Scale-Up of Planar SOFC Stack Technology for MW-Level Combined Cycle System

Final Report

Submitted to NETL

October 3, 2003

TIAX LLC
Acorn Park
Cambridge, Massachusetts
02140-2390

Reference: D0136

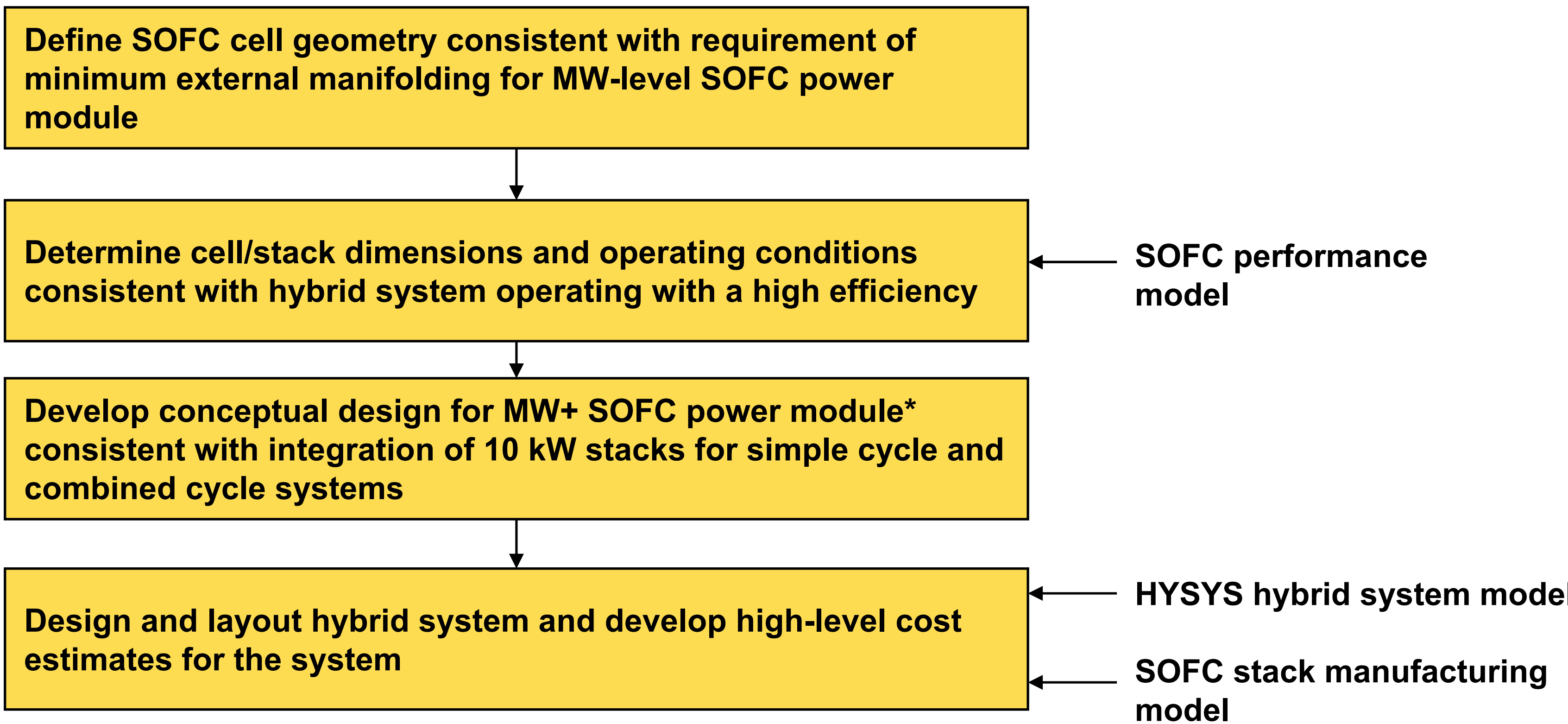
NETL wanted to understand if and how SECA-style anode-supported SOFC stacks could be scaled-up for use in MW-level combined cycle plants.

- SECA strategy relies on the use of modular, mass produced, SOFC stacks in the 3 - 10 kW capacity range for a wide range of applications.
- Technical feasibility small-scale applications has been evaluated by SECA:
  - 5 kW POX-based truck APU;
  - 5 kW stand-alone residential power system;
  - 250 kW distributed generation system.
- SOFC-Gas Turbine (GT) hybrid systems, that have the potential for very high efficiencies (~ 60 - 70 %) could potentially be another application.
- Combined cycle systems based on Gas-Turbines, are typically rated at the MW-level capacity.
- Therefore, a MW-level SOFC power module must be built from kW-level SECA SOFC stacks.
- For example, ~ 100 stacks of nominally 10 kW power have to be integrated to form the 1 MW SOFC power module.

In order to achieve reliability, good performance and low costs, the scale-up strategy must:

- *Minimize high temperature piping and manifolding connections* associated with connecting a large number of individual stacks having both inlet and outlet reactant streams.
- *Build-up voltage* to levels consistent with low cost power conditioning, low ohmic voltage losses, and efficient grid interfaces.
- *Minimize contact resistance losses* associated with electrically interconnecting a large number of individual stacks.
- *Configure hybrid system for high efficiencies (60 % +)* for use with stacks operating at nominally 700 - 800°C, consistent with SECA strategy.
- *Reduce parts counts* by using large diameter cells consistent with acceptable thermal stresses and power density characteristics.

The key issues were systematically addressed using models developed in previous NETL-SECA assignments and assessing the performance/cost of cells, stacks, and system.



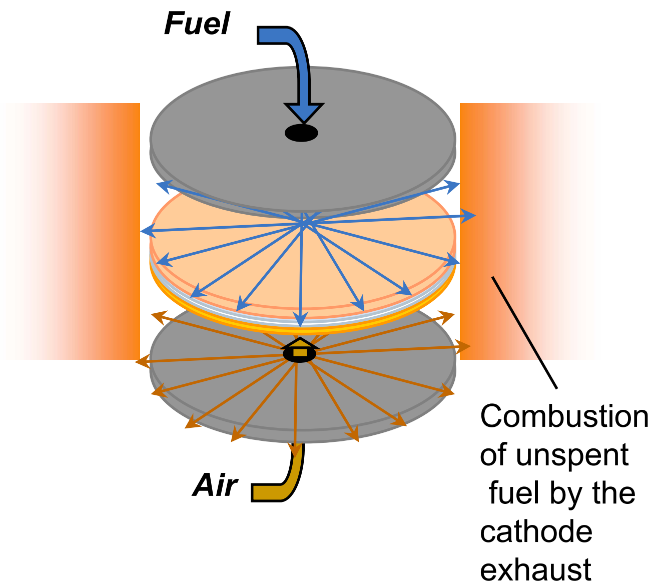
*This report discusses one approach to the scale-up of power from modular SOFC stacks. Other approaches may work equally well depending upon the specifics of the basic cell design: planar, separate fuel and air outlets, etc.

A single design was selected for the purpose of assessing the scale-up strategy for SECA 10 kW modules for use in a high efficiency hybrid plant.

- A circular cell geometry with anode-supported ceramic structure was selected to reduce manifolding/interconnect requirements.
- The baseline cell/stack performance was estimated assuming a nominal 800°C stack temperature (sensitivity analyses were performed, however, on the operating variables)
- A direct fuel cell - gas turbine hybrid configuration operating at 3 atm was assumed (consistent with a design pursued by Siemens-Westinghouse).

Circular stack design was selected for analysis because of the potential for flexibility in designing the SOFC power module, with minimal manifolding.

Circular Stack with Radial Outflow



- The stack geometry can be chosen such that the SOFC power module design can be simplified.
- The majority of the developers of anode supported stacks are considering either a rectangular or a circular geometry for the stack.
- Our previous study of a 250 kW simple cycle system, designed for SECA stacks, showed that use of circular stacks might simplify the manifolding requirements.
  - In a rectangular stack, manifolding is required for both the fuel cell inlet and exit streams.
  - In a circular stack, the spent fuel and oxidant streams mix and burn at the periphery of the stack.
  - In the circular stack, manifolding of the exhaust gases is eliminated thereby simplifying the piping arrangement and allowing for more flexible arrangement of the stacks.

Previously developed detailed model, updated with internal reforming, was used to determine the cell diameter consistent with stress considerations.

Model Highlights

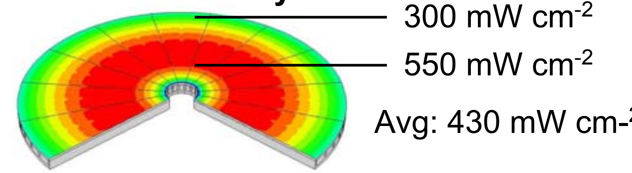
- Powerful tool for simulating the chemo-electro-thermo-mechanical performance of any three-dimensional SOFC cell
- Solves for heat, mass, and charge transport in the interconnects, porous electrodes, and solid electrolyte
- Includes kinetics of electrochemical charge transfer reactions, on-anode steam reforming, water-gas shift.
- Calculates distribution of concentrations, overpotentials, current, temperature, and stresses
- Simulates both steady state and dynamic performance, both adiabatic and heat loss boundary conditions

Primary Uses

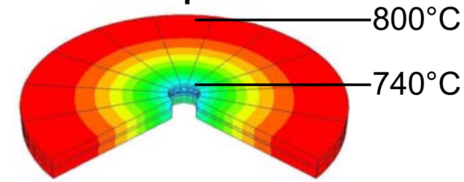
- Assess impact of changes in operating conditions / cell design on performance
    - Assess limiting factors on area-scale-up of SOFC cells
- Provide boundary conditions for system model
- Assess mechanical stresses due to temperature gradients, CTE mismatches and applied compressive forces
- Assess effect of hardware properties and modifications on the performance before hardware testing to minimize cost and time

Sample Results From SOFC Model

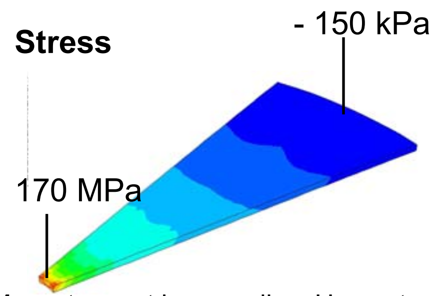
Power Density



Temperature



Stress



Max. stress at inner radius. Hoop stresses at the inner edge of the annulus are exacerbated by temperature gradients across the cell.

Operating Conditions: 5 cm dia. Anode-supported cell, 100 % internal reforming of methane, 90 % fuel utilization, 380 % excess air, 1 atm, inlet gases at 650°C

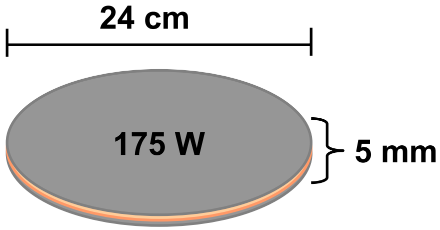
Complete internal steam reforming of natural gas was assumed for the SOFC stacks based on the modeling results.

- Cell performance for both internal and external reforming options were simulated with the performance model
- Model results indicated that internal reforming is attractive at the low operating temperatures (800°C) of anode supported stacks.
  - Proceeds relatively uniformly over the cell area leading to reduced stress levels
  - Good power density
  - Significant advantage is the reduced excess air requirement and the associated decrease in BOP cost and increase in system efficiency
- Given that MW level systems assume a mature technology - internal reforming was selected for the baseline analysis.

However, the conclusions regarding the scale-up potential for SECA stacks will not be altered by using an external reformer.

Based on model results, the following geometry and operating parameters were selected* for integration into the stacks, and power module.

Parameter	Value	Comment
Cell Diameter	**24 cm**	• This cell diameter will result in a 42 V, 10.5 kW stack, consistent with mass produced SECA stacks.
Cell Voltage	**0.7 V**	• Voltage is sufficiently high to avoid mass transport limitations, but also can provide reasonable power densities and system efficiencies
Power Density	**400 mW cm^{-2}**	• Power density was estimated for 90 % fuel utilization
Reforming Strategy	**100 % internal reforming**	• Modeling results showed that 100 % internal reforming was possible for the assumed reforming kinetics and steam to carbon ratio of 2.3:1
Fuel Utilization	**90 %**	• Model results indicated that operation at 90 % utilization of methane was possible without significant stress generation.
Excess Air	**330 %**	• Calculated such that the maximum cell temperature (at the exit) was less than 800 °C
Pressure	**3 bar**	• 3 bar was close to the pressure optimum in a hybrid system study[1]
Inlet Gas Temperatures	**650°C**	• Inlet temperatures were specified to keep the temperature gradient across the stack < 150°C.



Single Cell Dimensions

• *These stack operating conditions were found to be consistent with reasonable system efficiency in parallel system modeling (described in a subsequent section)

Note that for the cell dimensions selected, scale-up issues would be similar to those faced in the scale-up of the Siemens-Westinghouse tubular cell.

	Planar Design (This work)	Siemens-Westinghouse Tubular Cell Design
Single cell power output	175 W	~ 175* W
Number of Cells for 1 MW power module	5715	5715#
Surface area per cell	438 cm^2	1035 cm^2
Power density per cell	400 mW cm^2	~ 160 mW cm^2
Operating pressure	3 atm	3 atm

* Estimated from the published data on Siemens-Westinghouse tubular stack performance, and conceptual designs for 250 kWe SOFC-microturbine combined cycle and 1 MW SOFC-GT combined cycle systems.

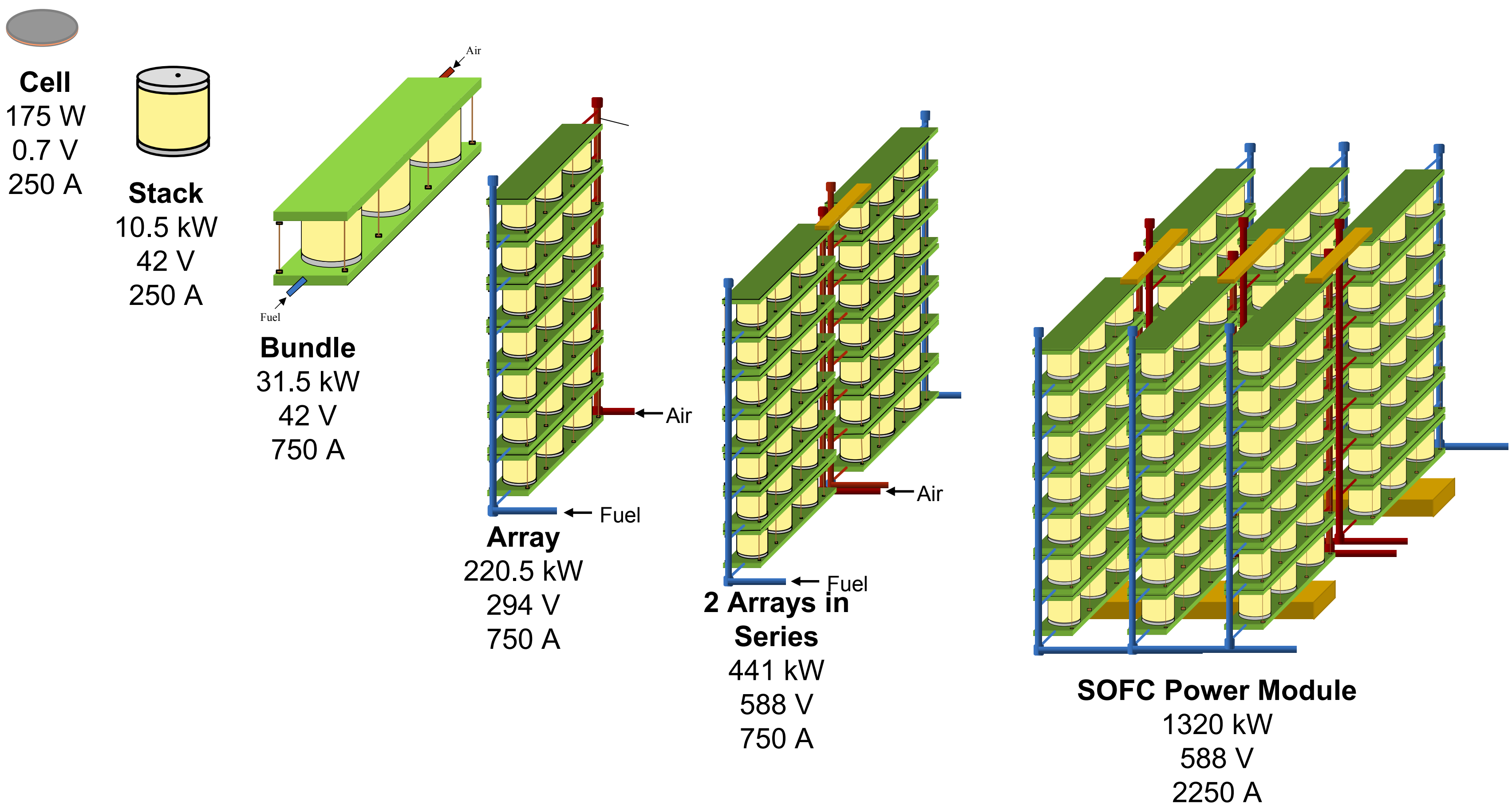
Siemens-Westinghouse demonstrated a 100 kW^e system based on 1152 individual cells.

Refs: K. Hassmann, "SOFC power plants, the Siemens-Westinghouse approach," Fuel Cells, V1, n1, 2001., S.C. Singhal, "Progress in tubular solid oxide fuel cell technology," SOFC-VI, ECS Proceedings Volume (1999).

Note that the Siemens-Westinghouse tubular cell has been successfully scaled-up to 100 kWe and 220 kWe, and scale-up to 500 kWe combined cycle systems are underway.

Design of planar SOFC power module, consistent with minimizing the piping and interconnection, involved systematic scale-up of voltage and current.

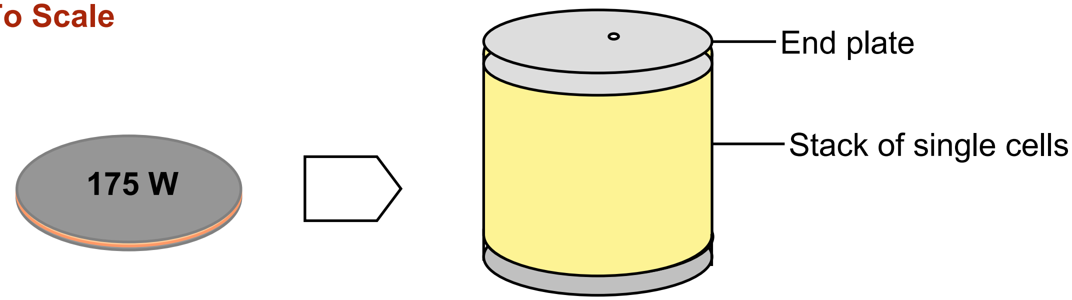
Power Scale-up Strategy for Planar Stacks



The single cell design results in an internally manifolded, 42 V, 10.5 kW stack with dimensions of 24 cm diameter and 35 cm height.

