use with SOFC:** Tsujikawa, Y., Kaneko, K., Suzuki **(2004).** "Proposal of the Atmospheric Pressure Turbine (APT) and High-Temperature Fuel Cell Hybrid System" JSME International Journal, Series B, Vol. 47, No. 2, pp. 256 – 260
  - **Operation of IBC**: K. Inoue, E. Harada, J. Kitajima, K. Tanaka**, (2006).** "Construction and Performance Evaluation of Prototype Atmospheric Pressure Turbine (APT)", ASME GT2006-90938.



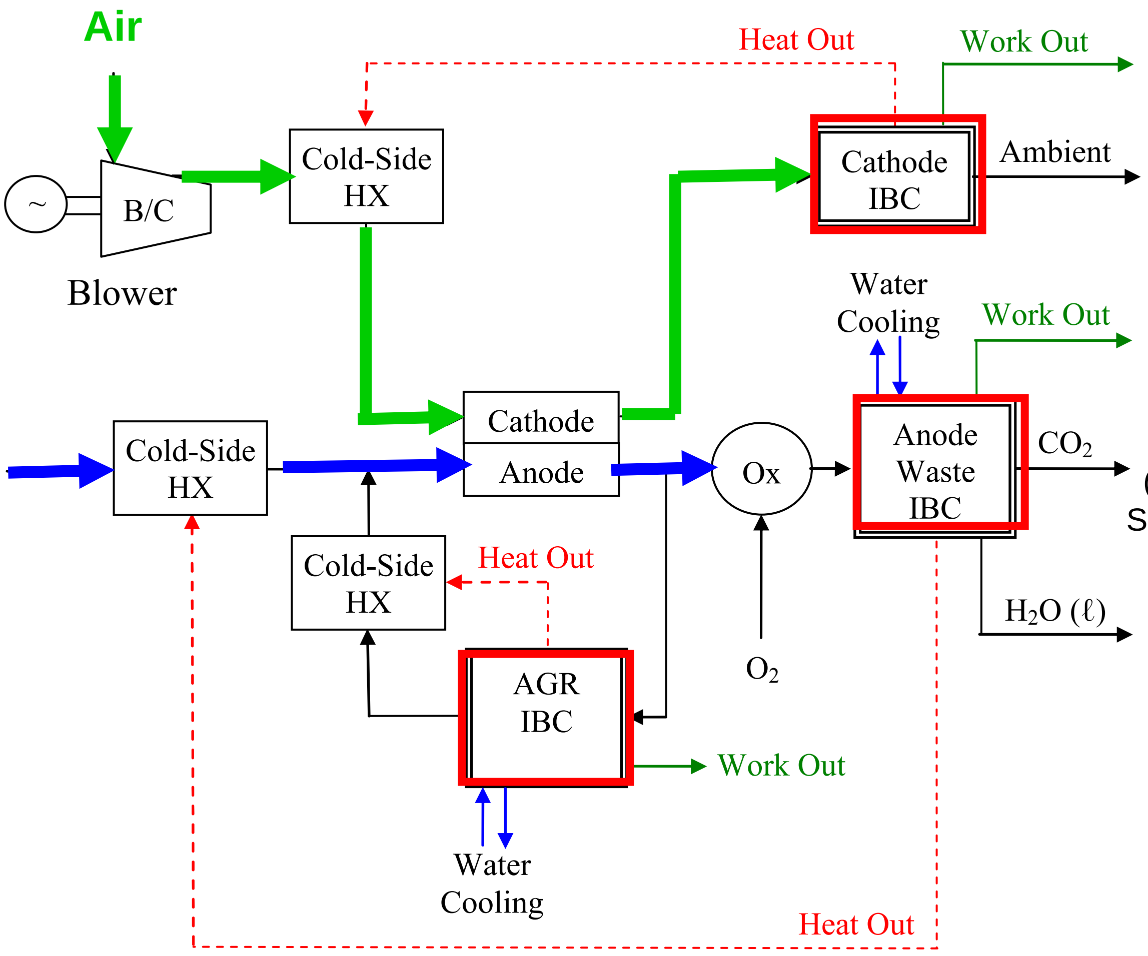
More about inverted brayton cycles

- **General IBC (below):**
  - The hot-side, cold-side HX correspond to a recuperator in more conventional cycles.
  - The “cooler” corresponds to the variable heat subtraction (e.g., the inverse analogue of usual brayton cycle fuel addition).



