# FINAL SCIENTIFIC/TECHNICAL REPORT

## LGFCS SOFC Prototype System Testing

Revision 0, January 31, 2019

## WORK PERFORMED UNDER AGREEMENT

## DE-FE0031180

(Period of performance October 1, 2017 through January 31, 2019)

## SUBMITTED BY

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# ABSTRACT

In the project, LGFCS assembled and tested its modular SOFC Power System that incorporates all critical technology improvements identified for its “product-like” demonstration. This product demonstrator is expected to meet customer and LGFCS performance expectations for operation, availability, durability and serviceability. The principal technology improvements are aimed at increasing the fuel cell power output and reducing the stack degradation rate. Improvements were also made for added system robustness and increased reliability.

The objective of this program is to test a 250kWe thermally self-sustaining modular solid oxide fuel cell (SOFC) Power System for a minimum of 5,000 hours while advancing this commercial prototype product demonstrator to a Technical Readiness Level (TRL) 7. The SOFC system was tested on a site provided by Stark State College in North Canton, Ohio. System performance and degradation as well as cost estimates were compared to established SOFC Program performance metrics to assess progress.

The major achievements were to assemble, and QA qualify 70 fuel cell strips for 12 integrated blocks into a fuel cell vessel and install it into a generator module with the fuel and power electronics modules on the test site. Performance to date included over 1800 hours on load at 250 KW-AC to the grid with a DC efficiency of 61% and AC efficiency of 55%. Power degradation was less than 0.4% per 1000 hours and NOx emissions met standards. The LGFCS SOFC Prototype System (GEN0) was demonstrated in an operational environment and therefore achieving Technical Readiness Level 7.

The work presented here represents the efforts of all the employees of LG Fuel Cell Systems. Their dedication and hard work made GEN0 possible and successful.

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# EXECUTIVE SUMMARY

The objective of this program is to test a 250kWe thermally self-sustaining modular solid oxide fuel cell (SOFC) Power System for a minimum of 5,000 hours while advancing this commercial prototype product demonstrator to a Technical Readiness Level (TRL) 7.

The scope of work includes:

- The assembly of the Fuel Cell Vessel (FCV)
- Assembly and packaging of the Generator Module and Balance of Plant (BOP)
- Installation and interconnection of the power system packages and connection to the fuel supply and power grid
- Commissioning and shakedown testing to validate assembly and safe operation
- 5,000 hours operation at a base load power rating to the grid

The SOFC system was tested on a site provided by Stark State College in North Canton, Ohio. System performance and degradation as well as cost estimates were compared to established SOFC Program performance metrics to assess progress.

The major achievements were:

- Assemble and QA qualified 70 fuel cell strips for 12 integrated blocks and 2 spare integrated blocks
- Assemble and QA qualified 12 integrated blocks and 2 spare integrated blocks and installed in fuel cell vessel
- Delivered fuel cell vessel to test site and installed in generator module
- Installed fuel and power electronics modules on test site
- Interconnected generator, fuel and power electronics modules on test site
- Commissioned and started the LGFCS SOFC Prototype System
- Performance to date:
    - Over 1800 Hours on Load
    - Power to Grid = 250 KW-AC
    - Efficiency = 61% DC / 55% AC
    - Power Degradation = 0.4% per 1000 hours
    - Emissions meet NOx standards
- The LGFCS SOFC Prototype System (GEN0) was demonstrated in an operational environment and therefore achieving Technical Readiness Level 7

LG Fuel Cell Systems Inc. (LGFCS) provided written notice of termination of this Cooperative Agreement No. DE-FE0031180 effective January 31, 2019 prior to completing the 5000 hours of testing. LGFCS terminated the Cooperative Agreement due to the need of its member companies to re-focus resources and capital to meet new global energy market challenges in the near term.

# 1.0 REPORT DETAILS

## Introduction

The components of the LGFSC Solid Oxide Fuel Cell (SOFC) power plant are shown in

Figure 1. Flat porous ceramic tubes (1) are the substrate for fuel cells printed with industrial screen-printing equipment (2). The fuel cell tubes (3) are assembled into strips (4) with manifolds to direct the flow of fuel inside the tubes. The strips are incorporated into Integrated Block (IB) (5), which direct the flow of air and fuel, control the thermal environment and extract electrical power. The IB's are combined into a fuel cell vessel (6) with a turbo generator (8) to supply air and pressure to form the Generator Module (GM) (7). The GM is packaged with Balance of Plant (BOP) equipment to form the system.

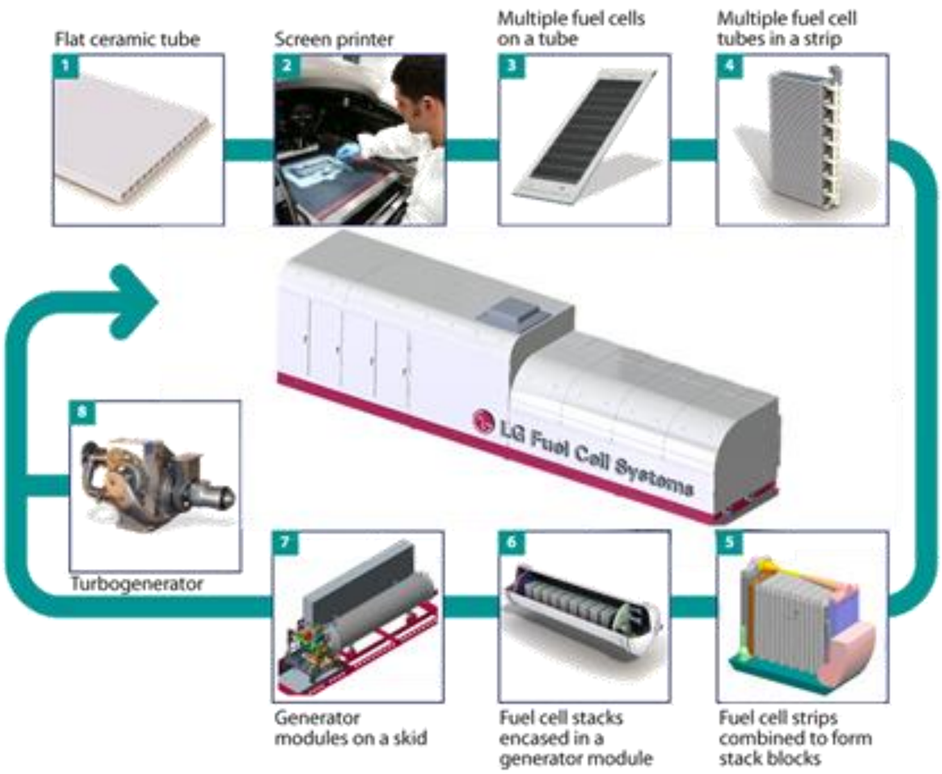



**Figure 1 LGFSC Solid Oxide Fuel Cell (SOFC) Power Plant**

## Task 1.0 - Project Management

LG Fuel Cell Systems Inc. (LGFCS) will manage and direct the project in accordance with a Project Management Plan to meet all technical, schedule and budget objectives and requirements. LGFCS will coordinate activities to accomplish the work. LGFCS will ensure that project plans, results, and decisions are appropriately documented, and project reporting and briefing requirements are satisfied.

**Results and Discussion**

LG Fuel Cell Systems Inc. (LGFCS) provided written notice of termination of this Cooperative Agreement No. DE-FE0031180 effective January 31, 2019. LGFCS terminated the Cooperative Agreement due to the need of its member companies to re-focus resources and capital to meet new global energy market challenges in the near term. Recent activity in the fuel cell market has confirmed profitability challenges for the technology, despite a competitive cost structure and product specifications. Continuation of LGFCS's research under the Cooperative Agreement is not consistent with member company needs to address these challenges.

The milestone log is shown in Table 1.

**Table 1 Milestone Log**

| Budget Period | Milestone No. | Task No. | Milestone: Title/Description | Planned Completion Date | Actual Completion Date |
|---|---|---|---|---|---|
| 1 | 1 | 1 | Submit Revised PMP/TMP | 15-Nov-17 | 20-Dec-17 |
| 1 | 2 | 3 | Receipt of Fuel Cell Tubes | 15-Feb-18 | 16-Feb-18 |
| 1 | 3 | 4 | Complete GM and BOP Packages | 15-May-18 | 30-Jul-18 |
| 1 | 4 | 3 | Complete FCV Assembly | 15-Aug-18 | 12-Jul-18 |
| 2 | 5 | 4 | Complete Installation of GM and BOP Packages | 15-Oct-18 | 22-Aug-18 |
| 2 | 6 | 5 | Submit Test Plan (45 days prior to start of test) | 15-Nov-18 | 25-Sep-18 |
| 2 | 7 | 5 | Complete 1,000 hour of test | 15-Feb-19 | 29-Oct-18 |
| 2 | 8 | 2 | Cost Report Submitted | 15-Apr-19 | |
| 2 | 9 | 5 | Complete 5,000 hour test | 15-Aug-19 | |

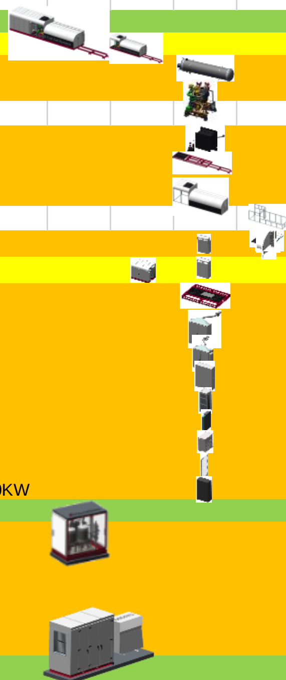
## Task 2.0 – Cost Modeling

LGFCS will utilize the Factory Cost Model to estimate the cost of the SOFC stack. Cost estimates will be compared to the established SOFC program cost metric. LGFCS will prepare a Factory Cost Report estimating the costs for the SOFC stack design and materials of the system test, but at future high-volume production rates. Cost estimates will utilize DOE recommendations for materials where available.

**Results and Discussion**

A detailed Bill of Materials (BOM) was developed for the GEN0 system with internal funds. The BOM included the one-off, first-of-a-kind cost of every component in the system. An example of this data is shown in Figure 2.

The system can be separated into 3 main subsystems: Cell and Stack (C&S), Fuel Cell Vessel (FCV) and Integrated Blocks (IB), and Balance of Plant (BOP) consisting of turbo generator, power electronics, fuel processor and packaging. For GEN0 the highest cost is the C&S which accounts for 50%, next is the FCV and IB which is 30% and lastly the BOP which accounts for 20%.



| Level | Parts Number | Picture 1 | 2 | 3 | 4 | 5 | 6 | Parts Name |
|---|---|---|---|---|---|---|---|---|
| 0 | | | | | | | | FUEL CELL SYSTEM |
| 1 | FCP000987652 | | | | | | | GENERATOR MODULE |
| 2 | FCP000881682 | | | | | | | FCV & TGA ASSEMBLY |
| 3 | FCP000920510 | | | | | | | FUEL CELL VESSEL ASSEMBLY |
| 3 | TGA2_Package_Assy | | | | | | | TGA PACKAGE |
| 4 | TGA2_Module_Assy | | | | | | | TGA Moudle Unit |
| 3 | FCP000858133 | | | | | | | AIR FILTER FOR TGA |
| 3 | FCP000881685 | | | | | | | FCV BASE |
| 3 | FCP000881730 | | | | | | | FCV ENCLOSURE |
| 4 | FCP000881732 | | | | | | | ENCLOSURE STRUCTURE |
| 3 | FCP000922510 | | | | | | | TGA FCV IO ENCLOSURE |
| 2 | FCP000881683 | | | | | | | GM BOP ASSEMBLY |
| 3 | FCP000881687 | | | | | | | BOP BASE |
| 3 | FCP000881688 | | | | | | | APG & AUX FUEL |
| 3 | FCP000919292 | | | | | | | FUEL CONTROL & ISOLATION |
| 3 | FCP000922520 | | | | | | | GMPDUIO ENCLOSURE |
| 3 | FCP000922620 | | | | | | | DC POWER ENCLOSURE |
| 3 | FCP000919980 | | | | | | | AIR CONDITIONER |
| 3 | FREEDOM_BULL428 | | | | | | | TG LOAD BANK |
| 3 | AC LOUVER | | | | | | | AC LOUVER |
| 3 | EATON_93PM_UPS_50KW | | | | | | | TG UPS |
| 1 | FCP000895918 | | | | | | | Fuel Module Assembly |
| 2 | DES Module | | | | | | | SulfurTrap R2G, R8C (70Gal, 2X) |
| 2 | 2100PGM0001 | | | | | | | DES Plant Supply Pressure Gauge |
| 2 | 2100PRM0001 | | | | | | | DES Plant Supply Pressure Transduce |
| 2 | | | | | | | | Junction Box |
| 2 | | | | | | | | Enclosure |
| 3 | | | | | | | | Interconnection between Modules |
| 1 | FCP000872811 | | | | | | | PCS Module Assembly |
| 1 | | | | | | | | Pipes |

**Figure 2 Example of GEN0 Bill of Materials Data**

A should cost model was developed for the product using internal funds, this contract and DE-FE 0031638, Techno-Economic Analysis of an LGFCS MWe-Class SOFC System. The model is based on the material cost plus the manufacturing cost as follows.

1) Material cost = Raw material cost + Manufacturing cost (Machining cost + Profit)

The raw materials cost can be estimated as:

2) Raw material cost = (Volume X Density) x $\alpha$ x Unit Price [$/kg]

Where $\alpha$ is machining allowance factor:

$$\alpha = \frac{\text{Required Mass}}{\text{Final Mass}}$$

Since there is scrap from parts during machining, the required mass of the raw material is always greater than the final machined mass. If the machining allowance factor is 1, the required mass for machining is the same as the final mass after machining.

The raw manufacturing cost can be estimated as:

3) Manufacturing Cost = $\beta$ x Raw material cost

The manufacturing cost ratio, $\beta$, is a function of the manufacturing method, manufacturing difficulty, machine depreciation, manufacturing volume, labor wage, and so on.

$$\beta = \frac{\text{Manufacturing Cost}}{\text{Raw material Cost}}$$

Plugging 2 and 3 into 1 gives the material cost as:

4) Material Cost = ($\beta$ +1) X Raw material cost

= ($\beta$ +1) X (Volume X Density) X $\alpha$ X Unit Price [$/kg]

Once the volume and material type (cost) of each component is calculated from the BOM, the material cost can be estimated.
Figure **3** shows a comparison between Gen0 first-of-a-kind cost and should cost for the FCV and IB components.

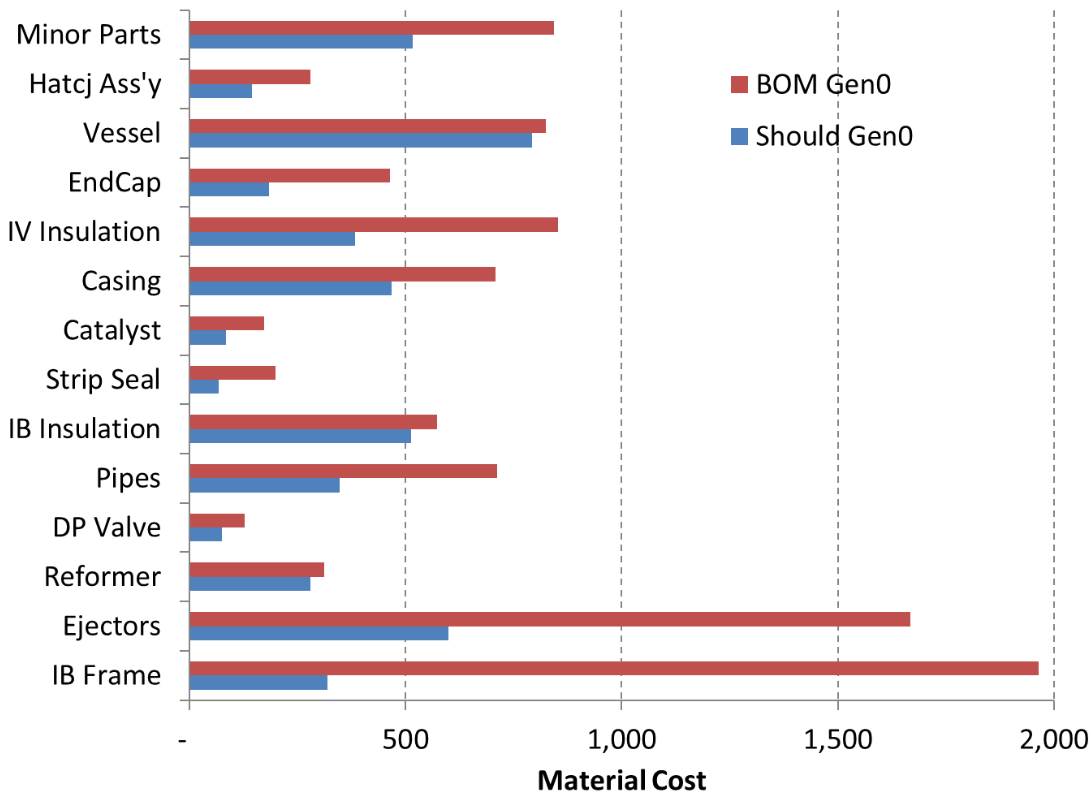



**Figure 3 Comparison of Gen0 first-of-a-kind cost and should cost**

Even though we may reduce the material cost through appropriate cost analysis, more cost reduction is required. For reducing the raw material cost, design and material changes are needed. Manufacturing cost reduction can be achieved through low cost design, low-cost manufacturing and development of competitive supply chain. Figure 4 shows the cost reduction for the integrated block frame.

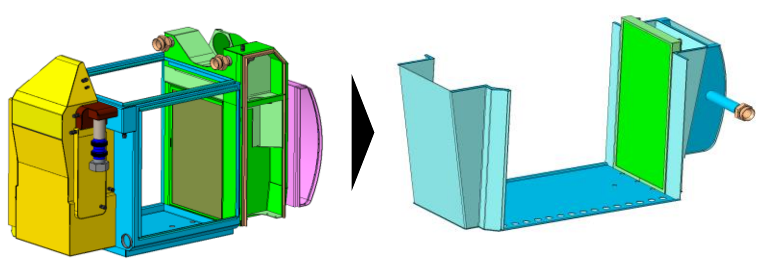


**Figure 4 Cost Effective Design Changes for Integrated Block Frame**

Appling these methods to the system and assuming a production rate of 8MW/year, the cost target of $5,000/kW can be achieved. The Cell & Stack accounts for 40% of the cost with reduction in tube manufacturing and improving cell processing methods. The FCV and IB accounts for 30% of the cost with reduction through doubling the power density and design simplification. Lastly the BOP accounts for 30% of the cost with reductions through supply chain development.