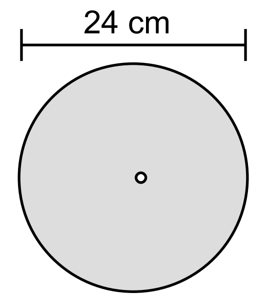
Single Stack Configuration

To Scale



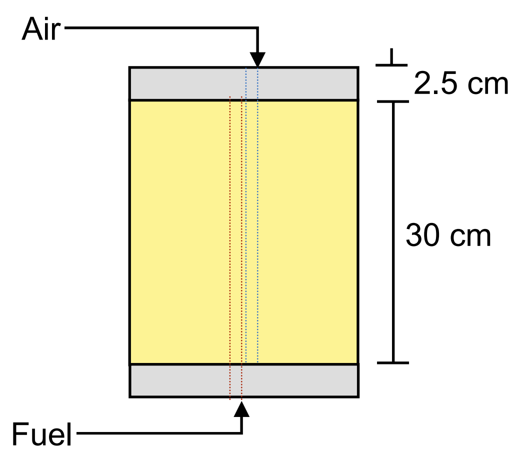
Single Cell

Single Stack



Top View

Stack Power		10.5 kWe
Number of Cells		60
Pitch		5 cells /inch
Stack Voltage		42 V*
Power Density		400 mW/cm^2
SOFC Operating Voltage		0.7 V
Pressure Drop		0.05 atm
Stack Dimensions	Radius	13 cm
	Height	37 cm



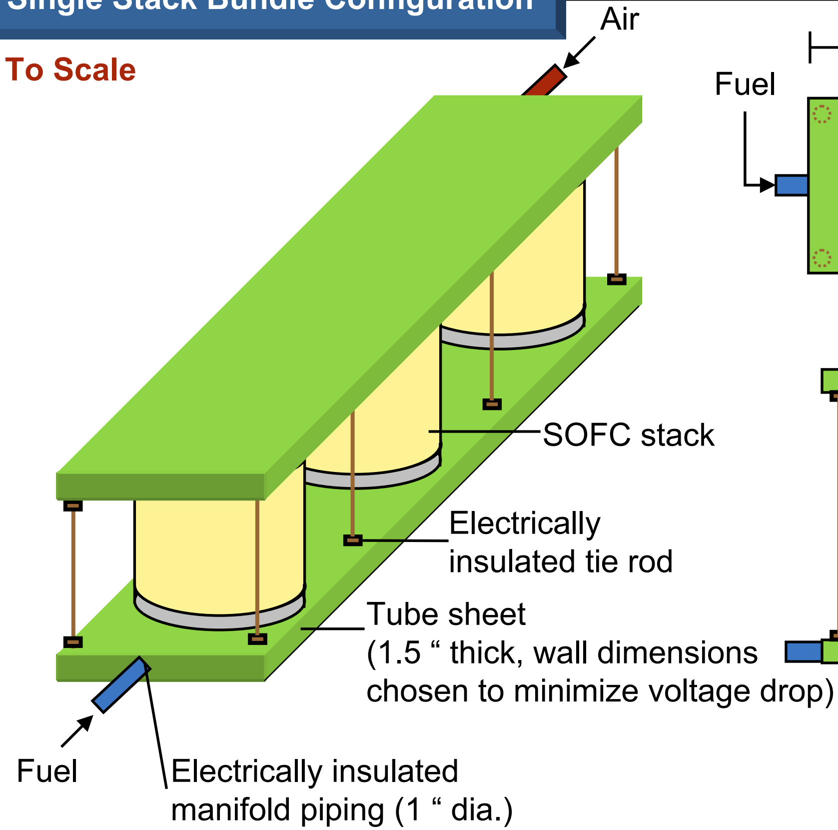
Side View

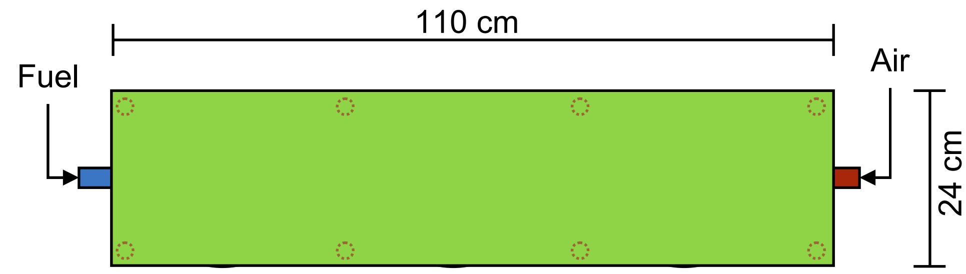
* In previous assessments we performed for NETL, we assumed that the SECA stacks would operate at 42 V. The voltage rating is critical in determining for voltage scale-up and hence the piping and manifolding requirements. Details of the internal manifolding within the stack were not considered in this assignment.

For current scale-up, single stacks are manifolded between tube sheets to form a stack bundle.

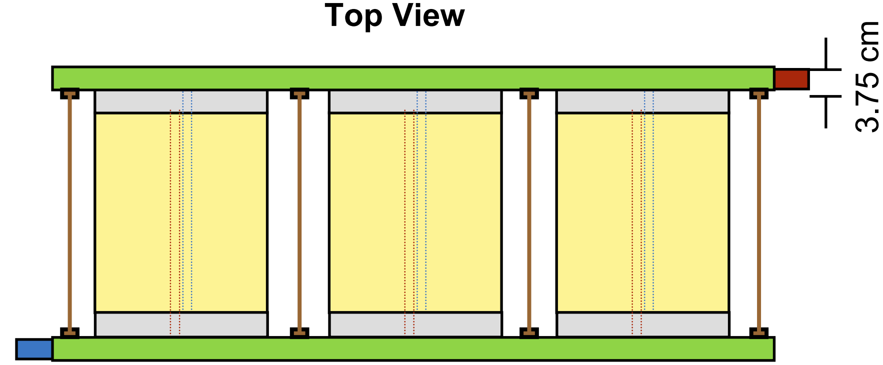
Single Stack Bundle Configuration

To Scale





Top View



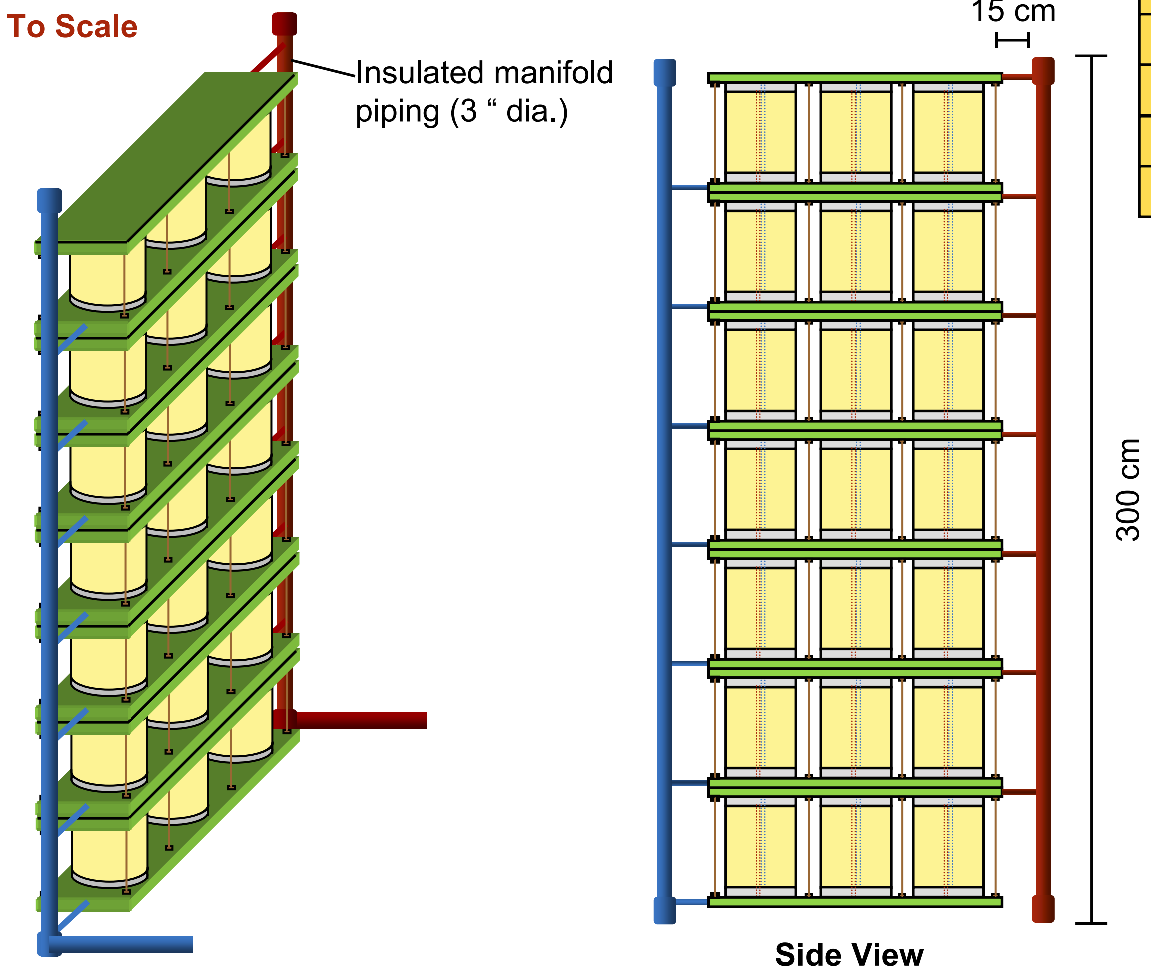
Side View

Tube sheets help with uniform gas distribution, a support for the stacks and an anchor for applying compressive force, and allow for serial electrical connection of stacks

Stack Bundle Power	**31.5 kWe**
Number of Stacks	**3**
Bundle Voltage	**42 V**
Bundle Current	**750 A**

Stack bundles are manifolded together for reactant delivery, to form an array.

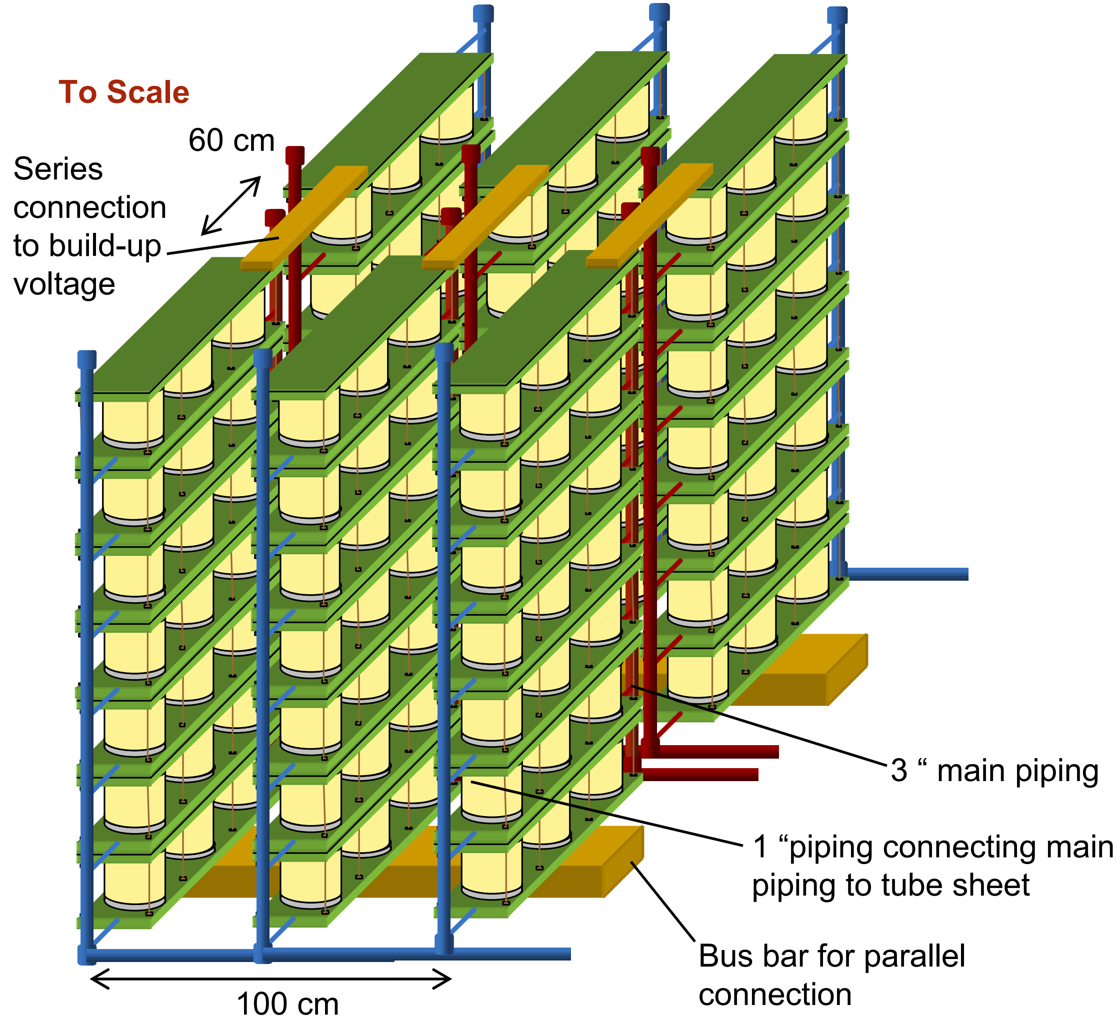
Array Configuration



Array Power	220 kWe
Array Voltage	294 V
Array Current	750 A
Number of Bundles	7
Number of Stacks	21

- Expansion joints, such as bellows may be required to allow for stress relief in the piping.
- Piping and tie-rods may have to be insulated so as to limit exposure to high temperature gases.

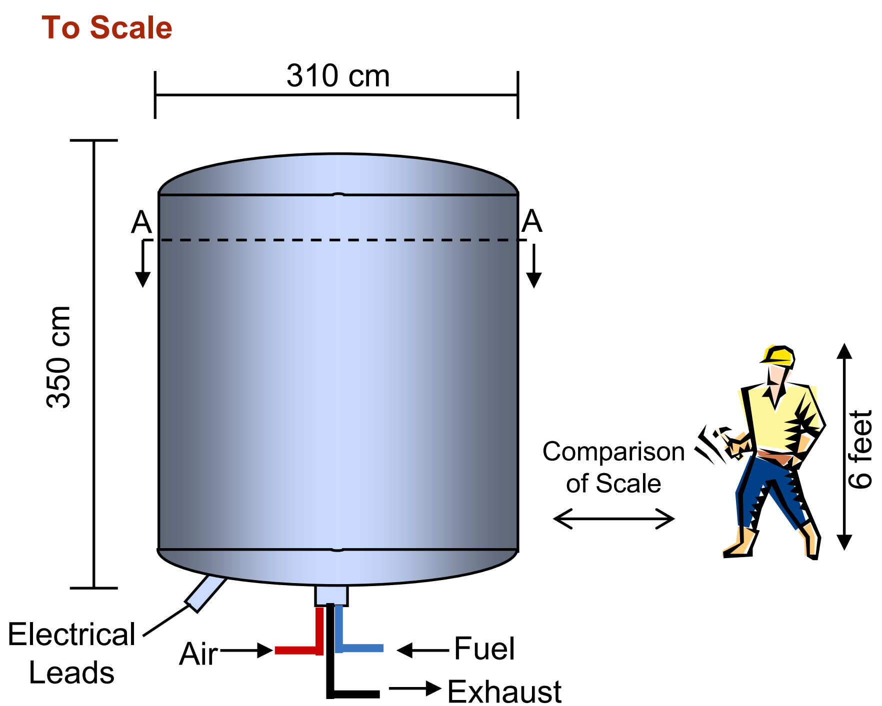
Multiple stack bundles and arrays are manifolded together to provide a 1.3 MW* SOFC power module, with modest piping requirements (only 5 cm/kW).



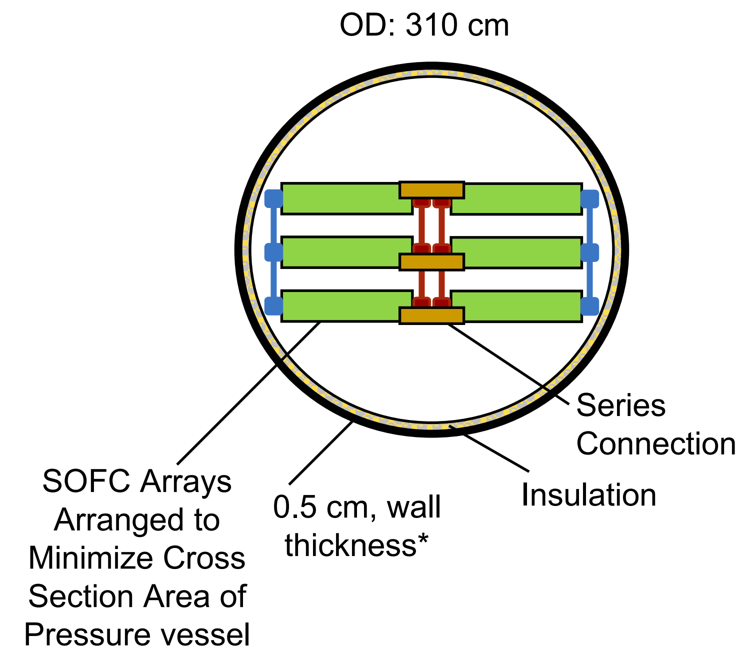
Module Power	**1320 kWe**
Module Voltage	**590 V**
Module Current	**2250 A**
Number of Stacks	**126**
Length of 1" Piping	**26 m**
Length of 3 " Piping	**44 m**
Total piping per kW	**5 cm/kW 2 "/kW**

* Two such 1.3 MW SOFC power modules will be connected in series in a 3 MW power plant, described in a subsequent section

For operation at 3 bar, the module will be housed in a pressure-vessel.



Side View of Pressure vessel

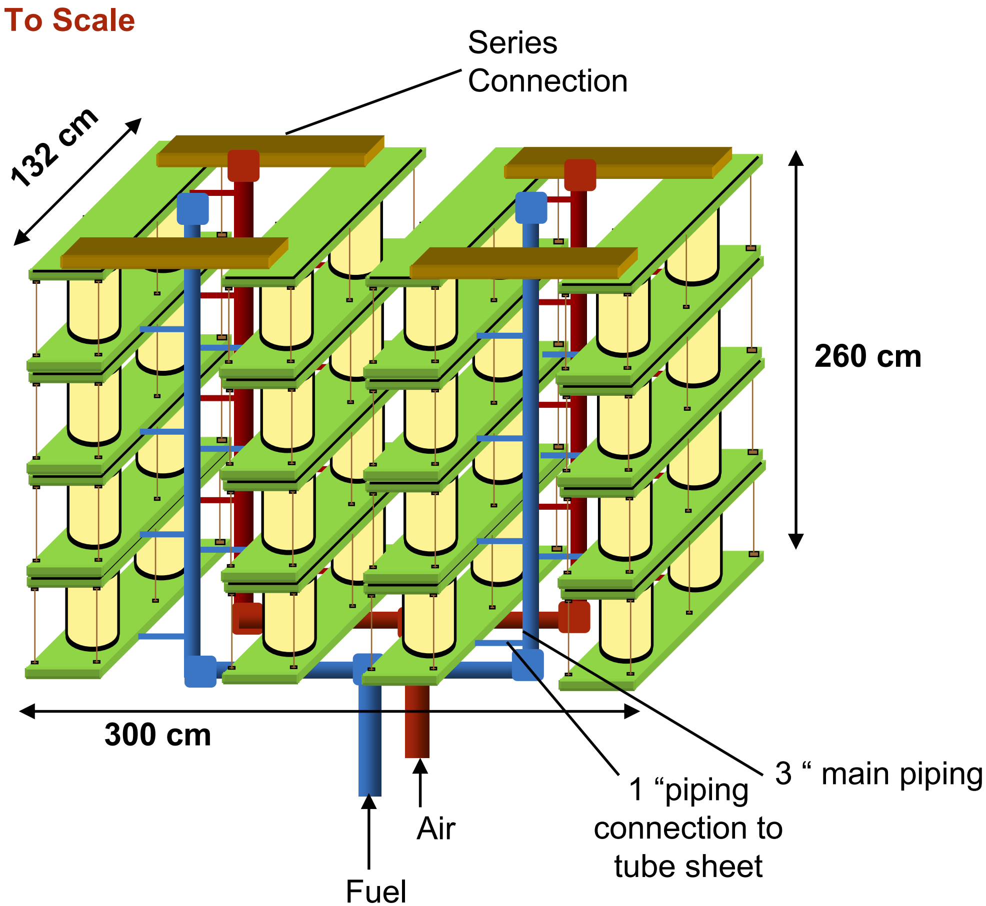


Along Section A-A

Vessel dimensions consistent with over the road transportation and skid mounted installations with minimal site work.

