Siemens SOFC Test Article and Module Design

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EXECUTIVE SUMMARY

Preliminary design studies of the 95 kWe-class SOFC test article continue resulting in a stack architecture of that is 1/3 of 250 kWe-class SOFC advanced module. The 95 kWe-class test article is envisioned to house 20 bundles (eight cells per bundle) of Delta8 cells with an active length of 100 cm. Significant progress was made in the conceptual design of the internal recirculation loop.

Flow analyses were initiated in order to optimize the bundle row length for the 250 kWe-class advanced module. A preferred stack configuration based on acceptable flow and thermal distributions was identified. Potential module design and analysis issues associated with pressurized operation were identified.

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Task 2.0 – Advanced Test Article and Advanced Module Design

This task encompasses the preliminary design of a solid oxide fuel cell advanced test article and an advanced module. It will extend the technology demonstrated in the stack tests of companion program DE-FC26-05NT42613. The test article shall include two full-length bundle rows and have nominal capacity of 95 kWe. The advanced module design will extend previous work and further mature the design of a six bundle row module producing nominally 285 kWe under atmospheric pressure conditions. The design work shall focus on an atmospheric pressure design, with additional emphasis on the specific stack components that would be impacted in adapting the design for pressurized operation.

Work on this task was initiated under the companion program and was subsequently redirected to this program. The activities completed under the companion program are included herein with no distinction being made between the two respective efforts.

TASK 2.1 – PRELIMINARY DESIGN OF A 95 kWe-CLASS ADVANCED TEST ARTICLE

The objective of this task is to develop the preliminary design of 95 kWe-class advanced stack test article based on the Delta8 cell technology. This shall include the preliminary design of the following:

- Fuel delivery system and anode recirculation system
- Air/exhaust collection system
- Test article instrumentation
- Power system components
- Start-up heater
- Test article containment
- Peripheral insulation system
- Recirculation loop.

Furthermore, the preliminary designs shall be, where applicable, scalable to the 285 kWe-class advanced module.

The 285 kWe-class advanced module features an air inlet manifold along with an exhaust plenum, which distribute process air and collect exhaust air respectively along the bundle row. The distribution and collection of the exhaust along the bundle row leads ultimately to a flow mal-distribution and a temperature variation within the bundles in a bundle row due to the static pressure variation in the respective manifolds. In addition, the variation in bundle air flows along with the side recirculation collection induce stack

and combustion zone fuel flow variations, which can further aggravate the stack temperature distribution thereby limiting its performance.

The flow maldistributions arising from the process air distribution and exhaust flow collection can be mitigated to acceptable levels by decreasing the number of bundles in a bundle row while increasing the number of bundle rows. However, transverse stack flow variation increases since the process air is distributed between bundle rows. Also addition of bundle rows can lead to further costs due to increased row-connects and increased number of serial manufacturing operations. The objective of this analysis is to seek the optimum bundle row and stack configuration for the 285 kWe advanced module and to define the 95 kWe test article to serve effectively in validating the 285 kWe module design. A network model of the various airflow paths and fuel flow paths along a bundle row were developed using the network software SINDA/FLUINT.

A model of the flow networks present within a bundle row was developed using the fluid/thermal network software SINDA/FLUINT and is shown in Figure 1.1, where stack locations represented by nodes are connected by air flow paths whose flow resistances are calculated based on the stack components in the path. It should be noted that the present advanced module features ten bundles in a row, which is considered to be the upper limit of the number of bundles within a bundle row based on previous evaluations. The airflow resistances of the exhaust manifold (formed by the exhaust castings), the combustion zone, and the recuperator were evaluated using detailed CFD models as highlighted in the Figure. The flow resistance of the cell stack was also obtained from a CFD model of the cell that was developed earlier. The pressure drops variation in the air inlet manifold and the exhaust manifold were modeled using correlations from Idelchik. Note that temperature variations due to flow variations and the corresponding feedback were not included in these calculations and will be taken into account in future models. Both the syngas and natural gases are being analyzed, the latter could have a pronounced fuel distribution effect due to the higher anode off-gas recirculation flows as compared to the former where the air flow and exhaust flows tend to dominate.

The variation of fuel and air flows along the bundle row for the coal gas are shown in Figure 1.2 for the maximum current case of 1432 A. It is clear from this figure that while the airflow and exhaust flow distributions are somewhat acceptable with an air inlet orifice pressure drop of 5 in of H₂O, stack fuel flow distribution and the distribution of the depleted flow into the combustion zone are well above acceptable limits, in particular considering a fuel consumption of 88% for the syngas case. A graded air inlet orifice configuration along the bundle row only aids in making the airflow and exhaust flow distributions more uniform and does not improve the relevant fuel flows as shown in Figure 1.3. A better overall flow distribution is obtained if an exhaust side resistance is used in lieu of the air side orifice as shown in Figure 1.4. However, the practicality of placing a resistance on the exhaust side needs to be investigated. The corresponding results of Figure 1.2 for the natural gas case at its maximum current of 1173 A are shown in Figure 1.5 and vary in a fashion similar to that of the syngas.

A further objective is to develop a design concept of an internal recirculation loop for the 95 kWe-class test article which is scalable for the 285 kWe-class advanced module.

A study was initiated as an attempt to identify new cost effective design solutions for the advanced module with internal recirculation loop suitable for implementation in coal-based fuel cell systems. The design strategy was to develop a solution that consolidates all the loop components into one compact configuration solution. Instead of having external separate components for fuel heaters, circulator, pre-reformer, ejector and hot piping, the most recent design incorporates all these components into one integrated system which is housed inside the container and peripheral insulation system. The primary advantage of this concept is better utilization of the existing internal volumes, reduction of insulation and support structures and ultimately lower cost.

High temperature circulator, gas burner and means of distributing fuel uniformly to the cells received the most attention because they are critical for a successful advanced module design.

Preliminary design studies of the 95 kWe-class test article were conducted and a detailed stack architecture of 1/3 of the advanced module stack including an internal recirculation loop was developed for internal reviews. The design approach was to develop a highly integrated SOFC stack by scaling up the existing design of the two-row POCD8R1 test article to include 20 bundles arranged in two rows of ten bundles each, with the addition of an internal recirculation loop.

The outer container is sized to accommodate a 285 kW stack with six rows of ten bundles each, for a total of 480 Delta8 cells. The same container, with appropriate partitioning, can accommodate 1/3 of a stack or two rows of ten bundles each, 160 Delta8 cells in total. An isometric model of the container is shown in Figure 1.6. Figure 1.7 is a detail sectional view showing the internal recirculation loop and fuel flow paths.

The 95 kWe test article will house 20 bundles of eight Delta8 cells, 100 cm active length, and will be integrated with an internal recirculation loop comprising a gas-fired burner for preheating the fuel side during startup, a high temperature circulator fan, extended side recirculation zone (SRZ) ducts and a recirculation plenum-pre-reformer installed on one end of the stack. Balance-of-plant (BOP) equipment related to process air, fuel and purge gas supply, module exhaust, and DC-to-AC power conditioning will complete the configuration of the test article.

Internal Recirculation Loop

For a natural gas application, typically 2/3 of the spent fuel exiting the stack, rich in water vapor (~50%) and carbon-dioxide (28%), is recirculated throughout the recirculation loop to provide the oxidizer required for fuel reformation in addition to inhibiting carbon deposition in the internal reformer. In a syngas application, only 1/10 of the anode gas is circulated, just enough to completely reform the small percentage (3-5%) of methane typically present in the syngas composition. However, during start-up of the unit, a large flow of gas is circulated through the loop to preheat the stack by the addition of heat provided by fuel heaters.

