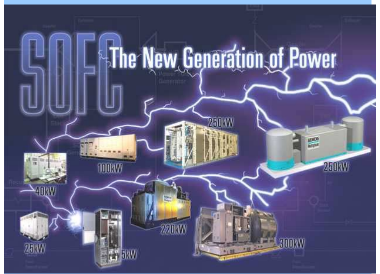
Stationary - Fuel Cells



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Tubular SOFC Hybrid Power Systems

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Tubular SOFC Hybrid Power Systems

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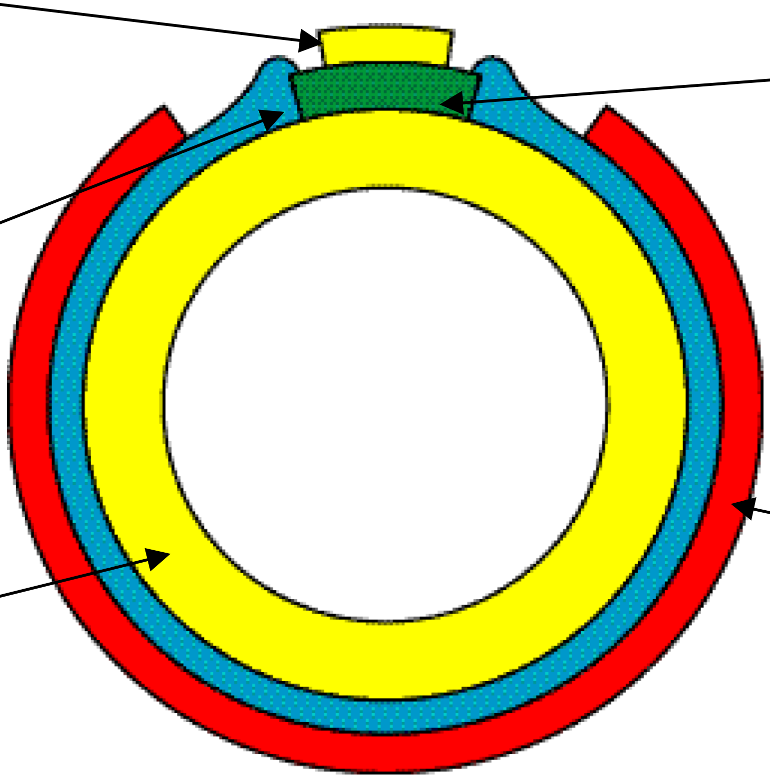
Air Electrode Supported Tubular SOFC

- **Dimensions**
  - **D = 22 mm**
  - **L = 1500 mm**
  - **A = 834 cmsq**
  - **m = 1 kg**
- **Watts @ 1 atm**
  - **In Stack = 110**
  - **Peak = 210**
- **Endurance**
  - **44,000 hrs**
  - **j=307**
  - **FU=85%**
  - **T=1000ºC**
  - **degradation**
  - **<0.1%/k-hrs**