*Pressure vessel wall thickness sizing consistent with ASME guidelines

Sensitivity analysis showed that with a 40 kW (36 cm dia.*) stack as the building block, piping and manifolding requirements reduced significantly.



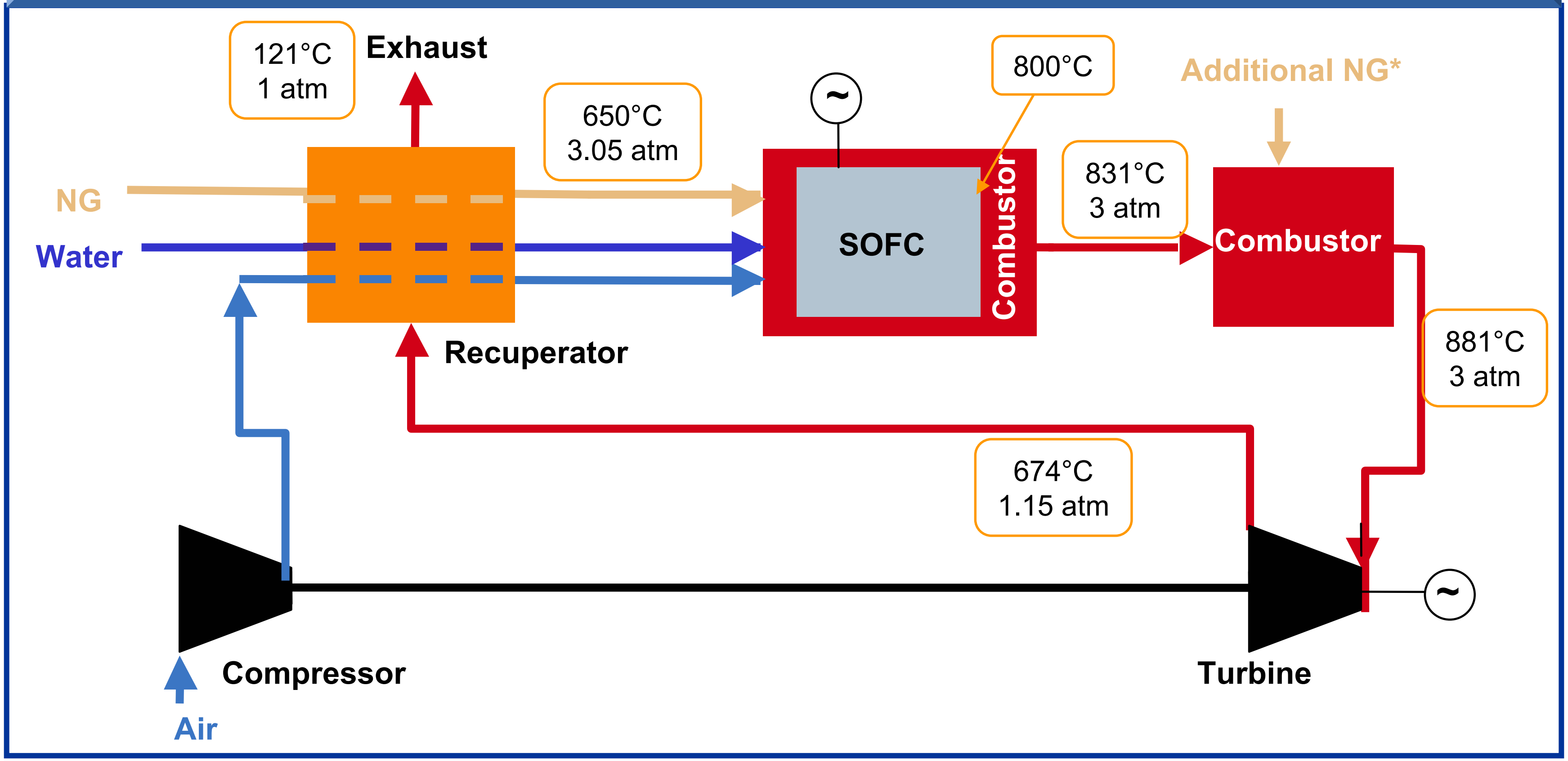
SOFC Stack	
Stack Power	40 kW
Stack voltage	73.5 V
Stack Current	540 A
Stack Diameter	36 cm
Cells	105

SOFC Power Module	
Power rating	1.3 MW
Terminal Voltage	590 V
Terminal Current	2150 A
Total Stacks	32
Length of 1" piping	3.8 m
Length of 3 " piping	14.4 m
Length of tube sheets	42 m
Total piping length	1.4 cm/kW 0.6 in./kW
Total piping length	3.2 cm/kW 1.2 in./kW

* Stack performance modeling indicated that 36 cm cell could operate at 90 % utilization of methane without generating damaging stresses.

A 3 MW “direct” hybrid architecture was utilized for defining a single design point for BOP sizing.

Direct SOFC-GT Hybrid System Configuration



* Note that with out auxiliary fuel firing prior to the turbine inlet, the turbine exhaust temperatures would too low to heat up the fuel cell inlet gases to 650°C.

Without optimization, a system efficiency of 66 % was achieved in the hybrid-cycle configuration (based on HYSIS modeling).

Heating Value of Primary Fuel Into Fuel Cell (LHV)	4210 kW
Heating Value of Fuel for Auxiliary Firing (LHV)	442 kW (10 % of total)

Fuel Cell Electric Power Output (DC)	2610 kW
Fuel Compressor and Water Pump Power	23 kW
Fuel Cell Energy Conversion Efficiency	61.5 %

Turbine Power Output	1700 kW
Turbine Power Output After Power Conditioning	1615 kW
Compressor Power Consumption	985 kW
Burner Compressor Power Consumption	2 kW
Net Turbine Power Output (AC)	624 kW

Net System Electric Power Output After Conditioning	3.1 MW
Overall System Energy Conversion Efficiency	66 %

* The calculations did not consider heat losses: in the piping from the SOFC power module to the gas turbine; in the recuperators; or, in the SOFC power module-which would reduce the system efficiency. Ohmic losses in the electrical interconnection within the SOFC power module were less than 1 % of the total module voltage. Ohmic losses in external interconnection were not considered.

High-level cost estimates show that the *installed cost* for the non-optimized SOFC-Gas Turbine hybrid system could be ~ 513 $/kWe.

	System Cost	Cost per kW AC system capacity
SOFC Power Module Total	**$406,059**	**$137**
SOFC Stacks	$290,400	$94
Vessel	$28,000	$9
Vessel Insulation	$20,000	$6
Manifolding	$48,800	$16
Assembly	$37,000	$12
BOP Total	**$900,830**	**$290**
Gas turbine	$460,035	$148
Recuperators	$99,314	$32
Power conditioning	$155,220	$50
Instrumentation and controls	$93,130	$30
Piping and valves	$93,130	$30
System Factory Cost	**$1,325,969**	**$421**
Installation*	**$265,194**	**$84**
Installed system	**$1,591,163**	**$513**

* Installation cost is assumed to be 20% of total equipment cost; includes costs of enclosure and foundation, grid interface equipment, fire protection.

* Assumed manufacturing volume of 100 units/year for costing purposes, equivalent to stack manufacturing volume of 250 MW/yr, which is consistent with previous cost estimates for stack manufacturing costs.

Mass produced SECA based cells/stacks can be cost effectively configured into MW-level power modules appropriate for high efficiency multi-megawatt hybrid power systems.

- Detailed stack modeling results show that large diameter circular cells can be assembled into 10 kW modules for a wide range of applications, consistent with SECA strategy.
- Preliminary designs indicate that 10 kW SOFC stacks can be assembled into MW+ power modules with modest piping and manifolding requirements.
- In fact, from a piping and manifolding viewpoint, scale-up individual SECA cells for a MW-level plant should be no more difficult than the scale-up of Siemens-Westinghouse single tubes for a MW-level power plant.
- System modeling showed that the SECA stack (nominally 800°C) based combined cycle system could deliver ~ 66 % efficiency (LHV) in a non-optimized system.
  - That is, even with the lower stack operating temperature, very high system level efficiencies are obtained.
- High level cost estimates indicate that the complete system could be installed for ~ $ 513 / kW

Refinement of the scale-up potential with increased levels of confidence can come from specific R&D (analytical and lab-based) to verify and refine key technology assumptions.

- Verification of allowable stresses for the stack materials
- Determination of maximum allowable temperature gradient across the stack
- Better definition of contact resistance specific to planar sandwich structures
- Assessment of the complete ramifications of the use of anode-supported SOFCs in combined cycle hybrid systems must be examined.
  - Effect of lowering stack temperature on hybrid system configuration and operation
  - Implications for reforming options (external reformer) if stack temperature < 700 °C
- Assessment of other hybrid options which allow near atmospheric operation of the SOFC system and hence help eliminate pressure vessel requirement (this will also simplify stack power scale-up).
  - “Indirect” turbine cycles
  - Steam bottoming cycle (possibility of co-firing at conventional steam plants)
  - Stirling engine (particularly in 50 - 500 kW power range)

NETL wanted to understand if and how SECA SOFC stacks could be scaled-up for use in MW-level combined cycle power plants.

- SECA strategy relies on the use of modular, mass produced, SOFC stacks in the 3 - 10 kW capacity range for a wide range of applications.
- Technical feasibility small-scale applications has been evaluated by SECA:
  - 5 kW POX-based truck APU;
  - 5 kW stand-alone residential power system;
  - 250 kW distributed generation system.
- SOFC-Gas Turbine (GT) hybrid systems, that have the potential for very high efficiencies (~ 60 - 70 %) could potentially be another application.
- Combined cycle systems based on Gas-Turbines, are typically rated at the MW-level capacity.
- Therefore, a MW-level SOFC power module must be built from kW-level SECA SOFC stacks.
- For example, ~ 100 stacks of nominally 10 kW power have to be integrated to form the 1 MW SOFC power module.

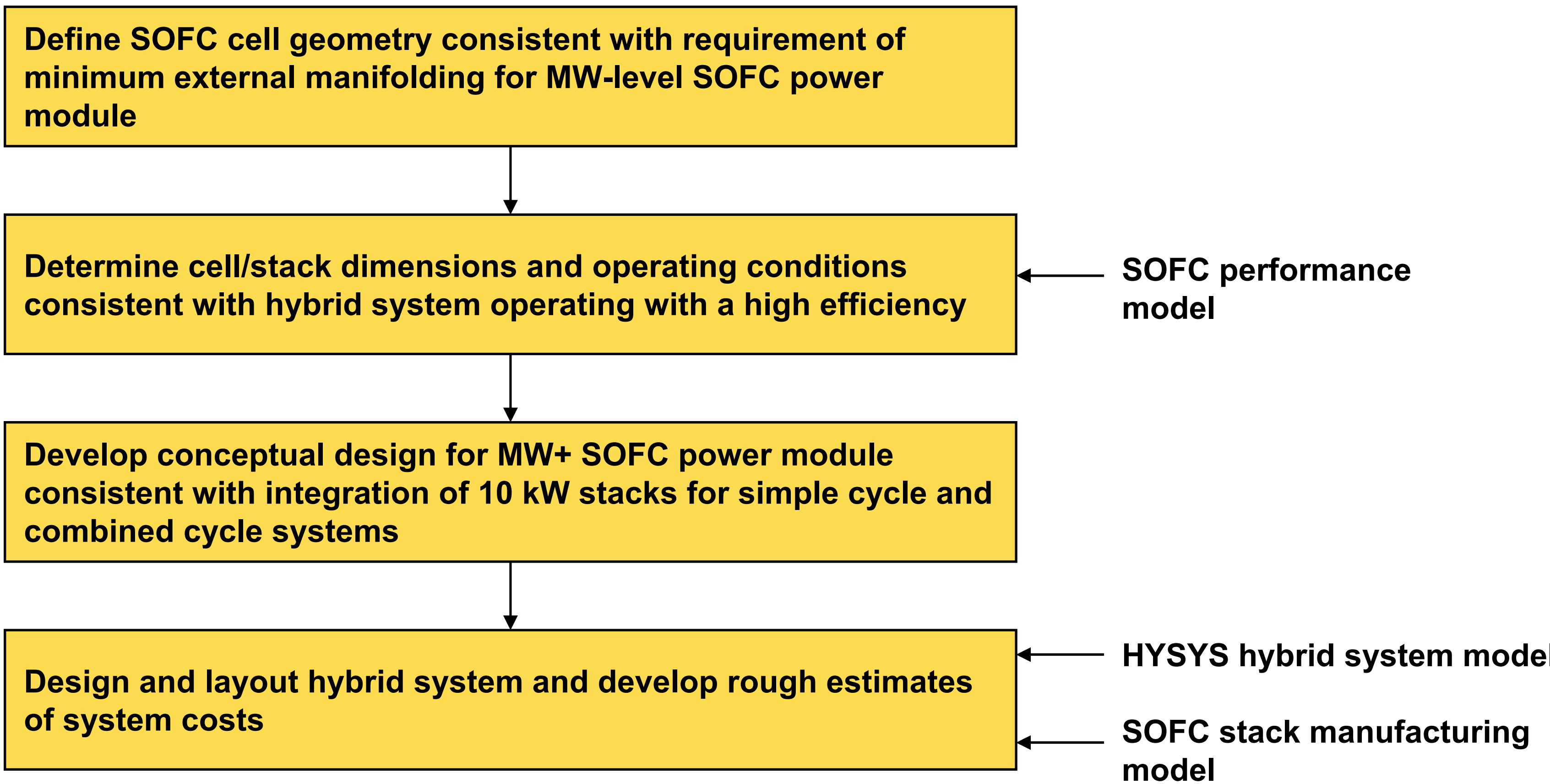
In order to achieve reliability, good performance and low costs, the scale-up strategy must:

- *Minimize high temperature piping and manifolding connections* associated with connecting a large number of individual stacks having both inlet and outlet reactant streams.
- *Build-up voltage* to levels consistent with low cost power conditioning, low ohmic voltage losses, and efficient grid interfaces.
- *Minimize contact resistance losses* associated with electrically interconnecting a large number of individual stacks.
- *Configure system for high efficiencies (60 % +)* for use with stacks operating at nominally 700 - 800°C, consistent with SECA strategy.
- *Reduce parts counts* by using large diameter cells still consistent with acceptable thermal stresses and power density characteristics.

The objective for this study was to determine how the power from individual SECA stack modules could be scaled-up for combined cycle power plants.

- Specifically, the project aimed to:
  - Conceptually design and layout a MW-level power module comprised of SECA SOFC stacks
    - Specify stack design that will simplify the stack reduce system components (on-anode internal reforming)
    - Size single SOFC stack for the specified design
    - Arrange stacks for power scale-up
  - Conceptually layout the combined cycle power plant
    - Obtain rough estimates for BOP sizes
    - Obtain rough estimates for power plant foot print
  - Obtain high-level estimates for the power plant costs
    - Use previous analyses as the basis for cost estimation

The key issues were systematically addressed using models developed in previous NETL-SECA assignments and assessing the performance/cost of cells, stacks, and system.



On-anode internal reforming was assumed for the SOFC stacks based on modeling results.

- Cell performance in the for both internal and external reforming options were simulated with the performance model (Data in the Appendix 1).

- Model results model indicated that internal reforming is attractive at the low operating temperatures (800°C) of anode supported stacks.
  - Proceeds relatively uniformly over the cell area leading to reduced stress levels
  - Good power density
  - Significant advantage is the reduced excess air requirement and the associated decrease in BOP cost and increase in system efficiency

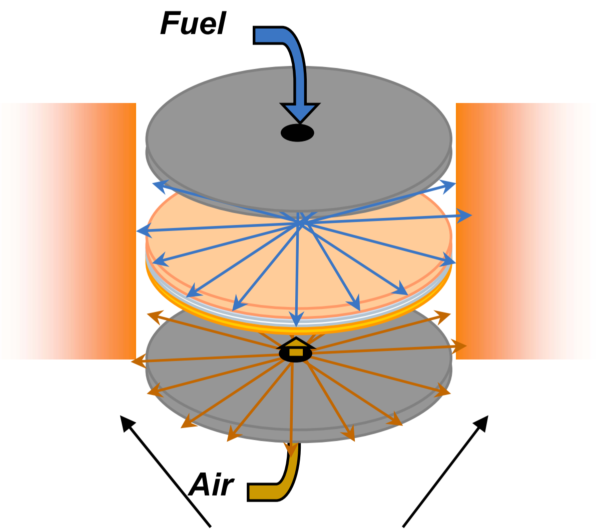
- Given that MW level systems assume a mature technology - internal reforming was selected for the baseline analysis.

A single design strategy was selected as a baseline for the purpose of assessing the scale-up strategy for SECA 10 kW modules for use in a high efficiency hybrid plant.

- A circular cell geometry was selected to reduce manifolding/interconnect requirements.
- The baseline cell/stack performance was estimated assuming a nominal 800°C stack temperature (sensitivity analyses were performed, however, on the operating variables)
- A direct fuel cell - gas turbine hybrid configuration operating at 3 atm was assumed (consistent with a design pursued by Siemens-Westinghouse).

Circular stack design was selected for analysis because of the potential for flexibility in designing the SOFC power module, with minimal manifolding.

Circular Stack with Radial Outflow

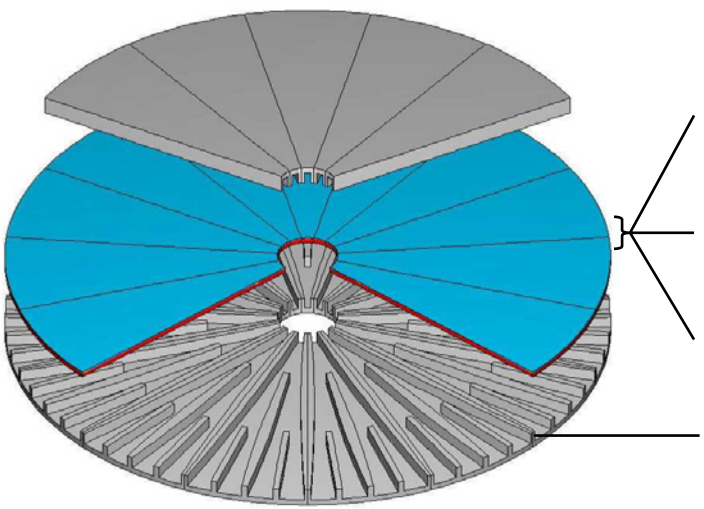


Combustion of unspent fuel by the cathode air

- The stack geometry can be chosen such that the SOFC power module design can be simplified.
- The majority of the developers of anode supported stacks are considering either a rectangular or a circular geometry for the stack.
- Our previous study of a 250 kW simple cycle system, designed for SECA stacks, showed that use of circular stacks might simplify the manifolding requirements.
  - In a rectangular stack, manifolding is required for both the fuel cell inlet and exit streams.
  - In a circular stack, the spent fuel and oxidant streams mix and burn at the periphery of the stack.
  - In the circular stack, manifolding of the exhaust gases is eliminated thereby simplifying the piping arrangement and allowing for more flexible arrangement of the stacks.