The key requirements for the internal recirculation loop design are:

- Provide heat and gas flow for startup heating and stack operation
- Incorporate a start-up heater which must be gas-fired (not electric)

- Provide sufficient pressure head to circulate recirculation flow
- Provide pre-reforming of the incoming hydrocarbon fuel and sufficient pressure head/flow through reforming catalyst bed
- Provide adequate NHmix purge flow during startup and shutdown
- Support maximum current conditions, namely: 1432 A ($J = .55\text{A/cm}^2$) on syngas, 1171 A ($J = .45\text{A/cm}^2$) on natural gas
- Ensure uniform mixing of fresh fuel and recirculation gas and provide uniform inlet flow distribution to the stack
- Materials compatible with SOFC reducing environment and high temperatures
- Accommodate differential thermal expansion between components .

The internal recirculation loop includes a centrifugal circulator, twin start-up burners, an integral recirculation plenum with pre-reformer and fuel mixing tube.

A rendering of the internal recirculation loop comprehensive of all the components is shown in Figure 1.8.

High Temperature Circulator

Conventional SOFC modules produced to date have employed an ejector pump, or a parallel-connected array of such units, for purposes of recirculating anode gas and freshly reformed fuel gas throughout the stack. Incoming fresh fuel is the motive gas used to drive the ejector which is essentially a fixed operation point device. Unfortunately, a compressor is required to elevate the fuel pressure to the required level at entry to the ejector nozzle. POCD8R1 was the first test article to incorporate a combination of ejector and high temperature circulator both mounted externally to the container in a separate recirculation loop.

Preliminary operating experience with the POCD8R1 circulator appears to be largely positive. The unit was capable to startup the module by recirculating a large volumetric flow rate of NHmix and subsequently hydrated hydrogen successfully demonstrating gas side startup heating. The ejector was never used during operation and the entire anode gas recirculation was handled by the circulator.

The POCD8R1 circulator was a small unit acquired from Creative Applications (CAP) of Japan for experimentation in a 5 kW SOFC system. The unit was refurbished and certain design modifications, such as the addition of a metallic scroll and interface inlet/outlet nozzles, were implemented by CAP.

The preferred configuration locates the circulator downstream of the reformer where the gas temperature is at its lowest. Vertical orientation of the rotor shaft vertical is the best configuration to simplify bearing design. This configuration greatly simplifies assembly and servicing of the component, including motor and seals maintenance. Figures 1.9 illustrates this arrangement.

An important aspect of the design of a fuel gas circulator is the volute chamber that surrounds the 360 mm (14") diameter impeller. In this zone, the kinetic energy associated with the gas leaving the impeller is recovered as potential energy, or head. Ideally, volute chambers take the shape of logarithmic spirals. A 4-point discharge

volute directs the flow into passages that are formed in a squared ceramic board. These passages feed into the fuel plenum below that turn the fuel gas stream downward to a lower level along the right and left hand sides of the ceramic board, in correspondence to the entrance of the fuel heater section.

The volute chamber design must be compatible with the impeller and with the constraints that are placed upon how the gas flow must be directed after it leaves the circulator. These constraints are imposed by the overall design of the internal recirculation loop. In view of this, a volute chamber having 4 discharge points was found to be most satisfactory. Figure 1.10 shows the detail of the volute chamber.

The most important functional requirements for the 95 kW circulator are:

- Circulator shall be a direct drive type with sealed shaft or magnetically coupled to the motor
- Shaft seals shall be compatible with the pumped gases and the operating temperatures and pressures expected in normal and abnormal operation and during normal and emergency shutdowns. Shaft seals shall be designed such that hazardous CO gas leakage is avoided.
- Passive cooling shall be used for bearings or seals
- Circulator speed modulation shall be achieved by a high efficiency variable frequency AC drive.

Circulator specifications for the 95 kWe test article gas composition, temperature, and flow rates are shown in Figure 1.11. Performance curves supplied by the vendor are also shown.

Start-up Heater

The start-up heater is designed to provide fuel side start-up heating and supplemental heating for natural gas pre-reforming. POCD8R1 employed a series of electric heaters installed in the external recirculation loop, downstream of the ejector-circulator section. For the 95 and 285 kW systems, it would be preferable to use gas-fired heaters to avoid the need to have high power electricity demand at a test site.

The choice fell on single-ended recuperative (SER) burners for a number of reasons, primarily reliability, since technology for radiant tube furnaces with controlled atmospheres fired with fossil fuels has been part of standard furnace design for at least 60 years, and secondly efficiency, since recuperative air preheating is accepted as the most effective way to increase energy efficiency for high-temperature process heating. In addition, there are many suppliers of gas-fired radiant tubes and the technology is widely used in the furnace heating industry.

In a SER burner, fresh air and fuel are combusted in an inner tube within a burner assembly while exiting exhaust gases are recovered, passed back through an outer tube that surrounds the inner tube and used to heat the incoming fresh air in a recuperator region.

The functional requirements for the 95 kW start-up heaters are:

- Indirect heating of the following gases:

- Air (up to 400°C)
- 95% nitrogen/5% hydrogen mix (from 400 to 950°C)
- Unreformed fuel with the following gas composition (from 600 to 950°C)

H ₂	28% (volume fraction)
CO	12%
H ₂ O	32%
CO ₂	18%
N ₂	1%
C _x H _y	9%
- Preheated gas mass flow range: 3000 slpm NHmix, 4300 slpm unreformed fuel
- Total heat required with 2 burner: 24 kW (~342,000 Btu/hr) net
- Fuel: natural gas

The burner system which best meets the above requirements is a Kanthal Ecothal 4-20 SER burner. For the 95 kW test article, a twin SER burner system with the following characteristics was selected:

- Gross power consumption: 20 kW (68,300 BTU/hr)
- Max. net power: 16 kW (54,600 BTU/hr)
- Max. efficiency: 80%
- Min. net power: 6.4 kW (21,800 BTU/hr) min. controllable firing rate
- Turn down ratio: 2.5

Figure 1.12 is a rendering of the SER burner assembly showing the inner tube, outer tube, exhaust housing, and internal recuperator.

In summary, significant progress was made in the conceptual design of the internal recirculation loop for the 95 kW test article. A detail model was developed in Pro/Engineer software and the assembly sequence of the internal loop components was studied in great detail.

Key components of the recirculation loop such as circulator and gas burner were sized for a 20 bundle/160 Delta8 cell stack configuration. A number of design simplifications and improvements were made to the existing POCD8R1 recirculation loop and module container. Significant interaction took place with Suppliers of high temperature circulator and gas-fired burners. Preliminary quotes were received and technical discussions were initiated to finalize the design of the components.

In all these activities, there was a concerted effort to develop a number of new innovative features that are aimed at reducing the manufacturing and assembly cost and providing greater compactness to the Module than any other previous design approaches.

A specific objective of this effort was to determine a module architecture that is most advantageous with respect to module capital cost and aggregation of multiple modules to form a large SOFC system. This objective has been accomplished as a module

architecture has been defined that provides an efficient internal packaging of the recirculation loop. The internal recirculation loop concept is scalable and it is applicable to both 95 and 285 kW test articles. Particular effort was spent in designing for servicing.

TASK 2.2 – PRELIMINARY DESIGN OF A 250 kWe-CLASS SOFC GENERATOR MODULE

The work in this task applies to specific design features of the 285 kWe advanced module design. The current focus of the stack concept development is in the determination of the optimum bundle row length, incorporation of the functionality of the POCD8R1 external recirculation loop inside the container, and selection and design integration of a gas fired fuel side heater.

Flow analyses were completed to optimize the bundle row length. See the following discussion in Task 2. for detailed analysis information. Conceptual design work was completed incorporating the new bundle row length into the module design. The original advanced module design contained a ten bundle row length, with a total of six rows as shown in Figure 1.13. Based on flow analyses, the proposed row length consists of six bundles in a row, with a total of 10 rows, see Figure 1.14. Preliminary layout work was completed and no major module design obstacles were identified

An ASPEN system model developed previously to evaluate the 250 kWe-class module was updated using the latest available measurements of stack internal electrical connector losses.