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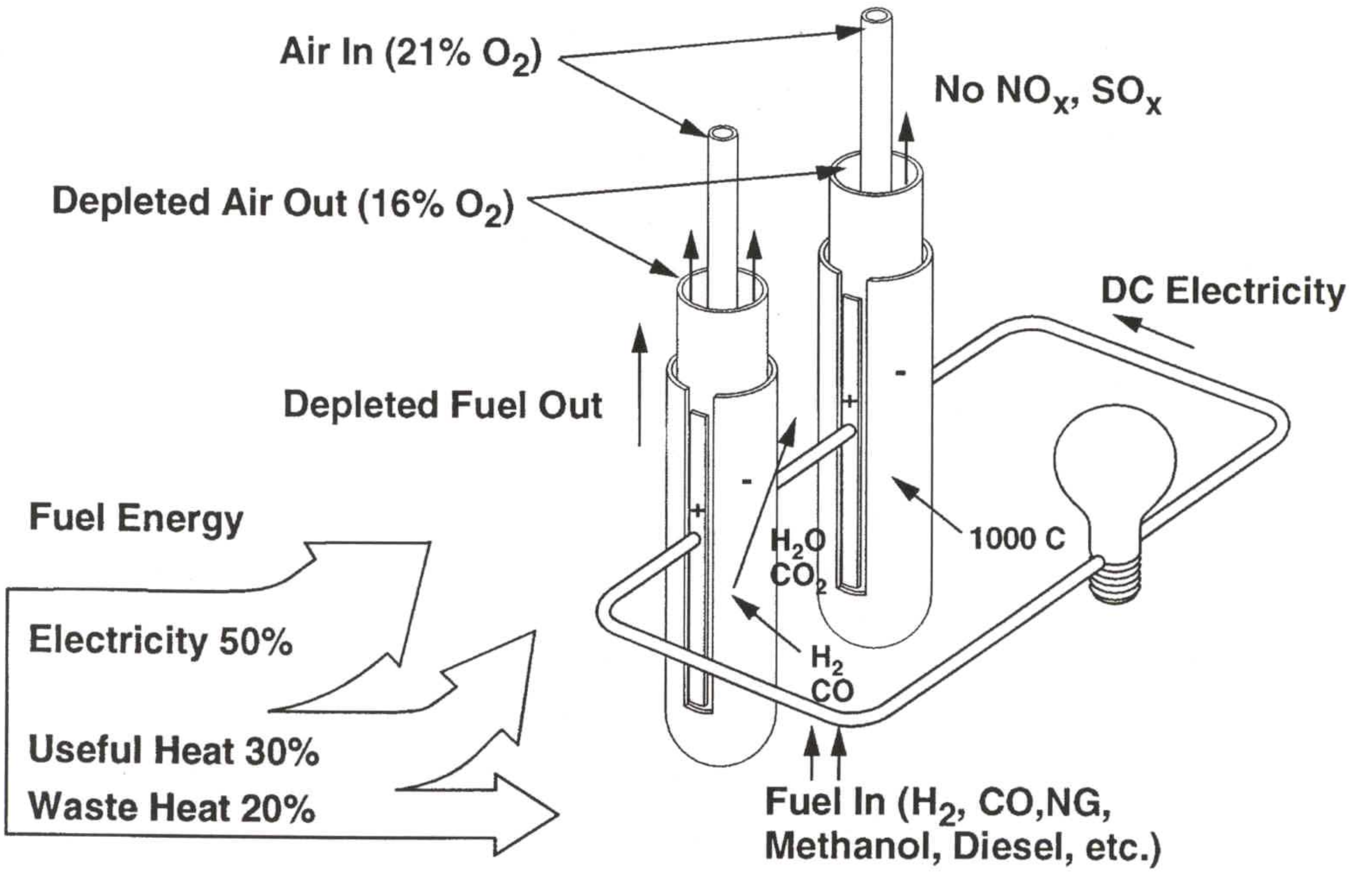
Tubular SOFC Stack Basics

Air inside

Fuel outside



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Westervort, The Netherlands

NUON

[host utility]

district heating booster station

1152 cells

PNG fuel

16,610 hours

110 kWe to grid

46% Efficiency [net ac/LHV]

No Degradation

Completed SOFC Demonstration Programs

EDB/ELSAM CHP100 SOFC Power System Installation

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Tubular SOFC Hybrid Power Systems

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Essen,

Germany

RWE

[host utility]

district heating

PNG fuel

3870 hours

110 kWe to grid

46% Efficiency
[net ac/LHV]

No Degradation

Completed SOFC Demonstration Programs

CHP100 SOFC Power System at RWE Site

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CHP250 SOFC Power System for Ontario Power Generation – proof of concept