The cell component dimensions and materials were chosen to reflect the current practice for anode-supported SOFC designs.

Cutaway of anode supported cell structure and cell components used in the performance model



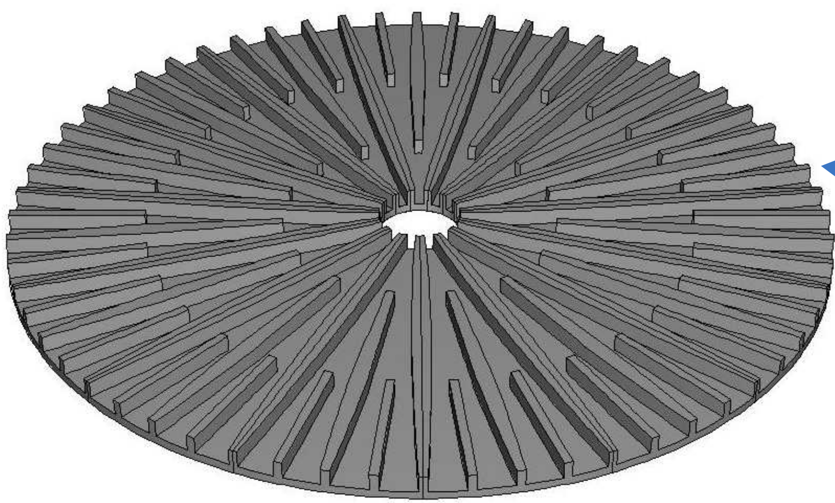
Note: *In the model, the reactants flow was specified as a boundary condition at the inside edge of the cell. Details of the internal manifolding and associated sealing were not considered in this assignment.*

Circular radial cell structure is similar to earlier TIAX studies and is also outlined in the U.S. Patent 5,549,983 assigned to Allied Signal.

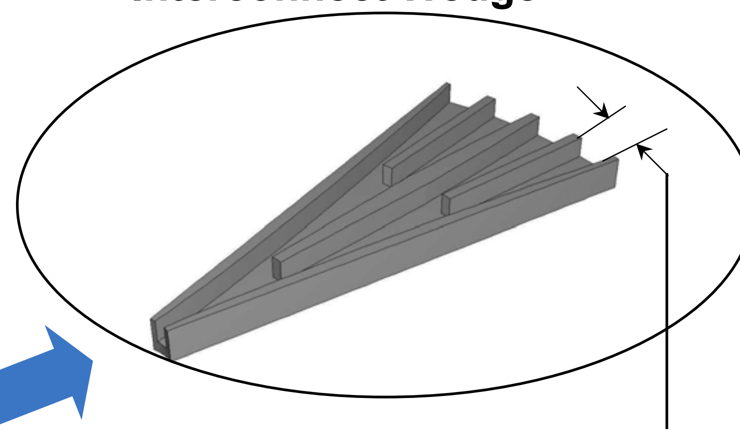
The flow channels for the SOFC interconnect used in the model were designed so as to minimize electrical resistance losses and pressure drop.

SOFC Interconnect Architecture (SOFC radius 5 cm)

Entire Interconnect



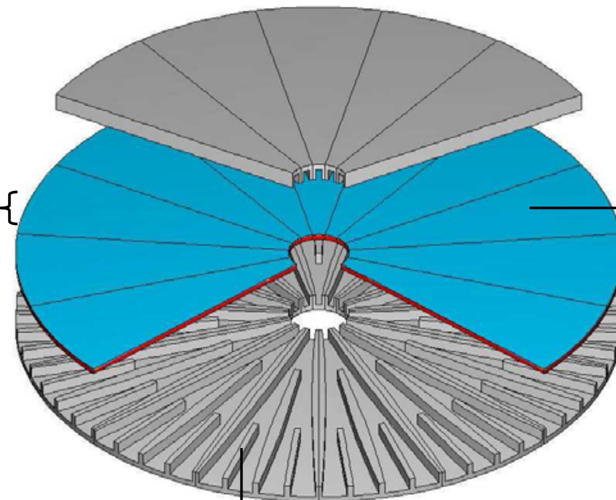
Interconnect Wedge*



- Maximum channel spacing < 5 mm
- Minimum ridge thickness > 2 mm

* We took advantage of axial symmetry and simulated a single wedge segment of the fuel cell

Previously developed SOFC model was augmented with on-anode internal reforming kinetics and adapted for the circular geometry.



- *Ceramic Electrode Electrolyte Assembly (EEA)*
  - Species diffusion and heat conduction in the porous electrodes
  - Electrocatalytic reactions and heat generation in the reaction zones of the anode and cathode
  - Ion conduction through the electrolyte

- *On anode steam reforming*
  - Methane steam reforming kinetics from literature data
  - Water-gas shift reaction assumed to be in equilibrium
  - Electrooxidation rate of CO assumed to be much slower than that of H_2.

- *Interconnect*
  - Plug flow of gases in the flow channels
  - Heat conduction, convection and radiation

Solution of equations for:
•Energy conservation
•Mass conservation
•Charge conservation

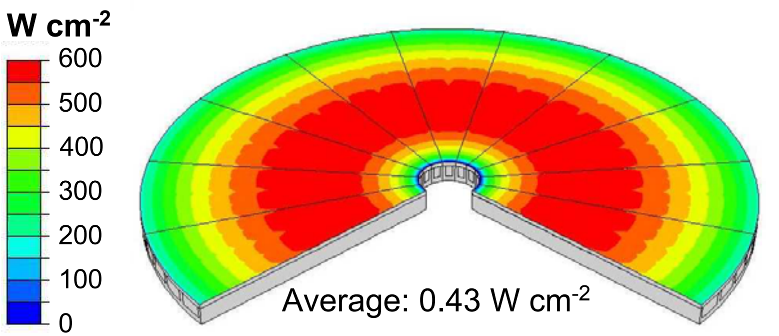
→ **Temperature gradients in the cell during operation**

→ **Mechanical stress distribution during operation**

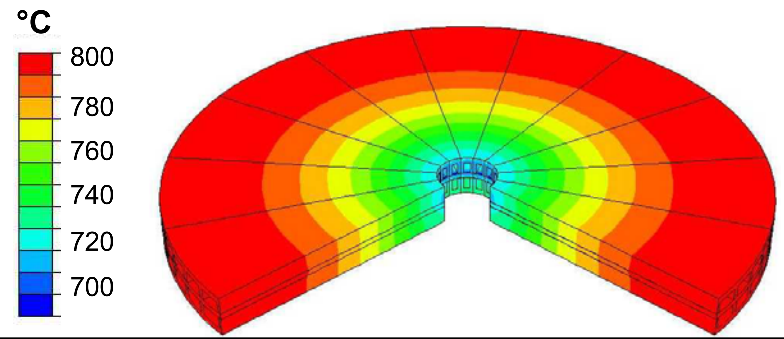
← **Constraints**

The results demonstrated that reduced cell operating temperature might allow internal reforming without causing damaging stresses.

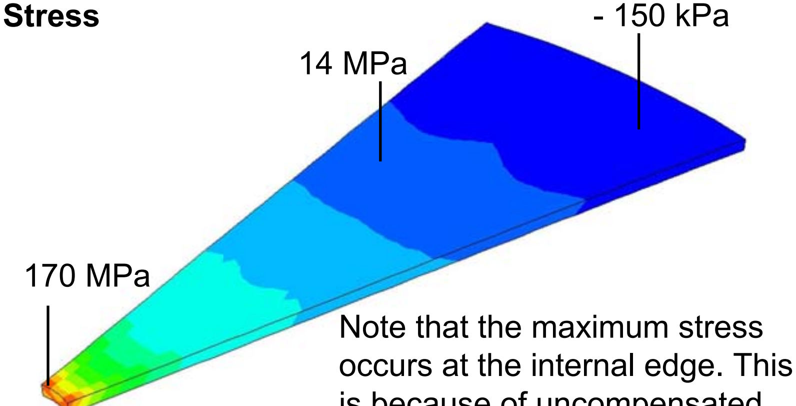
Power Density



Temperature



Stress



Note that the maximum stress occurs at the internal edge. This is because of uncompensated hoop stresses that are exacerbated by temperature gradients across the cell.

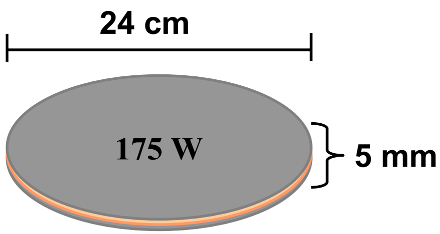
Operating Conditions	
Pressure	1 bar
Fuel utilization	90%
Internal reforming	100%
Inlet gas temperatures	650°C
Exit gas temperatures	800°C
Cell radius	5 cm
Contact resistance	No

The model results (details in Appendix 1) provided guidance for selecting cell dimensions and operating conditions.

- Reforming strategy:
  - Model results show that for a cell operating nominally at 800°C , internal reforming results in relatively uniform temperature gradients in the cell.
  - Consequently, internal reforming is consistent with minimizing thermal stresses and high power density operation.
- Cell diameter:
  - Modeling results showed that cells with diameter in the range 10 - 36 cm can be considered for SECA stacks, consistent with thermal stress constraints.
- Power density:
  - When operating at nominally 800°C, power densities are in the range of 380 - 500 mW /cm2 depending on the fuel utilization.
- Excess air requirements:
  - Excess air requirement is reduced by roughly 50 % for 100 % internal reforming, compared to the case of 100 % pre-reforming.

Based on model results, the following geometry and operating parameters were selected* for integration into the stacks, and power module.

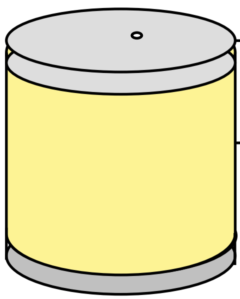
Parameter	Value	Comment
Cell Diameter	**24 cm**	• This cell diameter will result in a 42 V, 10.5 kW stack, consistent with mass produced SECA stacks.
Cell Voltage	**0.7 V**	• Voltage is sufficiently high to avoid mass transport limitations, but also can provide reasonable power densities and system efficiencies
Power Density	**400 mW cm^2**	• Power density was estimated for 90 % fuel utilization
Reforming Strategy	**100 % internal reforming**	• Modeling results showed that 100 % internal reforming was possible for the assumed reforming kinetics and steam to carbon ratio of 2.3:1
Fuel Utilization	**90 %**	• Model results indicated that operation at 90 % fuel utilization was possible without significant stress generation.
Excess Air	**330 %**	• Calculated such that the maximum cell temperature (at the exit) was less than 800 °C
Contact Resistance	**0.1 Ω cm^2**	• Assumed to be the resistance in a future stack. This value Value corresponds to ~ 40 % of the internal resistance estimated in state-of-the-art anode supported SOFC stacks.
Pressure	**3 bar**	• 3 bar was close to the pressure optimum in a hybrid system study[1]



Single Cell Dimensions

•*These stack operating conditions were found to be consistent with reasonable system efficiency in parallel system modeling (described in a subsequent section)

Consistent with our previous studies for NETL-SECA, we used a 42 V stack as the basis for determining the stack height.



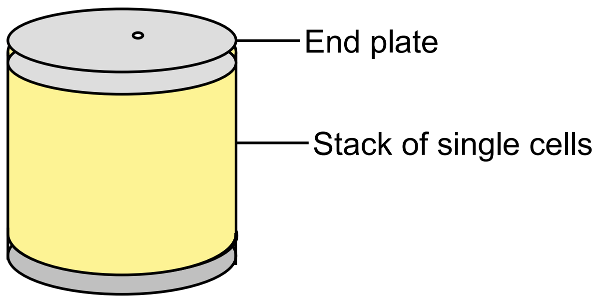
Single Stack

- The stack height is determined from the stack voltage and the single cell voltage.
- In previous studies for NETL-SECA we used a 42 V SOFC stack with ~ 0.7 V single cell operating voltage and a pitch of 5 cells per inch:
  - 5 kW SOFC POX-APU system
  - 5 kW grid-independent residential system
  - 250 kW distributed generation system
- Here, we assume that mass produced SECA stacks will be based on the 42 V architecture.

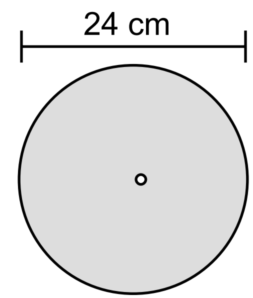
Stack area is determined from the power density, which depends on the operating conditions and is estimated from performance model as described in the previous section.

The dimensions of a ~ 10.5 kW stack were estimated to be 24 cm OD and 35 cm height.

Single Stack Configuration

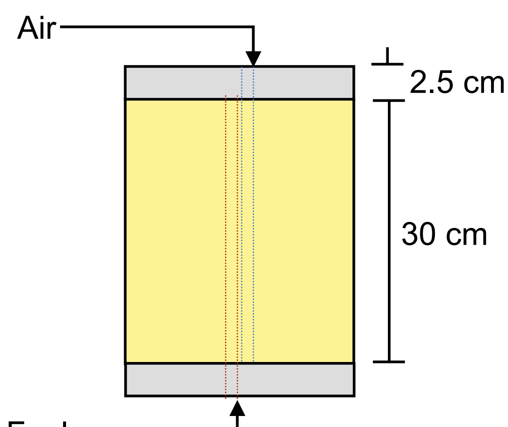


Single Stack



Top View

Stack Power		10.5 kWe
Number of Cells		60
Pitch		5 cells /inch
Stack Voltage		42 V
Power Density		400 mW/cm^2
SOFC Operating Voltage		0.7 V
Pressure Drop		0.05 atm
Stack Dimensions	Radius	13 cm
	Height	37 cm



Side View

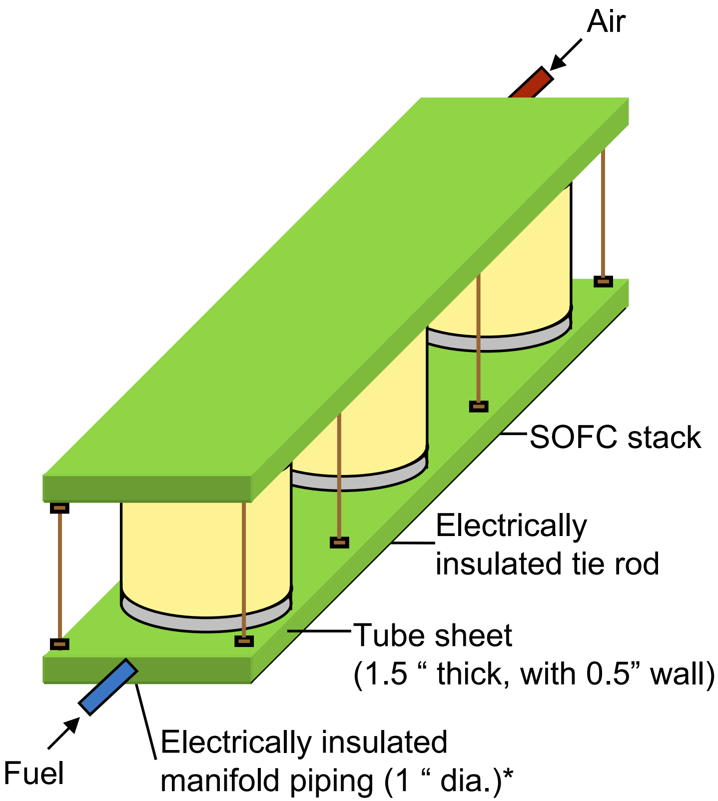
Multiple considerations influence the layout of a MW-level SOFC power module based on ~ 10 kW SOFC stacks.

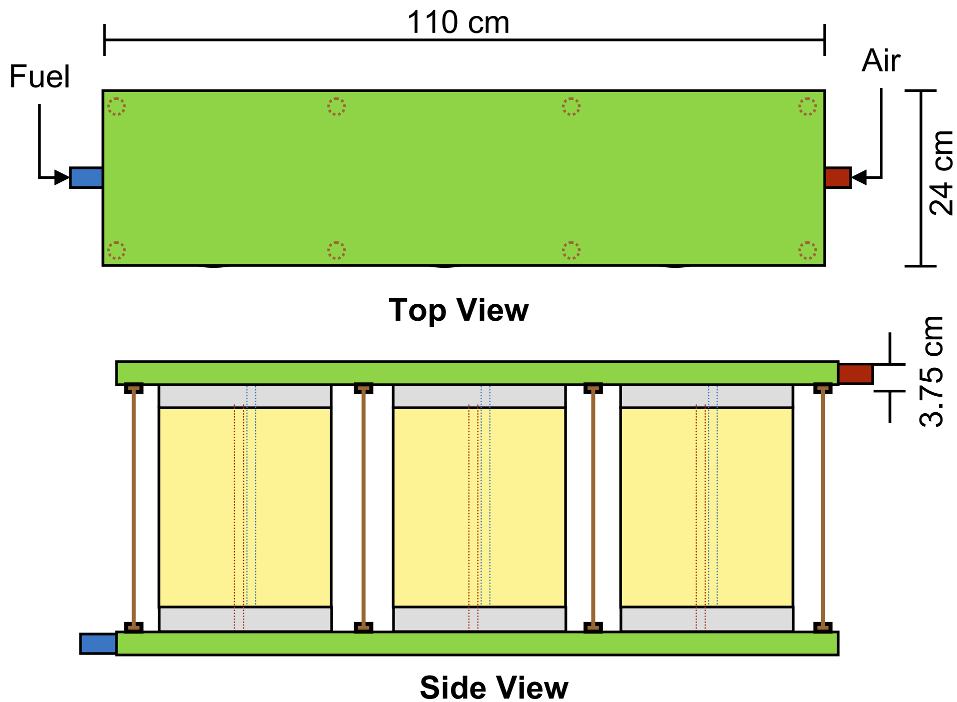
- The lay out must:
  - Minimize the required piping
  - Build up voltage while minimizing ohmic losses
  - Facilitate easy stack replacement
  - Provide a facility for stack compression
  - Allow for redundancy in power generation

For current scale-up, single stacks are manifolded between tube sheets to form a stack bundle.

Single Stack Bundle Configuration

To Scale





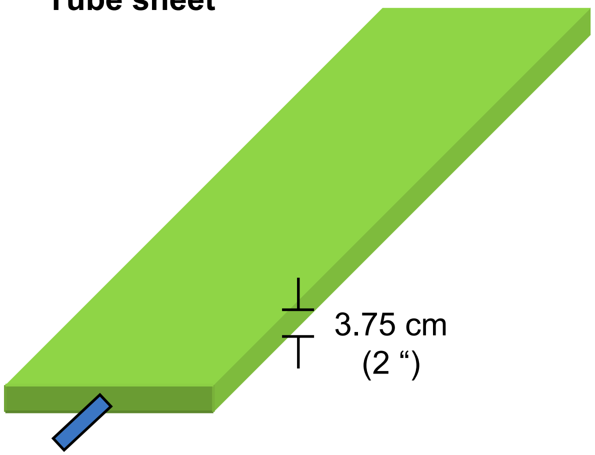
Stack Bundle Power	**30 kWe**
Number of Stacks	**3**
Bundle Voltage	**42 V**
Bundle Current	**750 A**

*The tubing must be electrically isolated from the tube-sheet. Several approaches are possible for this. One approach might be to use a ceramic sleeve on the tubing so that the metal tube does not contact the tube-sheet.