The cell-cell connector losses, the bundle to bundle connector losses, the row-row connector losses, and the bus bar losses were evaluated based on available test data from a two cell Delta8 cell test and from the POCD8R1 stack test. The resistances were then used to update the 250 kWe system performance reported in the previous period. The resistance indices based on the cell active area for the various components are listed in Table 1.1.

The updated preliminary system performances for the syngas and natural gas for the 250 kWe-class module are shown Tables 1.2 and 1.3 respectively.

TASK 2.3 – MODULE ANALYSIS

The system model developed for the POCD8R1 test article using the ASPEN system analysis software was extended to model the 95 kWe test article and the 285 kWe advanced model. Both natural gas and syngas fuel inputs were considered in determining the air and fuel flow rates for these units. The syngas fuel corresponds to the composition entering the stack in the coal gas fueled baseline system conceptualized in Phase I and was simulated using a mixture of hydrogen, natural gas, and NHMIX, in accordance with the planned POCD8R1 testing. The performance maps developed for the Delta8 cell were used in evaluating the system performance. The POCD8R1 recuperator model was assumed in these models and the corresponding

recuperator effectiveness vs. cell air flow profile was integrated with the cell performance map to determine the required cell-stack air flow rate, given input values for the cell current and the desired average cell temperature, and the prevailing module air inlet temperature. Resulting from the calculation (in addition to air and fuel flow rate) are estimates of cell voltage, peak cell temperature, and maximum-to-minimum axial cell temperature differential, as well as estimates of the system electric performance parameters.

The key assumptions used in evaluating the systems for both the fuels are listed in Table 1.4, while Table 1.5 lists other inputs which are specific to the fuel under consideration. The air bypass allowance and the fuel bypass allowance are assumed to be 5% for the 95 kWe unit, typical values used in evaluating the POCD8R1 system performance, although significantly lower values have been predicted in component analyses. The fuel bypass is assumed to be about 1.5% for the 285 kWe unit, which is typical for generators of its size. The recirculator blower parasitic was not included in these calculations as its characteristics are not known presently. In addition, the module heat loss and the I & C losses were approximately estimated based on historically used values. It should be noted that the stack inlet temperature was fixed as per Table 1.5.

Results of these preliminary analyses including a listing of the fuel and air flow rates and the system electrical performance over the operating range of the 95 kWe and the 285 kWe units are shown in Table 1.6 for both fuels. Temperatures at key locations in the module are also shown in the table. System temperature maps at the nominal current density of 320 mA/cm² are shown in Figure 1.15 and Figure 1.16, respectively, for the 95 kWe test article for the syngas and natural gas cases. Statepoint listings at locations corresponding to these figures are provided in Tables 1.7 and 1.8.

The flow network model of the bundle row that was developed using the software SINDA/FLUINT in the previous reporting period was extended to include cell thermal characteristics to simulate expected thermal feedback effects. The number of bundles in the bundle row was varied to seek the optimal stack configuration from a flow and thermal distribution perspective.

In addition, potential module design and analysis issues and concerns associated with pressurized operation were identified and listed.

The flow network model of a ten bundle row developed using the fluid/thermal network software SINDA/FLUINT is shown in Figure 1.18, where stack locations represented by nodes are connected by air flow paths whose flow resistances are calculated based on the stack components in the path. It should be noted that the present advanced module design features 10 bundles in a row, which is considered to be the upper limit of the number of bundles within a bundle row based on previous evaluations. The airflow resistances of the exhaust manifold (formed by the exhaust castings), the combustion zone, and the recuperator were evaluated using detailed CFD models as highlighted in Figure 1.18. The flow resistance of the cell stack was also obtained from a CFD model of the cell that was developed earlier. The pressure drop variation in the air inlet manifold was modeled using correlations from Idelchik.

The stack flow resistance was calculated from a multivariate regression expression developed based on a detailed model of the cell developed earlier using the CFD software Fluent. In general,

where S_{air} , I , FC , & OTC denote the air stoichs (1/air utilization), the cell current, the

$$\Delta P_{air-side-cell} = f(T_{air-in-cell}, S_{air}, I, FC, OTC)$$

$$T_{ave} = f(T_{air-in-cell}, S_{air}, I, FC, OTC)$$

$$V_{cell} = f(T_{air-in-cell}, S_{air}, I, FC, OTC)$$

$$T_{cell-peak} = f(T_{air-in-cell}, S_{air}, I, FC, OTC)$$

$$\Delta P_{fuel-side-cell} = f(T_{air-in-cell}, S_{air}, I, FC, OTC)$$

$$T_{air-out-cell} = f(T_{air-in-cell}, S_{air}, I, FC, OTC)$$

fuel consumption, and the oxygen to carbon ratio in the recirculation (in essence the recirculation flow rate) respectively. For a given FC and OTC , maps representing the relevant cell characteristics were developed using a surface response approach. A multivariate regression surface of the general form,

$$\begin{aligned} X = & C_o + C_1 I + C_2 S_{air} + C_3 T_{air-in-cell} + C_4 I^2 + C_5 S_{air}^2 + C_6 T_{air-in-cell}^2 + C_7 I S_{air} \\ & + C_8 I T_{air-in-cell} + C_9 S_{air} T_{air-in-cell} \end{aligned}$$

that includes quadratic and interaction terms was fitted to the data generated using Fluent. Figure 1.19 shows examples of the maps for the syngas fuel at the maximum current of 1432 A.

In conjunction with an expression for the internal recuperator effectiveness as a function of the flow, the cell thermal conditions can be calculated using the regression equations. By using the expression for the cell air side dP in the flow network model of Figure 1.18, it is possible to couple indirectly the simplified network model, which is quite sufficient for other flow components in the stack, with a comprehensive Fluent model. Note that this coupling automatically models any thermal feedback effects. The fuel feedback effect on the temperature distribution is not included at this optimization stage although it will be considered once an optimal configuration is determined. The cell voltage, the cell peak temperature and other relevant cell parameters can also be obtained once the flow network and the multivariate regression models have converged.

Both the syngas and the natural gas fuels were considered in these investigations. Figure 1.20 shows the relevant flow distribution normalized by the corresponding

average flow for the coal gas case at the maximum condition. The corresponding stack temperature and cell voltage variations are shown in Figure 1.21. Note that the total airflow was adjusted so that the peak cell temperature is about 970 C. While the process air flow distribution and the cell temperature distribution appear to be within acceptable limits the flow mal-distributions of the stack fuel and of the depleted fuel flow into the combustion zone (CZ) are not desirable. The results for the ten bundle row are summarized in Table 1.9, which shows that the mal-distributions, characterized by the minimum and the maximum deviations from the average, only vary slightly with cell current. It is also evident from the table that an air inlet orifice is not effective in mitigating the stack and depleted fuel flow mal-distributions. Reducing the exhaust collection pressure drop or the introduction of an exhaust side pressure drop downstream of the internal recuperator has a beneficial effect on the flow distributions, as seen in Table 1.10, which shows the sensitivity of the flow and temperature mal-distributions to some relevant model parameters. The flow and temperature distributions for the natural gas case for the ten bundle row, shown in Figures 1.22 and 1.23 at the max current of 1171 A, are relatively better than the distributions shown in Figures 1.20 and 1.21 for the coal gas case, due to the lower air flow rates in addition to the higher stack fuel recirculation rates. However, the stack fuel flow and the depleted fuel flow distributions are not still within the desirable limits. The results for the natural gas case for the ten bundle row at different currents are summarized in Table 1.11 as for the syngas case, which again shows the ineffectuality of the air inlet orifice in smoothing the flow variations.