P=1 atm

2292 cells

225 kWe @ η_{LHV} > 45%

250 kWe max

Fuel = PNG

w = 3.6 m
h = 3.6 m
l = 9.7 m

Started 27_April_2003

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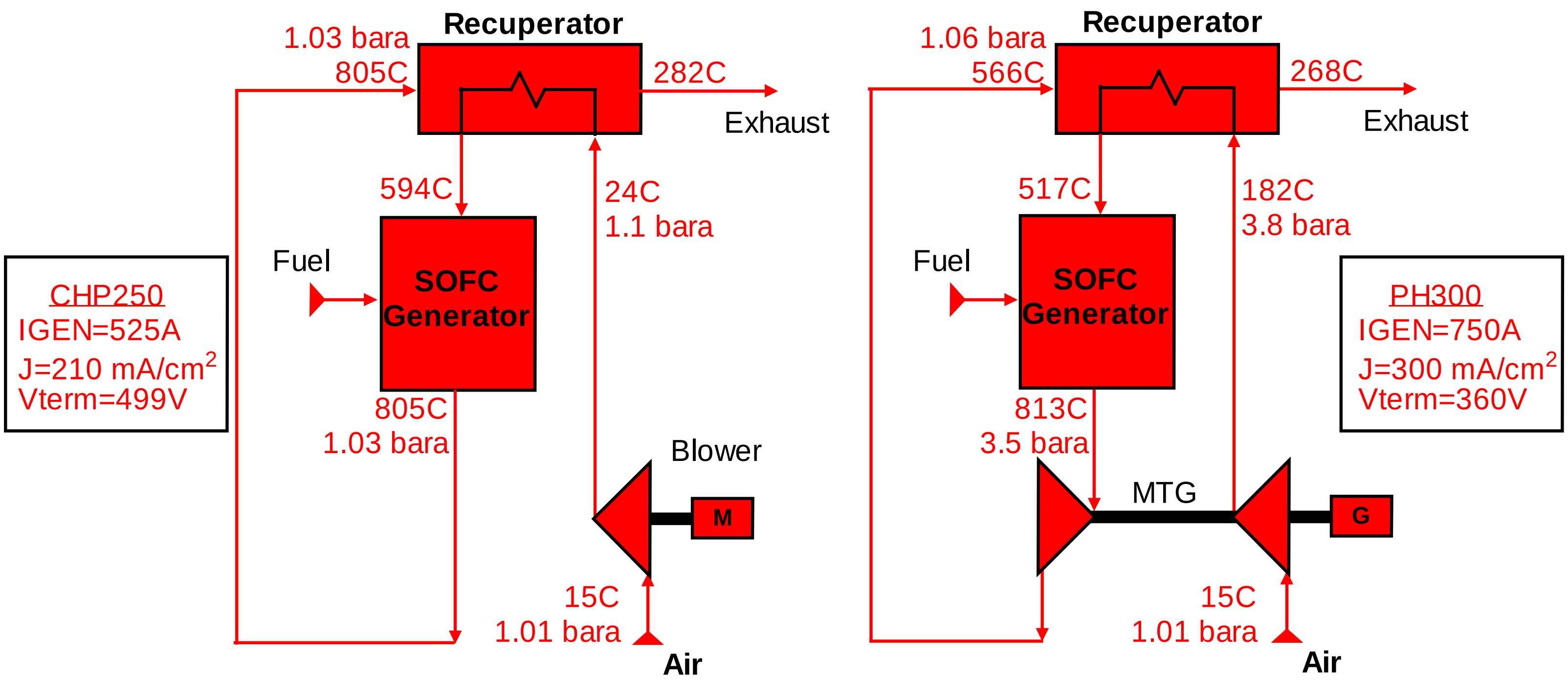
Typical Expected Conditions in the Cycle



Atmospheric Pressure
(CHP100, CHP250)

Pressurized Hybrid
(PH220, PH300)

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PH220 Proof-of-Concept System

- Built for Southern California Edison (SCE).
- Other participants:
  - US DOE
  - EPRI
  - California Energy Commission
  - South Coast Air Quality District
  - University of California at Irvine [UCI].
- Located at and operated by UCI NFCRC
- SCE owns all project data; data are included in this presentation with SCE permission.