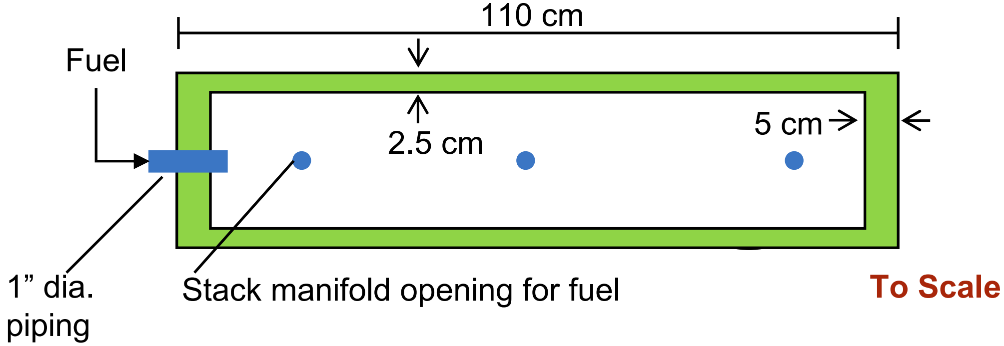
A “tube-sheet” manifolding design was selected in order to:

- Provide an architecture for uniform, low pressure-drop, distribution of reactant gases that also results in simplified and robust manifolding.
- Provide a support for the stacks and an anchor for applying compressive force on the stacks (using tie-rods) in a high-temperature environment.
- Allow for serial connection of stacks, consistent with low ohmic voltage drop.

Tube sheet



Tube sheet in Cross-Section

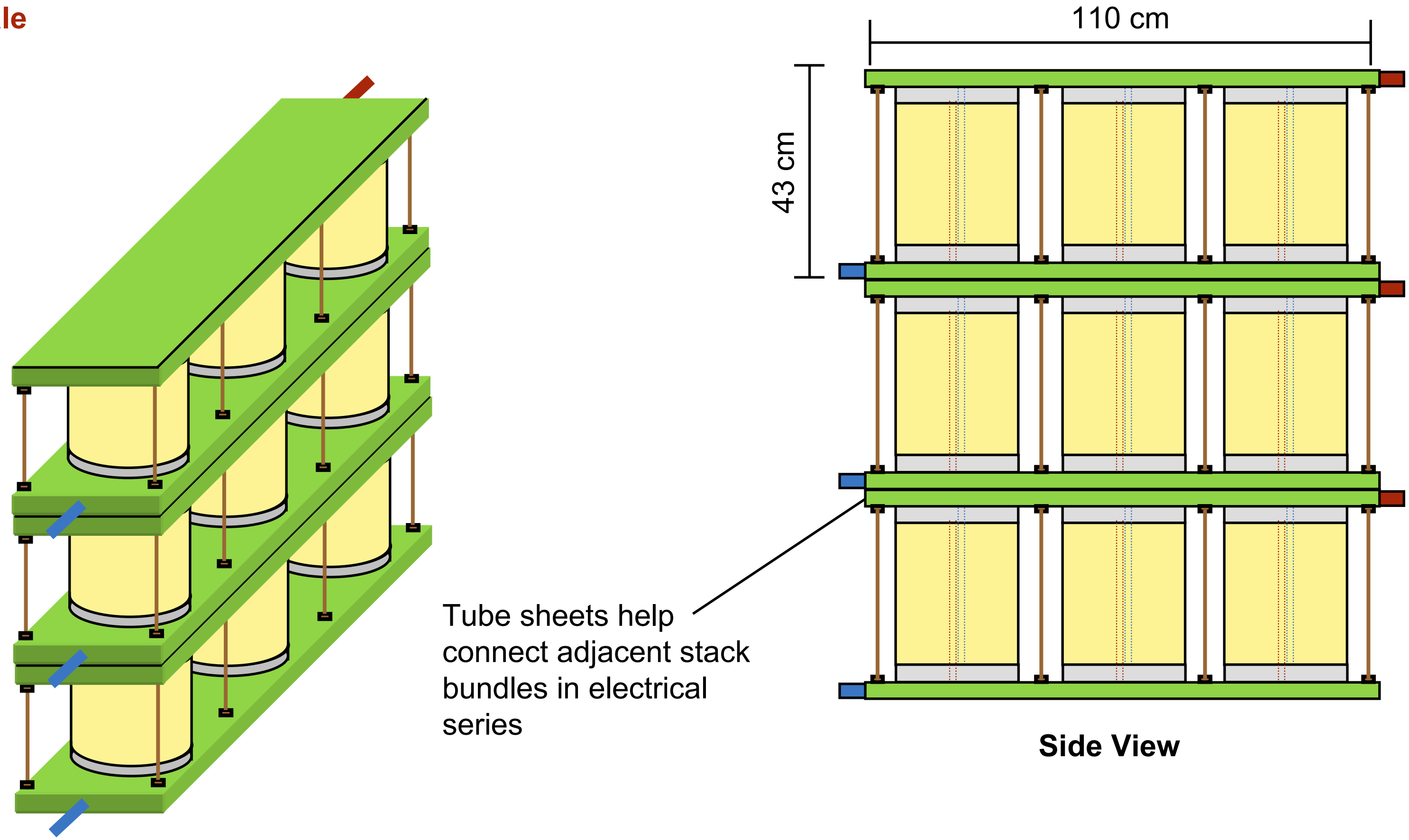


Wall thickness of the tube-sheets estimated such that the voltage loss due to ohmic resistance is less than 1 % of the total stack voltage

For voltage scale-up, stack bundles are ‘stacked’ together.

Array Configuration

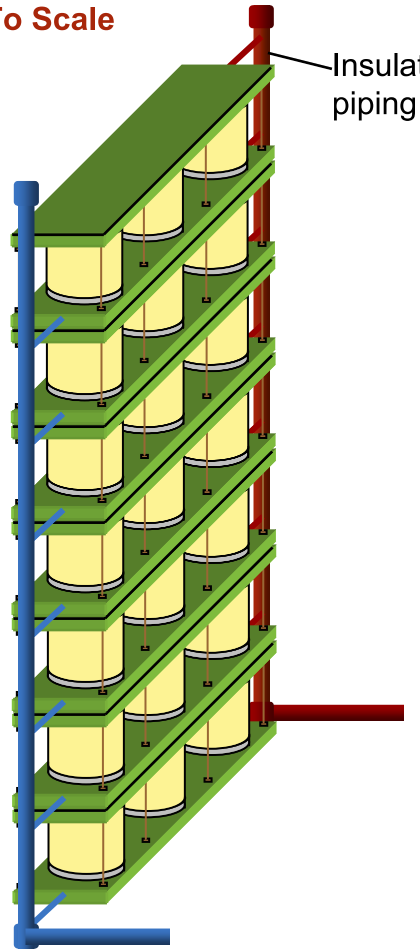
To Scale

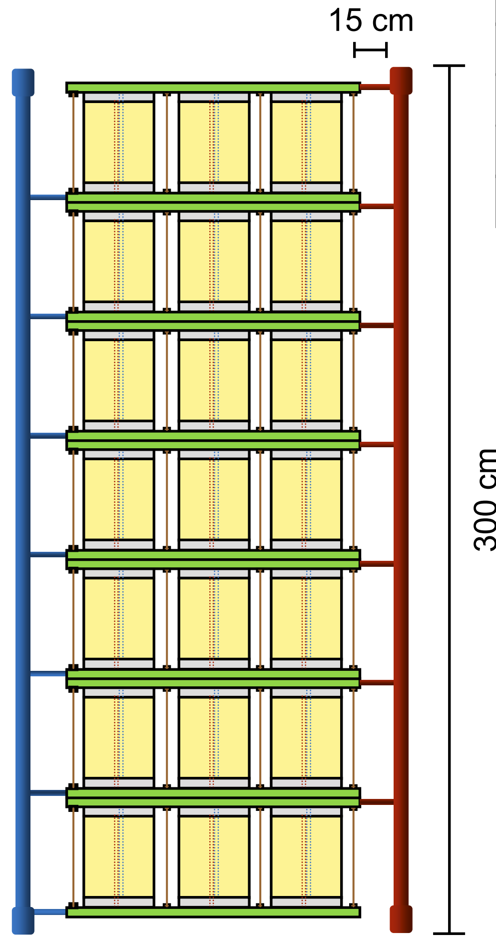


Stack bundles are manifolded together for reactant delivery, to form an array.

Array Configuration

To Scale



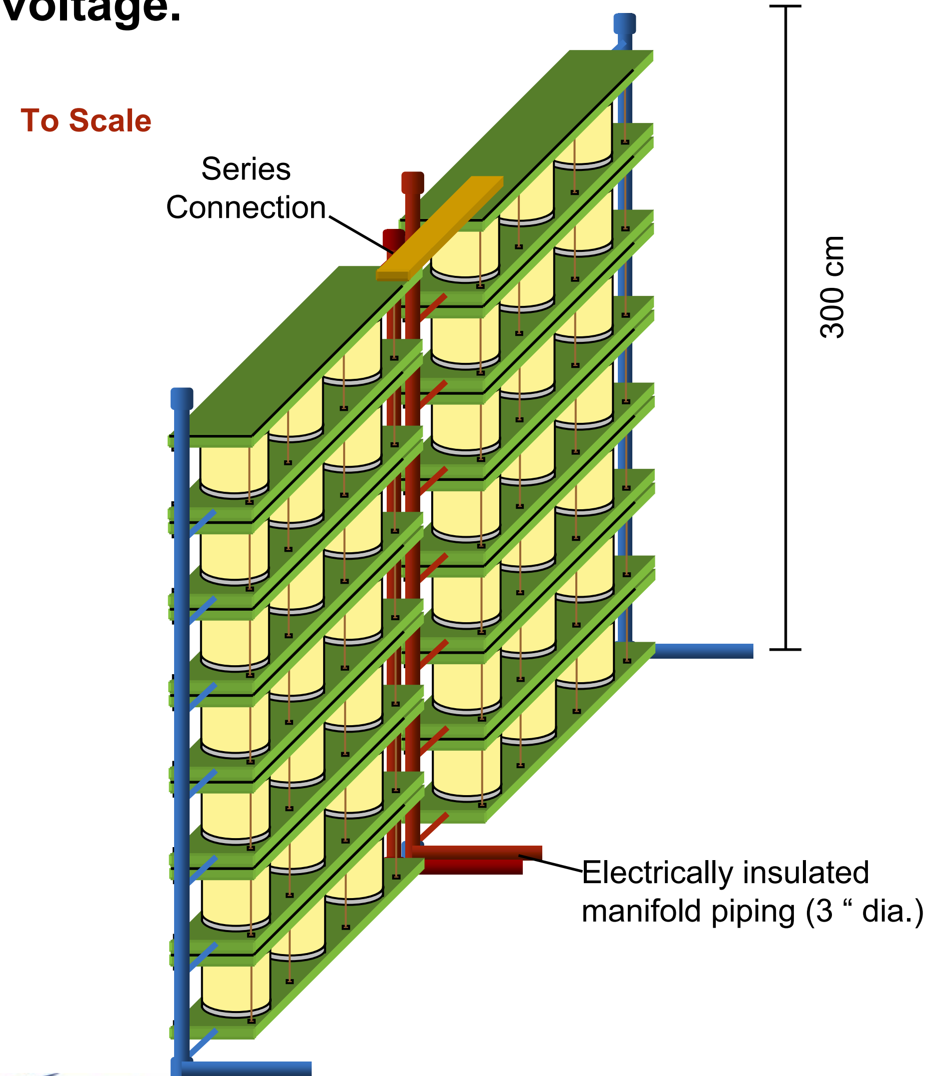


Side View

Array Power	**220 kWe**
Array Voltage	**294 V**
Array Current	**750 A**
Number of Bundles	**7**
Number of Stacks	**21**

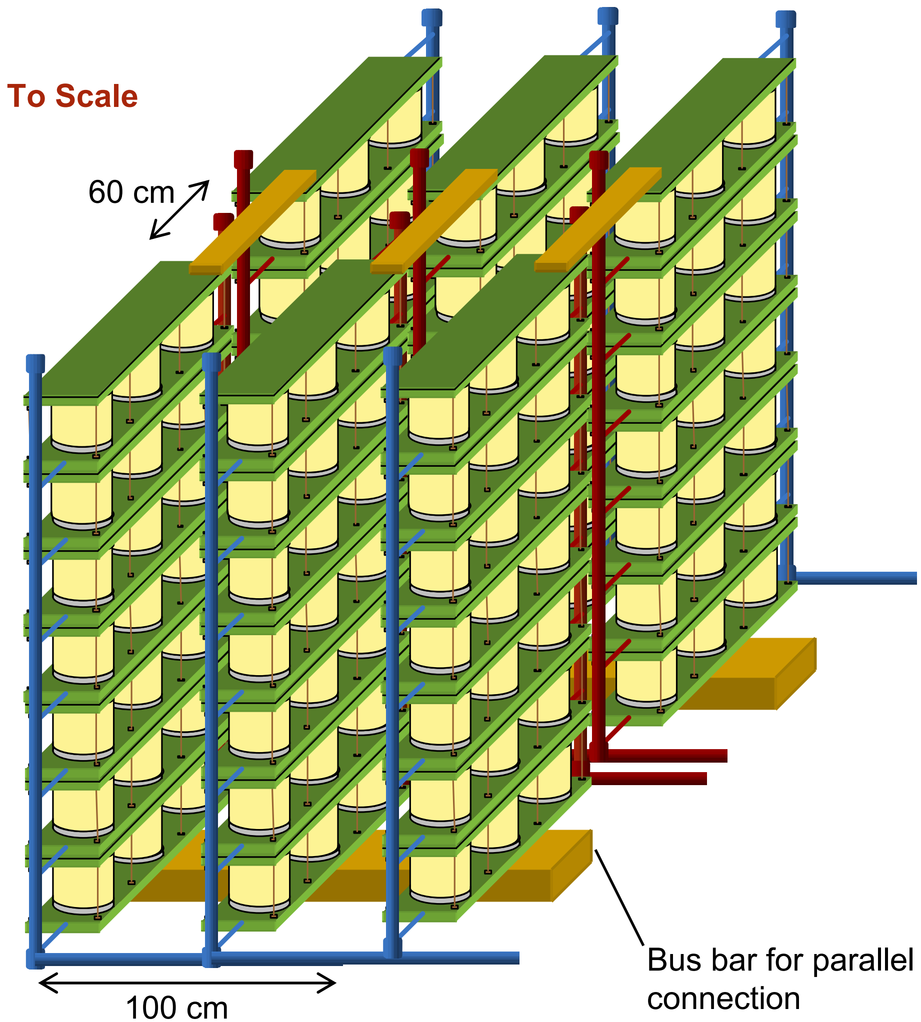
- Expansion joints, such as bellows may be required to allow for stress relief in the piping.
- Piping and tie-rods may have to be insulated so as to limit exposure to high temperature gases.

Two individual arrays are connected in electrical series to increase the voltage.



Array Voltage	590 V
Array Current	750 A

Multiple arrays are manifolded together to provide a 1.3 MW* SOFC power module.



Module Power	**1320 kWe**
Module Voltage	**590 V**
Module Current	**2250 A**
Number of Stacks	**126**
Length of 1" Piping	**26 m**
Length of 3 " Piping	**44 m**
Total piping per kW	**5 cm/kW 2 "/kW**

* Two such 1.3 MW SOFC power modules will be connected in series in a 3 MW power plant, described in a subsequent section

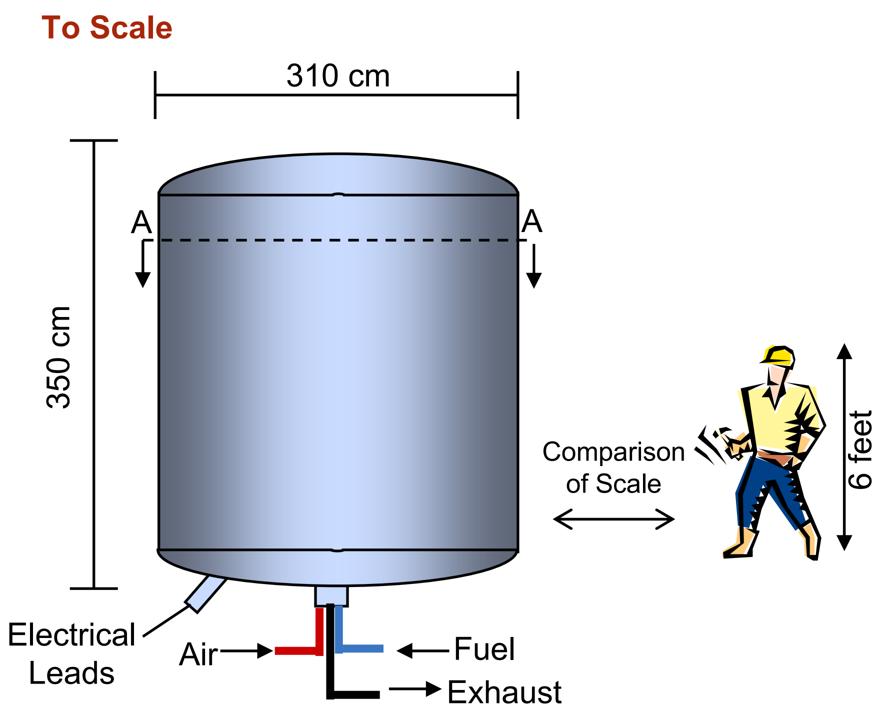
The baseline configuration utilizes highly flexible modules consistent with minimal requirements for high-temperature manifolding.

- Piping diameters are in the 3” (main supply) to 1” (tube sheet connections) range. Length required
  - 1 “ piping: 26 m
  - 3 “ piping: 44 m
- Tube sheet length required: 92 m

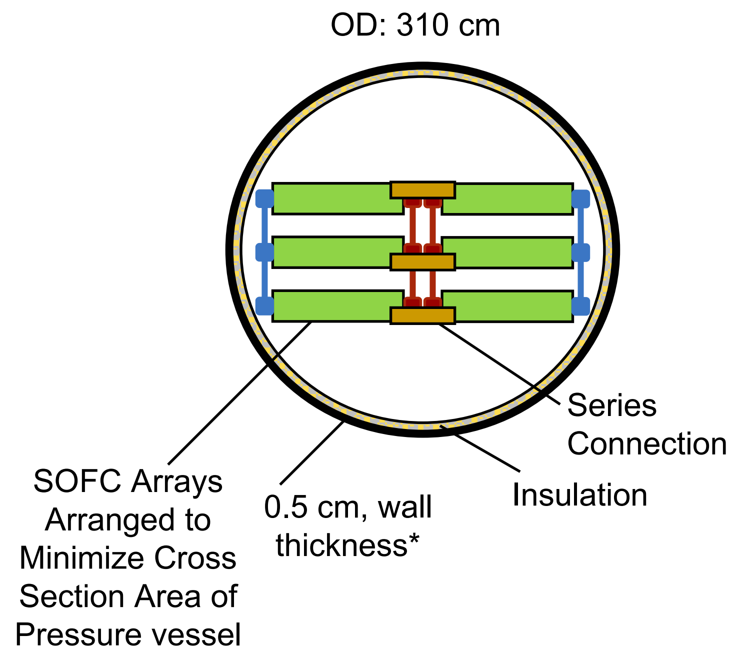
- Total length of piping required: 5 cm/kW (2 in./kW)
- Total length of tube sheet required: 7 cm / kW (2.75 in./kW)

Note : Larger stacks (20 - 40 kWe) would result in even lower requirements for piping and tube sheet manifolding.