Decreasing the number of bundles in a bundle row decreases both the air distribution pressure drop and the exhaust collection pressure drop, which are beneficial in mitigating flow mal-distributions, as shown in Tables 1.12 and 1.13, where results are summarized for number of bundles in a row varying from five to ten at different currents for the syngas and natural gas fuels respectively. The variation of the flow and temperature mal-distributions are shown graphically in Figures 1.24 and 1.25 respectively for the syngas fuel at a current of 1432 A and for the natural gas fuel at 1171 A. It is clear from these tables and figures that a six bundle row configuration is preferable to limit the stack fuel flow and depleted fuel flow into CZ maldistributions to within $\pm 2\%$ and $\pm 5\%$ while limiting the stack temperature variation to less than 10 C for both the fuels. A preliminary design investigation shows that the outer canister aspect ratio is more favorable for the 6 bundle row case (with 10 bundle rows in all to make for the 285 kW) without increasing the parts count drastically. Also, with the 6 bundle row configuration, the air and fuel flow distribution to the bundle rows spans 5 rows on each side and can become limiting as the number of bundle rows increase.

Identification of module design and analysis issues for pressurized operation

Pressurization of the module entails changes to the module design. Potential design and analysis issues associated with pressurized operation were identified and a preliminary listing is provided in Table 1.14. It should be noted that this list is only preliminary and will be updated depending on specific design requirements.

A preferred stack configuration, which was found to be optimal from a flow and temperature distribution perspective, was recommended. Potential module design and analysis issues associated with pressurized operation were identified and listed.

The effect of bundle row length on stack thermal and flow distribution was investigated culminating in the recommendation of an optimal stack configuration. It was also found that the air inlet orifice was not effective in mitigating fuel flow maldistributions.

TASK 2.4 – TECHNICAL COORDINATION

No significant activity to report this quarter.

TASK 3.0 – Design and Analysis of the POCD8R2 Stack Test Article

No significant activity to report this quarter.

LIST OF ACRONYMS AND ABBREVIATIONS

BOP	Balance-of-plant
CTE	Coefficient of Thermal Expansion
EDS	Energy Dispersive Spectroscopy
EGA	Evolved Gas Analysis
EL	Electrolyte
FE	Fuel Electrode
H ₂	Hydrogen
HPD	High power density
HTL	High Temperature Leak Rate
I&CS	Instrumentation and Control System
I/O	Input/Output
IC	Interconnection
IL	Interlayer
NH	nitrogen hydrogen mixture
NHMIX	95% Nitrogen/ 5% Hydrogen
OLE	Object Linking and Embedding
OPC	OLE for Process Control
P&ID	Process and Instrumentation Diagram
Pcf	pounds per cubic foot
PLC	Programmable Logic Controller
POC	Proof-Of-Concept
Ppm	part per million
RBS	Rutherford Back Scattering
SCG	Slow Crack Growth
SCR	Silicon Controlled Rectifier
ScSZ	Scandia stabilized zirconia
SEM	Scanning Electron Microscope
SER	single-ended recuperative burner
SFC	Stationary Fuel Cells
SIS-D8	Siemens Imaging System for Delta-8 Bundle Open Ends
SIS-D8 DA	Data analysis and GUI component of SISD-D8
SIS-D8 IA	Image acquisition component of SIS-D8
slpm	standard liters per minute
SOFC	Solid Oxide Fuel Cell
SOW	Statement of Work
SRZ	Side Recirculation Zone
TA	Test Article
TGA	Thermal Gravimetric Analyzer
TGA-MS	Thermal Gravimetric Analysis – Mass Spectroscopy
UPS	Uninterruptable Power Supply
XPS	X-ray Photoelectron Spectroscopy
XRD	X-ray Diffraction

Figure 1.1 - SINDA/FLUINT Flow Network of a Ten Bundle – Bundle Row

Figure 1.2 - Flow Distribution for Syngas Case
(I = 1432 A, air inlet orifice dP = 5 in of H2O)

Figure 1.3 - Flow Distribution for Syngas Case
(I = 1432 A, air inlet orifice dP varying, nominal dP = 5.876 in of H₂O)

Figure 1.4 - Flow Distribution for Syngas case
(I = 1432 A, No air inlet orifice, Exhaust side orifice dP = 10 in of H₂O)

Figure 1.5 - Flow Distribution for the Natural Gas Case
(I = 1432 A, air inlet orifice dP = 2.3 in of H2O)

Figure 1.6 – 95 kWe – 285 kWe Module with Internal Recirculation Loop

Figure 1.7 – Section View of Internal Recirculation Loop

Figure 1.8 – 95 kWe-class Test Article Internal Recirculation Loop

Figure 1.9 – Anode Gas Circulator

Figure 1.10 – Circulator Lower Volute Chamber

Design point		Nominal	Maximum
Oxygen to Carbon ratio		2.1	2.1
Fuel composition		0.89	0.79
Inlet gas composition			
Mole fraction		%	%
Hydrogen	H ₂	23.7	28.3
Carbon monoxide	CO	9.9	15.3
Water vapor	H ₂ O	26.6	26.6
Carbon dioxide	CO ₂	26.8	18.9
Hydrocarbon	C ₂ H ₆	10.2	7.9
Nitrogen	N ₂	8.3	8.3
Gas temperature at inlet		°C	°C
Gas pressure at inlet		atm (bar)	atm (bar)
Pressure rise		Pa	Pa
Gas pressure at discharge		atm (bar)	atm (bar)
Pressure ratio			
standard	atm	2023	2023
	bar	194.1	194.1
	psi	284.8	284.8
	atm	8.14	8.14
Florida	atm	2023	2023
	bar	194.1	194.1
	psi	284.8	284.8
	atm	8.14	8.14
Mixture properties			
Molecular weight	atm	20.23	20.23
Gas constant	bar	0.287	0.287
Gas density	kg/m ³	1.292	1.292
Gas viscosity	atm	1.81e-05	1.81e-05

Figure 1.11 – Circulator Specifications and Performance Curves

Figure 1.12 – Start-up Gas Fired Burner

Figure 1.13 – Original Advanced Module Design

Figure 1.14 – Proposed Design for the 285 kWe-Class Advanced Module

Figure 1.16 – Temperature Map for the 95 kWe-Class Test Article
(Natural Gas Fuel, I = 834A)

Figure 1.18 - SINDA/FLUINT Flow Network of a Ten Bundle – Bundle Row

Figure 1.19 - Fluent Generated Maps – Multivariate Regression Model

Figure 1.20 - Flow Distribution for a Ten Bundle Row
 (Syngas Fuel, I = 1432 A, air inlet orifice dP ≈ 5 in of H₂O)

Figure 1.21 - Temperature Distribution for a Ten Bundle Row
 (Syngas Fuel, I = 1432 A, air inlet orifice dP ≈ 5 in of H₂O)

**Figure 1.22 - Flow Distribution for a Ten Bundle Row
(Natural Gas Fuel, I = 1171 A)**

**Figure 1.23 - Flow Distribution for a Ten Bundle Row
(Natural Gas Fuel, I = 1432 A)**

Figure 1.24 - Flow Maldistribution Variation with the Number of Bundles in a Bundle Row (Syngas Fuel, I = 1432 A)

Figure 1.25 - - Flow Maldistribution Variation with the Number of Bundles in a Bundle Row (Natural Gas Fuel, I = 1171 A)

Component	Resistance Index*
	$\Omega\text{-cm}^2$
Cell to Cell	0.028
Bundle to Bundle	0.048
Row to Row	0.096
Bundle to Bus Bar	0.048
Bus Bar	0.498