Inverted Brayton Cycles in Three Places

- **What is the relative power from each IBC (red box?)**



1 atm
(Note shaft could drive
Sequential compressors)

All cases: same coal syngas fuel producing 68MW power from SOFC.

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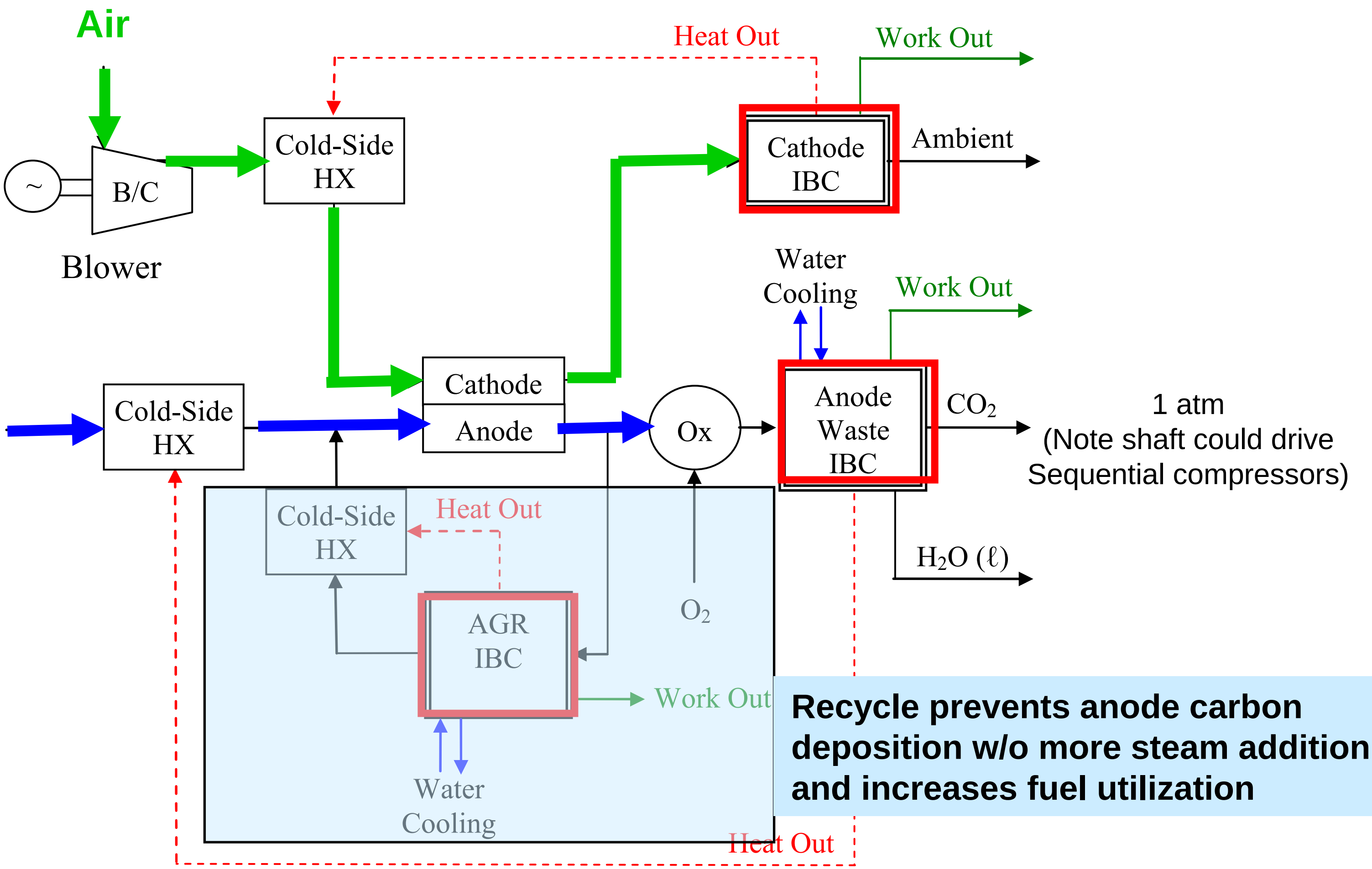