For high pressure operation, the module will be housed in a pressure-vessel.



Side View of Pressure vessel



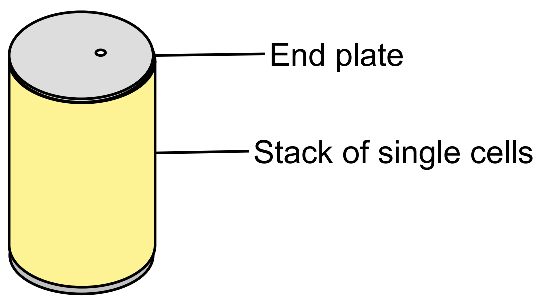
Along Section A-A

*Pressure vessel wall thickness sizing consistent with ASME guidelines

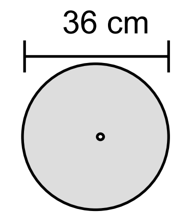
We also evaluated the power scale-up with the use of a 36 cm diameter*, 40 kW SOFC stack.

Single Stack Configuration

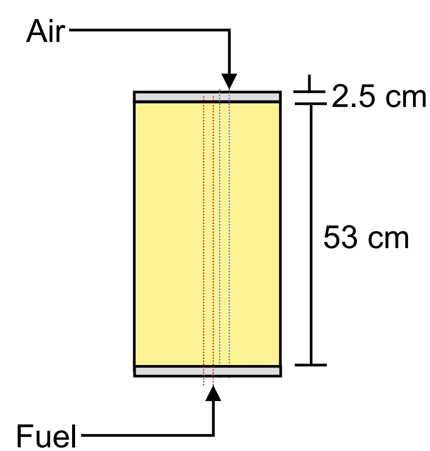
To Scale



Single Stack



Top View

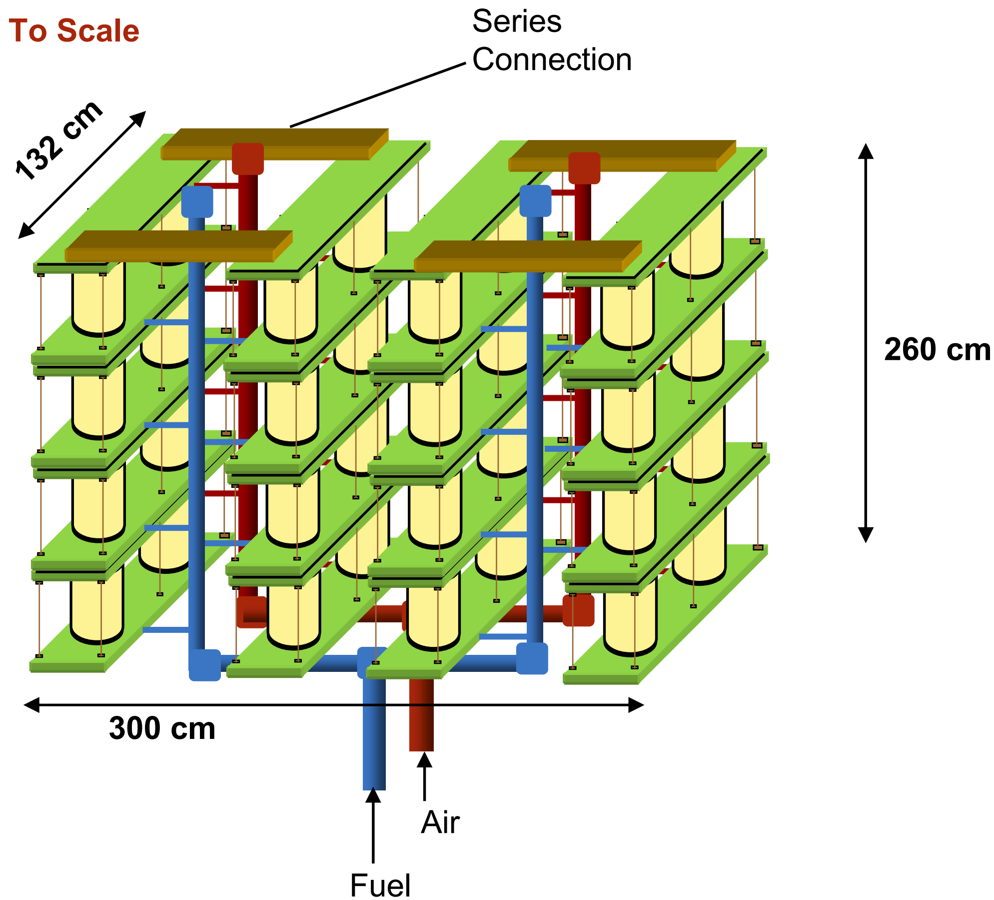


Side View

Stack Power		40 kWe
Number of Cells		105
Stack Voltage		73.5 V
Pitch		5 cells per inch
SOFC Operating Voltage		0.7 V
Pressure Drop		0.05 atm
Stack Dimensions	Radius	18 cm
	Height	53 cm

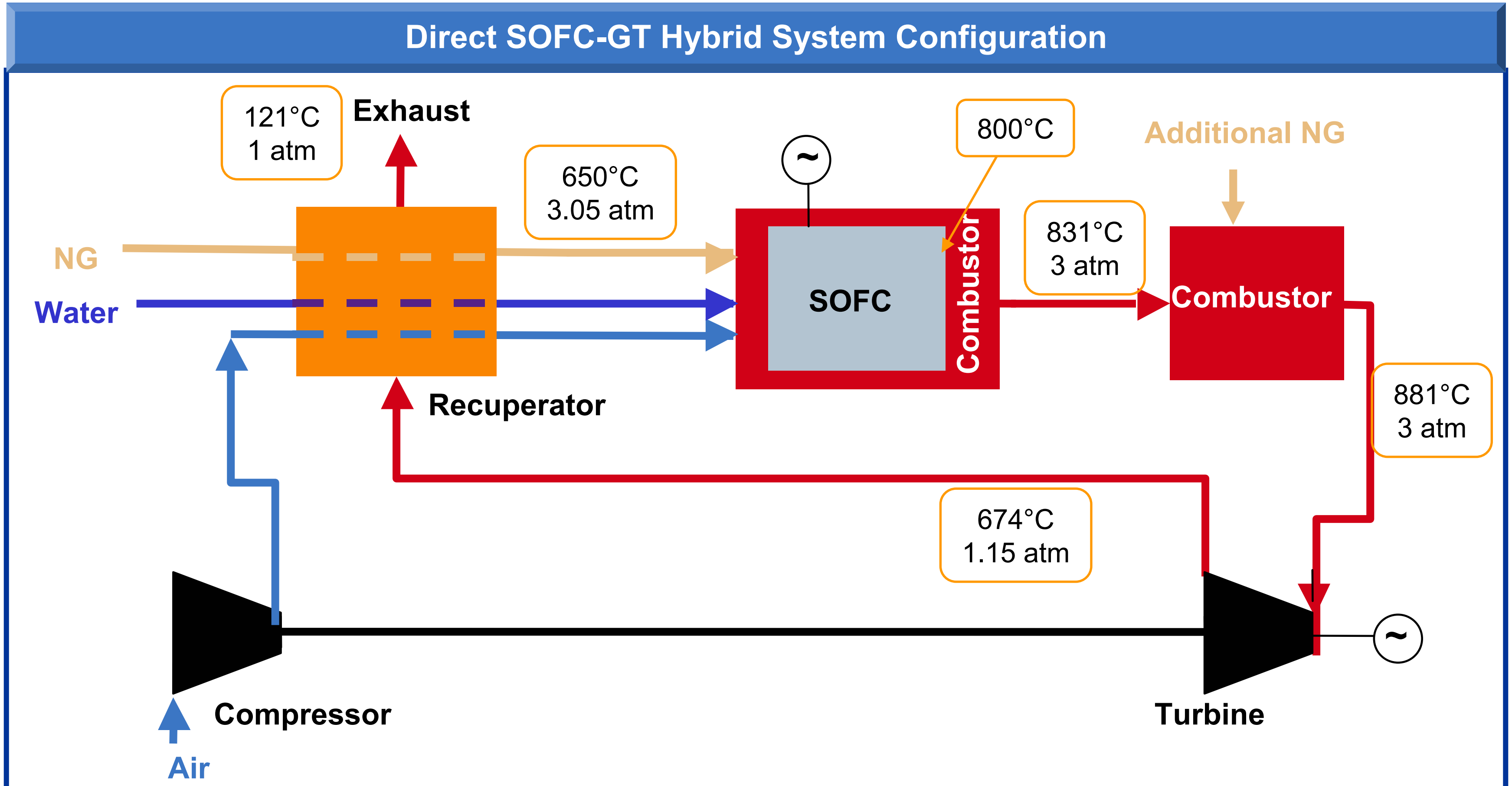
* Note that the power density of the 36 diameter stack was calculated with the performance model as described in the previous section and in the Appendix.

With the use of a 40 kW stack, the piping requirements reduce significantly.



SOFC Power Module	
Power rating	1.3 MW
Terminal Voltage (Under Load)	590 V
Terminal Current	2150 A
Total Stacks	32
Number of Arrays	2
Bundles Per Array	8
Stacks Per Bundle	2
Length of 1" piping	3.84 m
Length of 3 " piping	14.4 m
Length of tube sheets	42 m
Total piping length	1.4 cm/kW 0.6 in./kW

The 1.3 MW SOFC power modules were assumed to be utilized within a 3 MW hybrid power cycle.



A "direct" hybrid architecture was utilized to define a single design point for BOP sizing. Additional architectures could be considered.

The operating conditions and configuration of the hybrid power cycle were adjusted to reflect the 800°C temperature of the SOFC stacks (consistent with current trend of SECA technology)

- With fuel utilization of 90 %, hot gases exit the SOFC power module at 830°C (after the stack exhaust combusts within the pressure vessel).
- Turbine gas inlet temperature can be adjusted with small amounts of auxiliary firing so that the gas exiting the turbine (after expansion) has a temperature higher than 674°C.
  - Absent firing of ~ 10 % additional fuel prior to the turbine inlet, the turbine outlet temperature would be too low to heat the fuel cell reactant streams to acceptable temperatures (650°C).
- High levels of recuperation will be needed to both improve the system efficiency and to ensure appropriate reactant (fuel and air) temperatures to the stack.
- It may be possible to reduce the extent of auxiliary fuel firing by adjusting the fuel cell operating voltage, temperature, fuel utilization, excess air-requirements, etc.

Baseline hybrid system performance based on a base case design point based on the following specifications.

	Parameter	Value
System	Technology	Direct SOFC / Gas Turbine Hybrid System
	System Power Rating	3 MW
	Water Self-sufficiency	No, External water supply
	Power Conditioning Efficiency	96%
Fuel Cell	Technology	Planar circular anode-supported SOFC
	Fuel Cell Internal Reforming	100%, 2.3 steam to carbon ratio
	Fuel Cell Voltage	0.7 V
	Fuel Cell utilization	90 %
	Excess Air requirement	330 %*
Gas Turbine	Turbine Type	Similar to Solar Turbines Saturn 20
	Compressor Adiabatic Efficiency	75%
	Turbine Adiabatic Efficiency	85%
	Turbine Pressure Ratio	3:1

*Estimated from the stack performance model for a fuel utilization of 90 %

Without optimization, a system efficiency of 66 % was achieved in the hybrid-cycle configuration (based on HYSIS modeling).

Heating Value of Primary Fuel Into Fuel Cell (LHV)	4210 kW
Heating Value of Fuel for Auxiliary Firing (LHV)	442 kW (10 % of total)

Fuel Cell Electric Power Output (DC)	2610 kW
Fuel Compressor and Water Pump Power	23 kW
Fuel Cell Energy Conversion Efficiency	61.5 %

Turbine Power Output	1700 kW
Turbine Power Output After Power Conditioning	1615 kW
Compressor Power Consumption	985 kW
Burner Compressor Power Consumption	2 kW
Net Turbine Power Output (AC)	624 kW

Net System Electric Power Output After Conditioning	3.1 MW
Overall System Energy Conversion Efficiency	66 %

* The calculations did not consider heat losses-in the piping from the SOFC power module to the gas turbine; in the recuperators; or, in the SOFC power module-which would reduce the system efficiency. Ohmic losses in the electrical interconnection were not considered.

Rough sizing of the individual BOP components were used for preparing a conceptual system layout.

- SOFC power modules: Based on conceptual design described in the previous section.
- Recuperators* & Gas Turbine

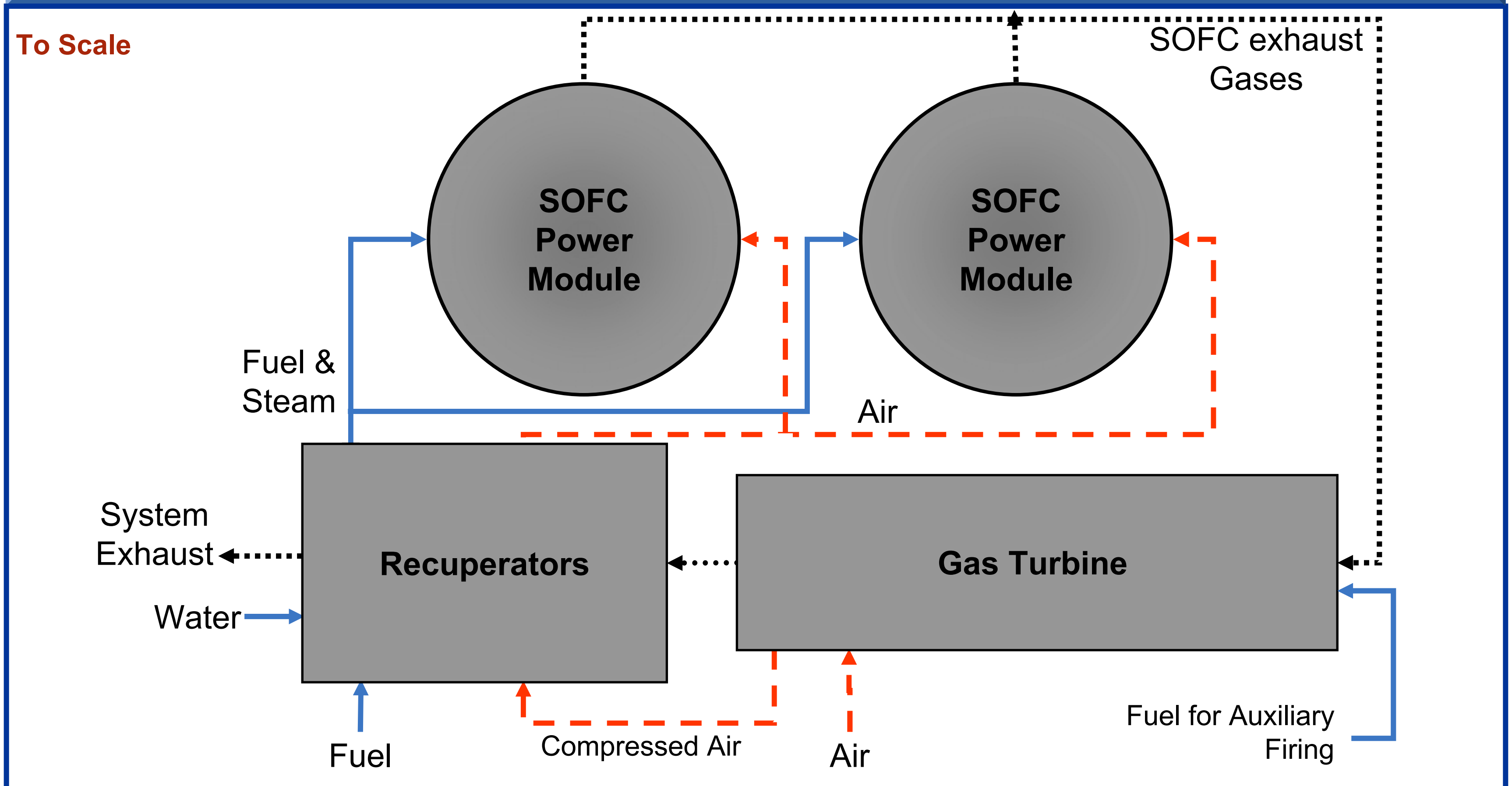
Recuperators	Cathode Air Preheat	16, 900 kg	200 cm x 280 cm x 250 cm
	Fuel and Steam Preheat	30 kg	15 cm x 16 cm x 90 cm
	Fuel Preheat	6 kg	14 cm x 14 cm x 23 cm
	Steam Generator	64 kg	47 cm x 36 cm x 23 cm
Gas Turbine		9,980 kg	580 cm x 170 cm x 200 cm

  - Plate & fin recuperators were sized based on our previous work on scale-up of SECA stacks for 250 kW DG application (where recuperators were sized based on inputs from Stewart Warner South Wind Corp.).
  - Gas turbines in the capacity identified in this project, are not articles of commerce today. Accordingly, we assumed that, if built, the gas turbine would have dimensions similar to that of the Saturn® 20 Gas Turbine (Rated at 1.2 MW) from Solar Turbines.

* Recuperator effectiveness is assumed as 95 % +.

Installed system might occupy approximately 74 m² (796 sq. feet).