## Task 3.0 – Assemble Fuel Cell Vessel

The purpose of this task is to assemble the FCV, a major component of the 250kW SOFC Power System. The principle components that make up an FCV are fuel cell tubes, fuel cell strips, integrated blocks (IBs), an inner vessel assembly, and the outer pressure vessel. The costs associated with materials used in fabricating the cells and stacks will be provided by the Recipient along with all purchased components used in the 250kW system will be incurred by the Recipient outside the DOE project costs. The engineering and design package for the 250kW SOFC prototype system is being carried out independently by the Recipient. This will include utilizing the Hazard and Operability Analysis (HAZOP) method to ensure that the 250kW system includes all required safety features. The detailed design will also address site preparations and installation requirements for the demonstration site. The fuel cells will be installed in an advanced cycle integrated block, which significantly reduces chrome-baring materials and includes a chrome getter. It also incorporates in-block-reforming to increase power density and reduce temperature. The fuel cell strip will be of the “Integrated System Testing” (IST) design and include a new ceramic-to-metal clamp joint and secondary interconnect. In addition, the fuel cells may incorporate new material sets for reducing degradation.

**Results and Discussion**

This section describes several activities aimed at improving the quality of the stack and IB by critical parts quality control. 3 Steps quality control applied for improving the quality.

- IQC (Incoming Quality Control): Incoming Inspection for all critical parts, printed tubes, dense parts, assembly glasses, ejectors, reformers, IB frame, etc.
- LQC (Line Quality Control): Quality inspection during assembly, visual check, leakage test for sub-assembly, bundles, strips and IBs.
- OQC (Outgoing Quality Control): Before out-going, inspect all OQC items, visual and leakage also performance check for the strips.

**Incoming Quality Control:** The QA team decided critical parts and set-up the specifications for improving the strip/IB quality. Some parts specifications are not clear, so we need several tasks for confirming the specification.

Printed tubes were received from the supplier. Before printing the tubes, the supplier agreed to specifications and all critical items including.

- Inspection all the bare tubes: Crack, dimension, properties
- Meet the ink deposition specifications
- Meet the dimension specifications

- 100% out going inspection: Visual, Leakage, Short circuit
- Performance test by sampling procedure: ASR target is 0.289 ohm-cm2 with a USL of 0.314 ohm-cm2

Modification of the ejector design and inspection technique was necessary to improve ejector performance. For the anode ejector, nozzle distortion issues lowered performance. Nozzle diameter CT scan inspection is shown in Figure 5.

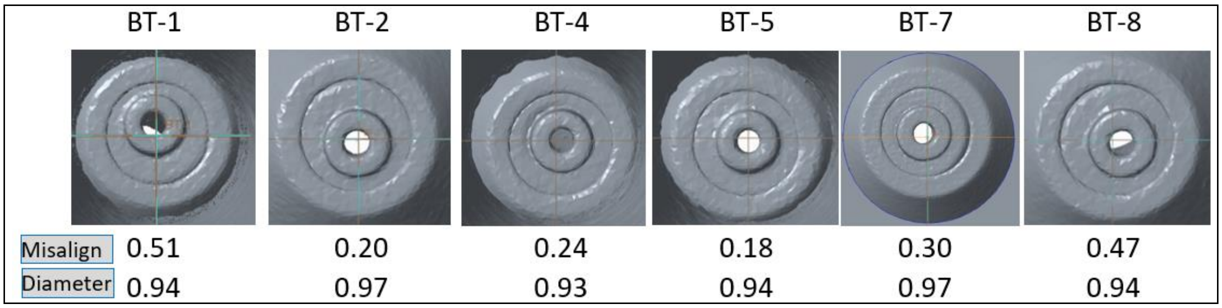



**Figure 5 Anode ejector nozzle mis-align and diameters**

Cracks were found on the cathode ejectors as shown in Figure 6.

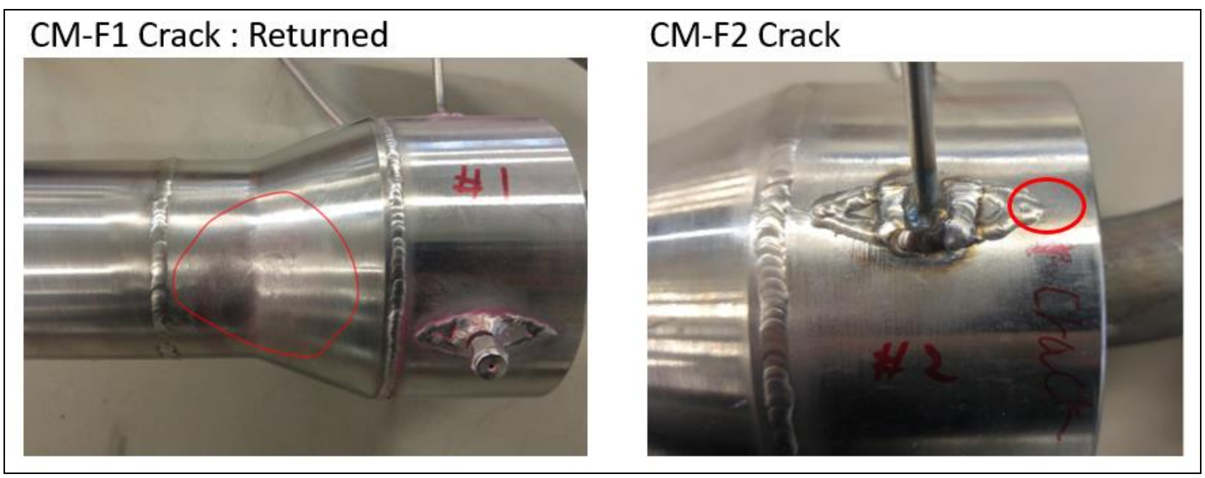



**Figure 6 Surface crack of the cathode ejectors**

Venders were informed of these quality issues and procedures were implemented to prevent them. The venders improved their quality inspection system and develop new inspection methods. A nozzle align inspection tool is shown in Figure 7.

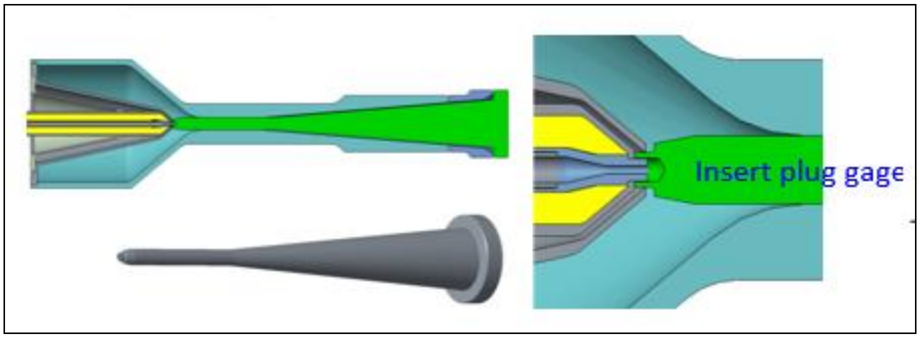



**Figure 7 Jig for inspection of the anode ejector nozzle mis-align**

After completing the ejector inspection activity, the anode/cathode/auxiliary ejectors performance inspection procedure was developed as shown in Figure 8.

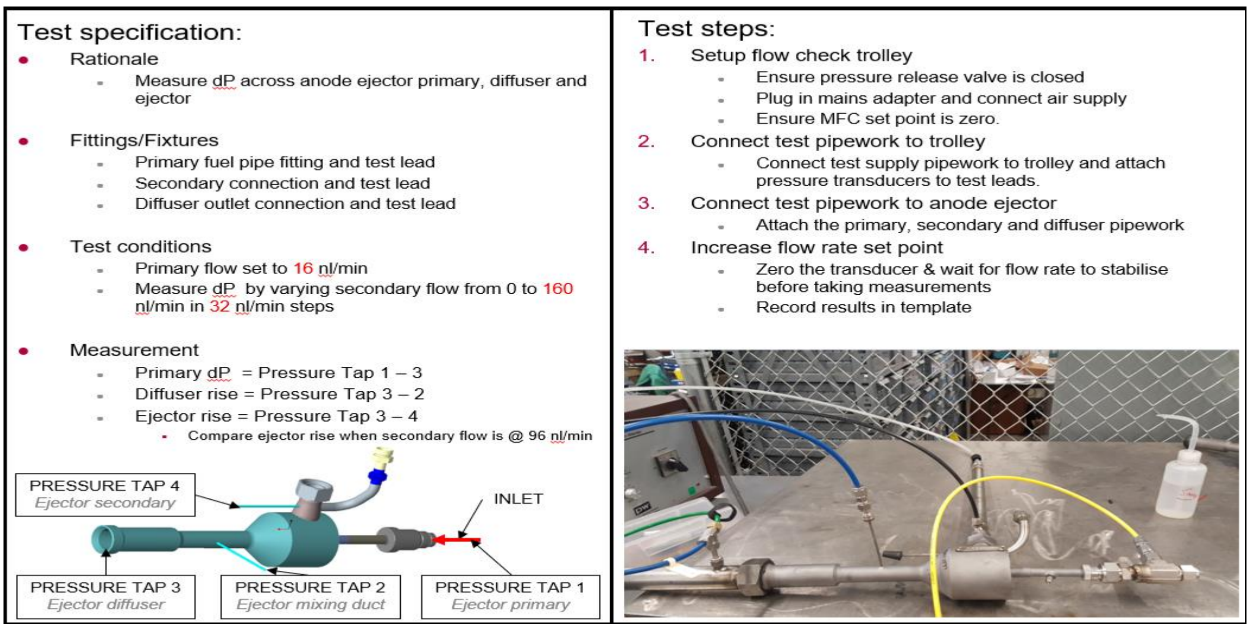



**Figure 8 Flow test procedure for anode ejector**

After quality improvement activities and active cooperation from the venders, a high-level incoming inspection yield was achieved as shown in Table 2.

**Table 2 Gen0 key parts incoming inspection results**

| Assy | Key parts | | Quantity | | | | Inspection | | | Remark |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Need | Order | Received | Rate | Passed | Reject | Yield | |
| ISR | Reformer | LG617 | 14 | 14 | 14 | 100% | 14 | 0 | 100.0% | |
| Ejector | Cathode ejector | F design | 14 | 14 | 15 | 107% | 14 | 1 | 92.9% | 1: nozzle out of spec |
| | Anode ejector | 0.9 nozzle | 14 | 14 | 15 | 107% | 14 | 1 | 92.9% | 1: Low ARR |
| | Auxiliary ejector | 2.5 nozzle | 14 | 14 | 14 | 100% | 14 | 0 | 100.0% | |
| IB | IB Frame | Ameco | 8 | 8 | 8 | 100% | 8 | 0 | 100.0% | |
| | | Qual-Fab | 6 | 6 | 6 | 100% | 6 | 0 | 100.0% | |
| | CMJ Clamp | Flange/ Support | 140 | 180 | 180 | 129% | 174 | 6 | 96.6% | 6:Surface defect |
| | | Band | 140 | 180 | 180 | 129% | 144 | 0 | 100.0% | |
| Strip | Printed Tube | LG CEM | 5,040 | 5,500 | 5,681 | 113% | 5,677 | 4 | 99.9% | 4: Visual defects |
| | Glass(g) | LG CEM | 18,000 | 19,800 | 19,830 | 110% | 19,830 | 0 | 100.0% | |
| | Strip total | | 70 | 70 | 70 | 100% | 70 | 0 | 100.0% | |

**Line Quality Control**: Each step of the assembly process was inspected, and data collected on quality. The results were analyzed statistically with Six Sigma tools. These results were used for understanding the status and corrective actions. The overall yield of the strip assembly was 94.3 %. as shown in Figure 9 and Figure 10.

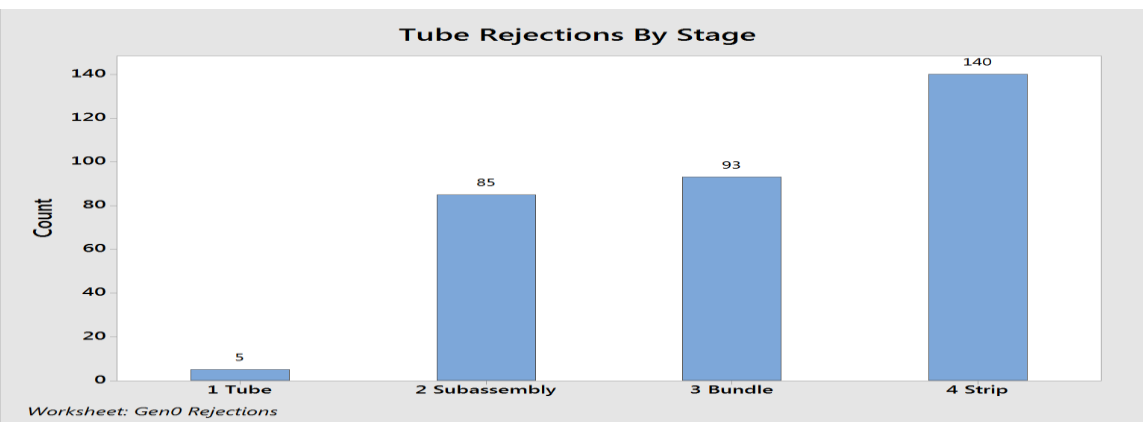



**Figure 9 Gen0 tube rejections by stage**

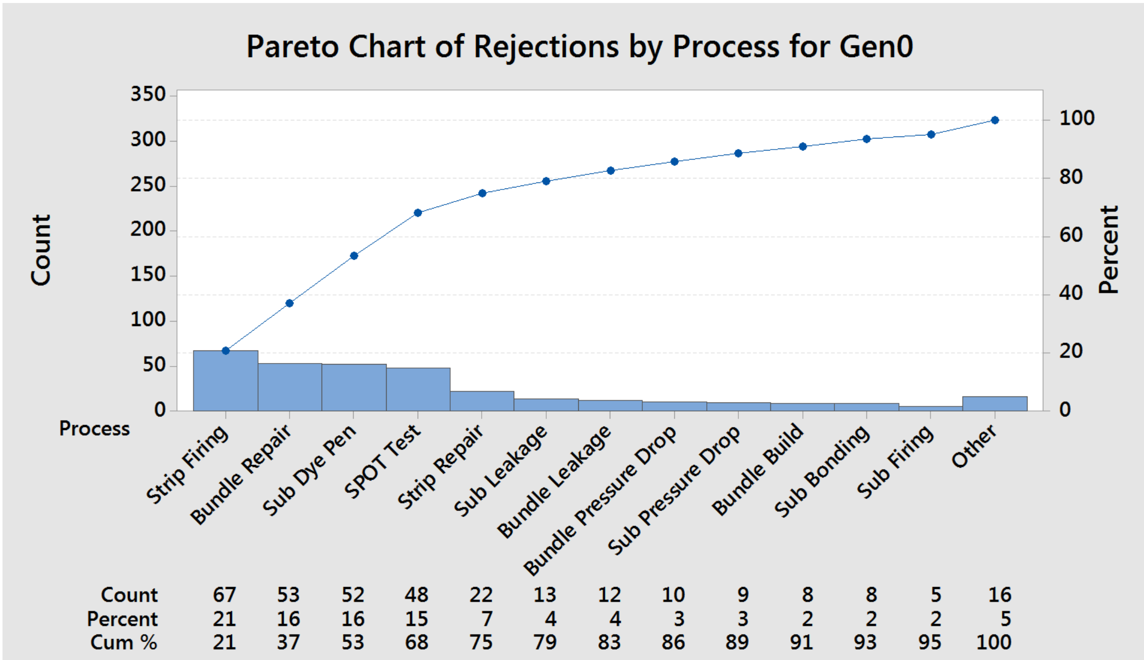



**Figure 10 Yield for detailed process's**

Figure 10 shows that the highest rejection stage was strips firing. This was caused by operator errors during strip installing in the furnace. A root cause analysis was performed, and corrective actions taken to improve the process as shown in Figure 11.

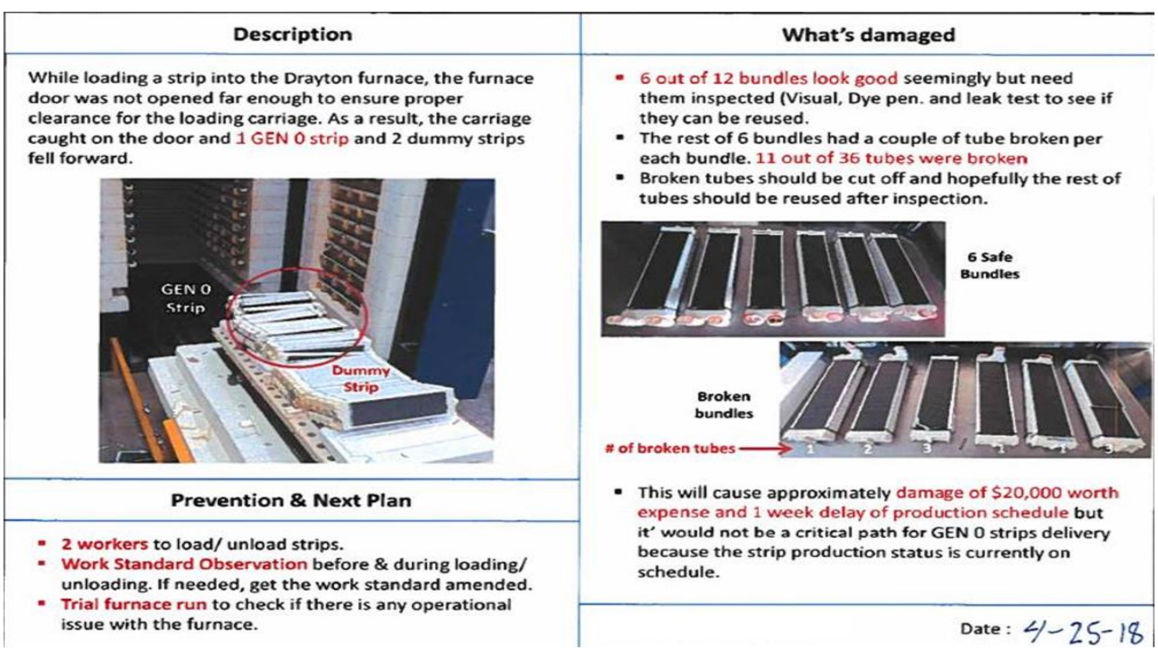



**Figure 11 Accident Report of the Strip damaged by mis-installing in the furnace**

For IB assembly, critical assembly process steps were defined, and checklist prepared for each step and applied go/no-go decisions as shown in Table 3.