Recycle prevents anode carbon deposition w/o more steam addition and increases fuel utilization

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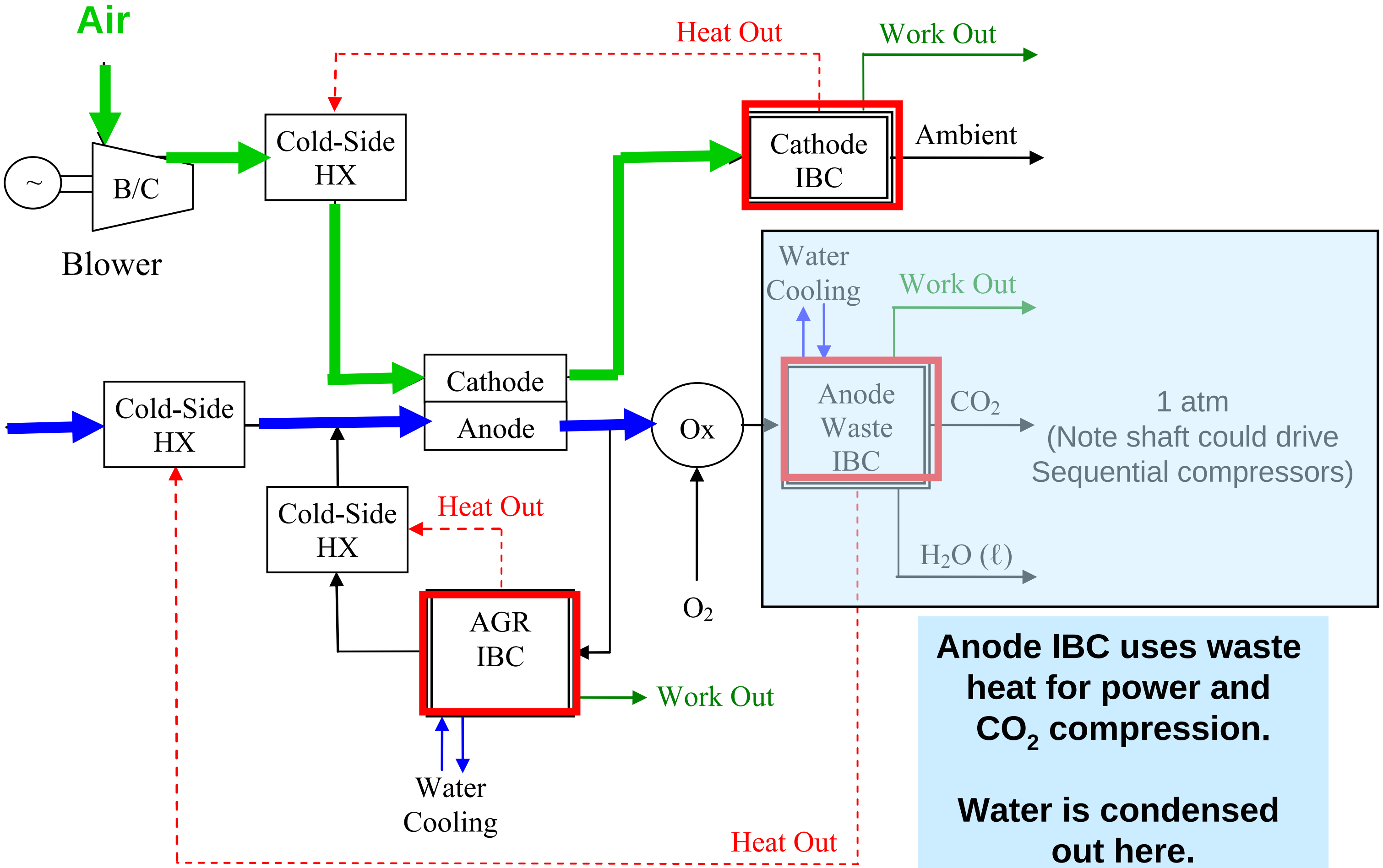