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Major design considerations for Pressurized Hybrid

- Avoid pressure transients
  - Protect against surge
  - Controlled depressurization rate
- Control MTG for air flow—not power
- Highly modulatable MTG combustor
- SOFC is an MTG "combustor" with extremely high volume
- Licensing and Code Compliance
- Downstream components must survive SOFC blow-down
- SOFC stack must survive blow-down

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Start, Stop,

Operation

46 < $\eta \rightarrow$ 60%

P/Patm $\rightarrow$ 4

$\tau \rightarrow$ 1000 hrs

$\tau \rightarrow$ 3000 hrs

Proof of Concept Project Objectives:

- Demonstrate the technical feasibility of the PSOFC/MTG hybrid cycle power system concept
- Demonstrate the efficiency enhancement benefits of the hybrid cycle
- Demonstrate the power enhancement benefits of the hybrid cycle
- Demonstrate unattended automatic unit operation
- Demonstrate operation for an extended period of time – 3000 hours

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1152 cells

4 barg

Derated to 40 kWe

Not grid connected

Site sub systems

PH220 Main Features:

- SOFC stack per EDB/ELSAM 100 kWe
- ASME pressure vessel & power piping
- IRES PowerWorks75 MTG – suitably modified
- SOFC dc dissipator
- Induction alternator ac dissipator
- Site supplied compressed natural gas fuel
- Site supplied compressed air for safety shutdown
- Bottled NHMIX for shutdown

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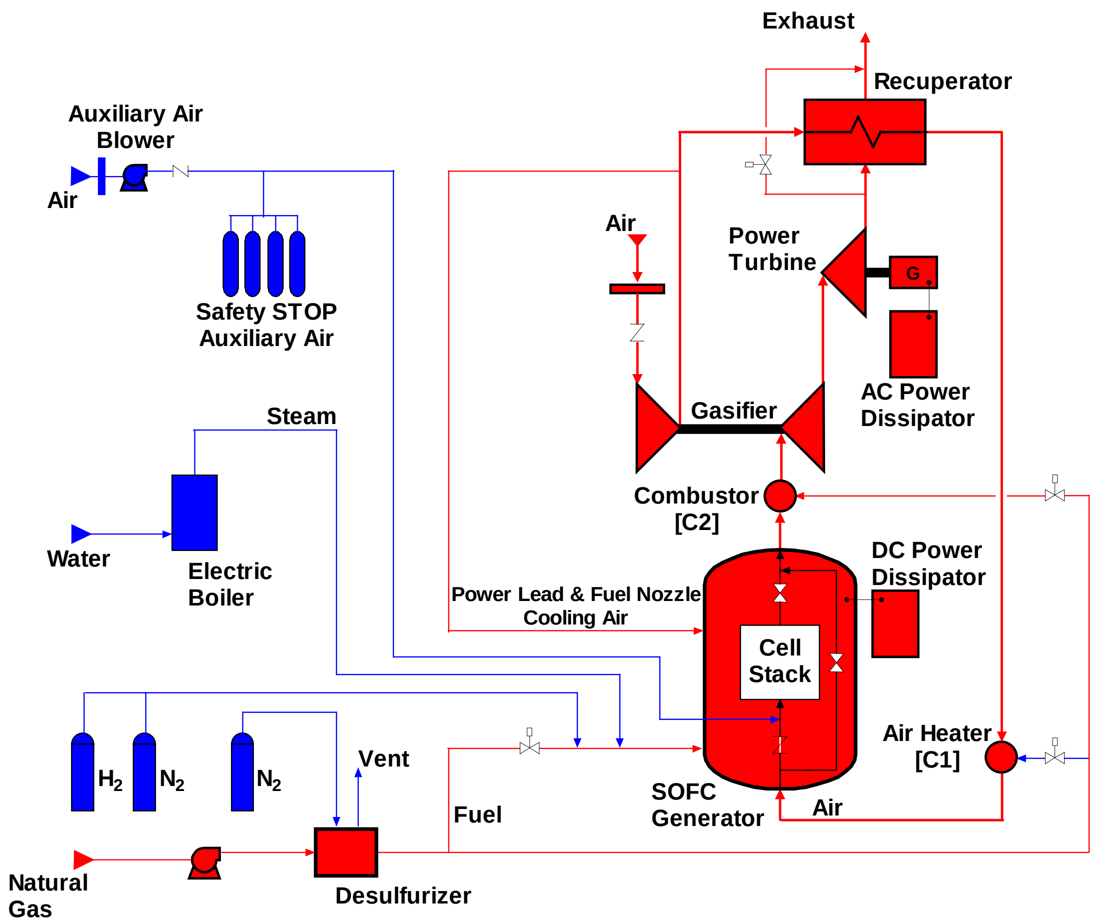
PH220 System Simplified Cycle Diagram with auxiliaries