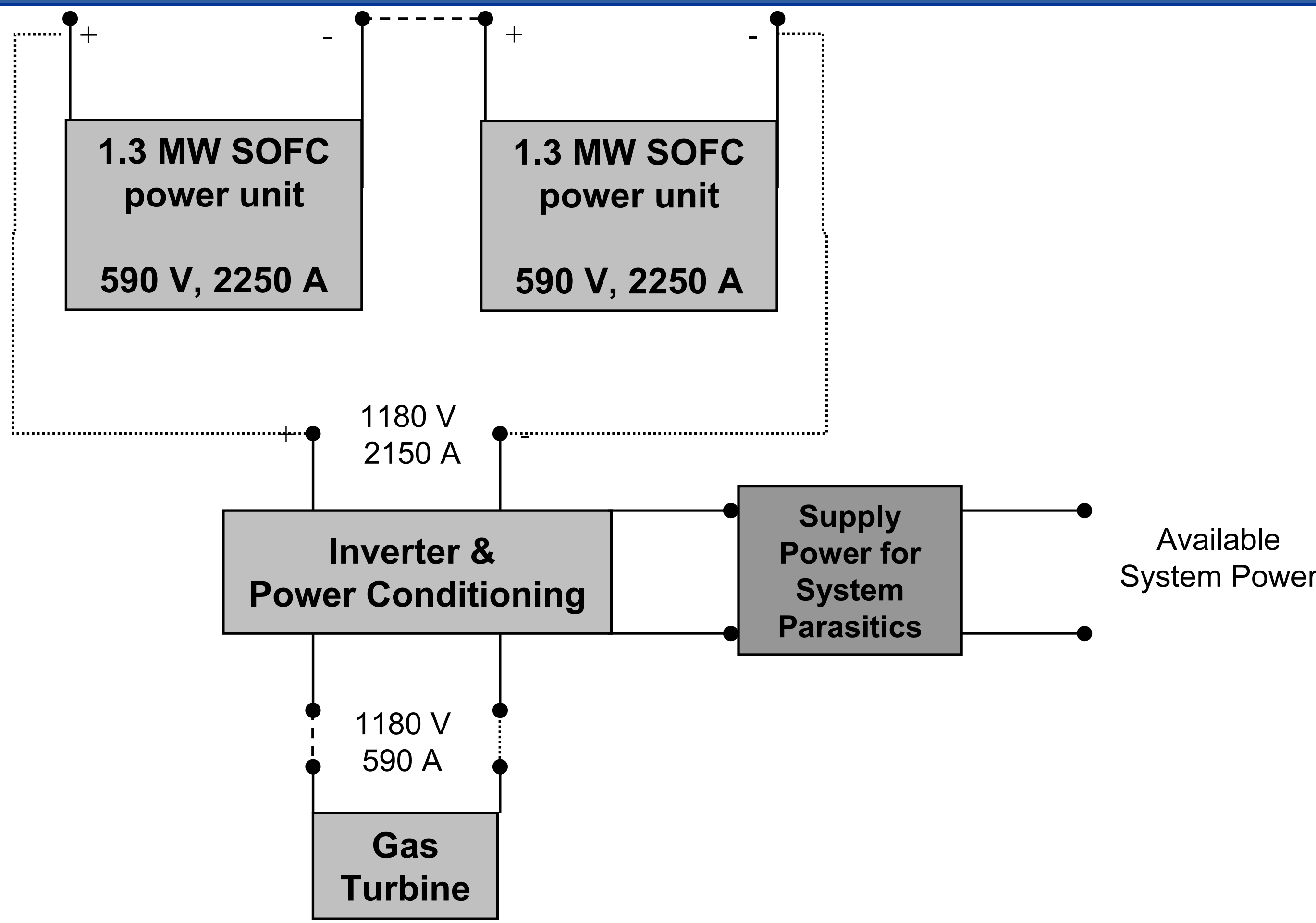
System Layout



All sub-systems are consistent with dimensions over the road transportation and skid mounted installations with minimal site work.

The two SOFC power modules are connected in series to give a 1180 V, 2250 A power source.

Electrical Connections



High-level cost estimates show that the installed cost for the non-optimized SOFC-Gas Turbine Hybrid system could cost ~ 513 $/kWe.

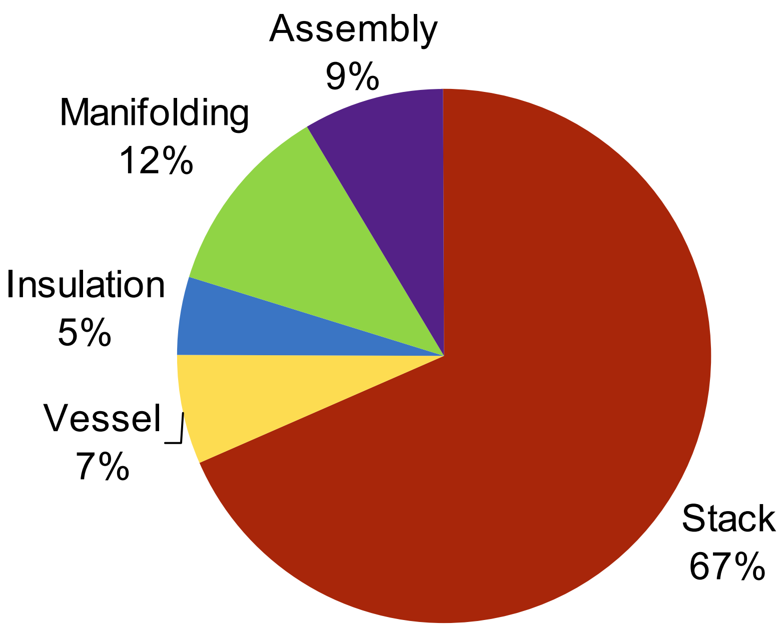
	System Cost	Cost per kW AC system capacity
SOFC Power Module Total	**$406,059**	**$137**
SOFC Stacks	$290,400	$94
Vessel	$28,000	$9
Vessel Insulation	$20,000	$6
Manifolding	$48,800	$16
Assembly	$37,000	$12
BOP Total	**$900,830**	**$290**
Gas turbine	$460,035	$148
Recuperators	$99,314	$32
Power conditioning	$155,220	$50
Instrumentation and controls	$93,130	$30
Piping and valves	$93,130	$30
System Factory Cost	**$1,325,969**	**$421**
Installation*	**$265,194**	**$84**
Installed system	**$1,591,163**	**$513**

* Installation cost is assumed to be 20% of total equipment cost; includes costs of enclosure and foundation, grid interface equipment, fire protection.

* Assumed manufacturing volume of 100 units/year for costing purposes, equivalent to stack manufacturing volume of 250 MW/yr, which is consistent with previous cost estimates for stack manufacturing costs.

Manifolding costs (piping & tube sheets) represents less than 10 % (16 $/kW) of overall power module costs.

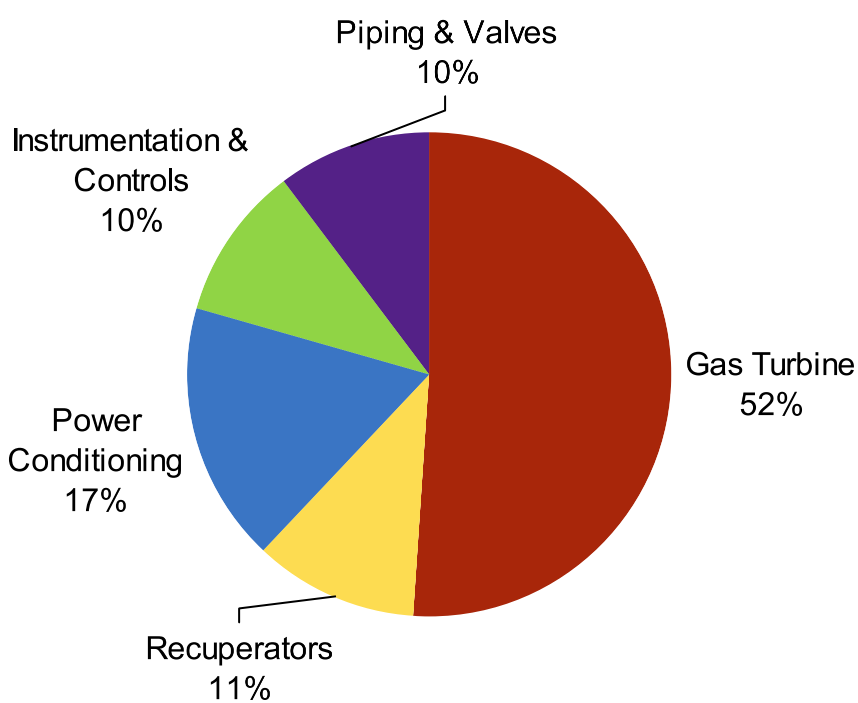
Breakdown of Power Module Costs



- **Total factory cost for 1.32 MW SOFC power module: $203,030**
- **Cost per kW based on module output: 153 $/kW**
- Stack costs were estimated from previously developed activities based cost model.
- Manifolding costs include the costs of: 1“ piping, 3” piping, tube-sheets, tie-rods and wiring.
- Assembly costs were assumed to be ~ 10 % of the total module costs.

Gas turbine costs dominate the cost of the BOP.

Breakdown of BOP Costs



- **Total factory cost of BOP: $931,904**
- **Cost per kW based on system AC output: 300 $/kW**
- Gas turbines, in the size range needed for the system design of this study, are not articles of commerce today.
- We assumed that, if manufactured, the gas turbine cost would be the same (on a $/kW basis) to that of a 1.23 MW gas turbine manufactured today (see Appendix for details).
- Recuperator costs were adapted from our previous study of a 250 kW DG system by accounting for the reduced cathode air-flow due to the internal reforming in the current case.
- Power conditioning costs, instrumentation costs, piping and valve costs were assumed to be the same as that from a previous cost assessment of the Siemens-Westinghouse tubular SOFC-GT hybrid system.

Mass produced SECA based cells/stacks can be cost effectively configured* into MW-level power modules appropriate for high efficiency multi-megawatt hybrid power systems.

- Detailed stack modeling results show that large diameter (24 cm) circular cells can be assembled into 10 kW modules with a wide range of applications, consistent with SECA strategy.
- Preliminary design indicate that 10 kW SOFC stacks can be assembled into MW+ power modules with modest piping and manifolding requirements.
- System level modeling results showed that operating at nominally at 800C the SECA stack based combined cycle system could deliver ~ 66 % efficiency (LHV) in a non-optimized system.
  - That is, even with the lower stack operating temperature, very high system level efficiencies are obtained.
- High level cost estimates indicate that the complete system could be installed for ~ $ 505 /kW

*This report discussed one approach to the scale-up of power from modular SOFC stacks. Other approaches may work equally well depending upon the specifics of the basic cell design: planar, separate fuel and air outlets, etc.

The following represents specific recommendations for continuing R&D (both analytical and lab based) to verify and refine key technology assumptions so that the scale-up potential can be defined with increasing levels of confidence.

- **SOFC Stack**
  - **Verification of allowable stresses in the stacks**
  - **Determination of the maximum temperature gradient allowed across the cell that will not result in damaging stresses**
  - **Refinement of internal reforming kinetics**
  - **Better definition of contact resistance specific to planar sandwich structures**
- **Hybrid systems**
  - **Complete ramifications of the use of anode-supported SOFCs in combined cycle hybrid systems must be examined.**
    - Effect of lowering stack temperature on hybrid system configuration and operation
    - Implications for reforming options (external reformer) if stack temperature < 700 °C
  - **Other hybrid options which allow near atmospheric operation of the SOFC system and hence help eliminate pressure vessel requirement (this will also simplify stack power scale-up).**
    - “Indirect” turbine cycles
    - Steam bottoming cycle (possibility of co-firing at conventional steam plants)
    - Stirling engine (particularly in 50 - 500 kW power range)

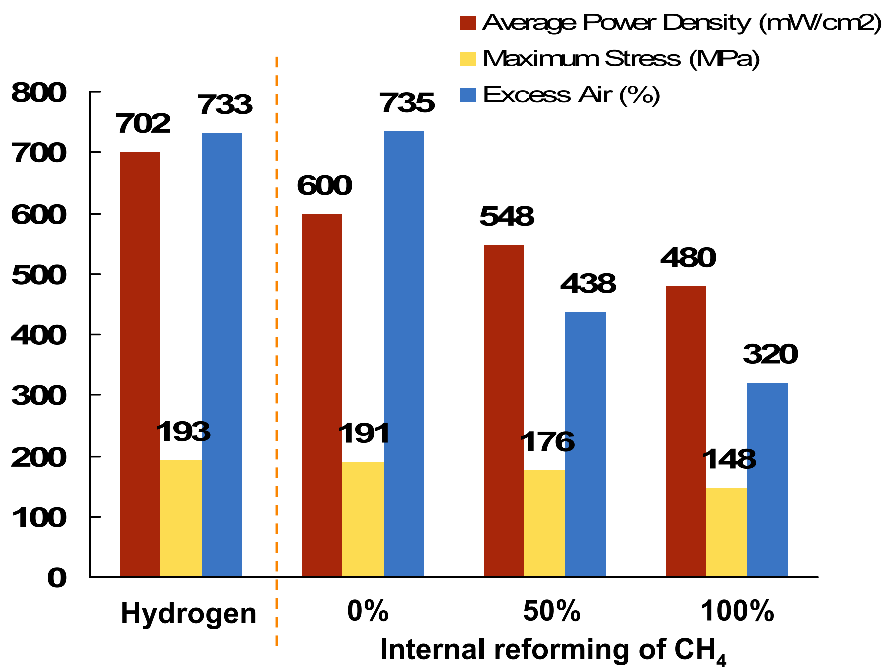
A sensitivity analysis was performed over a range of parameters and the results were used for the design of the SOFC stack module.

Conditions used for sensitivity analysis	
Parameter	**Value**
Pressure (bar)	1, 3*
Fuel utilization (%)	50, 90*
Extent of pre-reforming (%)	0*, 50
Inlet gas temperatures (^{0}C)	650*, 700
Exit gas temperatures (^{0}C)	800* , 900
Cell radius (cm)	5, 18
Anode thickness active for methane reforming (μm)	65*, 300
Contact resistance (Ω cm^2)	0 , 0.1*

* base case values

Model results show that it would be possible to operate an anode supported SOFC with 100 % internal reforming of methane*.

Effect of Internal Reforming



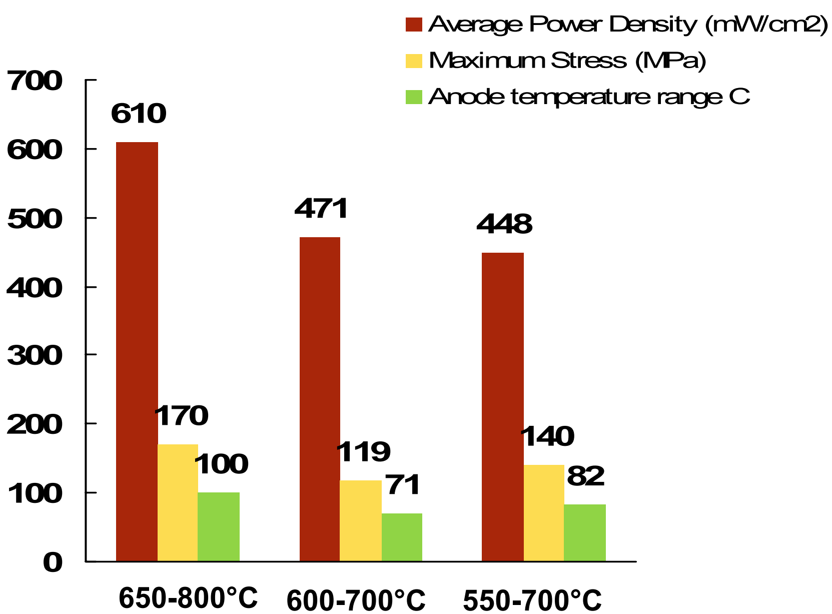
Operating conditions: 1 atm, 650°C inlet, 800°C outlet, 90% fuel utilization, 5 cm cell radius, no contact resistance

- Increasing extent of internal reforming results in more uniform distribution of temperature, which helps reduce stresses.
  - Essentially, internal reforming reduces the excess air flow requirement because of the endothermic reforming reactions.
  - Lower air-flow also means that the internal edge of the cell (where the maximum stress occurs) is cooled to a lower extent by the inlet air.

*The stresses generated depend on the assumed kinetics for the steam reforming reactions.

Power density decreases by approximately 25% when the fuel cell temperature range is reduced from 650-800°C to 550-700°C.

Effect of Decreased Operating Temperature



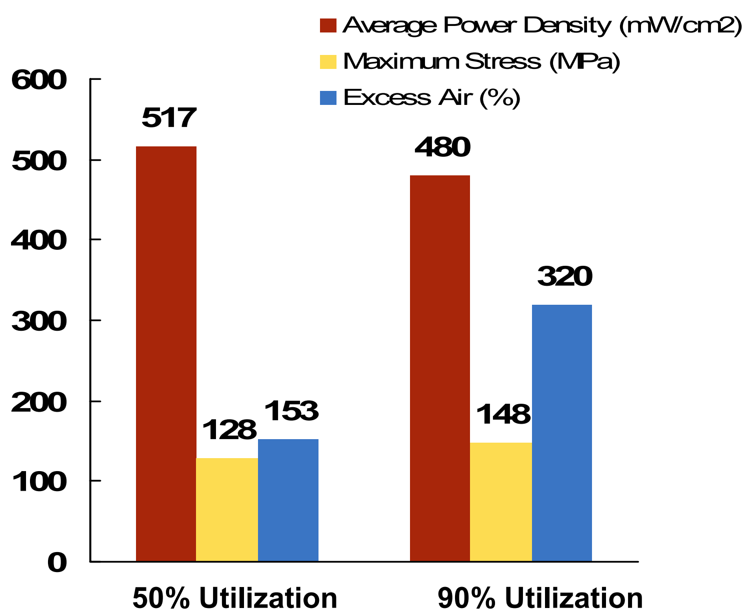
Operating conditions: methane, 3 atm, 90% fuel utilization, 5 cm cell radius, no contact resistance

- Reduction in cell operating temperatures leads to decrease in power densities and internal reforming rate
- Modeling results show that at temperatures much below 700°C, neither power densities nor internal reforming rates are sufficiently high for practical use
  - the actual power density might be more than 30% lower than reported on this chart due to the contact resistance

Based on modeling results, the baseline system assumed a nominal cell operating temperature range of 650 to 800°C.

Under high fuel utilization the average power density decreases and stress in anode increases compared with low utilization scenarios.

Effect of Fuel Utilization



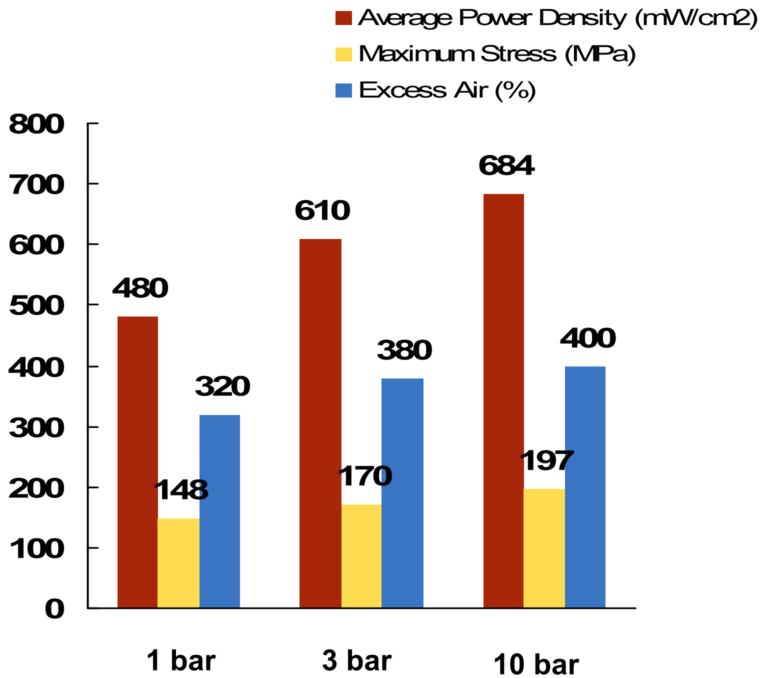
Operating conditions: methane, 1 atm, 650°C inlet, 800°C outlet, 90% fuel utilization, 5 cm cell radius, no contact resistance

- Lower fuel utilization in the fuel cell has a positive effect on such performance parameters as power density and maximum stress
  - Power density increases at low fuel utilization due to high reactants concentration across the cell
  - Maximum stress is reduced due to the excess air requirement reduction resulting from low fuel utilization
- System level implications of SOFC fuel utilization are significant
  - High fuel utilization in a more efficient part of the system (SOFC) has a positive effect on the overall system efficiency
  - At the same time, high levels of excess air required in case of high fuel utilization in the SOFC increases parasitic losses (air compressor)

The baseline system assumed a fuel cell operating with 90% fuel utilization.

Increasing operating pressure from 1 to 3 bar leads to 30% improvement in power density, but increase from 3 to 10 bar leads only to 12% improvement in power density.