Anode IBC uses waste heat for power and CO_2 compression.

Water is condensed out here.

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Inverted Brayton Cycles in Three Places

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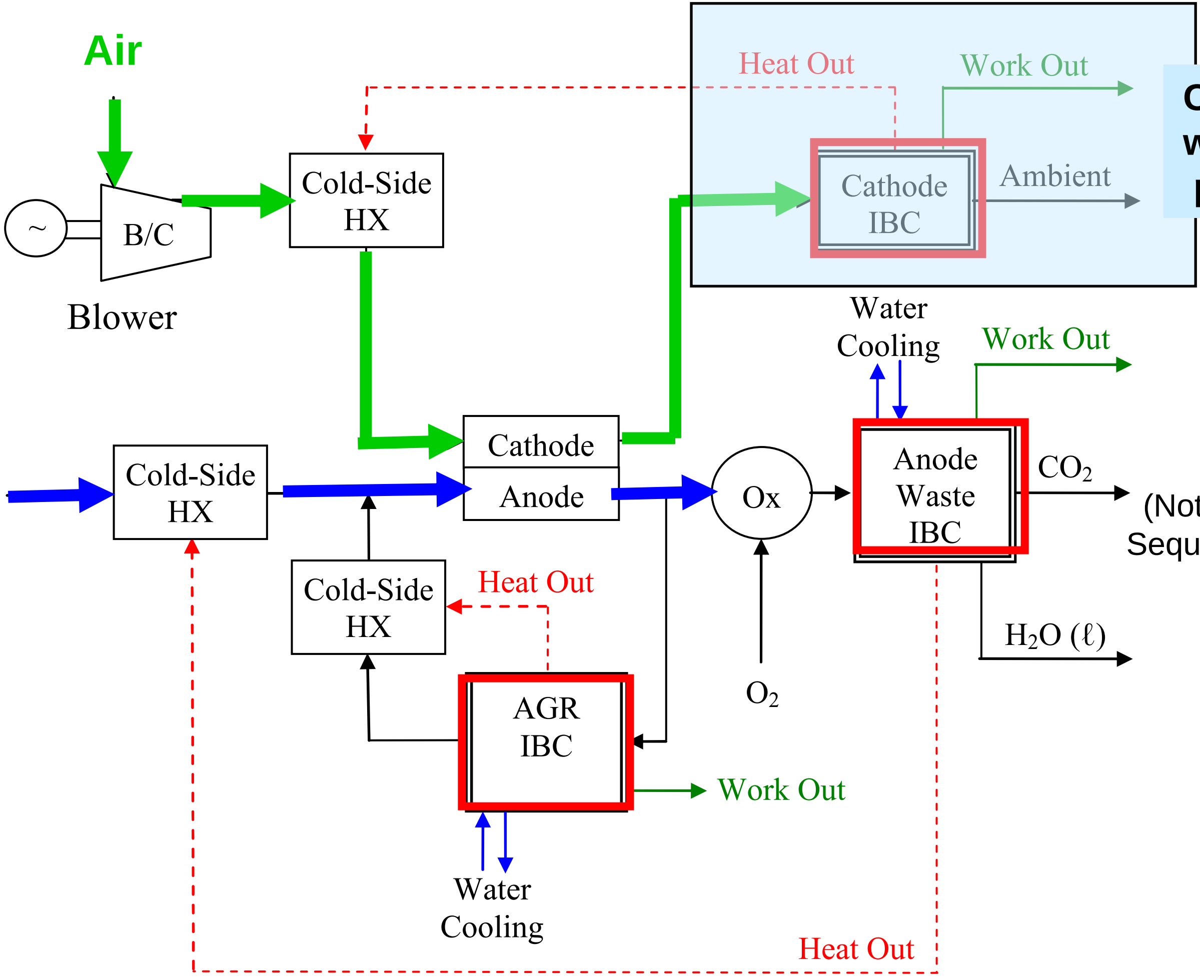