- SOFC stack
- 2-shaft MTG
- NHMIX
- Startup Steamer
- Dual Aux Air
- dc dissipator
- ac dissipator



Stationary - Fuel Cells

May 2003

Tubular SOFC Hybrid Power Systems

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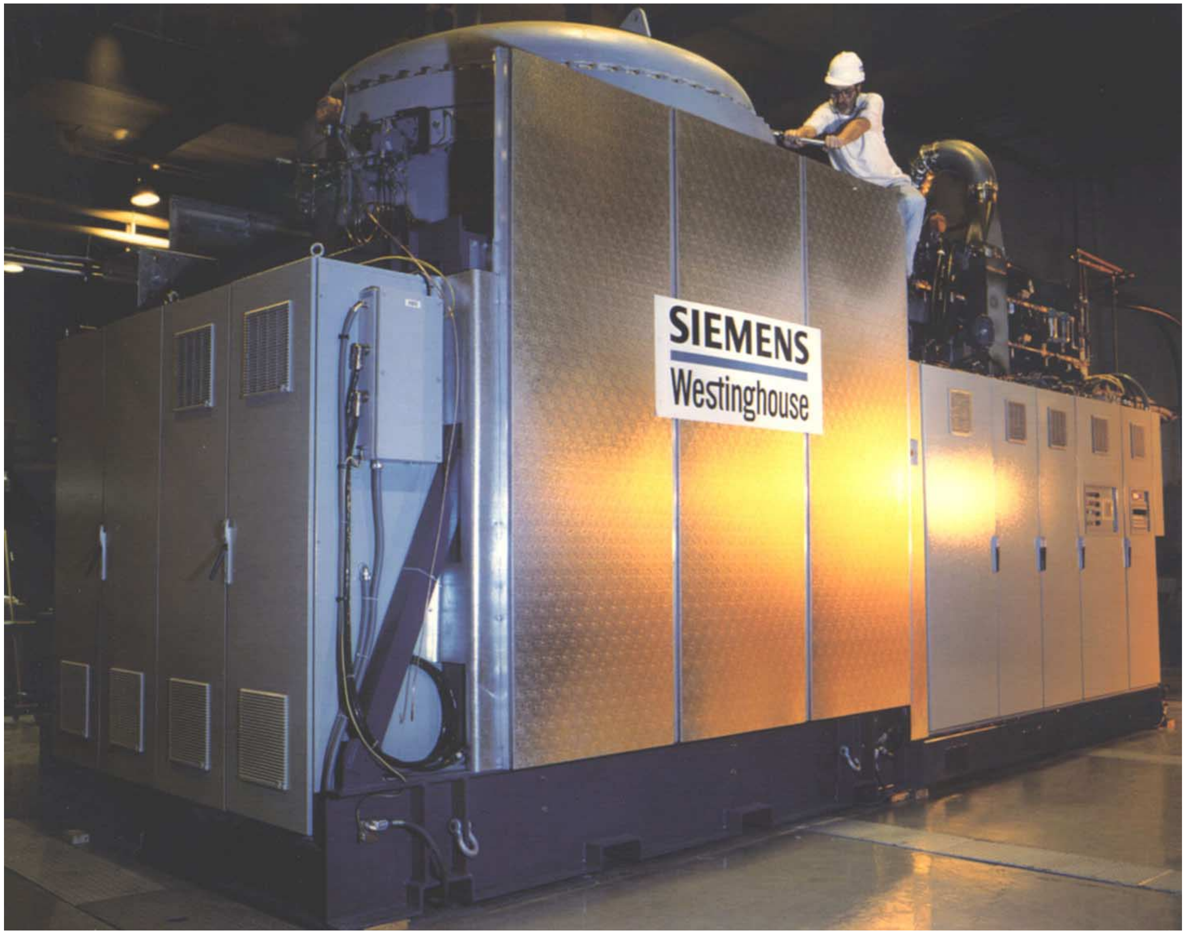
PH220 SOFC Power System Proof-of-Concept for SCE
[SCE, DOE, SWPC, EPRI, CEC, SCAQMD, UCI-Irvine NFCRC]