Table 1.1 – Component Resistance Indices

Current density		J (mA/cm ²)	150	320	550
Cell Current		A	391	834	1433
Module Air flow	Stoichs		5.97	4.66	3.94
	Mass flow	kg/s	0.424	0.706	1.026
	Vol. flow	slpm	19852	33050.2	48027.1
Fuel flow	H2	slpm	1267.0	2612.1	4426
	NG	slpm	86.2	173.6	293.7
	NHMIX	slpm	30.2	61.8	105.3
Recirculator flow	Vol. flow	slpm	1607.5	3296.7	5584
Cell characteristics	Voltage	Volts	0.794	0.712	0.613
	Ave. temp	C	893.8	907	928.6
	Max. temp	C	970.8	970.7	972.6
	Axial dT	C	286.4	219.8	168.9
Process air side temperatures	Blower air Inlet	C	15	15	15
	Module air Inlet	C	21.8	27.8	38.1
	Cell air Inlet	C	471.3	410.8	380.7
Fuel side temperatures	Module fuel Inlet	C	16	16	16
	Recirculation	C	819.6	843.8	711.6
	Pre-ref. Inlet	C	128.1	128.3	141.3
	Pre-ref. outlet	C	189.9	189.8	202.7
	Stack Inlet	C	300	300	300
Exhaust side temperatures	Cell exhaust	C	819.6	843.8	711.6
	Comb. Zone	C	707	747.8	830
	Module exhaust	C	290.1	398.4	619.3
Recuperator effectiveness			0.868	0.632	0.441
Pressure drops	Generator	In of water	7.38	12.62	19.12
	Recuperator	In of water	0.74	1.23	1.78
	Orifice	In of water	1.89	4.07	7.4
	BOP	In of water	1.84	4.66	9.8
	Total system	In of water	11.86	22.37	37.9
Power Use	Blower	kWe	6.7	18.2	44.2
	I&C	kWe	2.30	2.3	2.3
	PCS	kWe	12.19	18.14	26.28
	Total	kWe	20.22	38.83	72.77
Energy flows	Fuel	kW	330.9	679.2	1150.6
	Cell	kWe	148.9	285	421.5
	Stack DC	kWe	147.9	280.3	407.6
	Net AC	kWe	127.8	242.0	336.5
Efficiencies	Cell	%	45.0	42.0	36.6
	Stack DC	%	44.7	41.3	35.4
	Net AC	%	38.6	35.6	29.2

Table 1.2 – 250 kWe-Class System Performance for Syngas Fuel

Current density		J (mA/cm ²)	150	320	450
Cell Current		A	391	834	1173
Module Air flow	Stoichs		4.03	3.35	3.21
	Mass flow	kg/s	0.286	0.508	0.684
	Vol. flow	slpm	13389.5	23790.5	32013.2
Fuel flow	Vol. flow	slpm	392.0	806	1122.5
Recirculator flow	Vol. flow	slpm	2739.1	5637.7	7805.2
Cell characteristics	Voltage	Volts	0.773	0.691	0.631
	Ave. temp	C	908.0	914	926
	Max. temp	C	970.0	970.1	989.6
	Axial dT	C	200.0	184.4	169.7
Process air side temperatures	Blower air Inlet	C	15	15	15
	Module air Inlet	C	19.2	23.5	27.5
	Cell air Inlet	C	731.3	600.9	531
Fuel side temperatures	Module fuel Inlet	C	15	15	15
	Recirculation	C	835.1	796	785.4
	Pre-ref. Inlet	C	676	646.7	637.9
	Pre-ref. outlet	C	516.1	509.5	507.4
	Stack Inlet	C	600	600	600
Exhaust side temperatures	Cell exhaust	C	835.1	796	785.4
	Comb. Zone	C	982	964.9	960.4
	Module exhaust	C	333.6	449.3	512.4
Recuperator effectiveness			0.740	0.613	0.540
Pressure drops	Generator	in of water	5.08	9.25	12.73
	Recuperator	In of water	0.5	0.66	1.19
	Orifice	in of water	1.09	2.51	3.94
	BOP	in of water	0.75	2.36	4.27
	Total system	In of water	7.42	15	22.13
Power flows	Blower	kWe	2.47	8.829	17.426
	IAC	kWe	2.30	2.3	2.3
	Auxiliary	kWe	11.81	17.41	21.79
	Total	kWe	16.58	28.54	41.51
Energy flows	Fuel	kW	250.7	515.5	717.9
	Cell	kWe	145	276.7	355.1
	Stack DC	kWe	144.0	272.0	345.8
	Net AC	kWe	127.3	243.3	304.6
Efficiencies	Cell	%	57.8	53.7	49.5
	Stack DC	%	57.4	52.8	48.2
	Net AC	%	50.8	47.2	42.4

Table 1.3 – 250 kWe-Class System Performance for Natural Gas

		95 kWe	285 kWe
Cell Geometry		Delta 8	
Cell material set		AE - WPC3	
		Electrolyte - ScSZ	
		FE - NiScSZ	
Cell class		POCD8R1 class	
Cell active length	m	1	
Cell active area	sq. m	2606	
Number of cells		160	480
OCR		2.1	
Air bypass allowance	%	5	
Fuel bypass allowance	%	5	1.5
Cell peak temperature	C	970	
Blower air inlet temperature	C	15	
Fuel inlet temperature	C	15	
Air blower efficiency	%	35	
Recirculator blower efficiency		Not modeled	
Inverter efficiency		Based on a PCS model	
I & C allowance	kWe	1.0	2.3
Module heat loss	kW	7.0	15.0

Table 1.4 - Analysis Assumptions Common to both Natural Gas and Syngas Fuels

		Natural gas	Syngas
Fuel consumption		0.85	0.88
Fuel composition entering module Mole fractions		Pittsburgh NG	Mixture of H ₂ , Pittsburgh NG, NHMIX to simulate chosen coal gas
H ₂	%		-
CO	%	-	-
H ₂ O	%	-	-
CO ₂	%	-	-
CH ₄	%	94.41	5.78
C ₂ H ₆	%	3.08	0.188
C ₃ H ₈	%	0.56	0.034
C ₄ H ₁₀	%	1.76	0.108
N ₂	%	0.19	2.04
H ₂ equivalent		4.28	1.06
LHV	kJ/kg	49453	61686
Stack fuel inlet temperature	C	600	300