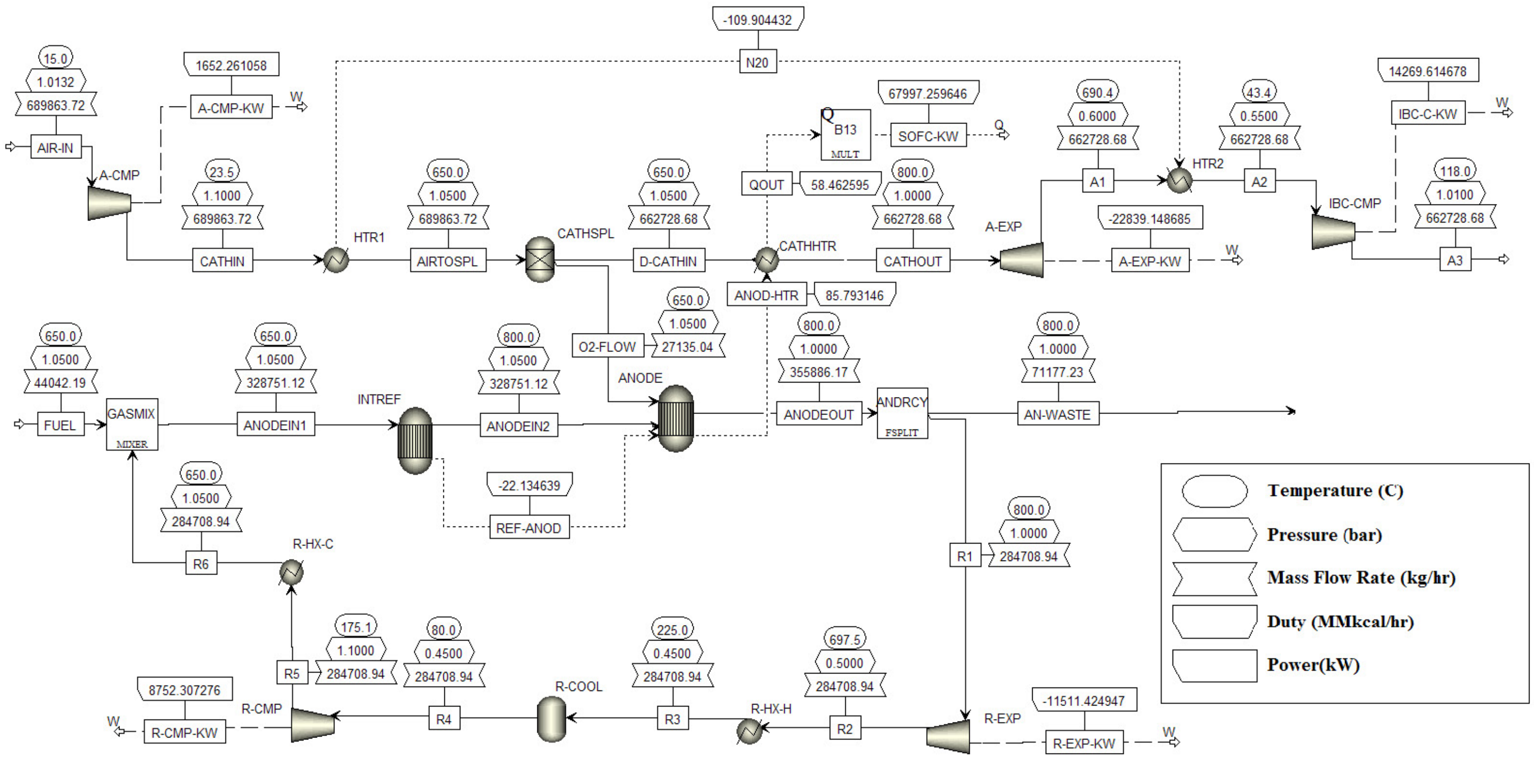
Cathode IBC uses waste heat for power production.