**Table 3 Gate Review for all the IB LQC process**

| IB frame | Borescope | Strip leak (LQC-2) | Full anode loop leak (Spec < 300) | Build check list |
|---|---|---|---|---|
| AMIB-G0-001 | O | O | 35.20 | 2-Jun |
| AMIB-G0-002 | O | O | 66.03 | 11-May |
| AMIB-G0-003 | O | O | 27.65 | 5-Jun |
| AMIB-G0-004 | O | O | 30.23 | 4-Jun |
| AMIB-G0-005 | O | O | 46.64 | 24-Jun |
| AMIB-G0-006 | O | O | 33.19 | 16-Jun |
| AMIB-G0-007 | O | O | 46.04 | 21-Jun |
| AMIB-G0-008 | O | O | 50.37 | 3-Jul |
| QFIB-G0-001 | O | O | 59.40 | 11-Jun |
| QFIB-G0-002 | O | O | 30.00 | 9-Jun |
| QFIB-G0-003 | O | O | 45.31 | 31-Aug |
| QFIB-G0-004 | O | O | 47.40 | 3-Jul |
| QFIB-G0-005 | O | O | 33.40 | 5-Jul |
| QFIB-G0-006 | O | O | 38.65 | 31-Aug |

In case of the IB frame, vender inspection checklists were set up and reviewed upon receipt of frames, see
Figure **12**. Other critical part vendors followed similar processes.

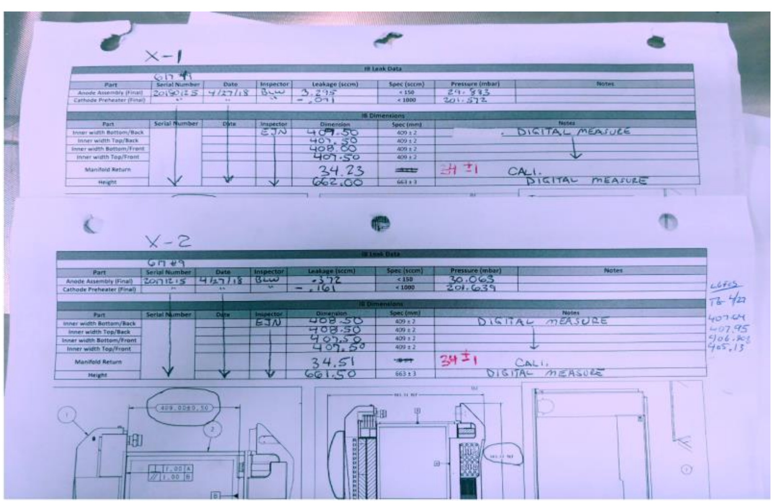



**Figure 12 IB inspection sheets from vender**

**Out-going Quality Control**: After completing the strips and IBs, out-going inspection was performed. When the strips and IBs passed the inspection, they moved to the next stage. For the strips, 14 steps of out-going inspections were performed as shown in Table 4.

**Table 4 Strip out-going inspection table**

| NO | Items | Total Counts | Completion % of 60 Strips | Completion % of 70 Strips |
|---|---|---|---|---|
| 1 | **Pre-Leak** | **70** | **116.7%** | **100.0%** |
| 2 | **Pre-pressure drop** | **70** | **116.7%** | **100.0%** |
| 3 | **SPOT** | **70** | **116.7%** | **100.0%** |
| 4 | **Post Leak** | **70** | **116.7%** | **100.0%** |
| 5 | **Post-pressure drop** | **70** | **116.7%** | **100.0%** |
| 6 | **Dimensions** | **70** | **116.7%** | **100.0%** |
| 7 | **Dye Pen** | **70** | **116.7%** | **100.0%** |
| 8 | **Cracks Measured** | **63** | **105.0%** | **90.0%** |
| 9 | **Video mapping** | **70** | **116.7%** | **100.0%** |
| 10 | **Inspection Sheet** | **70** | **116.7%** | **100.0%** |
| 11 | **Visual** | **70** | **116.7%** | **100.0%** |
| 12 | **Manager** | **70** | **116.7%** | **100.0%** |
| 13 | **Packed** | **70** | **116.7%** | **100.0%** |
| 14 | **Shipped** | **70** | **116.7%** | **100.0%** |

All the data was managed by statistical quality control process. Strip leakage and ASR were significantly improved compare to the Prototype A technology demonstrator (PT-A) strips as shown in Figure 13. PT-A was a technology demonstrator what had the same configuration as GEN0.

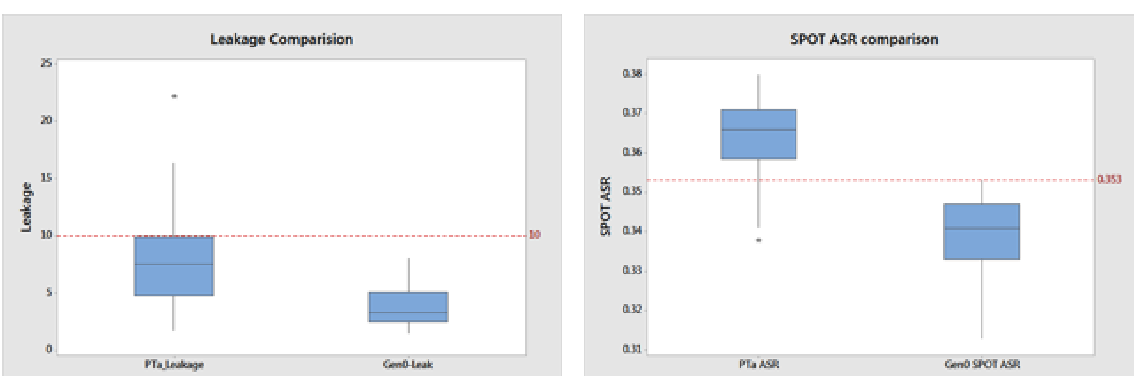



**Figure 13 Strip Leakage and ASR comparison**

For the IB's, fuel loop and air loop leakage and flow were checked. Figure 14 showed the flow test concepts.

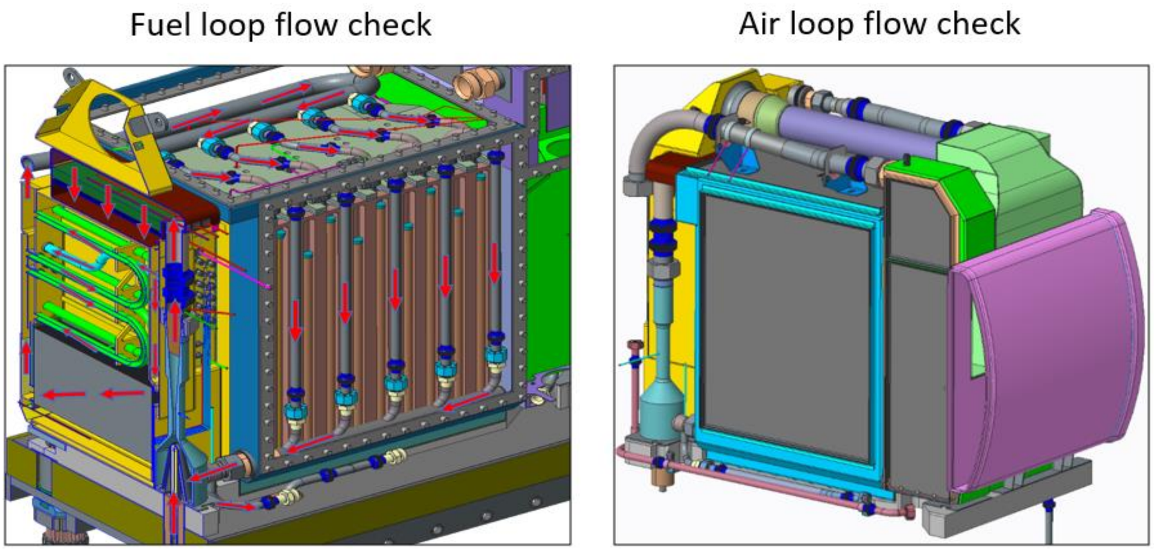



**Figure 14 IB Flow check concepts**

In terms of the IB fuel loop leakage, the results were significantly improved compared to the PT-A IBs as shown in Figure 15.

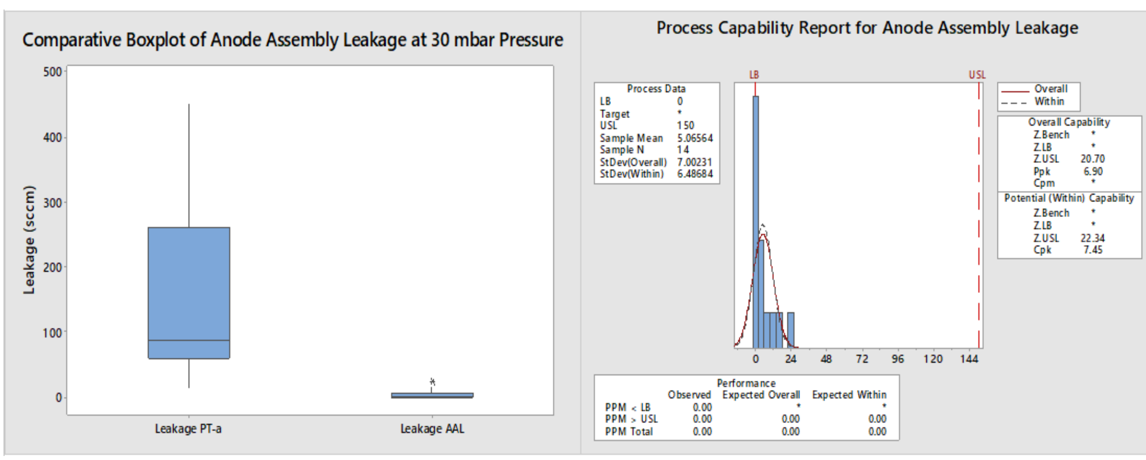



**Figure 15 IB Leakage comparison and capability**

### 3.1 Assemble Fuel Cell Strips

The fuel cell tubes will be inspected using existing procedures to assure specifications have been met. Fuel cell strips will then be constructed using established manufacturing Work Instructions. The strips will be thoroughly inspected and tested before being released for FCV

Assembly. Inspections include leakage, pressure drop to confirm flow characteristics, and dimensional checks against manufactured specifications. Testing includes continuity checks to insure no short circuits between tubes and a performance test. Following the performance testing, redundant leakage and short-circuit testing is again performed before the strips are released for FCV Assembly.

**Results and Discussion**

After receiving printed tubes from the supplier, incoming inspection is performed on the individual tubes to ensure no cells have short circuits and the tubes have a leakage less than 6 sccm. Once the single tube passes incoming inspection, the tube is then ready for the SIC trace. The SIC trace connects one side of the tube to the other using a Palladium and Glass paste (see Figure 16). This process is done automatically using an automated machine (see Figure 17). These traces are dried for 60 minutes at 120 degrees C and then fired for 120 minutes at 1060 degrees C. After firing, each ink trace is inspected to ensure no cracking is present. If cracking is present, a repair is needed by manually painting more of the Pd glass paste over the crack and refiring at 1060 degrees C. This ensures a uniform resistance and therefore current flow over the ink trace.

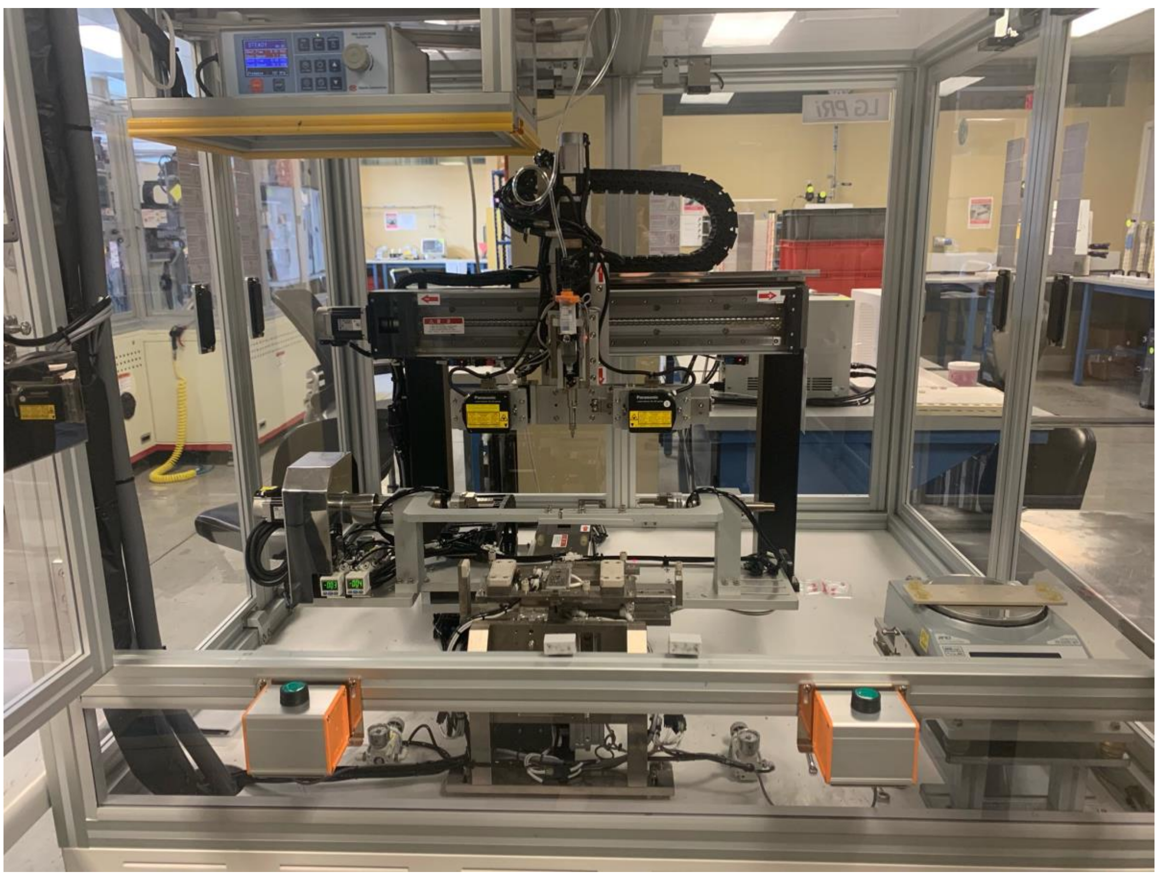


**Figure 16  SIC Trace Automated Machine**

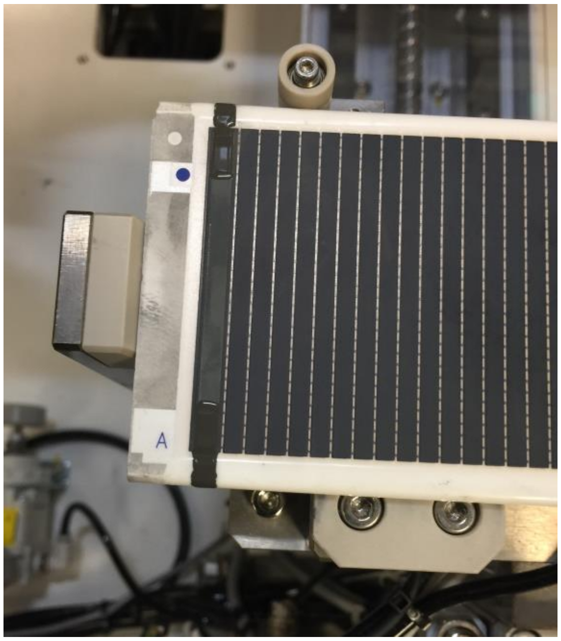



**Figure 17  Wet Ink Trace in Ink Trace Automated Machine**

When all ink traces on one tube passes inspection, SIC wire attachment is the next step in the process. Palladium wire at 0.4mm diameter is cut to 16mm long. Then, additional Pd glass paste is applied manually to each trace. The 16mm long wire is placed on to the paste, then the paste is brushed out to completely cover the wire. This process is repeated 7 times, so that 8 SIC wires are on each tube. These SIC wires are dried for 60 minutes at 120 degrees C and then fired for 120 minutes at 1060 degrees C. After firing, each SIC is inspected to ensure proper adhesion. If adhesion is not adequate, a repair is needed by manually painting more of the Pd glass paste over the SIC wire and refiring at 1060 degrees C.

The completed tubes are then ready for the subassembly process where end caps are bonded to the tubes using a glass paste. This process is done automatically using an automated machine (see Figure 18). Once the end caps are bonded to the tubes, an operator manually smooths out the excess glass using a brush and then dries the subassembly at 120 degrees C for 30 minutes. Once the subassembly is dry, it is fired for 2 hours at 1060 degrees C. The subassembly is then leak checked to ensure the leakage is less than 1 sccm. If the leakage is higher than 1 sccm then it is repaired with additional glass paste and refired at 1060 degrees C. This process is repeated until the subassembly passes leakage (see Figure 19).