Table 1.5 - Analysis Assumptions Specific to the Fuel Used

Fuel			Syngas						Natural gas					
System			95 kW			285 kW			95 kW			285 kW		
Cell Current			A	150	300	450	600	750	991	994	1179	150	300	450
Cell Current			A	391	694	1099	1499	1899	991	994	1179	391	694	1179
Module Air flow	Stoichi		6.00	4.69	4.00	5.97	4.66	3.94	4.09	3.41	3.26	4.26	3.41	3.24
	Mass flow	kg/s	0.142	0.237	0.249	0.424	0.706	1.026	0.097	0.172	0.232	0.302	0.517	0.69
	Vol. flow	slpm	6646.4	11095.4	16263.2	19852	33050.2	48027.1	4531.1	8070	10837.5	14147.4	24184	32272.8
Fuel flow	H ₂	slpm	433.4	893.6	1514.1	1267.0	2612.1	4426	-	-	-	-	-	-
	NG	slpm	29.6	59.4	100.5	86.2	173.6	293.7	135.5	278.6	388	392.0	806	1122.5
	NH ₃	slpm	10.4	21.1	36.0	30.2	61.8	105.3	-	-	-	-	-	-
Recirculator flow	Vol. flow	slpm	549.6	1126	1907.3	1607.5	3296.7	5584	949.4	1926.5	2698.9	2816.1	5595.7	7844.4
Cell characteristics	Voltage	Vdc	0.794	0.719	0.614	0.794	0.712	0.613	0.779	0.662	0.632	0.774	0.662	0.632
	Ave. temp	C	694.6	699	696.6	699.9	697	699.6	699.9	614.7	629	619.9	614	629
	Max. temp	C	978.6	979.6	989.9	979.9	970.7	972.6	978.6	970.9	979	989.9	989.9	989.9
	Ave. dT	C	289.1	216.4	194.4	209.4	210.9	199.9	199.9	193.9	199.2	199.2	199.3	199
Process air side temperatures	Generator inlet	C	16	16	16	16	16	16	16	16	16	16	16	16
	Module air inlet	C	71.7	71.9	71.9	71.9	71.9	71.9	71.7	71.7	71.9	71.9	71.7	71.9
	Cell air inlet	C	474.7	489.1	499.2	471.3	489.9	499.7	479.1	471.4	475.9	489.1	471.4	499.9
Fuel side temperatures	Module fuel inlet	C	19	19	19	19	19	19	19	19	19	19	19	19
	Recirculation	C	911.6	919	721.4	919.6	919.9	711.6	924.7	799.7	799.7	999.6	924.6	999.9
	Pre-ref. inlet	C	124.1	127.9	132.9	129.1	139.9	111.9	999.6	919	914.9	719.6	997.2	991.9
	Pre-ref. outlet	C	197.7	199.7	299	199.9	199.9	292.7	614.6	999.9	999.9	619.2	614.1	611.4
Exhaust side temperatures	Stack inlet	C	399	399	399	399	399	399	399	399	399	399	399	399
	Cell exhaust	C	911.6	919	721.4	919.6	919.9	711.6	924.7	799.7	799.7	999.6	924.6	999.9
	Comb. zone	C	719.2	799.2	999.6	797	747.9	839	994.9	994.2	996.7	1995.1	999.2	979.9
Pressure drops	Module exhaust	C	294	499.2	924.6	299.1	399.4	619.2	399.1	399.2	619.2	399.2	399.7	619.9
	Reheater effectiveness		0.666	0.666	0.667	0.666	0.632	0.441	0.737	0.666	0.634	0.729	0.666	0.636
	Generator	h ₂ O/steam	7.41	12.94	19.61	7.39	12.92	19.12	6.17	6.46	12.99	6.41	6.46	12.99
Pressure drops	Reheater	h ₂ O/steam	0.74	1.24	1.91	0.74	1.23	1.79	0.61	0.9	1.21	0.63	0.9	1.2
	Valves	h ₂ O/steam	1.9	4.13	7.99	1.89	4.12	7.4	1.11	2.69	4.94	1.89	2.69	4
	ROP	h ₂ O/steam	1.99	4.91	9.91	1.94	4.96	9.9	0.77	2.44	4.4	0.83	2.49	4.34
	Total system	h ₂ O/steam	11.71	22.92	39.92	11.99	22.97	37.9	7.99	19.27	22.91	7.99	19.29	22.1
Parameters	Gross	kWh	1.9	9.2	16.3	6.7	19.2	44.2	9.96	3.999	9.932	2.99	9.179	17.774
	UC	kWh	1.99	1	1	2.99	2.9	2.9	1.99	1	1	9.26	9.26	9.26
	Auxiliary	kWh	3.99	9.99	9.99	12.19	19.14	29.29	1.96	4.999	7.932	3.95	9.439	19.924
	Total	kWh	9.99	13.17	26.99	29.77	39.93	77.77	3.71	9.139	14.994	9.19	19.999	29.999
Energy flows	Fuel	kW	113.3	232.4	393.6	330.9	679.2	1150.6	86.7	178.1	248.1	250.7	515.5	717.9
	Cell	kWe	49.6	95.1	140.7	148.9	285	421.5	49.4	92.4	118.6	145.2	277	355.5
	Stack D/C	kWe	49.30	93.7	136.5	149.60	283.5	417.2	48	90.9	115.8	144.8	275.6	352.7
	Net A/C	kWe	42.40	80.5	111.5	128.40	244.8	344.4	42.2	81	101.4	129.8	248.3	312.3
Efficiencies	Cell	%	43.8	40.9	35.8	45.0	42.0	36.6	55.8	51.9	47.8	57.9	53.7	49.5
	Stack D/C	%	43.5	40.3	34.7	44.9	41.7	36.3	55.4	51.0	46.7	57.8	53.5	49.1
	Net A/C	%	37.4	34.6	28.3	36.8	36.0	29.9	48.8	45.5	40.9	51.8	48.2	43.5

Table 1.6 – Syngas Performance Summary for the 95 kWe-Class Test Article and 285 kWe-class Advanced Module

Syngas J = 330 mA/cm ²		Air into blower	Air into module	Fuel into module			Recirculated Anode off-gas	Pre-ref inlet	Pre-ref outlet	Fuel into stack	Post Combustion Inlet	Module exhaust
Component Mole Flow				H ₂	H ₂ O	HEMEX						
METHANE	kmol/hr	0	0	0	0.16	0	0	0.16	0.2	0.16	0	0
ETHANE	kmol/hr	0	0	0	0	0	0	0	0	0	0	0
PROPANE	kmol/hr	0	0	0	0	0	0	0	0	0	0	0
N-BUT-01	kmol/hr	0	0	0	0	0	0	0	0	0	0	0
NITROGEN	kmol/hr	22.1	22.1	0	0	0.05	0.01	0.03	0.03	0.03	22.16	22.21
CO ₂	kmol/hr	0	0	0	0	0	0.02	0.02	0	0	0.17	0.17
CO	kmol/hr	0	0	0	0	0	0	0	0	0	0	0
H ₂	kmol/hr	0	0	2.39	0	0	0.03	2.45	2.33	2.21	0	0
WATER	kmol/hr	0.38	0.38	0	0	0	0.37	0.37	0.48	0.4	3.01	3.02
O ₂	kmol/hr	0.64	0.64	0	0	0	0	0	0	0	43	43.1
PENTANE	kmol/hr	0	0	0	0	0	0	0	0	0	0	0
HEXANE	kmol/hr	0	0	0	0	0	0	0	0	0	0	0
Component Mole Fraction		0	0	0	0	0	0	0	0	0	0	0
METHANE		0	0	0	0.04	0	0	0.03	0.07	0.07	0	0
ETHANE		0	0	0	0.03	0	0	0	0	0	0	0
PROPANE		0	0	0	0.01	0	0	0	0	0	0	0
N-BUT-01		0	0	0	0.02	0	0	0	0	0	0	0
NITROGEN		0.79	0.79	0	0	0.05	0.02	0.02	0.02	0.02	0.75	0.75
CO ₂		0	0	0	0	0	0.06	0.01	0	0	0.01	0.01
CO		0	0	0	0	0	0.01	0	0	0	0	0
H ₂		0	0	1	0	0.05	0.12	0.8	0.77	0.77	0	0
WATER		0.01	0.01	0	0	0	0.31	0.12	0.14	0.14	0.1	0.1
O ₂		0.21	0.21	0	0	0	0	0	0	0	0.19	0.19
PENTANE		0	0	0	0	0	0	0	0	0	0	0
HEXANE		0	0	0	0	0	0	0	0	0	0	0
Total Mole Flow	kmol/hr	22.71	22.28	2.39	0.16	0.05	0.43	3.07	3.01	2.65	22.34	21.22
Total Mass Flow	kg/hr	933.95	910.59	498	2.77	1.61	8.19	17.39	17.39	19.48	920.09	928.74
Total Volume Flow	slm	11705.6	11001.7	942.7	62.7	22.3	639.0	1992.7	1904.0	2244.6	42126.9	20093.9
Standard Volume Flow	slm	11093.7	10391.0	891.4	63.4	21.1	172.1	1157.2	1125.2	1058.9	11071.3	11066.7
Temperature	C	19.0	27.6	19.0	19.0	19.0	249.0	197.9	199.7	300.0	799.2	410.2
Pressure	Bar	1.01	1.07	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Molar Enthalpy	kJ/mol	-2710935	-2337119	-287493.6	-7910920	-221043.6	-12392100	-328437	-342237	-35437	-327990	-12292380
Mass Enthalpy	kJ/kg	-24709.89	-21333.7	-14939.2	-493939	-10930.03	-12473.10	-690.989	-690.989	-690.984	-13079.1	-51920.1
Enthalpy Flow	W/kg	-22322.32	-12319.42	-190.69	-330.63	-4.98	-21343.38	-2220.6	-2220.6	-2407.2	-2737.97	-120215.4
Molar Entropy	kJ/mol-K	3249.09	4033.30	-690.67	-6639.12	87.6	10910.04	6180.23	7650.26	14004.46	4937.69	27199.1
Mass Entropy	kJ/kg-K	112.03	151.39	-493.42	-5081.74	24.92	826.35	814	1375.9	2000.93	1495.63	899.35
Mass Density	kg/m ³	1.22	1.23	0.09	0.74	1.13	0.24	0.17	0.16	0.12	0.32	0.99
Average Molecular Weight	kg/mol	28.74	28.74	2.02	17.4	28.71	17.79	6.63	6.74	6.74	27.67	27.72