1 atm
(Note shaft could drive Sequential compressors)

All cases: same coal syngas fuel producing 68MW power from SOFC.

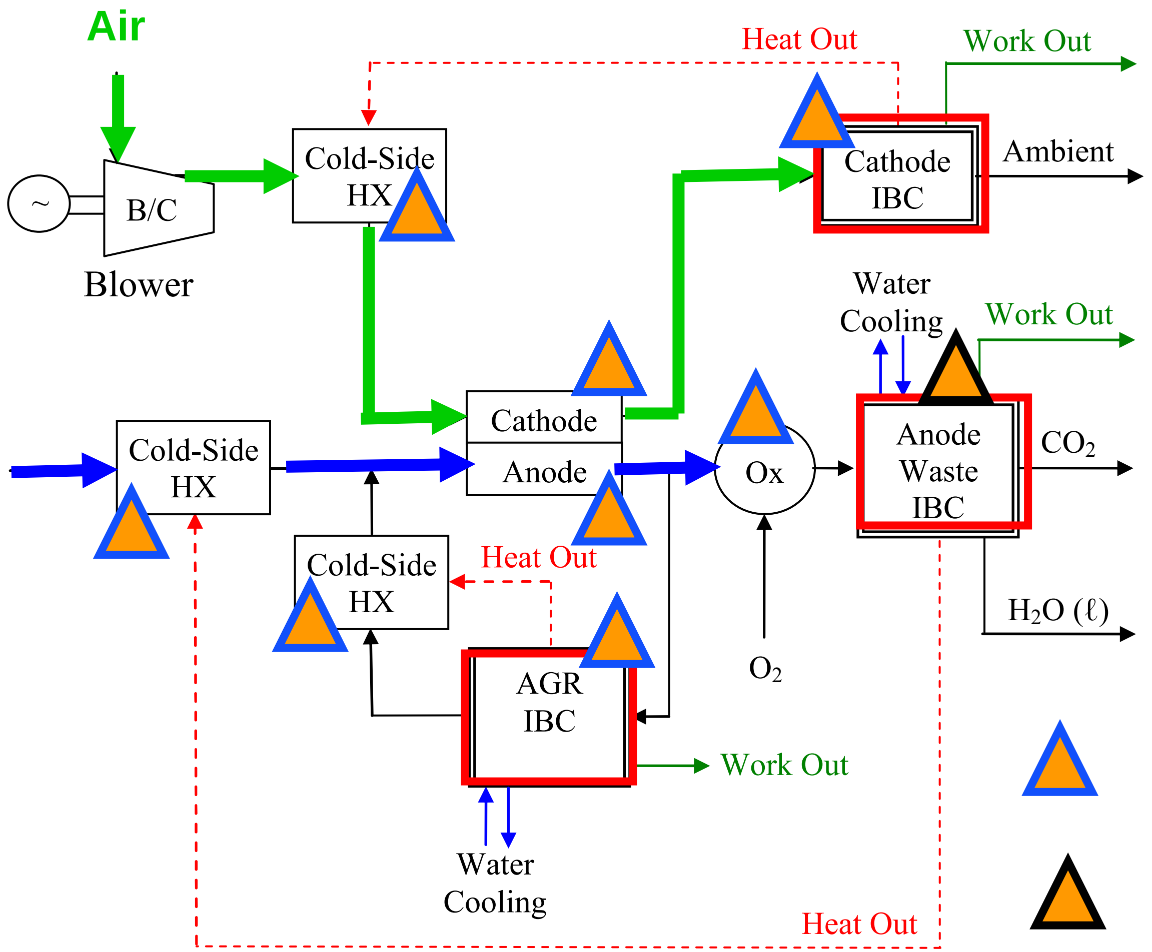
Aspen Plus® Analysis

- **Assumptions:**
  - Component efficiencies: all compressors 80%, expanders 85%, mechanical conversion 98%.
  - Supplied with syngas after cold-gas cleaning (dry).
  - Fuel cell model: 80% single-pass utilization



Assumptions (continued)

- **Pressure drops used for preliminary assessment:**



All cases produce 1 atm CO_2

△ **0.05 bar (5 %)**

▲ **0.1 bar (10 %)**

Results from Aspen Simulation

- Cathode IBC produces significant power.
- Anode gas recycle *produces* significant power.
- Without IBC recycle blower *requires* power.

Power summary in MW of base case and sensitivities for Example 1 (1 bar)

Item	Tag	Base Case 1 bar	No Cathode IBC	No Recycle Expander
Blower	A-CMP	-1.65	-1.65	-1.65
Cath. IBC Exp.	A-EXP	22.84	n/a	22.84
Cath. IBC Comp.	IBC-CMP	-14.27	n/a	-14.27
Net Cath. IBC & Blower		6.92	-1.65	6.92
AGR Exp.	R-EXP	11.51	11.51	n/a
AGR Comp.	R-CMP	-8.75	-8.75	-1.33
Net AGR		2.76	2.76	-1.33
Anode Waste IBC Exp.	W-EXP	3.98	3.98	3.98
Anode Waste IBC Comp.	W-CMP	-1.97	-1.97	-1.97
Net Anode Waste IBC		2.01	2.01	2.01
SOFC		68.00	68.00	68.00
Total		79.69	71.10	75.60
CO_2 Compression (Not included in Total)	CO2-CMP	-7.05	-7.05	-7.05

4 stage intercooled compression to 150 bar

Results from Aspen Simulation

- **How sensitive are these results to assumptions?**
- **Reduced component efficiency: (70% compressor, 75% turbine).**
- **Double pressure drops (at original component efficiency).**

Power summary in MW of base case and sensitivities for Example 1 (1 bar)