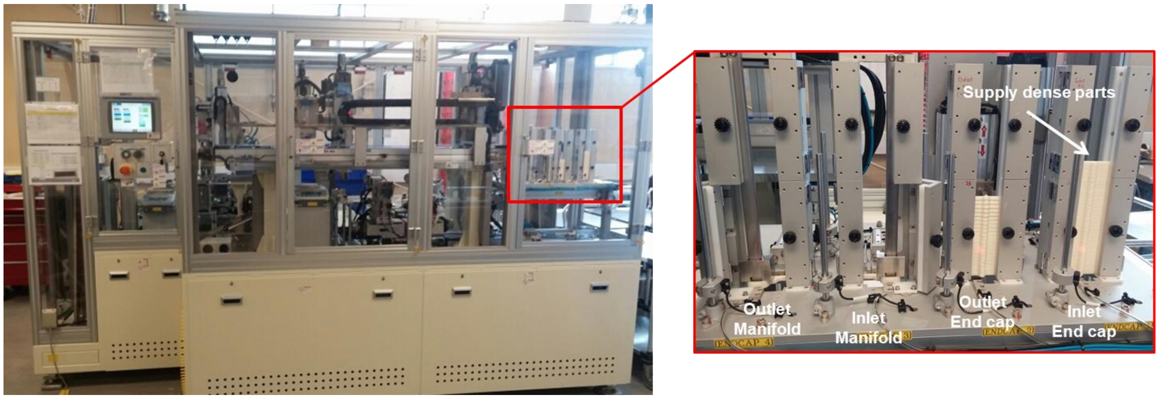



**Figure 18  Subassembly Machine with Dense Parts**

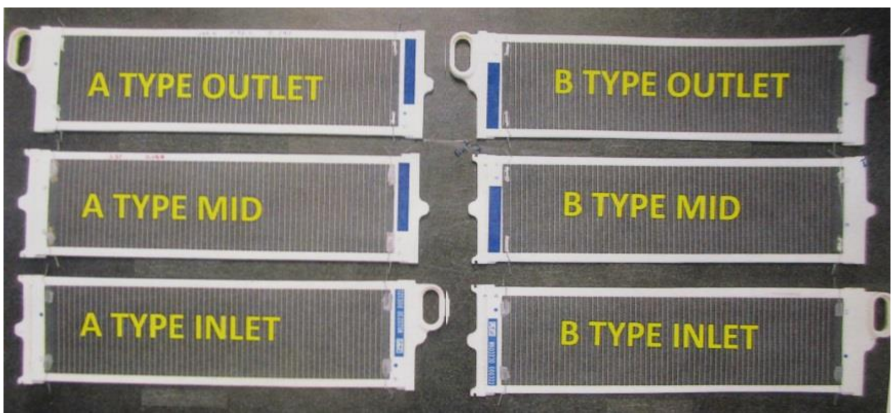



**Figure 19  Completed Subassemblies with Associated Types**

After the subassembly passes leakage it can be built into a bundle. Bundles are 6 subassemblies bundled together using glass tape including an inlet, outlet, and 4 middle subassemblies. Bundles are built manually taking care that the bundle is square before firing. A weight is placed on top of the bundle before firing to ensure the glass tape bonds each subassembly adequately and then it is fired at 1060 degrees C for 2 hours. After firing, the bundle is leak tested. Any bundle with a leakage over 1 sccm is repaired using additional glass paste and refired at 1060 degrees C. This process is repeated until the bundle passes leakage testing (see Figure 20).

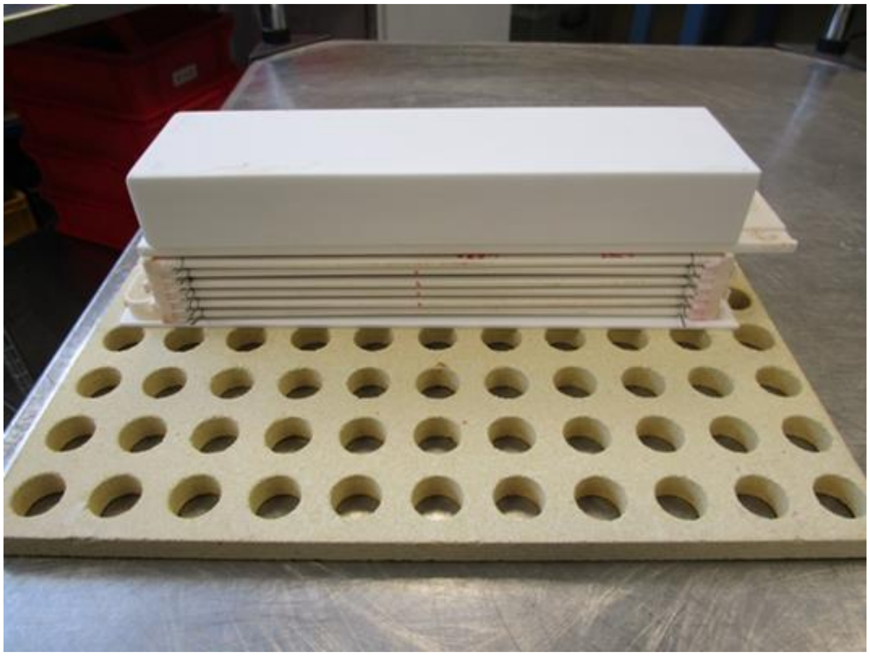


**Figure 20  Finished Bundle with Weight**

Once the bundle passes leakage testing it is inspected dimensionally against strict bundle specifications. If the bundle passes all inspections, the next step in the process is first stage bundle build. A strip consists of 12 bundles connected with fuel pipe connectors and sealed with glass paste and glass tape. A first stage build connects the tops of the 22 fuel pipes with the bottoms of subassembly manifolds. This upside-down method utilizes gravity to let the glass tape seal flow downwards and helps increase strip leakage yield. The first stage strip build is placed into a strip firing furnace and is fired for 2 hours at 1060 degrees C. The strip is then taken apart into individual bundles and is built using the same method but in reverse order. This second stage build seals the bottoms of the fuel pipes with the tops of the subassembly manifolds and thus creating the solid strip. The second stage strip is placed into the strip firing furnace and is fired for 2 hours at 1060 degrees C. The strip is leak tested with a USL of 20 sccm. If the leakage is higher than 20 sccm, it is repaired and refired at 1060 C until it passes leakage testing. Tertiary interconnects are welded into each bundle pair so that each bundle pair is in parallel and the SIC wires are welded so that they are into series. The strip is inspected for continuity, dimensions, and corner cracks using a dye penetrant. After the strip passes all QC inspections, it is reduced to verify the performance meets specification. Once the strip passes all inspections, it is ready for FCV assembly. The finished strips are shown in Figure 21.

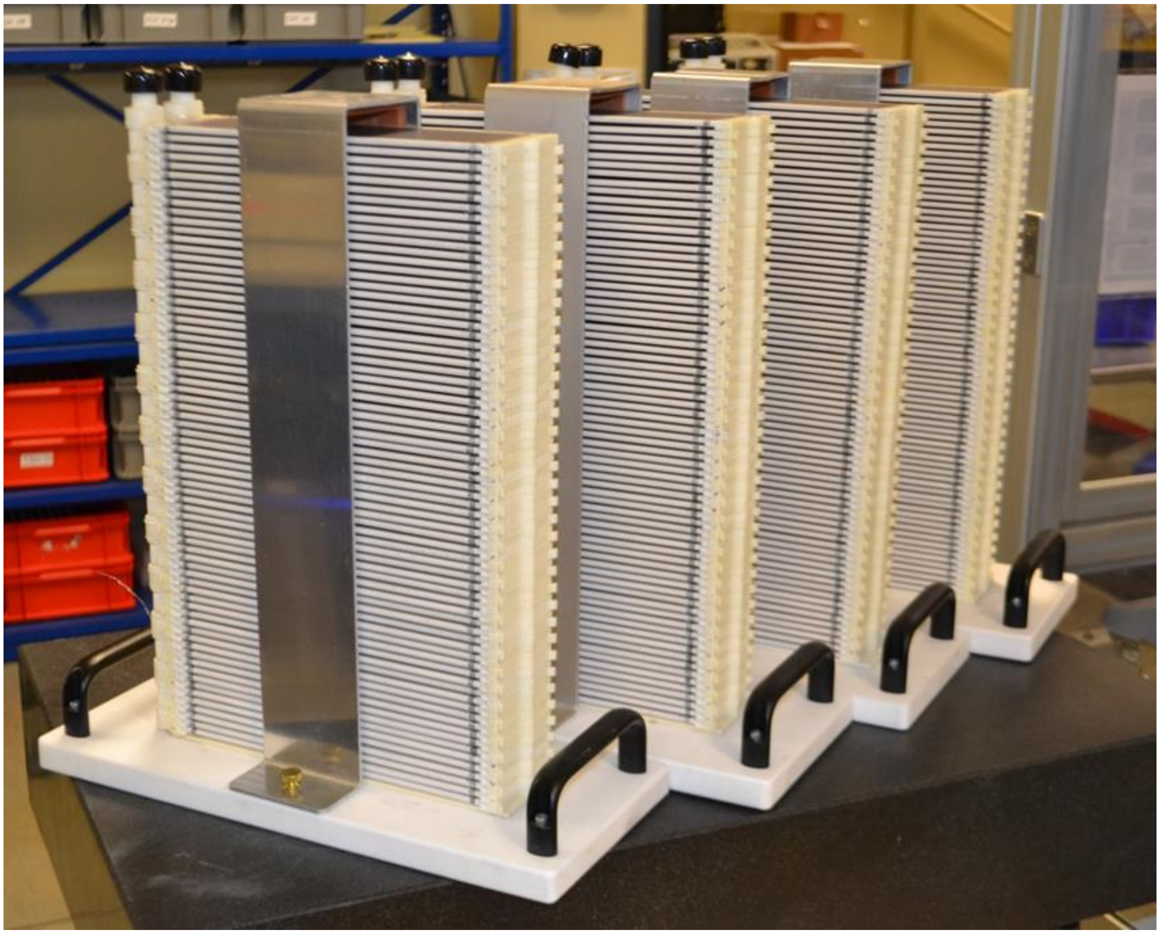


**Figure 21 Fuel Cell Strips Ready for Installation**

### 3.2 Assemble Fuel Cell Vessel

The fuel cell strips will be assembled into IBs, the IBs are then lowered onto a shelf, mated to an adjoining IB, service lines connected, then routed to bulkhead fittings that penetrate the pressure vessel. Quality checks are made to insure electrical and flow continuity, acceptable leak tightness, and functionality of the instrumentation. A pressure vessel shell is then glided over the inner vessel assembly and flanges secured. At this stage, the FCV is complete. Quality checks are again performed to insure leak tightness, electrical continuity and functionality of the instrumentation.

### Results and Discussion

The assembly of twelve (12) integrated blocks and inner vessel segments for GEN0 are complete as shown in Figure 22.

**Figure 22 Integrated Blocks in Inner Vessel Segments**

The assembly of two spare integrated blocks and inner vessel segments for GEN0 were completed. Qualification testing procedures including flow characterization and leakage were also performed. Installation of the inner vessel segments in the Fuel Cell Vessel (FCV) was completed as shown in Figure 23. Qualification testing procedures including instrumentation checks and leakage were performed on the FCV. The FCV was delivered to the test site and installed into the generator module as shown in Figure 24.

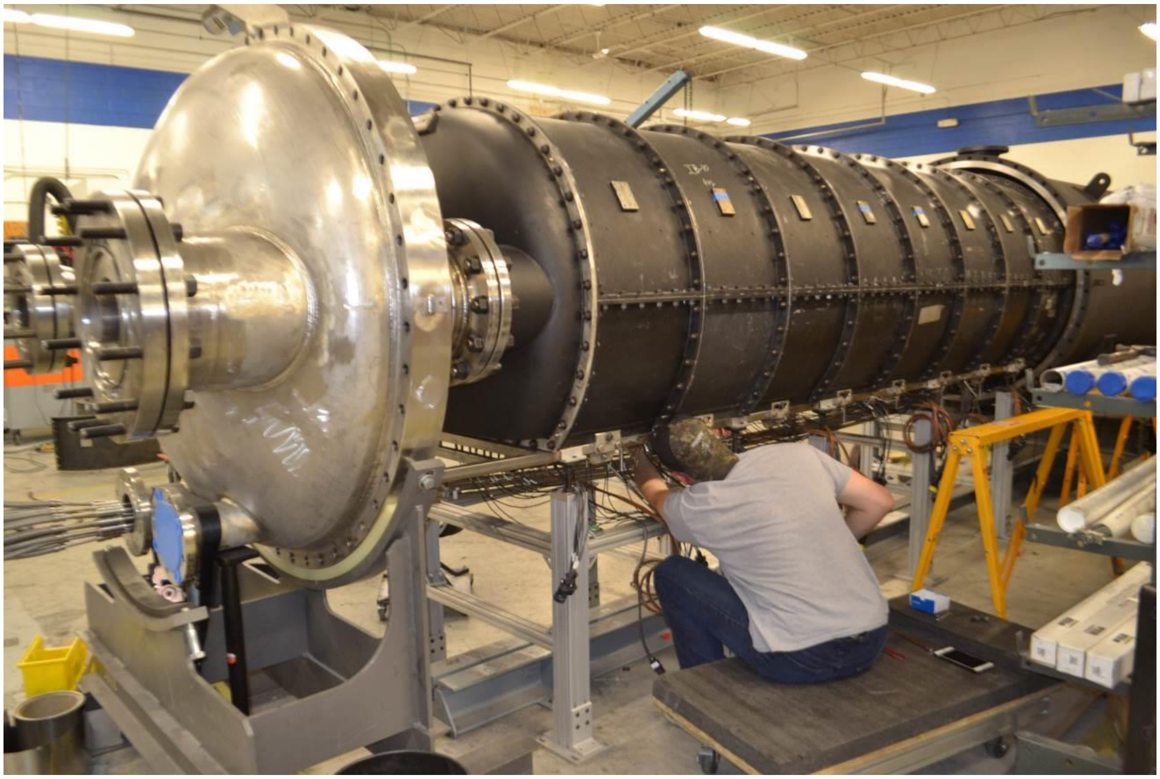


**Figure 23 Inner Vessel Segments Installed in Fuel Cell Vessel**

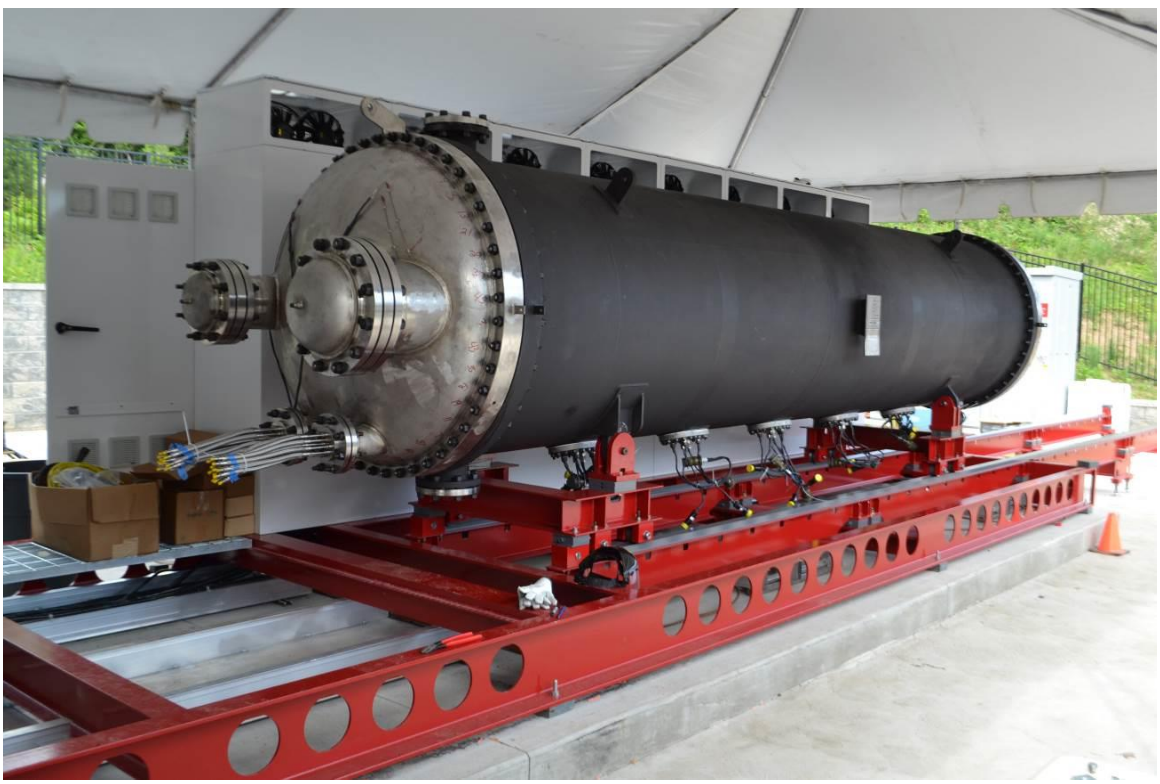


**Figure 24 Fuel Cell Vessel Installed on Generator Module Frame**

Table 5 shows the integrated block part allocation for critical components. Table 6 shows the strip part allocation.

**Table 5 Integrated Block Part Allocation**

| IB # | IB frame | Reformer | Anode | Cathode | Auxiliary |
|---|---|---|---|---|---|
| **IB-1** | AMIB-G0-006 | In617-24 | AEJ-G0-003 | CEJ-G0-008 | XEB-G0-008 |
| **IB-2** | AMIB-G0-002 | In617-6 | AEJ-G0-002 | CEJ-G0-001 (Weld in Whipple) | XEB-G0-002 (Weld in Whipple) |
| **IB-3** | AMIB-G0-001 | In617-4 | AEJ-G0-001 | CEJ-G0-003 | XEB-G0-006 |
| **IB-4** | AMIB-G0-007 | In617-22 | AEJ-G0-008 | CEJ-G0-002 | XEB-G0-009 |
| **IB-5** | AMIB-G0-005 | In617-8 | AEJ-0008 | CEJ-G0-005 | XEB-G0-010 |
| **IB-6** | AMIB-G0-004 | In617-20 | AEJ-G0-005 | CEJ-G0-010 | XEB-G0-005 |
| **IB-7** | QFIB-G0-001 | In617-19 | AEJ-G0-006 | CEJ-G0-011 | XEB-G0-003 |
| **IB-8** | QFIB-G0-002 | In617-9 | AEJ-G0-004 | CEJ-G0-009 | XEB-G0-007 |
| **IB-9** | QFIB-G0-004 | In617-7 | AEJ-G0-011 | CEJ-G0-012 | XEB-G0-011 |
| **IB-10** | QFIB-G0-005 | In617-21 | AEJ-G0-012 | CEJ-G0-013 | XEB-G0-001 |
| **IB-11** | AMIB-G0-003 | In617-18 | AEJ-G0-007 | CEJ-G0-004 | XEB-G0-004 |
| **IB-12** | AMIB-G0-008 | In617-25 | AEJ-G0-010 | CEJ-G0-007 | XEB-G0-012 |

**Table 6 Strip Allocation**

| IB # | IB frame | Strip ID | IB # | IB frame | Strip ID |
|---|---|---|---|---|---|
| **IB-1** | AMIB-G0-006 | KC1707G0000309 | IB-7 | QFIB-G0-001 | KC1706G0000570 |
| | | KC1707G0000665 | | | KC1706G0001988 |
| | | KC1706G0001782 | | | KC1707G0000334 |
| | | KC1707G0000870 | | | KC1707G0000010 |
| | | KC1708G0000151 | | | KC1612P1001312 |
| **IB-2** | AMIB-G0-002 | KC1706G0001646 | IB-8 | QFIB-G0-002 | KC1707G0000856 |
| | | KC1706G0001144 | | | KC1707G0000706 |
| | | KC1706G0000610 | | | KC1706G0001679 |
| | | KC1708G0000057 | | | KC1706G0000411 |
| | | KC1706G0000866 | | | KC1706G0000174 |
| **IB-3** | AMIB-G0-001 | KC1708G0001505 | IB-9 | QFIB-G0-004 | KC1711G0000185 |
| | | KC1706G0001978 | | | KC1708G0000779 |
| | | KC1708G0001089 | | | KC1706G0001163 |
| | | KC1706G0001371 | | | KC1711G0000094 |
| | | KC1706G0000405 | | | KC1708G0000589 |
| **IB-4** | AMIB-G0-007 | KC1708G0001333 | IB-10 | QFIB-G0-005 | KC1711G0000187 |
| | | KC1706G0000340 | | | KC1710G0000395 |
| | | KC1612P1000505 | | | KC1612P1001281 |
| | | KC1706G0000070 | | | KC1708G0000277 |
| | | KC1706G0000543 | | | KC1707G0000838 |
| **IB-5** | AMIB-G0-005 | KC1707G0000358 | IB-11 | AMIB-G0-003 | KC1710G0000416 |
| | | KC1706G0001493 | | | KC1706G0001960 |
| | | KC1708G0000533 | | | KC1706G0001764 |
| | | KC1706G0001762 | | | KC1707G0000497 |
| | | KC1707G0000908 | | | KC1706G0000242 |
| **IB-6** | AMIB-G0-004 | KC1704P1000123 | IB-12 | AMIB-G0-008 | KC1710G0000098 |
| | | KC1707G0000909 | | | KC1707G0000296 |
| | | KC1703P1000377 | | | KC1711G0000147 |
| | | KC1707G0000190 | | | KC1612P1000660 |
| | | KC1706G0000316 | | | KC1708G0001480 |

Table 7 shows the full anode loop leakage. This leak test is performed at 30 mbar. The highest full anode loop leakage being ~66 sccm. This value is significantly better than previous IB assemblies. The IB frames from PT-A had an average leakage of ~250 sccm.