Table 1.7 - Statepoints for the 95 kWe-Class Test Article (Syngas fuel, I = 834 A)

Inlet gas $I = 285 \text{ million}^1$		Air into blower	Air into module	Fuel into module	Recombined Anode off-gas	Pre-ref inlet	Pre-ref outlet	Fuel into stack	Fuel Combustion in CE	Stack outlet
Component Mole Flow										
MEthane	mol/s	0	0	0.7	0	0.7	0.63	0.0	0	0
CH4	mol/s	0	0	0.02	0	0.02	0	0	0	0
HCN	mol/s	0	0	0	0	0	0	0	0	0
H2	mol/s	0	0	0.01	0	0.01	0	0	0	0
NITROGEN	mol/s	18.87	18.07	0	0.01	0.02	0.02	0.01	18.07	18.08
CO2	mol/s	0	0	0	1.21	1.21	1.20	1.20	0.01	0.01
CO	mol/s	0	0	0	0.17	0.17	0.21	0.2	0	0
H2	mol/s	0	0	0	0.04	0.04	1.20	1.2	0	0
WATER	mol/s	0.31	0.31	0	2.01	1.60	1.60	1.0	1.70	1.70
O2	mol/s	1.20	1.20	0	0	0	0	0	2.00	2.00
Component Mole Fraction										
MEthane		0	0	0.04	0	0.03	0.12	0.12	0	0
CH4		0	0	0.00	0	0	0	0	0	0
HCN		0	0	0.01	0	0	0	0	0	0
H2		0	0	0.05	0	0	0.36	0.36	0	0
NITROGEN		0.70	0.70	0.00	0	0	0	0	0.70	0.70
CO2		0	0	0.00	0.3	0.26	0.20	0.20	0.04	0.04
CO		0	0	0.00	0.04	0.04	0.04	0.04	0	0
H2		0	0	0.00	0.10	0.13	0.36	0.36	0	0
WATER		0.01	0.01	0.00	0.5	0.42	0.33	0.30	0.09	0.09
O2		0.31	0.31	0.00	0	0	0	0	0.12	0.12
Total Mole Flow	kmol/s	21.0	31.07	1.70	4.03	4.70	3.10	4.1	21.31	22.30
Total Mass Flow	kg/s	600.17	800.00	12.30	60.04	100.01	100.01	100.04	602.0	601.00
Total Volume Flow	slm	601.7	800.0	20.0	60.0	60.7	60.0	60.0	600.0	600.0
Standard Volume Flow	slm	600.2	800.7	20.0	100.0	100.0	100.0	100.0	600.0	600.0
Temperature	C	100	200	100	700.7	600.0	600.0	600.0	600.0	600.0
Pressure	bar	1.01	1.05	1.01	1.01	1.00	1.01	1.01	1.01	1.01
Molar Enthalpy	kJ/mol	-170000	-200000	70000	-300000	-100000	-100000	-100000	-300000	-200000
Mass Enthalpy	kJ/kg	-200000	-200000	70000	-300000	-100000	-100000	-100000	-300000	-200000
Entropy Flow	W/K	-100000	-100000	100000	-200000	-200000	-200000	-200000	-100000	-100000
Molar Entropy	kJ/mol-K	100000	100000	100000	100000	100000	100000	100000	100000	100000
Mass Entropy	kJ/kg-K	100000	100000	100000	100000	100000	100000	100000	100000	100000
Mass Density	kg/m3	1.00	1.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Average Molecular Weight	g/mol	28.74	28.74	17.0	28.74	28.74	28.74	28.74	28.74	28.74

Table 1.8 - Statepoint for the 285 kWe-Class Advanced Module (Syngas fuel, $I = 834 \text{ A}$)

		With air inlet orifice		Without air inlet orifice	
Current density	mA/cm^2	559	320	550	320
Current	A	1432	833	1432	833
Temperature					
Max	C	970.8	881.4	970.1	881.8
Min	C	957.8	849.3	959.3	849.3
Average cell voltage	Vols	0.811	1.707	0.812	0.707
Stack fuel flow					
Max	%	20.5	19.1	20.3	19.1
Min	%	0.2	8.8	0.0	8.8
CZ depleted fuel flow					
Max	%	34.9	33.2	34.5	33.0
Min	%	-15.6	-14.8	-15.3	-14.9
Process air flow					
Max	%	0.53	0.22	-0.01	0.40
Min	%	-0.54	-0.22	-1.09	-0.38
Recup exhaust flow					
Max	%	10.8	8.2	-0.4	8.1
Min	%	-2.9	-2.1	-3.3	-2.3

Table 1.9 - Flow Maldistributions for a Ten Bundle Row, Syngas Fuel at Different Currents with and without an Air Inlet Orifice

		Nominal	High reirc (f = 0.88)	Small orz off dP	Exhaust resistance decreased by 25%	Exhaust resistance increased by 25%	CZ off die from 0.125" to 0.75"	Exhaust side orifice dP = 6 in of H ₂ O
Current density	mA/cm^2	320	320	320	320	320	320	320
Current	A	833	833	833	833	833	833	833
Temperature								
Max	C	880.8	880.8	880.2	870.6	870.1	880.0	880.8
Min	C	849.3	845	859.3	889.0	861.8	881.6	880.6
Average cell volt	Vols	0.707	0.842	0.722	0.718	0.717	0.712	0.711
Stack fuel flow								
Max	%	19.1	4.8	1.1	14.4	24.1	8.8	6.3
Min	%	-8.8	-2.8	-0.6	-8.3	-11.0	-6.8	-2.8
CZ depleted fuel flow								
Max	%	33.0	34.7	34.3	34.4	41.7	18.8	8.2
Min	%	-14.9	-18.6	-16.6	-11.0	-18.7	-10.0	-4.8
Process air flow								
Max	%	0.40	0.36	0.38	0.43	0.41	0.37	0.76
Min	%	-0.38	-0.60	-0.48	-0.61	-0.83	-0.63	-0.78
Recup exhaust flow								
Max	%	8.1	8.0	8.0	8.7	8.4	83.2	3.3
Min	%	-2.3	-2.2	-2.2	-1.8	-2.8	-13.7	-1.4

Figure 1.10 - Sensitivity of Flow Maldistributions for a Ten Bundle Row, Syngas Fuel to Different Model Parameters

		With air inlet orifice			Without air inlet orifice		
Current density	mA/cm^2	450	320	150	450	320	150
Current	A	1171	833	391	1171	833	391
Temperature							
Max	C	989.7	989.8	970.0	989.6	978.1	989.4
Min	C	954.5	947.9	932.1	955.6	947.8	929.6
Average cell voltage	Volt	0.628	0.688	0.771	0.628	0.688	0.770
Stack Fuel flow							
Max	%	8.7	7.3	5.3	8.7	7.3	5.4
Min	%	-3.7	-2.8	-2.1	-3.7	-2.8	-2.2
CZ depleted fuel flow							
Max	%	28.4	24.7	20.5	28.3	24.7	21.2
Min	%	-13.1	-11.5	-9.8	-12.9	-11.5	-10.3
Process air flow							
Max	%	0.32	0.13	0.53	0.45	0.19	0.85
Min	%	-0.33	-0.19	-1.54	-0.45	-0.28	-1.88
Recup exhaust flow							
Max	%	9.0	7.7	4.9	9.1	7.6	4.6
Min	%	-2.4	-4.9	-0.9	-2.5	-1.9	-0.8

Figure 1.11 - Flow Maldistributions for a Ten Bundle Row, Natural Gas Fuel at Different Currents with and without an Air Inlet Orifice