- Power Module
  - PSOFC
  - 1152 cells
  - MTG [IRES]
- Off Skid
  - NG Compressor
  - Desulfurizer
  - Dissipator
- Dimensions
  - L = 7.2 m
  - W = 3.8 m
  - H = 3.7 m
- Operation
  - 3000 hrs
  - η = 53% net ac



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PH220 System Operational Summary

FAT

ok

SAT1

Stack assembly Error

Power Lead Melted

SAT2

Failed Cell

OP-1

MTG Problem

OP-2

Stack Overheated

Fuel mal-distribution

turbine erosion

OP-3

Inadvertent trip; testing complete

Period of Operation	Date	Operating Hours [RUN]	SOFC DC Power Generator MWh	Total System AC Power* Generated MWh
FAT	25-Mar-2000 to 05-Apr-2000	110	16.1	17.4
SAT-1	03-Jun-2000 to 11-Jun-2000	154	23.8	25.5
SAT-2	08-Jan-2001 to 12-Feb-2001	514	84.1	88.2
OP-1	November 8, 2001	0	0	0
OP-2	31-Jan-2002 to 7-Apr-2002	1322	219	227
OP-3	19-Nov-2002 to 6-Jan-2003	1157	129	150

*Total system AC power [kW] = 0.94 * SOFC DC Power [kW] + MTG AC Power [kW] – 2.0 kW

Project Data are owned by the Southern California Edison Company and are presented here with permission

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PH220 System Operating Accomplishments

- Unmanned operation
- World's first SOFC hybrid power system
- Natural gas fueled
- In-stack reformation
- No external process water supply for SOFC generator operation
- Not grid connected
- Successful factory test
- Successful site start-up
- 182 kWe (SOFC dc plus MTG ac basis)
- 53% electrical generation efficiency (calculated ac/LHV basis)
- World's highest capacity SOFC power system
- World's most efficient natural gas powered fuel cell power system

PH220 system has established feasibility of the hybrid concept, but the hybrid concept requires further development particularly regarding the MTG & integration.

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Lessons Learned from PH220

- Two shaft turbine complicates air flow control
- Need air flow capacity match between MTG & SOFC
- Need integral control of ancillary systems
    - Gas compressor
    - Auxiliary air
- Oil lubrication is a complication
- Highly modulatable combustor with high temperature air not easy
- Pressurized SOFC stack operation exacerbates fuel maldistribution
- Long term “motoring” of MTG is highly desirable
- SOFC should be free of non-conformance issues

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PH300 Systems

- Contract was signed with RWE (as the leader of a European Consortium) in March 2000.
- Contract signed with Edison S.p.A (Italy) in July 2000.
- European MTG manufacturer [nominally 100 kWe]