**Table 7 Full Anode Loop Leakage**

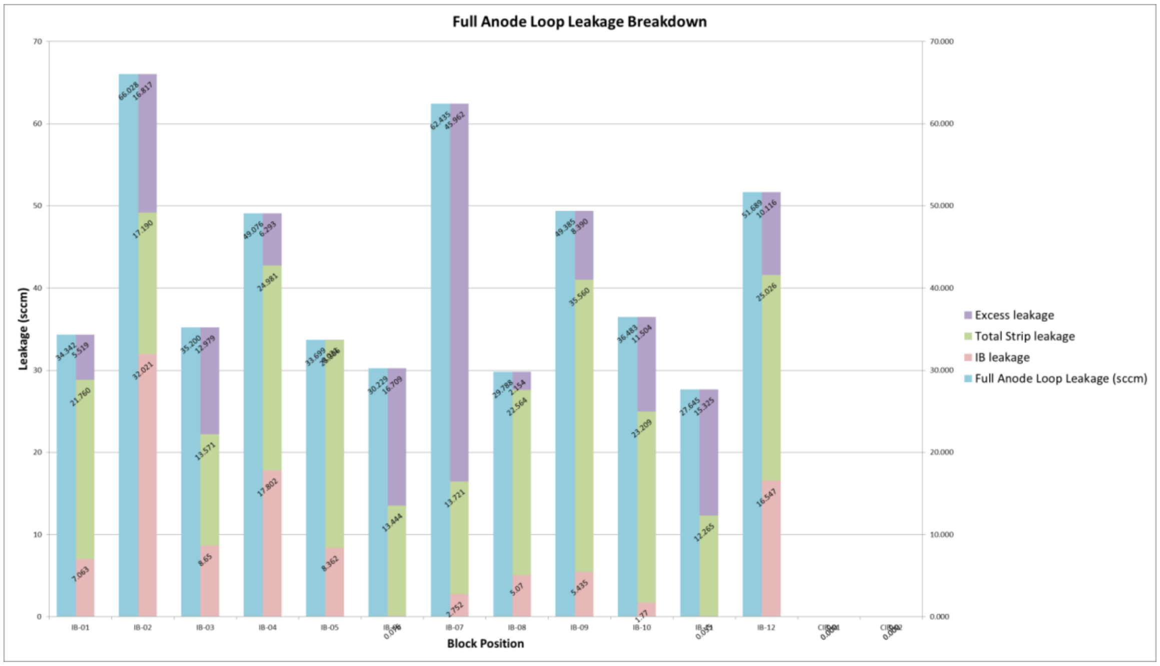
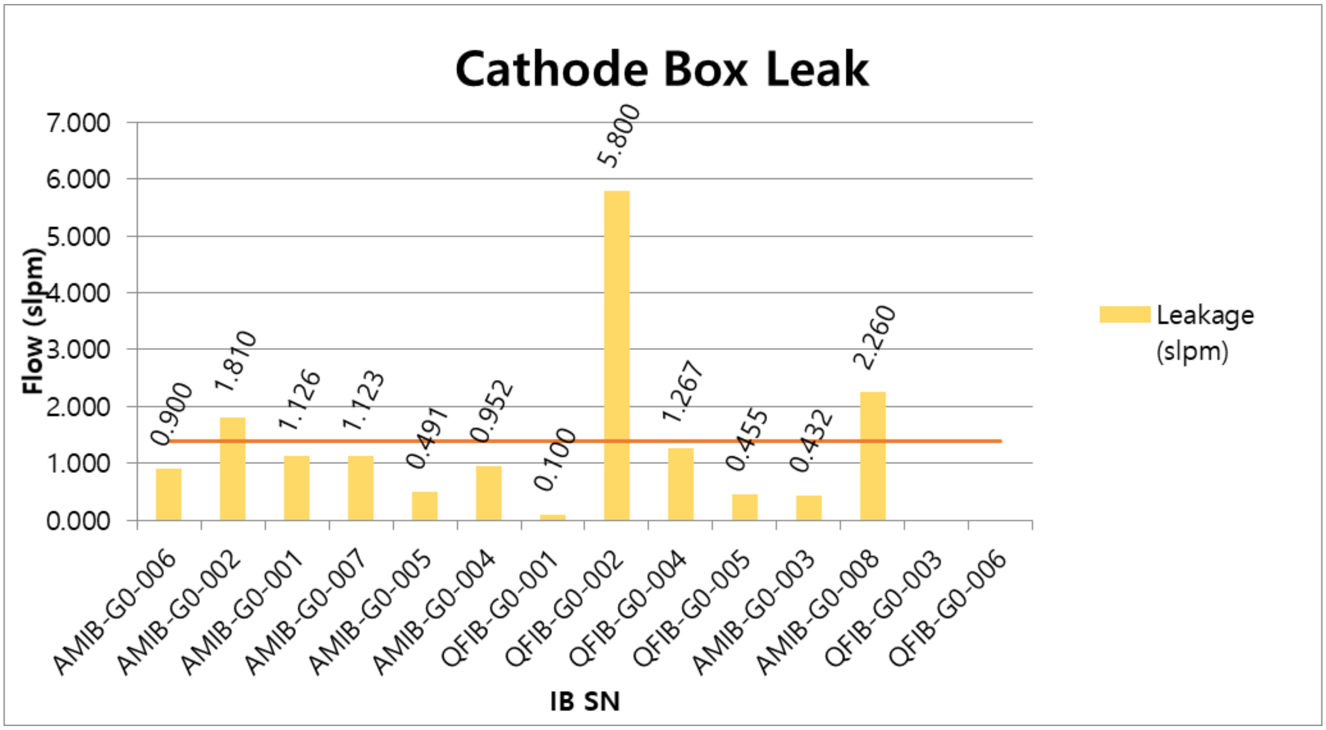



Table 8 shows the cathode loop leakage. The outlier in QFIB-G0-002, or IB-08, has a higher leakage due to a manufacturing error with the IB frame. When welding the cover plates to the frame, it became apparent that a leak had been formed in a location on the frame that was not accessible for repair in a timely manner. It was determined that this leakage would be allowed as tearing apart the entire IB would have been a setback worth several days of work. The leakage is still within spec (7 slpm @ 3 mbar), so the outlier should have no significant negative impact in the performance of Gen0. Even with this single outlier, these cathode loop results are still significantly better than the results from previous IB assemblies.

**Table 8 Cathode Loop Leakage**



Cathode Box Leak
7.000
6.000
5.000
4.000
3.000
2.000
1.000
0.000
Flow (slpm)
0.900
1.810
1.126
1.123
0.491
0.952
0.100
5.800
1.267
0.455
0.432
2.260
AMIB-G0-006
AMIB-G0-002
AMIB-G0-001
AMIB-G0-007
AMIB-G0-005
AMIB-G0-004
QFIB-G0-001
QFIB-G0-002
QFIB-G0-004
QFIB-G0-005
AMIB-G0-003
AMIB-G0-008
QFIB-G0-003
QFIB-G0-006
IB SN
Leakage (slpm)

Table **9** shows the individual Inner Vessel segment vacuum leak checks. See Figure 22. The inner vessel is at a lower pressure than the outer vessel. So, this test is done with a 500-mbar vacuum. The results show the pressure increase over 10 minutes. The limit is 100 mbar. Again, these results are much better than PT-A which had a limit of 200 mbar over 10 minutes.

**Table 9 IV Vacuum Leak Checks**

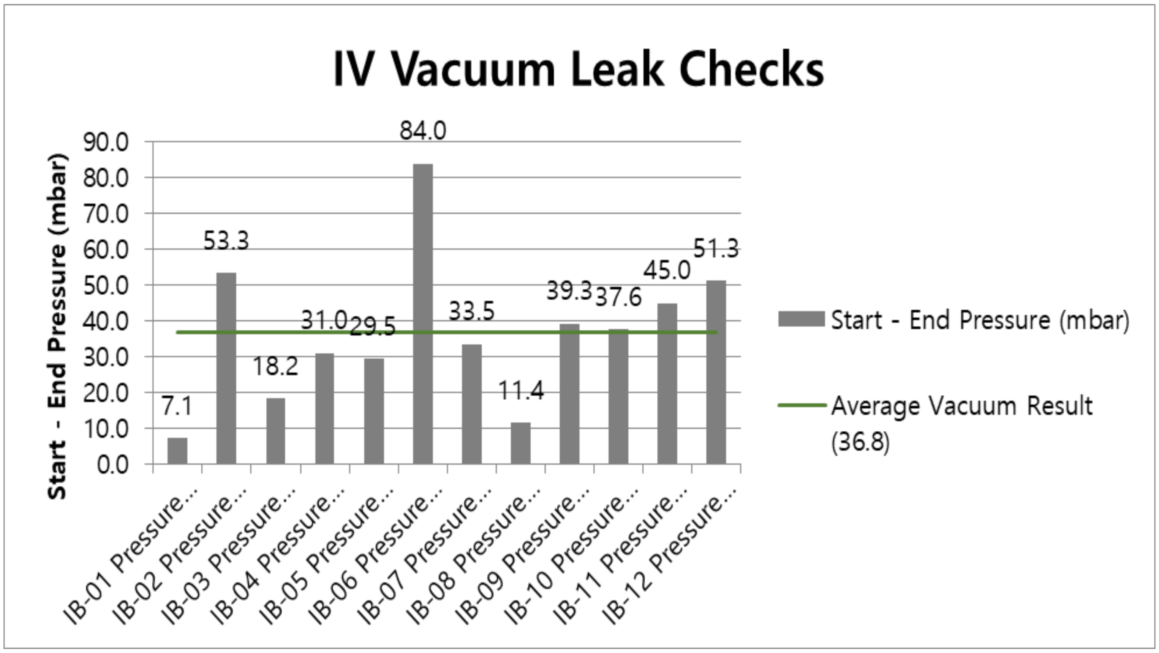



Table 10 shows the Inner Vessel Assembly vacuum leak check. See Figure 23. The inner vessel is at a lower pressure than the outer vessel. So, this test is done with a 500-mbar vacuum. The results show the pressure increase over 10 minutes. The limit is 100 mbar.

**Table 10 Whole IV Vacuum Check**

| Gen0 Inner Vessel Vacuum Check | | | |
|---|---|---|---|
| **Time (min)** | **Pressure (mbar)** | **Who** | **Date Completed** |
| 0 | 504 | SPK/DS | 7/7/2018 3:41 PM |
| 2 | 502.6 | | |
| 4 | 501.3 | | |
| 6 | 500 | | |
| 8 | 498.7 | | |
| 10 | 497.3 | | |

| | | |
|---|---|---|
| **Start Pressure - End Pressure (mbar):** | 6.7 | **Start - End Pressure must be less than 100** |

Table 11 shows the whole pressure vessel leak check. See Figure 24. The whole pressure vessel check is completed after the OPV shell has been fully installed over the IV and all flanges have been installed and torqued as per their specification. It tests the pressure drop starting at 1000 mbar over 30 minutes with a limit of 10 mbar.

**Table 11 Whole Vessel Pressure Check**

| Gen0 Whole Vessel Pressure Check | | | |
|---|---|---|---|
| **Time (min)** | **Pressure (mbar)** | **Who** | **Date Completed** |
| 0 | 1002.5 | SPK | 7/11/2018 2:45 PM |
| 30 | 1002.4 | | |

| | | |
|---|---|---|
| **Start Pressure - End Pressure (mbar):** | 0.1 | **Start - End Pressure must be less than 10** |

## Task 4.0 – System Assembly

The purpose of this task is to assemble the Generator Module and BOP Packages, and to install and interconnect the Packages at the test site. The proposed SOFC Power System for demonstrating commercial readiness will be comprised of stand-alone “Packages” for the Generator Module, Fuel Processing, and Power Electronics. The Packages will be interconnected at the test site to form an integrated SOFC Power System.

### 4.1 Assemble Generator Module Package

The Recipient will assemble the FCV and the Turbo-Generator Assembly (TGA) into an enclosure that will constitute a 250kW Generator Module (GM) Package. The enclosure will contain features and functionality to facilitate the installation and removal of the FCV and/or TGA subsystems, as well as their interconnection. The enclosure will include all the necessary equipment for electrical, instrumentation, and maintenance access to the FCV and TGA subsystems, as well as the required safety and control systems. Appropriate connectors will be provided to interface the GM Package with the BOP Packages. The enclosure for the GM will be assembled and tested at the vendor’s factory to insure the functionality of its supporting systems. Once the enclosure is verified, it will be shipped to the Recipient’s site where the FCV and TGA will be installed to create the GM Package.

**Results and Discussion**

The package layout for the Generator Module is shown in Figure 25. The GM includes the Fuel Cell vessel with 12 integrated blocks incorporated in the inner vessel, the turbo-generator assembly, and the balance of plant equipment (BOP). The BOP includes the power distribution panel, controls and I/O, air conditioning, block power controllers, and fuel control and measurement as shown in Figure 26.

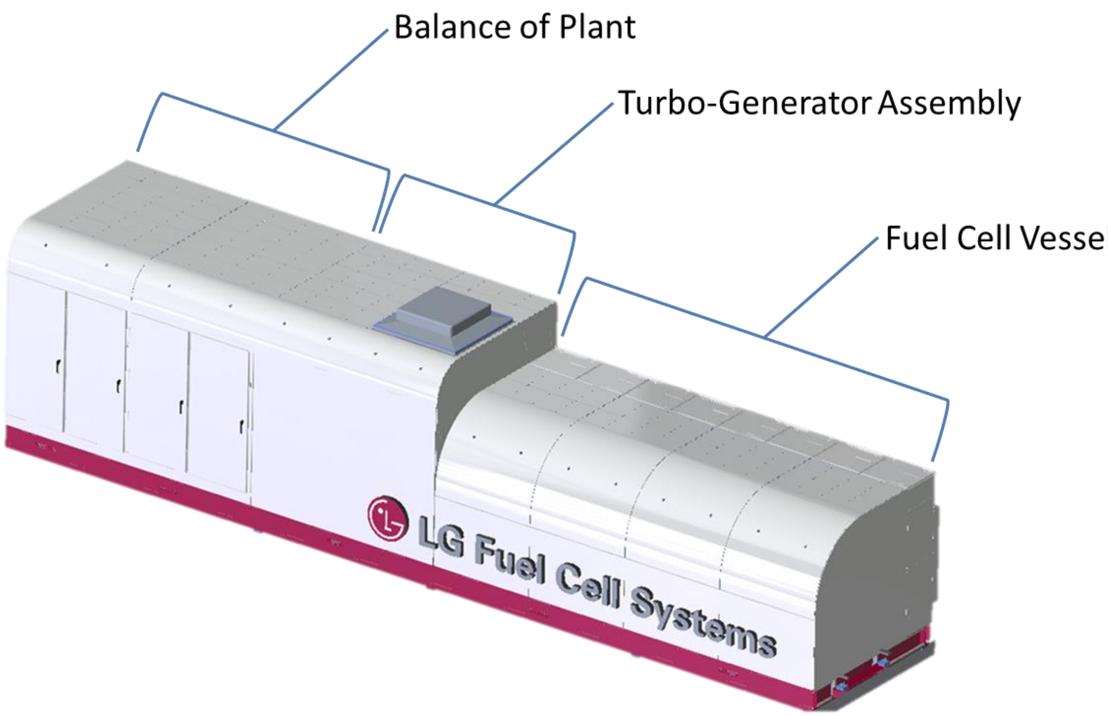



**Figure 25 Generator Module Package**

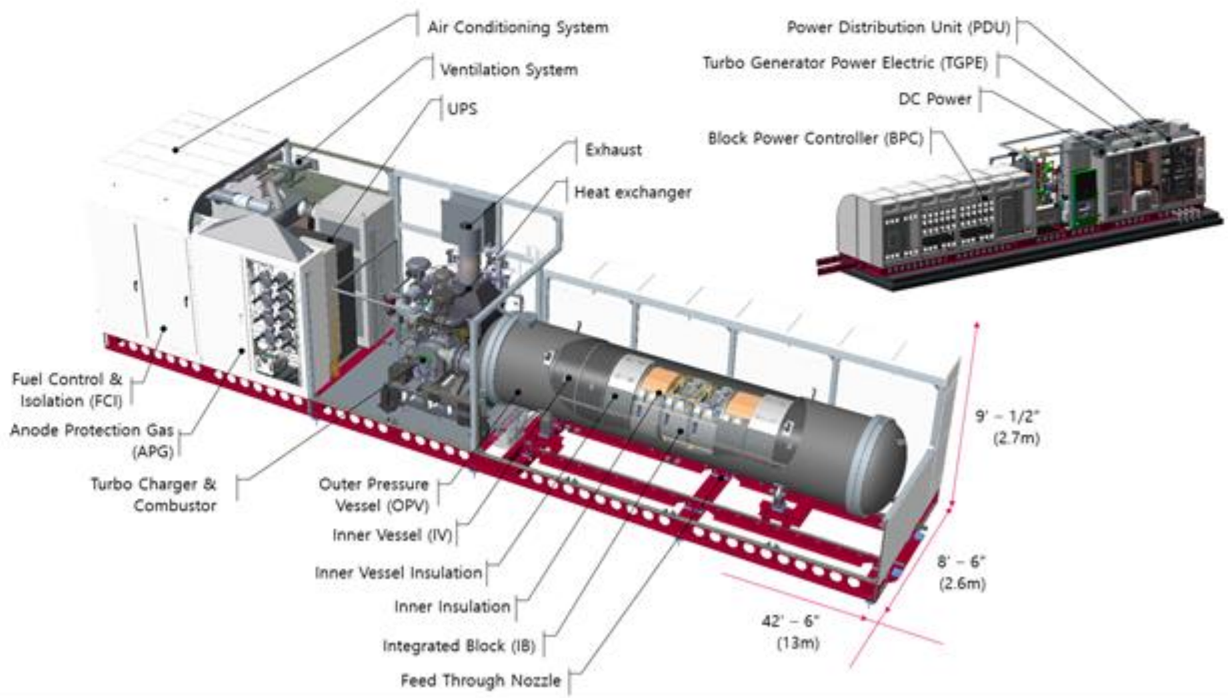



**Figure 26 Generator Module Package Details**

### 4.2 Installation and Interconnection of Power System Modules

The packaged modules of the SOFC Power System will be installed and secured at the test site mutually agreed upon by the Recipient and DOE, interconnected to the adjacent modules, and connected to the site interfaces for pipeline natural gas and the power grid, and data umbilical for controls.