Number of bundles		10	9	8	7	6	5	10	9	8	7	6	5
Current density	mA/cm^2	650	650	650	650	550	650	320	320	320	320	320	320
Current	A	1432	1432	1432	1432	1432	1432	833	833	833	833	833	833
Temperature													
Max	C	970.1	989.6	970.2	989.8	969.9	970.3	989.8	970.3	989.8	970	970.3	989.8
Min	C	959.3	959.8	959.7	959	952.2	952.9	959.3	955.4	959.8	959.8	956.4	959.3
Cell dT	C	10.8	9.7	9.6	8.8	7.7	7.4	21.6	14.9	9.2	6.2	3.9	3.3
Average Cell Voltage	Volt	0.812	0.812	0.812	0.812	0.613	0.813	0.707	0.710	0.711	0.713	0.714	0.713
Stack Fuel Flow													
Max	%	20.3	16.1	10.8	7.0	4.3	2.3	19.1	14.0	9.7	8.4	3.9	2.1
Min	%	-9.0	-8.7	-4.8	-3.3	-2.1	-1.2	-8.8	-8.3	-4.6	-3.0	-1.9	-1.1
Min OEH2 Mole-Fraction	%	4.1	8.3	7.9	9.3	10.3	11.0	4.6	8.8	8.2	9.6	10.4	11.1
CZ Depleted Fuel Flow													
Max	%	34.6	25.2	17.7	11.7	7.2	3.9	33.0	23.7	16.6	10.8	6.9	3.6
Min	%	-16.3	-11.6	-8.3	-6.7	-3.6	-2.2	-14.9	-11.1	-7.8	-6.2	-3.6	-2.0
Process Air Flow													
Max	%	1.01	1.03	0.93	0.80	0.69	0.68	0.40	0.36	0.32	0.30	0.24	0.30
Min	%	-1.09	-0.91	-0.74	-0.67	-0.43	-0.27	-0.38	-0.33	-0.30	-0.28	-0.20	-0.14
Recup Exhaust Flow													
Max	%	10.4	8.7	7.1	6.8	4.2	3.0	8.1	8.8	6.8	4.4	3.4	2.6
Min	%	-3.3	-2.9	-2.6	-2.1	-1.7	-1.4	-2.3	-2.0	-1.7	-1.6	-1.3	-1.1

Figure 1.12 - Flow Maldistributions Variation with Number of Bundles in a Row (Syngas Fuel)

Number of bundles		10	9	8	7	6	6	10	9	8	7	6	6	10	9	8	7	6	6
Current density	mA/cm²	450	450	450	450	450	450	320	320	320	320	320	320	160	160	160	160	150	160
Current	A	1171	1171	1171	1171	1171	1171	833	833	833	833	833	833	391	391	391	391	391	391
Temperature																			
Max	C	989.8	970.1	989.7	989.6	969.6	989.7	970.1	989.7	989.8	989.7	969.9	970.0	989.4	989.8	989.2	970.4	970.3	989.0
Min	C	956.8	980.4	982.8	985.8	967.8	989.7	947.8	963.9	969.0	983.2	966.3	988.3	929.8	940.1	949.8	988.8	962.1	984.6
Cell dT	C	14	8.7	7.1	3.7	1.8	1	223	168	108	8.6	3.6	1.7	398	28.6	20.8	13.8	8.2	4.6
Average cell voltage	Volts	0.628	0.629	0.630	0.630	0.630	0.691	0.688	0.689	0.690	0.690	0.691	0.691	0.770	0.771	0.772	0.772	0.772	0.772
Stack fuel flow																			
Max	%	8.7	8.2	4.3	2.8	1.6	0.9	7.3	6.2	3.6	2.2	1.3	0.7	6.4	3.7	2.4	1.6	0.8	0.4
Min	%	-3.2	-2.4	-1.7	-1.1	-0.7	-0.4	-2.8	-2.0	-1.4	-1.0	-0.6	-0.3	-2.2	-1.8	-1.1	-0.7	-0.5	-0.3
Min O₂ H₂ Mole-Fraction	%	18.7	19.1	19.4	19.6	19.8	19.9	18.9	19.3	19.6	19.7	19.9	20.0	19.2	19.3	19.6	19.8	19.9	20.0
2% depleted fuel flow																			
Max	%	28.3	20.2	14.1	9.4	5.6	3.1	24.7	17.7	12.3	8.1	4.8	2.8	21.2	14.7	10.1	6.4	3.7	2.2
Min	%	-12.9	-9.6	-8.7	-4.8	-3.0	-1.7	-11.8	-8.3	-8.2	-4.1	-2.6	-1.6	-10.3	-7.8	-6.0	-3.3	-2.5	-1.6
Process air flow																			
Max	%	0.48	0.41	0.27	0.32	0.27	0.23	0.19	0.14	0.13	0.12	0.10	0.12	0.86	0.60	0.34	0.23	0.11	0.09
Min	%	-0.45	-0.37	-0.22	-0.23	-0.17	-0.11	-0.28	-0.12	-0.10	-0.10	-0.08	-0.08	-1.88	-1.36	-0.91	-0.57	-0.32	-0.13
3a cm exhaust flow																			
Max	%	9.1	7.6	6.9	4.8	3.5	2.4	7.8	8.3	6.1	4.0	3.0	2.1	4.8	3.9	3.3	2.8	2.0	1.5
Min	%	9.1	7.6	6.9	4.8	3.5	2.4	7.8	8.3	6.1	4.0	3.0	2.1	4.8	3.9	3.3	2.8	2.0	1.5

Table 1.13 - - Flow Maldistributions Variation with Number of Bundles in a Row
(Natural Gas Fuel)

Category	Design considerations	Possible design modifications
On cell information	Pressure effect	Is information redundancy necessary?
Thermal centering philosophy	Individual thermal centers for bundles?	OE casing and air inlet manifold modifications
Hot air inlet	Hot air inlet manifold	Suitable higher temperature material selection
	Thermal expansion	Bellows needed to accommodate thermal growth as per thermal centering philosophy
	Air inlet to AFT seal	New grommet design
	Hot air inlet box and components	Suitable higher temperature material selection
	Air inlet interface to BOP	Needs revision to accept hot air inlet
	Insulation to canister	Revise insulation design as per canister design
Internal recuperator	Height	Height needs to be reduced based on boltoning cycle temperature requirements
Hot exhaust plenum	Exhaust casing thermal expansion	Additional thermal growth considerations
	Exhaust outlet interface to BOP	Suitable higher temperature material selection
Electrical connections	Power leads	Design for higher currents?
	Connectors	Design for higher currents?
Stack containment	Canister	Design for same temp as atmosphere?
	Blowback and base plate	Temperature issues?
	Peripheral insulation	Insulation pack (lower level) to suit canister and baseplate design
Recirculation loop	Reductor feasibility	Reductor seal and hot temperatures may preclude the use of reductors
	Fuel side heater	Location and access and temperature limitations
	Recirculation piping	May not need change if enclosed in pressure vessel
Flow distribution	Increased ΔP due to hot air inlet	Bundle row length?
	Increased ΔP due to hot exhaust	Bundle row length?
	Buoyancy related thermal channeling	Buoyancy fuel side flow distribution feedback needs to be included with other effects
Start-up	Generator Start-up with fuel side heating	Needs to be integrated with pressurization
Pressure vessel	Space between pressure vessel and canister	Possible IAA
	Air cooling?	OE Casing thermal shock mitigation
	Fuel, air and exhaust penetrations	Need to purge insulation
Depressurization	Fuel into side gaps between bundles during depressurization	Burning around the bundles and direct flow into exhaust
	Thermal transient effect on casing	OE Casing thermal shock mitigation
	Cool down philosophy	
	Insulation filled with fuel	Need to purge insulation

Table 1.14 - List of Module Design and Analysis Issues Associated with Pressurized Operation