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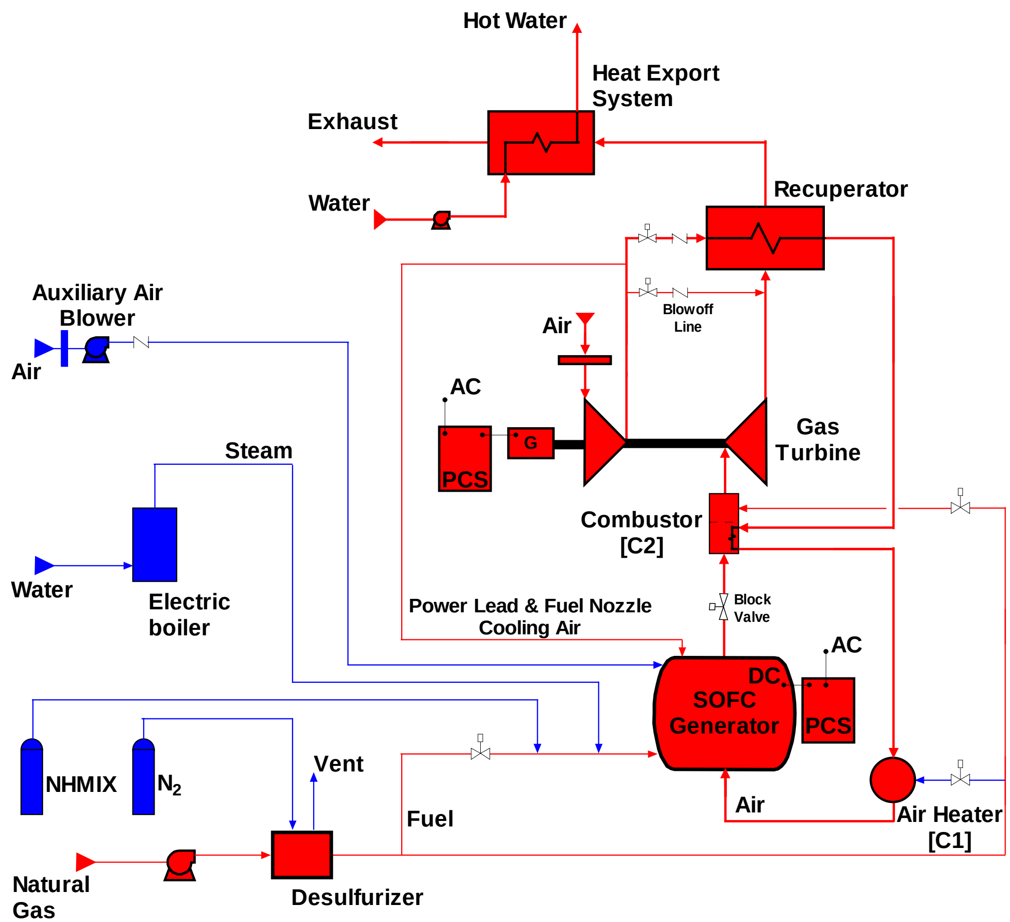
PH300 System Simplified Cycle Diagram