**Results and Discussion**

The Generator Module (GM), Fuel Modules (FM) and Power Electronic Modules have been assembled on the test site as shown in Figure 27.

**Figure 27 GM, FM and PE Modules Assembled on Test Site**

**Power Electronics Package:** The three packages, GM, FM, and PE (PCS) are shown in the electrical system configuration in Figure 28. The GM package electrical BOP is classified into critical BOP, tolerant BOP and non-product BOP depending on operation environments.

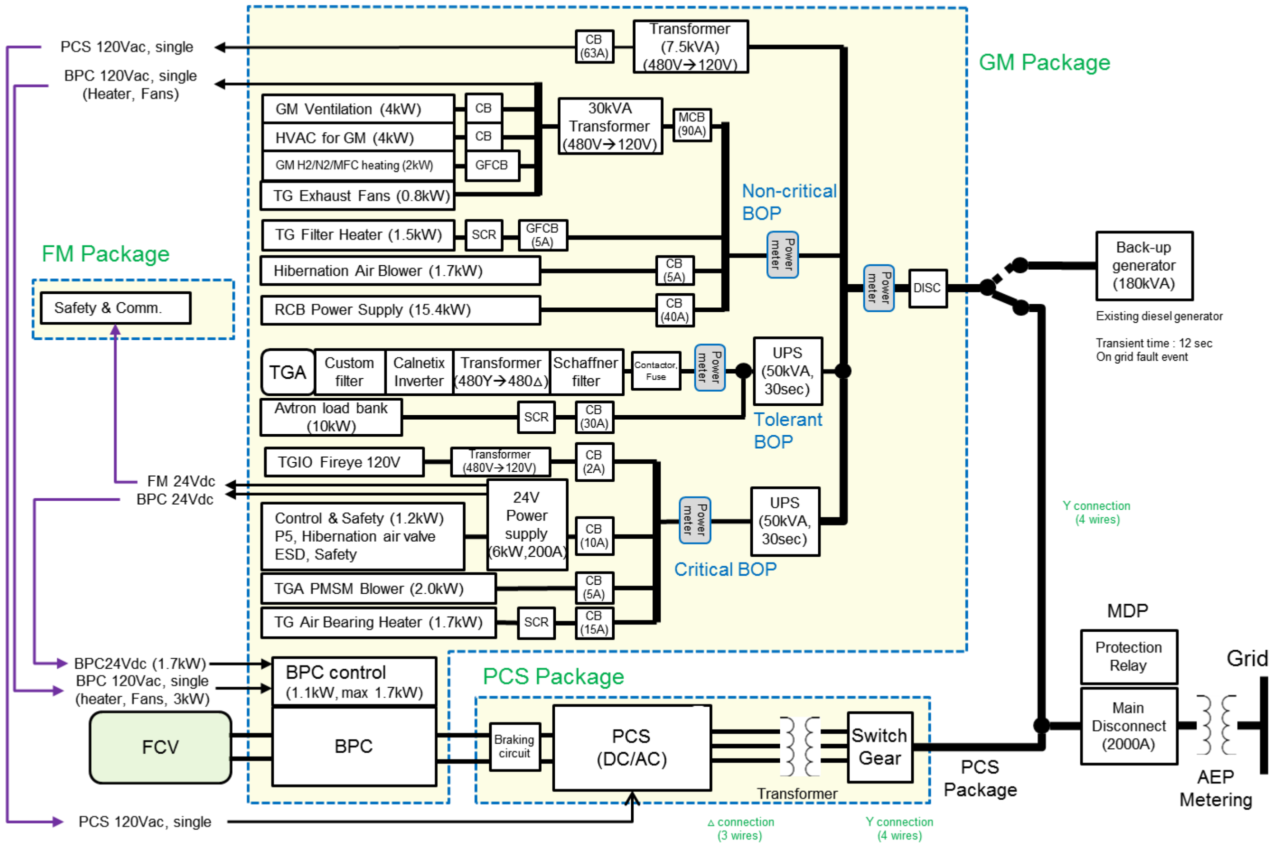



**Figure 28 Electrical Configuration**

The Power Control System (PCS) is required to deliver the DC power generated by fuel cell to AC 480V grid. The PCS package consist of ventilation fans, six inverters, braking resistor, switch gear and control parts as shown Figure 29. Six inverters are connected in parallel and make the maximum power up to 375kVA, braking resistor is added to prevent the DC bus over voltage, switch gear is added to protect the electrical components can be damaged by AC over current and control parts are needed for system control and communication with fuel cell main controller. In addition, a transformer is needed to adjust the voltage ratio, which is 320V:480V.


**Figure 29 PCS package including transformer**

The factory test result for the PCS is good as shown in Figure 30. The PCS was operated up to 375kVA at PF 0.8 and the operating temperature was at most 73℃ (for reference, trip temperature is 120℃)

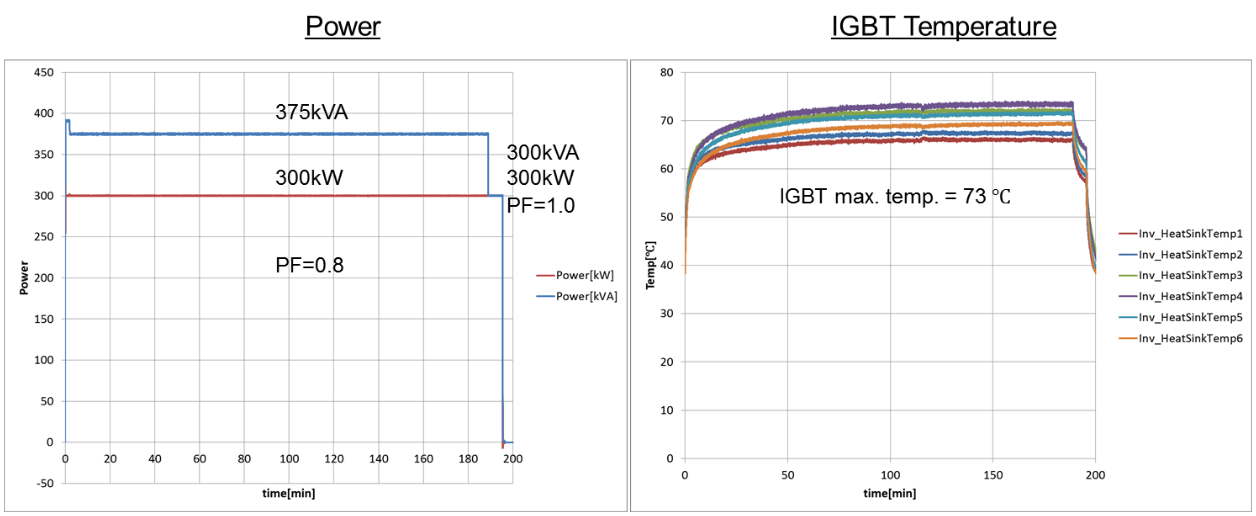



**Figure 30 PCS Test Result**

Other electrical cabinets on the system are shown in Figure 31 and include:

- Block Power Controller (BPC)

- Block Power Master (BPM)
- Turbo Generator Assembly (TGA)
- Turbo Generator Power Electronics (TG PE)
- Generator Module Power Distribution Unit (GM PDU)
- DC Power


**Figure 31 Electrical cabinets in GM package**

The BPC includes a DC/DC converter to control twelves block currents of fuel cell system and measurement parts for sensing temperature, pressure and communication part for communicating with main controller.  The commissioning test result for the BPS' is shown in Figure 32. The BPC and BPM cabinets are as shown in Figure 33.

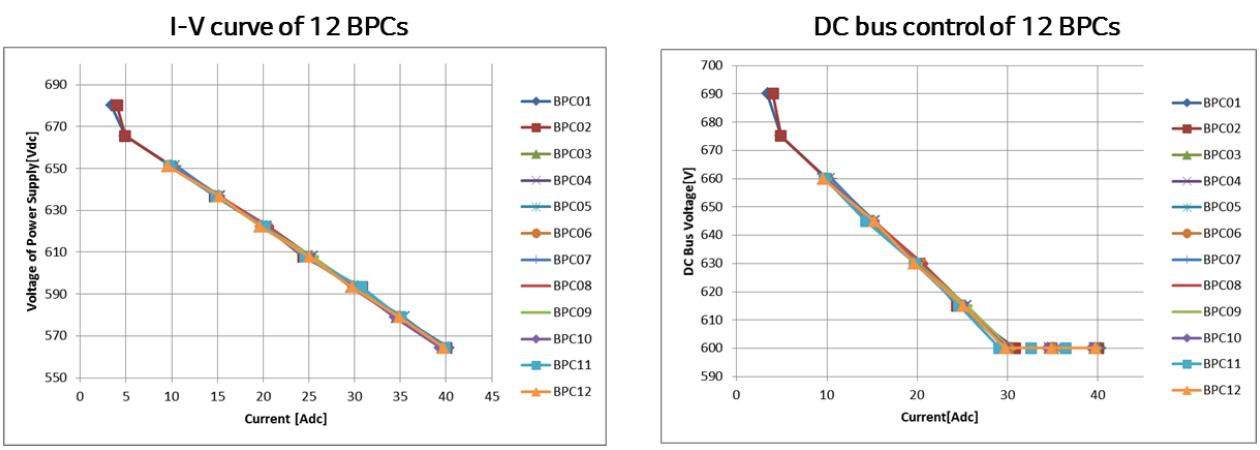



**Figure 32 BPC test result**


**Figure 33 BPC and BPM cabinets in GM package**

The GM PDU and DC Power cabinets are as shown in Figure 34. The TG PE and TGA cabinets are as shown in Figure 35.

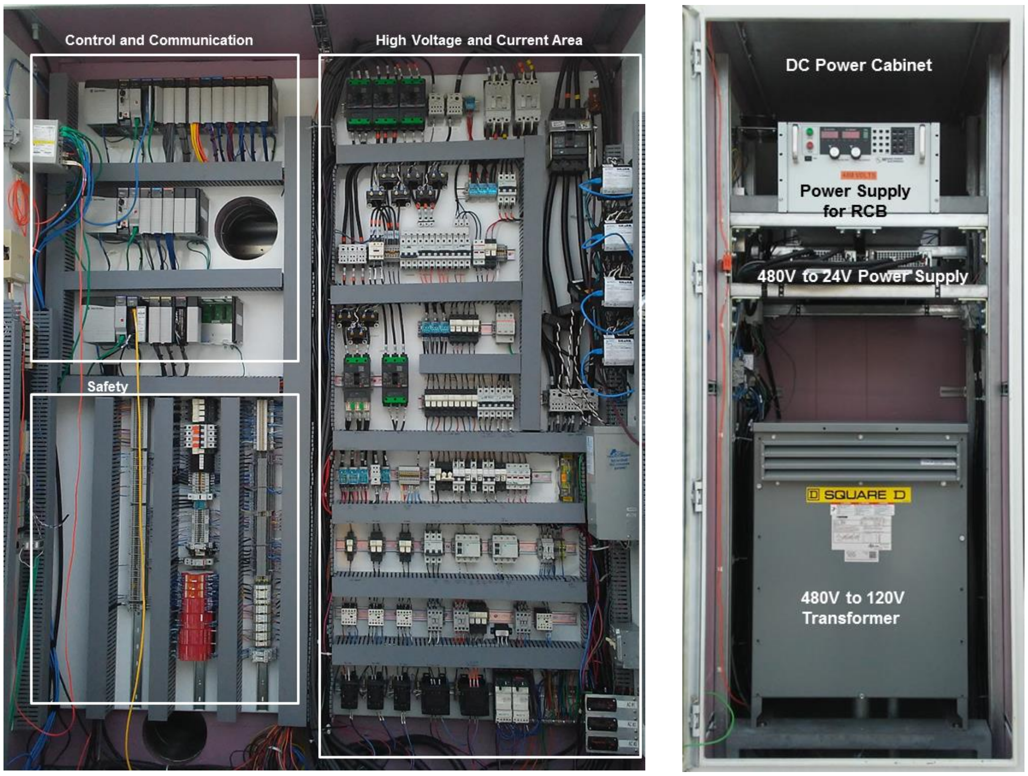



**Figure 34 GM PDU and DC Power cabinets in GM package**


**Figure 35 TG PE and TGA cabinets in GM package**

**Fuel Module Package**: The fuel module primary component is the desulfurizer. A commercial off the shelf unit was purchased for GEN0 as shown in Figure 36.

**Figure 36 Fuel Package Desulfurizer**

# Task 5.0 – SOFC Prototype System Testing

This task supports the labor, fuel and consumable costs for a 5,000-hour test of a 250kW SOFC Prototype at the test. The testing will be preceded by a series of commissioning tests to validate assembly and safe operation of the power system. The SOFC prototype system testing is divided into two subtasks: Commissioning, and Extended System Testing.

## 5.1 Commissioning

Functional commissioning will confirm that the interfaces between the electrical, mechanical, and controls are appropriately connected. The Human Machine Interface (HMI) will be checked to ensure that feedback from the control system can be viewed and managed by operating personnel. Remote monitoring and operation will be verified. Operational commissioning will verify the control and safety systems for plant operations. An initial system test will be performed to validate the automated control and safety system and identify any infant mortality.

## Results and Discussion

Gen0 Commissioning was separated into two main groups: Cold Commissioning and Hot Commissioning. Cold Commissioning was limited to sub-system checks without the use of flammable gases, high temperatures or high pressures. After Cold Commissioning was completed, the operation progressed to Hot Commissioning.

**Cold Commissioning Activities Performed**

- Confirm all hardware and labelling against the P&ID
- Point to Point checks within and between packages
- Megger checks within and between packages
- Confirm input / output signals and do range verifications for GM instrumentation, control modules, etc.
- Test the safety system and all its component software and hardware
- Start-up and confirm operation of package ancillary equipment
- Verify operation of equipment modules
- Verify constants in control software
- Pressurize all supply piping and tubing and perform leak tests
- Calibrate or confirm calibration of all instrumentation across expected operating range
- Perform bench testing of controls sequencer
- Tune acceptable PID Fuel loops via simulation through vents
- Execute pre-test checks lists

**Hot Commissioning Activities Performed**

Once Cold Commissioning was completed, activities proceeded to confirming operation in Hot Commissioning. Activities included:

- Confirm operation of TG and spin TG at low speed
- Perform leak check at low pressure to confirm piping and FCV integrity
- Execute a “GM Protect” and verify that system shuts down properly

- Confirm expected system response during a simulated grid failure
- Perform functional performance tests including cycling the system through all Gen0 Sequencer states

Functional performance of Gen0 was confirmed by cycling the system through the applicable operating states using the automatic control system. Initial operation was in a step-wise mode to verify each segment of the control software. Flow rates, temperatures, pressures, gas compositions, strip currents and strip voltages were measured and compared to system predicted values. System performance was also compared to model predictions and block testing operational data, where applicable.

## 5.2 Extended System Test

The extended system test will commence once commissioning is completed. Once the system achieves stable operation, the exhaust gas will be tested for emissions. Project testing will proceed through 5,000 hours operation at the base load condition. Once the 5,000-hour milestone is achieved, the exhaust emissions will again be tested. A Test Plan will be submitted for approval to the DOE Project Officer 45 days prior to the start of the Extended System Test and testing will be conducted in accordance with a DOE-approved Test Plan.

### Results and Discussion

A detailed system test plan was developed and submitted to DOE in fulfilment of Milestone 6. The system obtained full load operation with pipeline natural gas and power to the grid on September 11th. The completed system is shown in Figure 37.


**Figure 37 LGFCS GEN0 250 KWac Product Demonstrator**

The performance of a fuel cell power system focuses on the power generated, the overall system efficiency and the project life or power degradation rate (increase in system's electrical resistance). The targets for these parameters were 250kWe AC, 60% DC efficiency and 3 milliohms-centimeter squared per thousand hours, respectively.  Also, of interest are the systems gaseous emission. These items, among others, were measured during the Gen0 demonstration test of the LGFCS 250 kWe generator. The details for the system performance area discussed below.

**Health Monitoring System**: The purpose of the health monitoring system (HMS) is to:

- Manage performance variation and reduce risk of system failure
- Detect potential failure and automatically protect the system
- Provide real-time information for manufacturing, assembly and test operators

The health monitoring system overview is shown in Figure 38.