Effect of the Operating Pressure



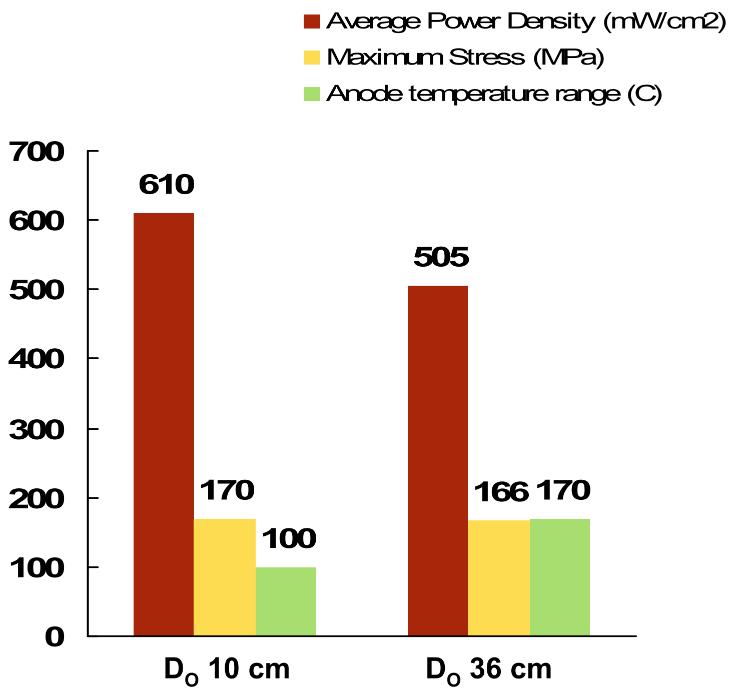
Operating conditions: methane, 650°C inlet, 800°C outlet, 90% fuel utilization, 5 cm cell radius, no contact resistance

- The overall system architecture determines the operating pressure flexibility
- For the fuel cell stack, increasing operating pressure has both positive and negative effects
  - Power density tend to increase with pressure (but only to a limited level)
  - Pressurized fuel cell system will require to be enclosed in a pressure vessel with potentially large cost implications
- Based on the fuel cell performance characteristics there is only marginal benefit in increasing pressure levels beyond 3-5 atm

Based on the model results, the baseline system assumed an operating pressure of 3 bar.

The stress levels in the cell are not strongly influenced by cell diameter indicating that cells larger than 5 cm are feasible, however the power density is reduced.

Effect of the Cell Size

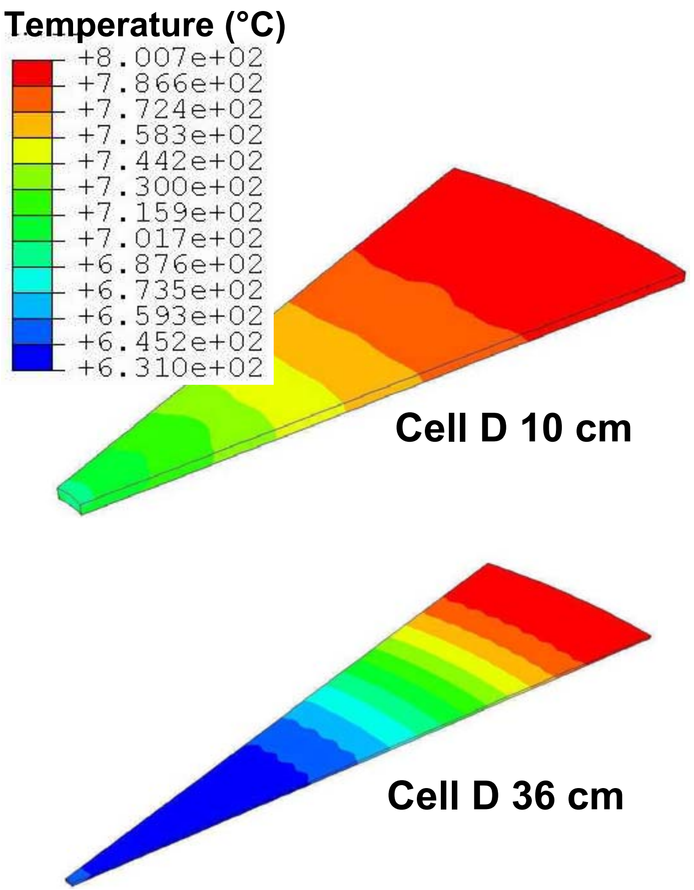


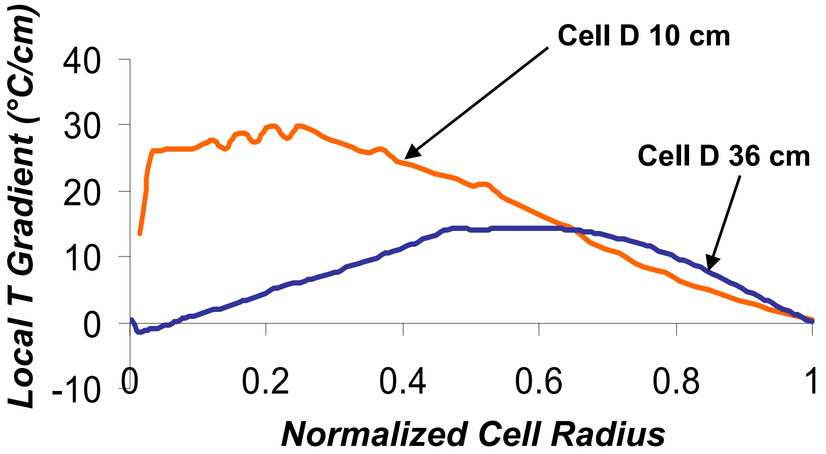
Operating conditions: methane, 3 atm, 650°C inlet, 800°C outlet, 90% fuel utilization, no contact resistance

- Currently, individual cells tend to be approximately 5 cm in radius due to manufacturing and stability issues
- To use planar SOFC in MW-scale applications it might be necessary to utilize larger cells
  - to reduce the number of manifolds
  - to reduce the number of parts to manufacture and assembly
- Modeling results suggest that the maximum principal stress in the anode is governed by the local gradient in temperature

Local temperature gradient is higher in a small cell, which is likely to be the reason for lower maximum stress in the anode in a larger cell.

Effect of the Cell Size

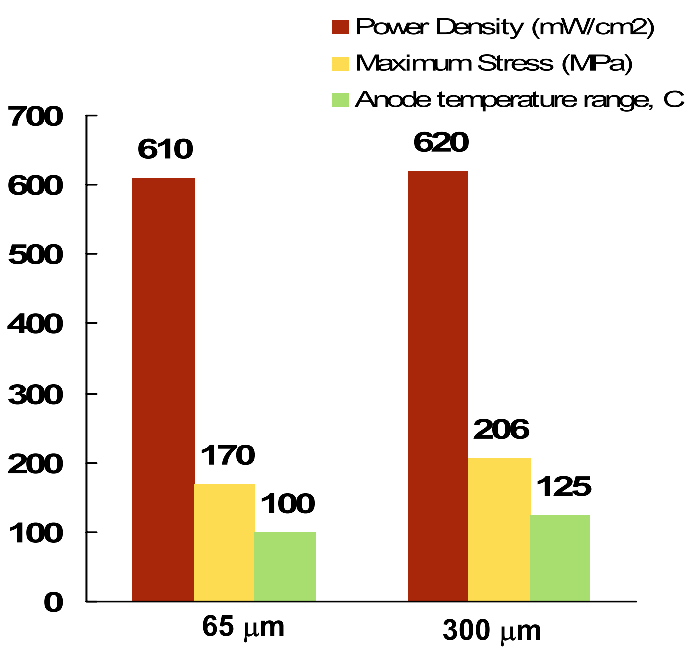




Operating conditions: methane, 3 atm, 650°C inlet, 800°C outlet, 90% fuel utilization, no contact resistance

Assumed thickness of the anode layer active for internal reforming does not affect the power density as strongly as it does maximum stress.

Effect of the Assumed Anode Thickness Active for Internal Reforming



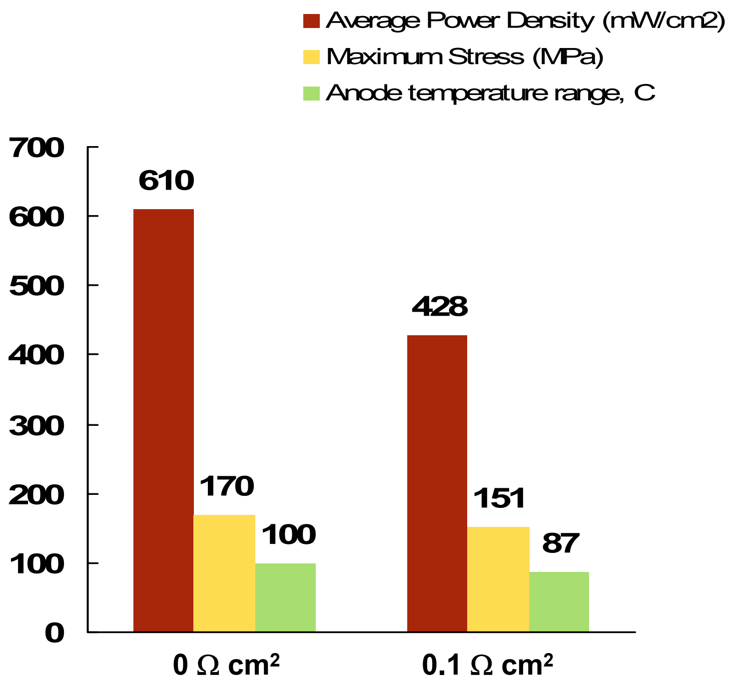
Operating conditions: methane, 3 atm, 650°C inlet, 800°C outlet, 90% fuel utilization, 5 cm cell radius

- 65 micron was the suggested by literature thickness of the anode that might be active towards internal reforming.
- However, assessment of the actual depth of the anode that might be active requires more accurate kinetics information.

The baseline system assumed anode thickness active for internal reforming of 65 µm.

Reducing contact resistances in the cell could improve performance dramatically but it also increases stresses.

Effect of the Contact Resistance



Operating conditions: methane, 3 atm, 650°C inlet, 800°C outlet, 90% fuel utilization, 5 cm cell radius

- Contact resistance for the baseline system was assumed at 0.1 Ω cm^2
  - assumed value represents approximately 40% of the the contact resistance currently measured by Global Thermoelectric for their stacks

The baseline system assumed contact resistance of 0.1 Ω cm^2.

Base case SOFC operating conditions, consistent with a reasonable system (described in the main body of the report), were selected for the model.

Parameter	Value	Comment
Operating Pressure	**3 bar**	• Corresponds to the operating pressure used in the Siemens-Westinghouse Tubular SOFC - GT Hybrid System
Maximum Stack Temperature	**800°C**	• The maximum allowable temperature is limited by the operating temperature range for of the interconnect material (~ 800 ^{0}C for ferritic steel). Note that in a co-flow design, the maximum temperatures occur typically near the exit. • In the model, the cathode inlet air flow rate was adjusted such that the exit temperatures did not exceed 800 °C.
Inlet Temperatures (Fuel and Air)	**650°C**	• Inlet gas temperature is constrained by thermal management issues: – at the low end by the allowable temperature gradient that will not cause damaging thermo-mechanical stresses – at the high end by the available excess heat in the system to pre-heat the inlet streams
Extent of internal reforming	**100%**	• Assumed no pre-reforming of the natural gas fuel. • Steam to carbon ratio of 2.3:1 was assumed to preclude carbon formation.
Fuel Utilization	**90%**	• Fuel utilization based on % methane and hydrogen consumed in the cell
Single Cell Voltage	**0.7 V**	• Voltage is sufficiently high to avoid mass transport limitations, but also can provide reasonable power densities and system efficiencies
Contact Resistance	**0.1 Ω cm^2**	• Assumed to be uniform over the stack area. This value corresponds to ~ 40 % of the internal resistance estimated in state-of-the-art anode supported SOFC stacks.

Model results shows that the cell size has a marginal impact on the performance for the base case operating conditions.

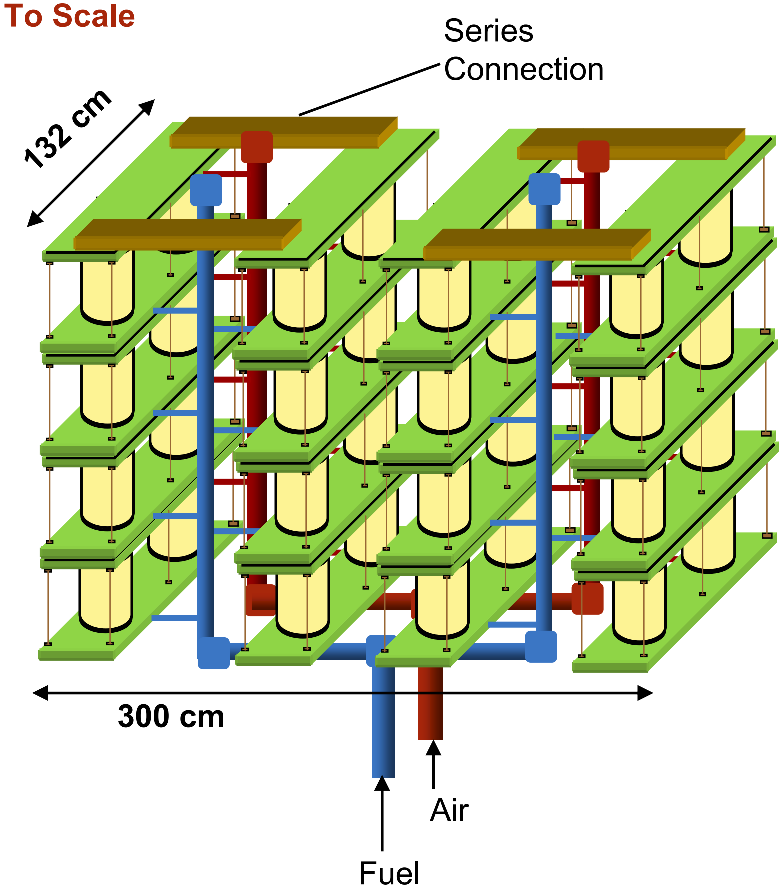
Parameter	10 cm OD	36 cm OD
Energy Conversion Efficiency (%)	64 %	62.5 %
Power Density (W cm^{-2})	430 mW cm^{-2}	380 mW cm^{-2}
Excess Air (%)	290 %	335 %
Exit Fuel Composition	-	-
Exist Gas Temperature (°C)	842 °C	833 °C
Power From a 42 V, 60 Cell Stack*	2 kW	23 kW

Based on the model results, we concluded that a ~ 10 kW stack would have an OD of 26 cm.

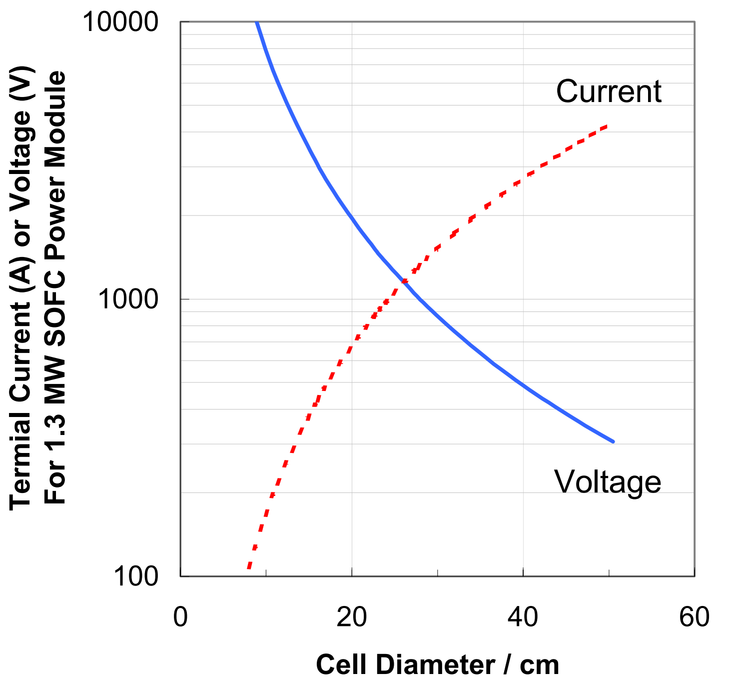
For a given arrangement of stacks, analysis shows that increase in the cell diameter will lead to high current and low voltage, which might affect the performance of the power electronics.

Arrangement of Stacks:

To Scale



Implications for Terminal Voltage and Current



Assuming that the stack comprises of 105 cells operating at 0.7 V, regardless of the cell diameter.

To reduce pressure vessel wall thickness a microporous flame resistant insulation material was chosen for internal vessel insulation.

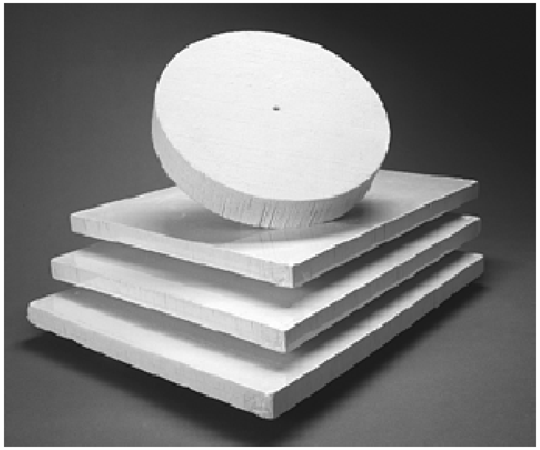
Internal Vessel Insulation

Insulation Properties	
Material	**BTU block 1800**
Density (kg/m^3)	**288**
Thermal Conductivity (W/mK)	0.047 (ΔT = 900°C)
Maximum Temperature (°C)	982
Volume Required	880L
Cost ($)	$4.9/liter

Material can be machined to specific designs as well as in blocks or boards.

Insulation thickness is 8.1cm for a heat loss of 5.34 kW and a flattened dome.

The thermal expansion coefficient was not optimized.



A high temperature cable suitable for this application was identified.

Manufacturer	**Dacon Systems, Inc.**	Wire rated for operation up to 1200°C
Material	**Nickel**	
Cable size	**1 awg**	O.D. of 1.6 cm with insulation
Electrical resistivity	**$7.0 \times 10^{-8}\ \Omega$ m**	At 295K
Temperature coefficient of resistance	**0.004**	For pure nickel
Price	**$10.71/ft**	For orders of 50,000 feet

310 stainless steel can be used as the pipe material, tube sheets inside the pressure vessel, and for the pressure vessel itself.

- Corrosion and stress resistance are suitable for the given operating conditions.
- Rated for stress up to 89.3 bar (1300 psi) at 1000°C -- well above operating pressure.
- Temperature limit of 1040°C (1900°F) for intermittent service with rapid heating or cooling.
- Typical applications include
  - Furnace parts
  - Heat treating fixtures
  - Jet engine sheet metal components
  - Boiler supports
- $1.2 /lb was used as the material cost for stainless steel sheet. For the pipes and tube sheets, the processing cost was assumed to be 30 % of the material cost and for the pressure vessel the processing cost was assumed to be 50 % of the materials cost.

Cost/size characteristics of the Saturn® 20 Gas Turbine (Rated at 1.2 MW) from Solar Turbines, but operating with a pressure ratio of 3, were assumed for the gas turbine

Gas Turbine

ISO Performance/Specifications	
Power	1.21 MWe
Pressure ratio	6.5
Exhaust flow	23,540 kg/hr
Approximate weight	8,980 kg
Estimated cost	$737/kWe