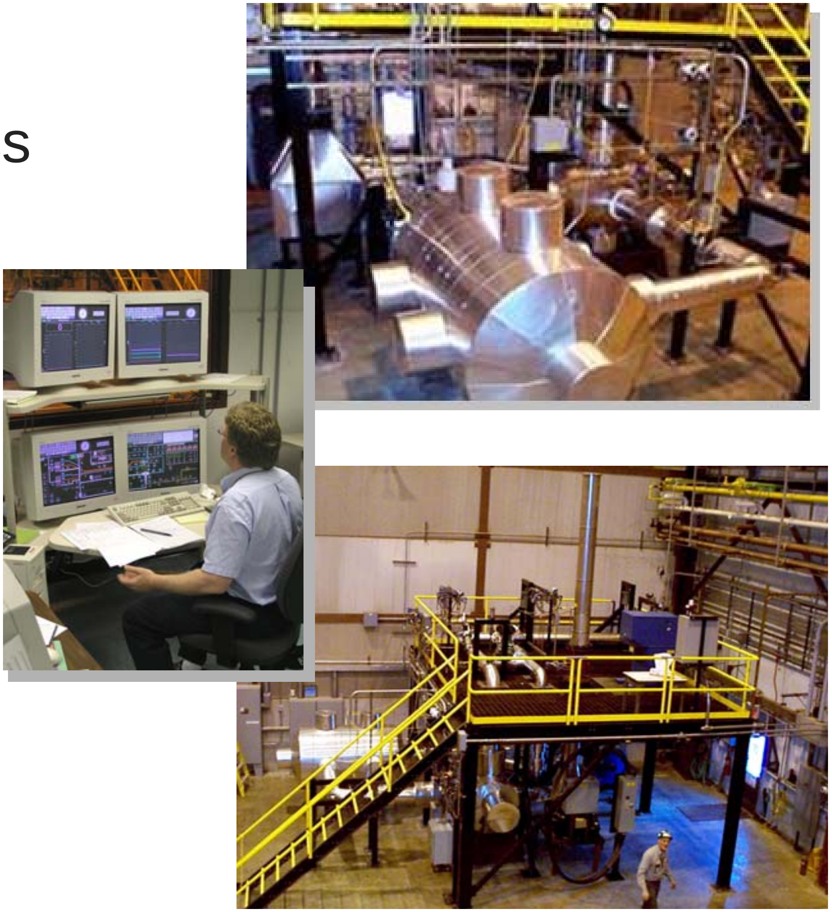
Item	**Tag**	**Base Case 1 bar**	**No Cathode IBC**	**No Recycle Expander**	**Reduced Efficiency Turbines**	**2x ΔP**
Blower	A-CMP	-1.65	-1.65	-1.65	-1.89	-3.45
Cath. IBC Exp.	A-EXP	22.84	n/a	22.84	21.50	22.84
Cath. IBC Comp.	IBC-CMP	-14.27	n/a	-14.27	-16.75	-17.24
Net Cath. IBC & Blower		6.92	-1.65	6.92	2.86	2.15
AGR Exp.	R-EXP	11.51	11.51	n/a	10.83	11.51
AGR Comp.	R-CMP	-8.75	-8.75	-1.33	-10.00	-11.01
Net AGR		2.76	2.76	-1.33	0.83	0.50
Anode Waste IBC Exp.	W-EXP	3.98	3.98	3.98	3.75	3.98
Anode Waste IBC Comp.	W-CMP	-1.97	-1.97	-1.97	-2.25	-3.00
Net Anode Waste IBC		2.01	2.01	2.01	1.50	0.98
SOFC		68.00	68.00	68.00	68.00	68.00
Total		79.69	71.10	75.60	73.19	71.63
CO_2 Compression (Not included in Total)	CO2-CMP	-7.05	-7.05	-7.05	-7.05	-7.05

4 stage intercooled compression to 150 bar

Anode recycle still a power producer!

Related work at NETL:
Control of isolated cathode/anode system

- **Unique hybrid facility allows control development:**
  - Real-time fuel cell model mimics expected fuel cell dynamics.
  - 100 kW turbine, heat exchangers, control development.
  - Fuel cell dynamic model with isolation being developed.
- **Collaborations welcome!**



Experimental hybrid facility at NETL

Summary and Conclusions

- **Isolated cathode/anode system can inherently separate CO_2.**
  - Separate streams = unique options for waste heat recovery.
  - Greatest work recovery via high-temperature heat engine.
- **Inverted Brayton Cycle considered for special applications:**
  - "Low-temperature-rise" cathode flow.
  - Anode gas recycling to prevent anode coking.
  - Condensing water in the anode exhaust for sequestration.
- **Net power from cathode flow, recycle, and condensing.**
  - Results sensitive to component efficiency, pressure drop.
  - Conservative assumptions: recycle still produces power.