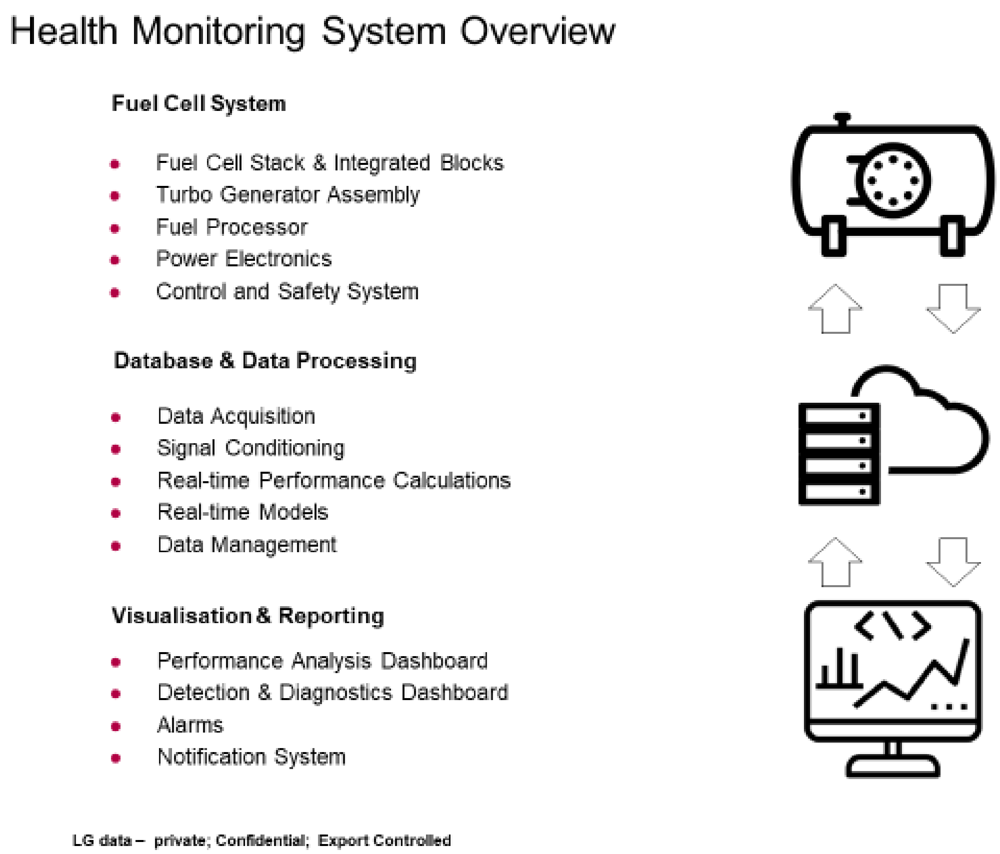



**Figure 38 Health Monitoring System Overview**

The health monitoring system includes many components as shown in Figure 39. Starting with characterization (gray), then data flow (orange) and finally the Gen0 operations (green).

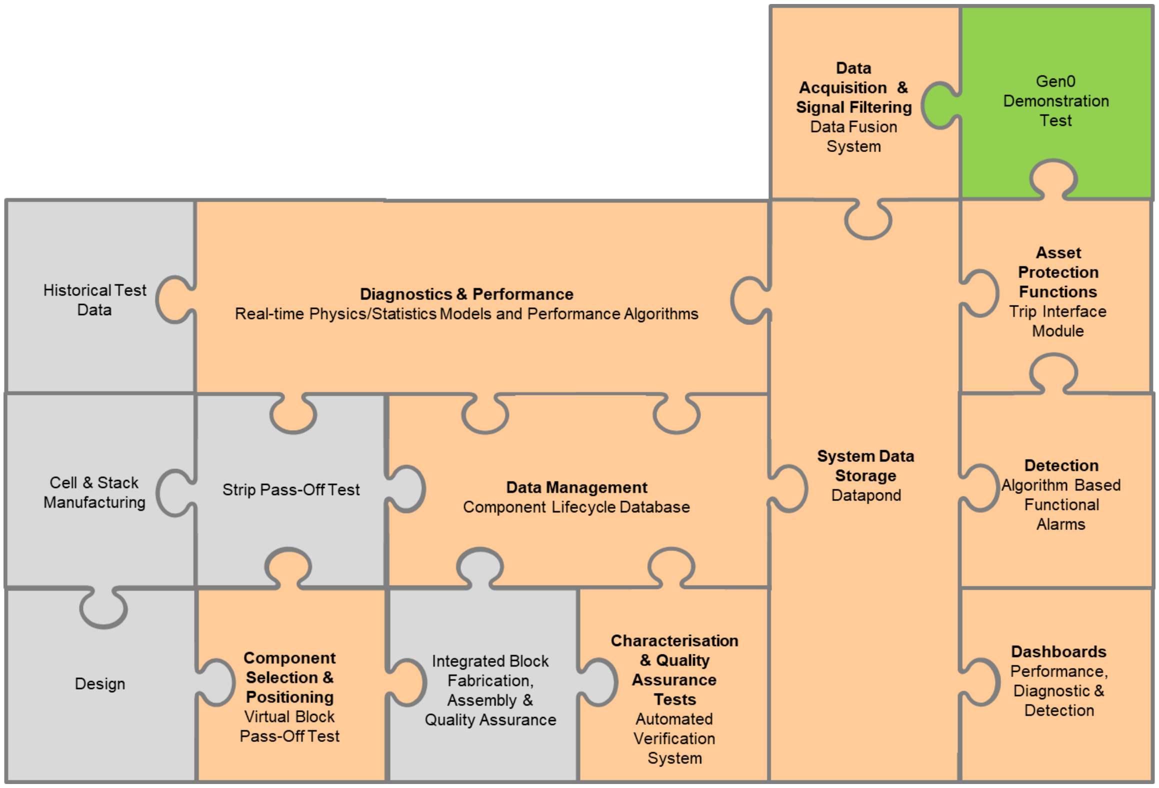



**Figure 39 HMS Components, Characterization (gray), data flow (orange), Operations (green)**

**Component selection and positioning** for the fuel cell strips is based on manufacturing variations with the objective of producing uniform performance as shown in Figure 40.

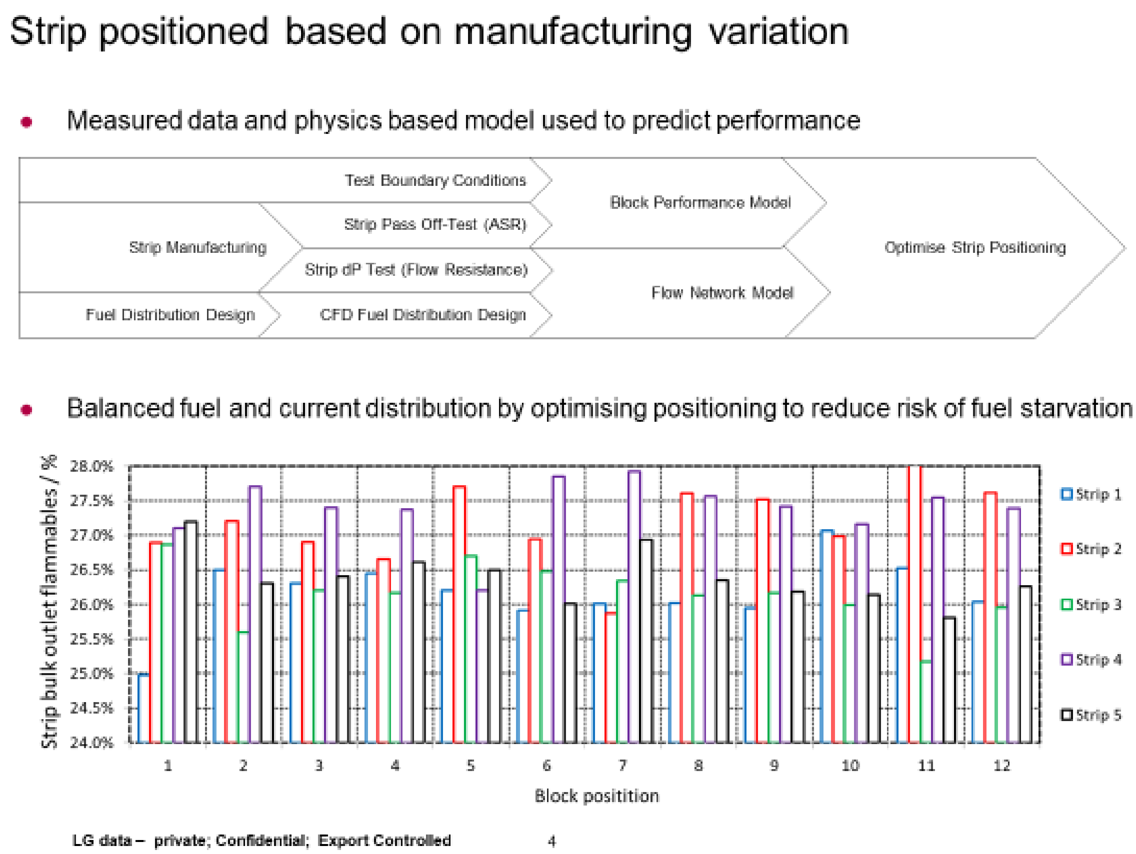



**Figure 40 Component selection and positioning for the fuel cell strips**

**Characterization and quality assurance testing** cover components, assembly and instrumentation within the Integrated Block. Recording of data and pass/fail criteria are built into test and automatically characterized flow resistances are used in real-time model prediction. See Figure 41.

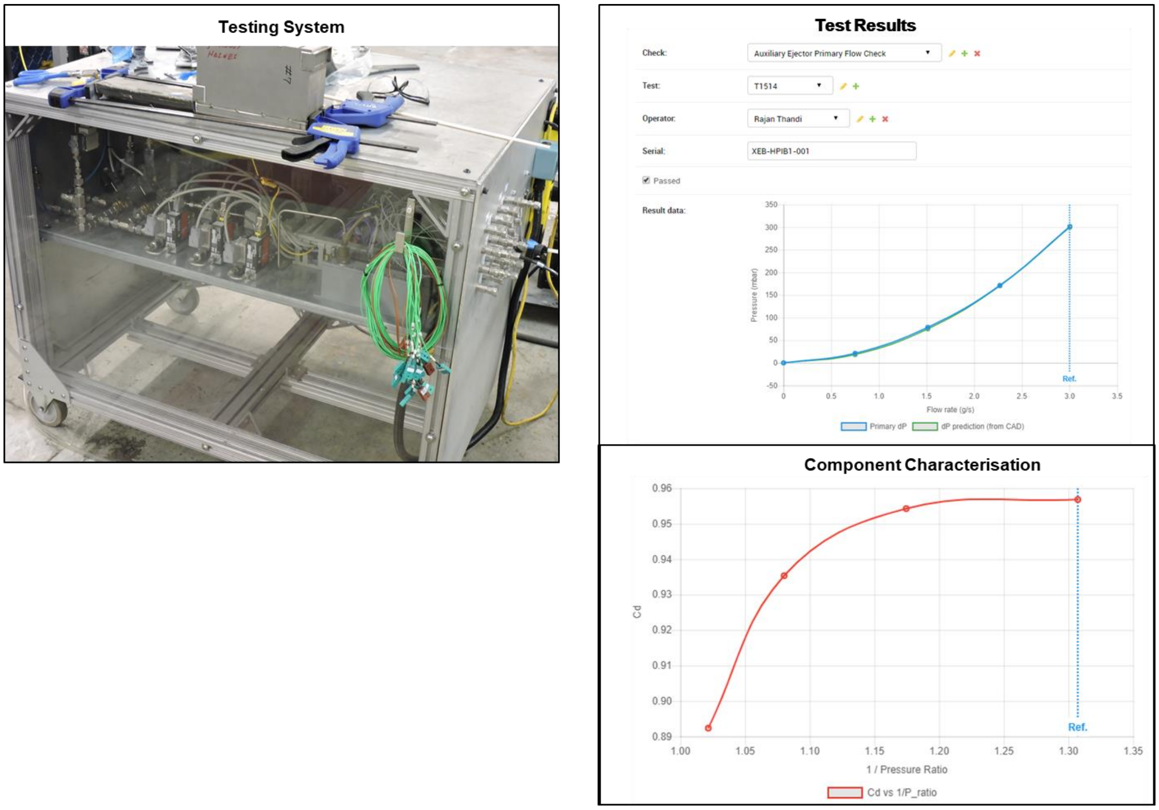



**Figure 41 Component Automated Verification System**

Manufacturing and characterization data is used for **Diagnostics & Performance** as input to Real-time Physics/Statistics Models and Performance Algorithms as shown in Figure 42. These predictions are compared to operating data and used to alarm the system when it is out of range. Once confidence in this system is developed it can be used to adjust controls and turn off the system before damage can occur.

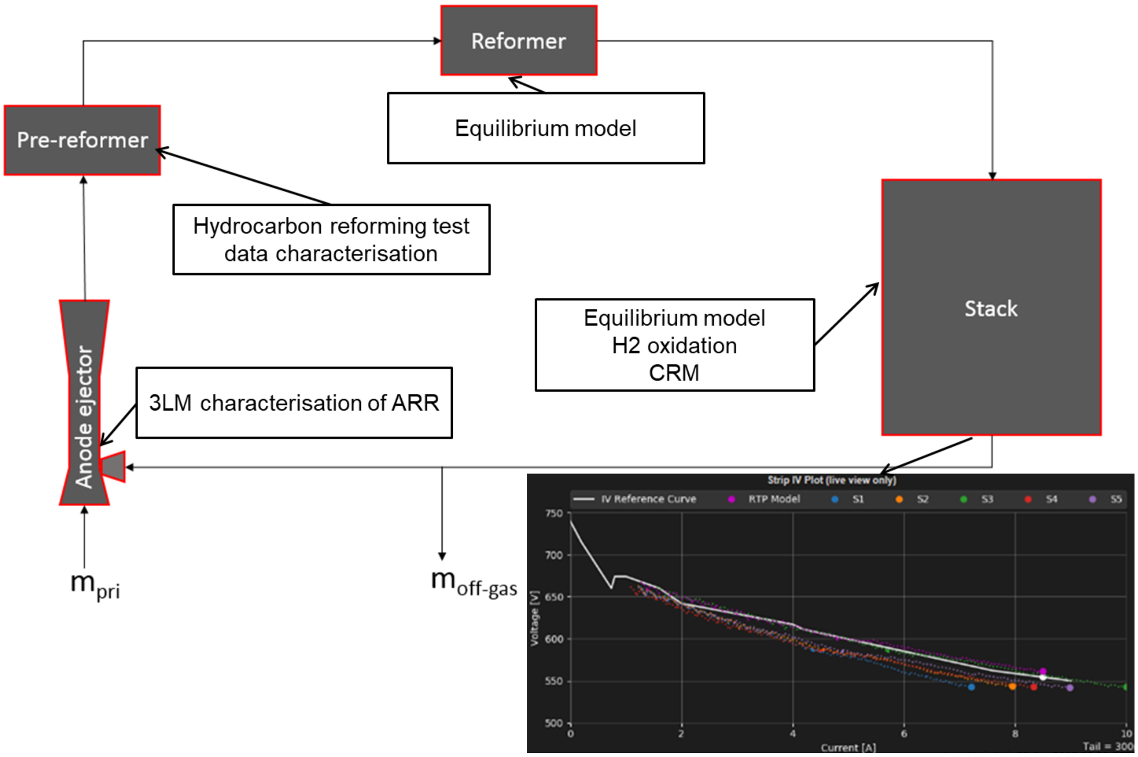



**Figure 42 Real-time physics model fault detection overview**

A web-based **dashboard** is used to display real time data and performance for the system as shown in Figure 43.

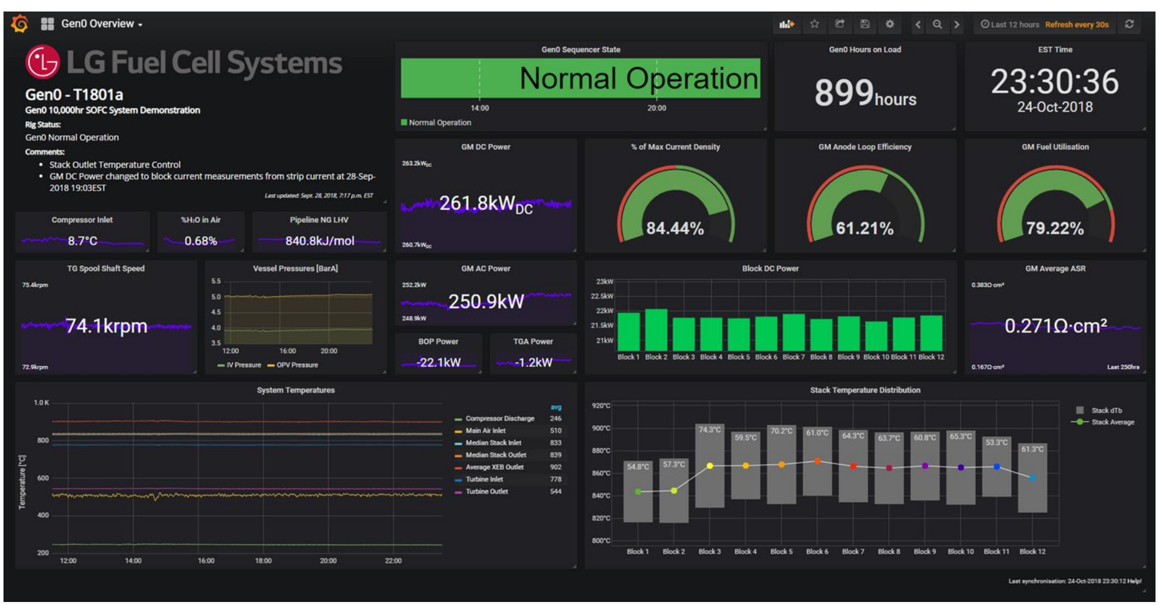



**Figure 43 Real time dashboard**

**System Description**: In 2017 LGFCS initiated work on Gen0, the 250 kW SOFC integrated power system, to demonstrate fuel-in to AC power-out. The system was installed at the LGFCS facility in North Canton, Ohio. The Gen0 system uses the controls architecture of a 1MW SOFC power system. The fuel cell system was designed to operate on pipeline natural gas with its output conditioned for connection to the local utility power grid. The integrated system consists of the Fuel Module (FM), the Generator Module (GM) with fuel cell vessel (FCV) and Compact Turbo Generator Assembly (CTGA), the Power Electronics Module (PE) with Block Power Controllers and Power Conditioning System (PCS) and the Balance-of Plant (BOP) with controls and safety system. The system demonstrated full system operation, from pipeline gas-in to AC power on the grid, as well as gathering data on overall system performance, reliability, and control robustness. The site rendering is shown in Figure 44.