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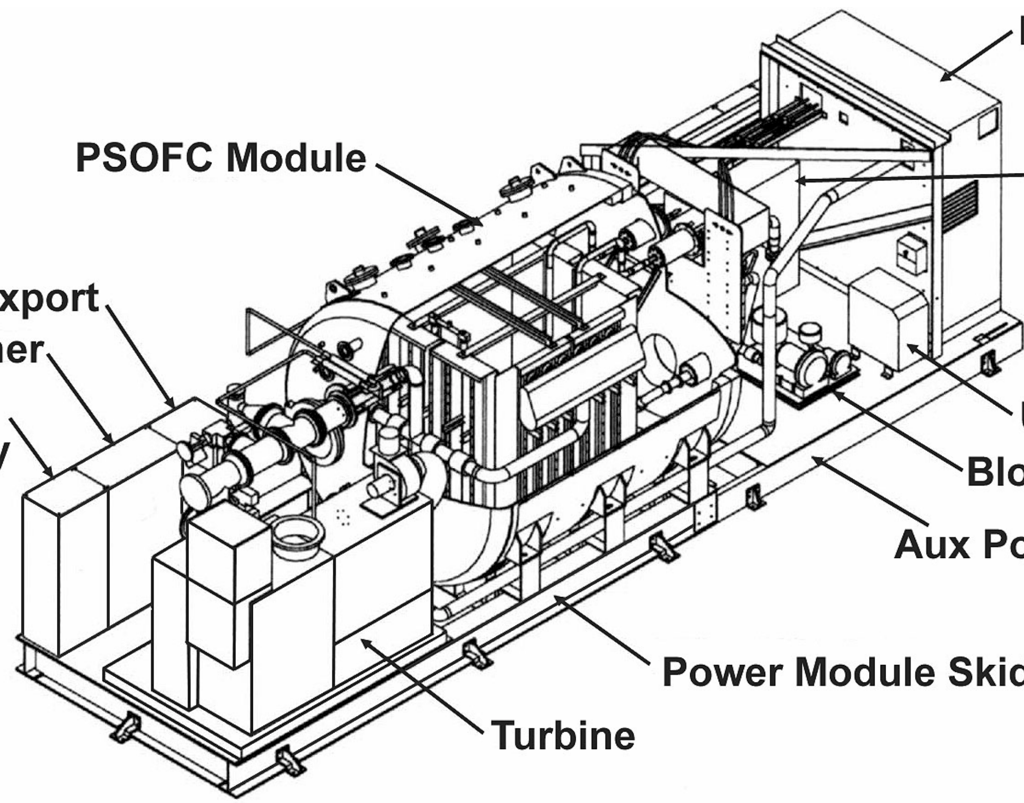
- Power Module
  - PSOFC
  - 1704 cells
  - MTG
  - Heat Export
  - Fuel Supply
  - Steam Supply
- Auxiliary Skid
  - PCS
  - Electricals
- Dimensions
  - L = 12.8 m
  - W = 3.6 m
  - H = 3.7 m
- Off Skid
  - NG Compressor
  - Desulfurizer
- Target Efficiency
  - η > 55%
  - Net_ac/ LHV

PH300 SOFC Power System Proof of Concept



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PH300 SOFC Power System Proof of Concept

- Power Module
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  - NG Compressor
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- Target Efficiency
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  - Net_ac/ LHV

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PH300 Status & Lessons Learned to Date

- Factory test in process
  - Some instrumentation & communication problems
- Lack of long term motoring capability causes difficulty
- Oil lubrication is a complication
- Code compliance and licensing a major issue
- Adaptation of existing MTG causes major compromises
  - Component temperature limitations
  - Turbine over-speed potential during shut down
  - Depressurization control via valves

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Tubular SOFC Hybrid Power Systems

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Ideal Gas Turbine Features for PSOFC/MTG Application

- Turbine inlet temperature: 820°C < TIT < 950°C
- Compressor pressure ratio: 3:1 < Pr < 4:1
- High-effectiveness recuperator: ε >90%
- High GT combustor inlet air temperature (820°C to 870°C)
- High reliability – 8000 hours continuous operation.
- Wide combustor fuel flow modulation range – 5% to 110%
- Variable high-speed alternator, with associated electronics.
- Never-seize shaft design.
- Air or magnetic bearing system – no oil.
- Close SOFC/MTG package integration.
- Long term turbine generator motoring capability.
- Fail safe over-speed control
- Survive SOFC blow-down

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Conclusions

- The PH concept is technically feasible.
- Simple PH cycle efficiency horizon is 60%.
- SOFC stack design requires refinement for pressurization.
- A suitable MTG for pressurized hybrids awaits development.
- The GT for the PH is non exotic in material or features.
- The PH system needs cycle integration development.
- As embodied to date the PH is too complicated, too heavy, and too costly.
- The PH as a product requires definition.

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