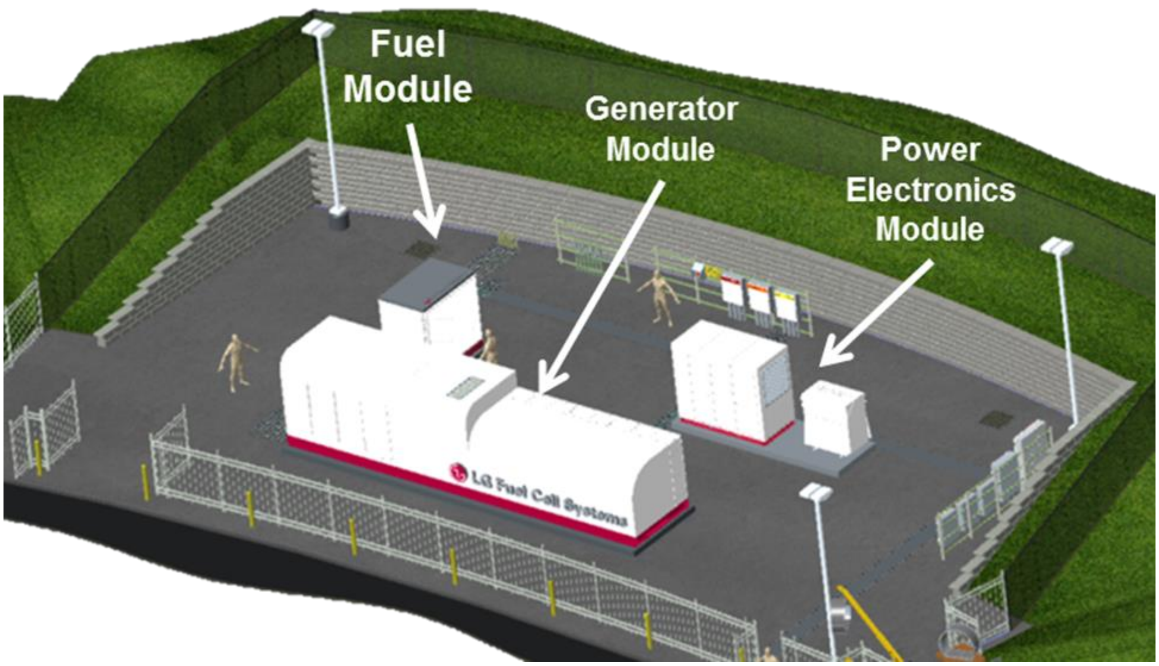



**Figure 44 GEN0 Site Rendering**

Figure 45 shows the process flow diagram. The GM uses air and fuel gas to generate power. The air is supplied from the CTGA while the main fuel gas is supplied from the FM that desulfurizes the pipeline natural gas. Auxiliary Fuel (AF), Anode Protection Gas (APG) and Main Fuel Gas flow from the BOP to the FCV. These gases are distributed to the 12 blocks. The gases are used for heat-up, anode protection, and power generation. The PEM converts the DC power generated by the fuel cells to AC power for export to the local utility grid. Additional details for each subsystem are given below:

- Fuel Module (FM)
    - Passive desulfurizer (DES) sub-system

- Generator Module (GM)
    - CTGA (TG with air bearings)
    - FCV with 12-off Active Integrated Blocks

- Power Electronics Module (PE)
    - Block Power Controllers
    - Inverter (DC to AC)
    - Transformer
- Balance of Plant (BOP)
    - Fuel control
    - Hibernation subsystem with reverse-current-bias
    - Control and Safety System

Each major subsystem (FM, GM, PM) has a software module for controls and safety. The GM Master Sequencer (A.K.A. the Sequencer) controls the interaction of the subsystems via their software modules.

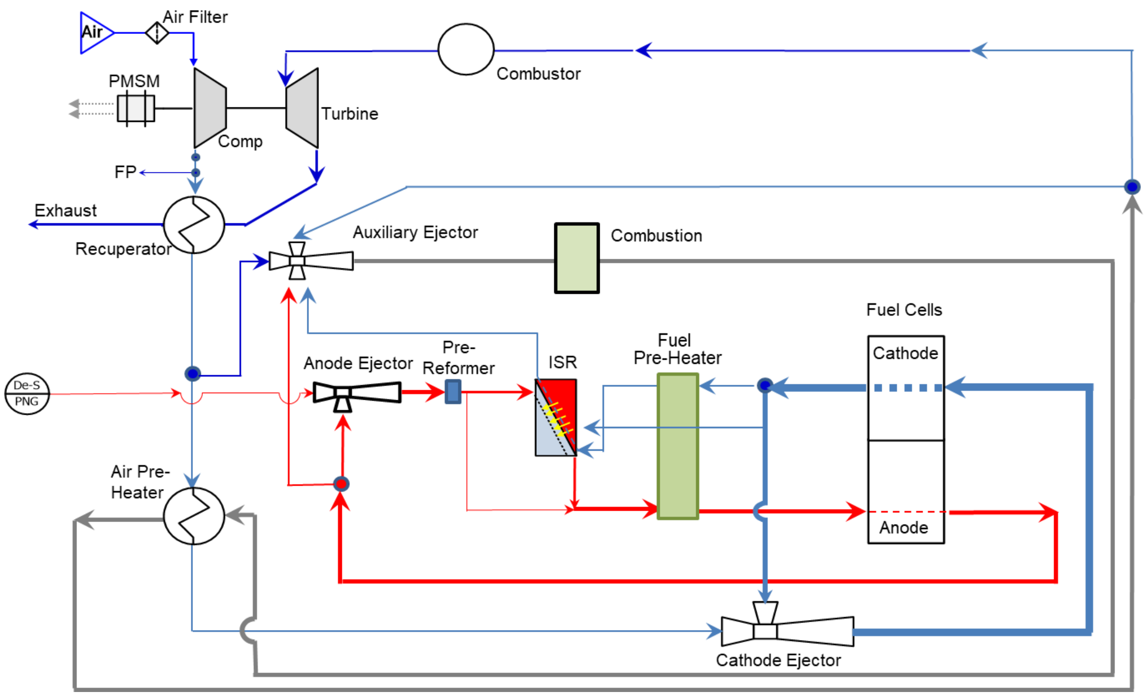



**Figure 45 Process Flow Diagram**

**Operations Log**: The system started on September 11th ,2018. The operations log is shown in Table 12. The utilization is shown in Table 13 for the start of the test and after IB #2 replacement. The system was considered on line when it was delivering over 225 KWac to the grid.

**Table 12 Operations Log**

| *Event* | Date and Time | Description | Time on Line, Hrs | Time Off Line, Hrs | Duration, Hrs |
|---|---|---|---|---|---|
| ***Official Start*** | 11-Sep-18 17:00:00 | | 57 | | 57 |
| ***Stop 1: PE trip*** | 14-Sep-18 02:00:00 | PE Trip due to PCS contactor control error. Adjust control settings and restart. | | 9 | 11 |
| ***Restart*** | 14-Sep-18 12:30:00 | | 24 | | 24 |
| ***Stop 2: IB low voltage*** | 15-Sep-18 12:30:00 | IB #2 showed signs of fuel leakage. Replace IB #2. | | 104 | 104 |
| ***Restart*** | 19-Sep-18 21:00:00 | | 55 | | 55 |
| ***Stop 3: TG trip*** | 22-Sep-18 04:00:00 | TG cooling air supply stoppage. Replace air supply. | | 29 | 30 |
| ***Restart*** | 23-Sep-18 10:00:00 | | 901 | | 901 |
| ***Stop 4: Comms error*** | 30-Oct-18 22:50:00 | Communications overload, operator error. Reset comms | | 32 | 34 |
| ***Restart*** | 01-Nov-18 09:00:00 | | 762 | | 762 |
| ***Stop 5: Instro Trip*** | 03-Dec-18 10:58:00 | System trip during instrument check. | | | |

**Table 13 Utilization**

| | Time on Line, Hrs | Time Off Line, Hrs | Duration, Hrs | Utilization |
|---|---|---|---|---|
| ***Total from Start*** | 1800 | 897 | 1986 | 91% |
| ***Total from IB #2 Replacement*** | 1718 | 784 | 1790 | 96% |

**Pre-Test Expectations:** The expected initial stack performance was based upon pre-test SPOT data for every strip in Gen-0, and a block test of one of the 12 blocks before its installation into Gen-0. The pre-test SPOT data summary is shown in Figure 46 (top chart) which demonstrates an overall average ASR of 0.339 Ω-cm² at 860°C. Note that the ASR in the SPOT test is typically higher than in a block by about 0.05 – 0.06 Ω-cm² because it is run at atmospheric pressure and half load. Based on the SPOT data it is expected that the block ASR would be in the range of 0.28 - 0.29 Ω-cm².

This expected performance was confirmed in Block Test T1613 which placed Gen-0 block IB #2 into the SOFC80 Test Rig for a short duration pass-off test of about 150 hours. The strip ASRs at 860°C were 0.285 Ω-cm² after 100 hours on load.

Actual GEN0 performance at 111 hours on load is shown in Figure 46 (bottom chart) with an average ASR of 0.276 Ω-cm² at 861.2°C, or approximately 0.29 Ω-cm² adjusted to 860°C.

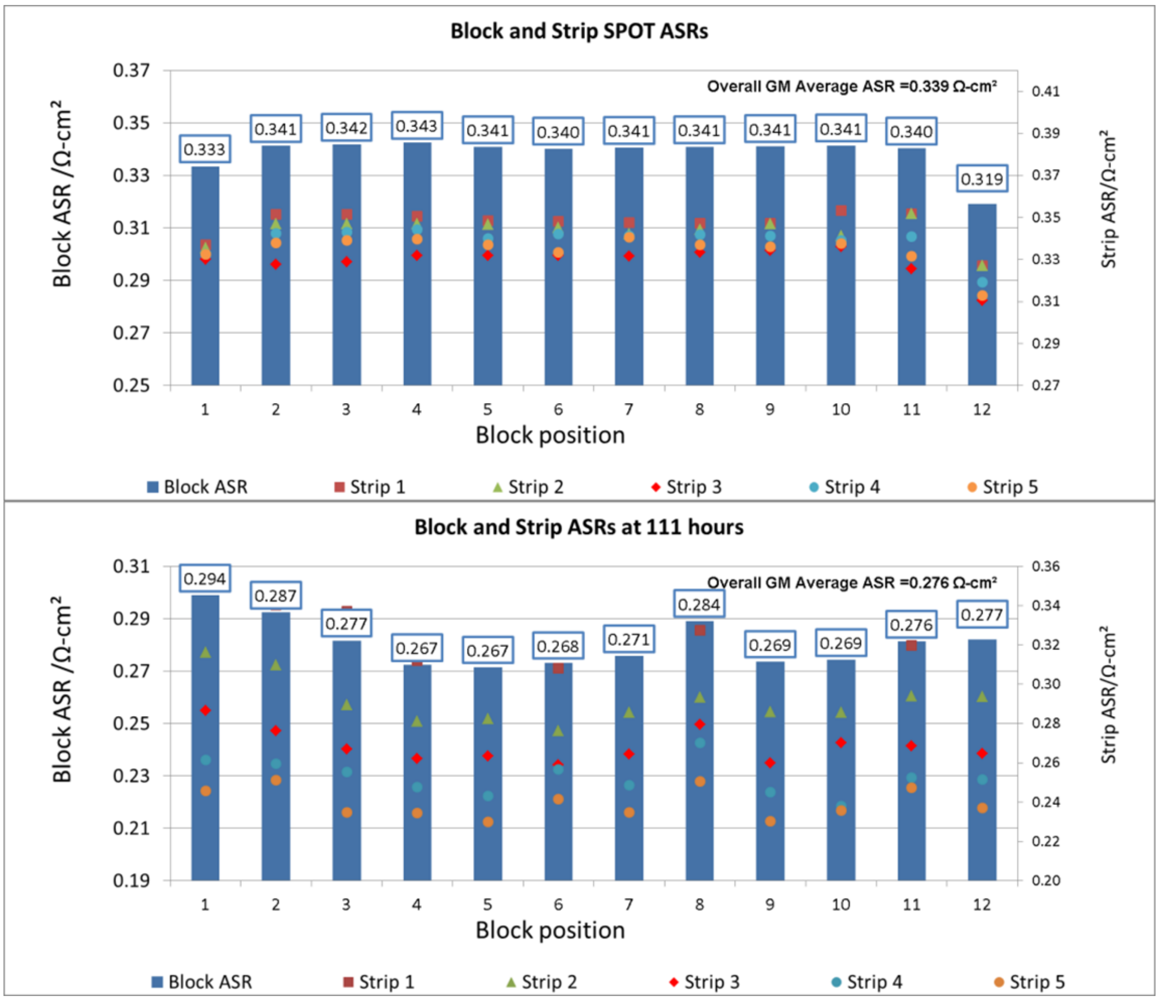



**Figure 46 Expected vs. Actual ASR**

**Early Performance and ASR**: Variations in operating conditions and its effect on ASR are shown in Figure 47. Early operations were hampered by temperature variations as control system tuning was in progress. This was stabilized at an overall average of stack temperature of 860°C. The TG air mass flow varied with ambient conditions (air density) and changing operating pressure and partial oxygen (PO2) percentage.  Early testing ran with warm humid air. This later changed to cool dry air. Stack performance improved as PO2 increased and with dryer air. In addition, the natural gas (NG) lower heating values (LHV) varied on the order of 2% daily. This was stabilized by adding an LHV meter to the system and adjusting the fuel flow accordingly. These factors and their control led to an increasingly stable ASR which decrease over time.

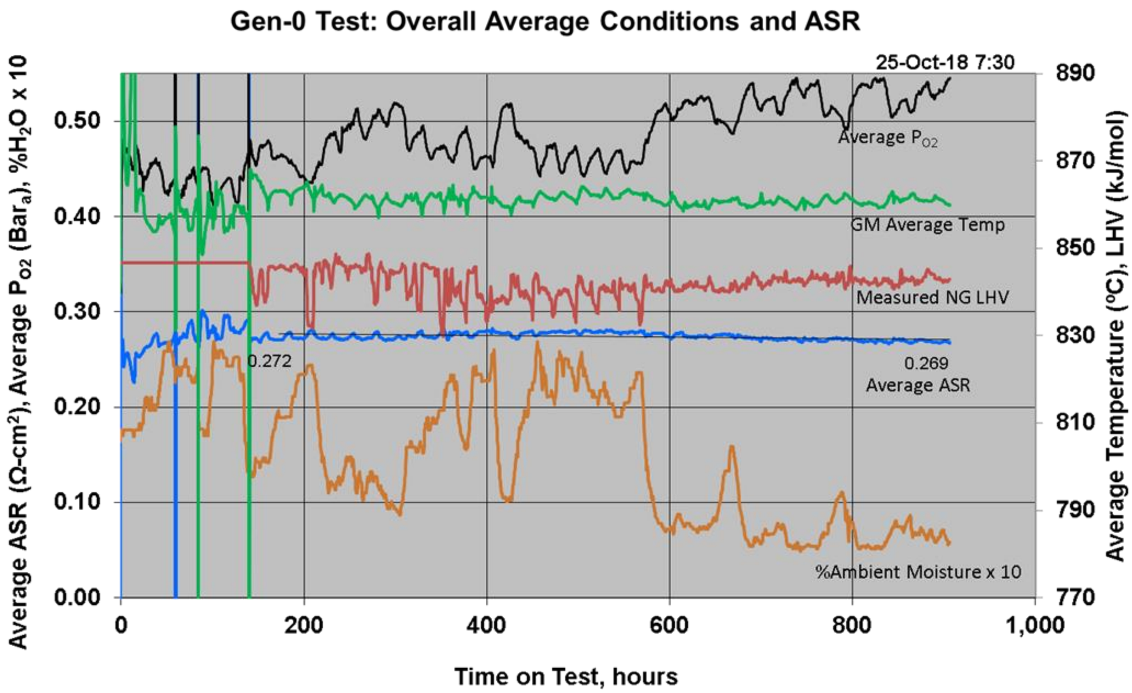



**Figure 47 Early Test Condition and ASR**

Overall performance looked very good at 900 hours as shown in Figure 48 and Figure 49. The average ASR decreased to 0.268 Ω-cm² with excellent uniformity. The DC efficiency was 61.7 with a fuel utilization of 80%. The average AC power was 248 KWac and the AC efficiency was 55.3%. Apparent degradation < 0 due to changing conditions ~ 0.014 Ω-cm² improvement due to PO2 increase.

The ASR comparison with previous systems tests is shown in Figure 50. The IST and PT-A test were performed on a technology demonstration unit about the same size as GEN0. The initial ASR of GEN0 was lower primarily do to the effects of IBR and an improved cathode. The long-term stability of GEN0 was due to chrome mitigation, improved temperature and fuel distribution, and lower temperature difference.

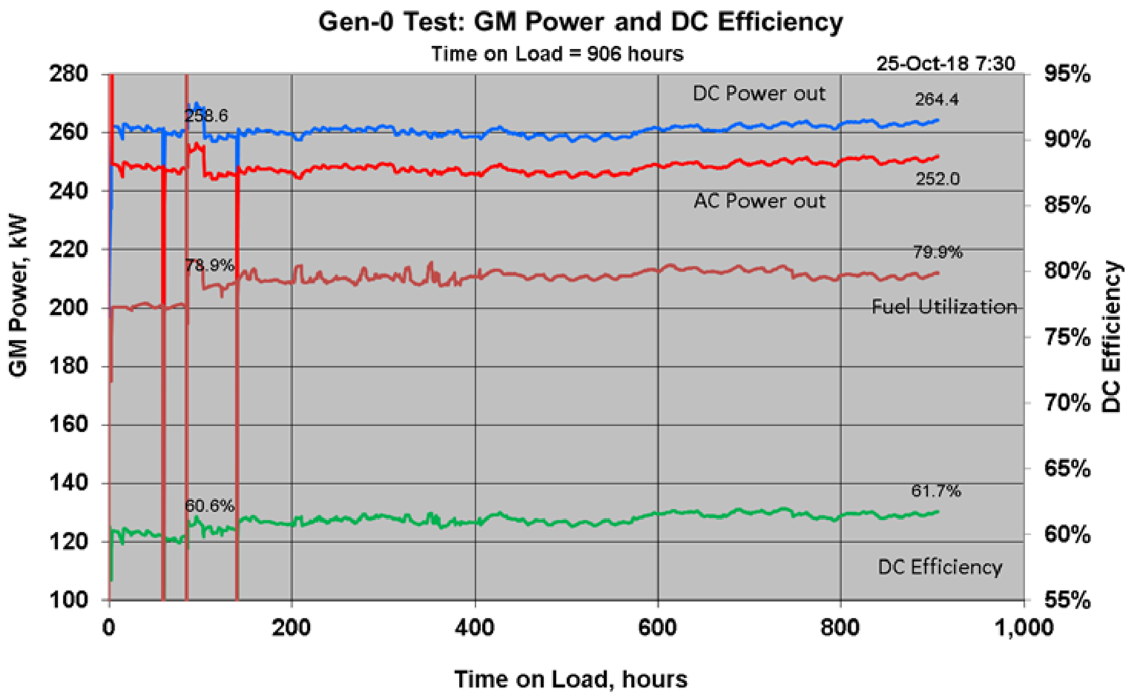



**Figure 48 Early Power and DC Efficiency**

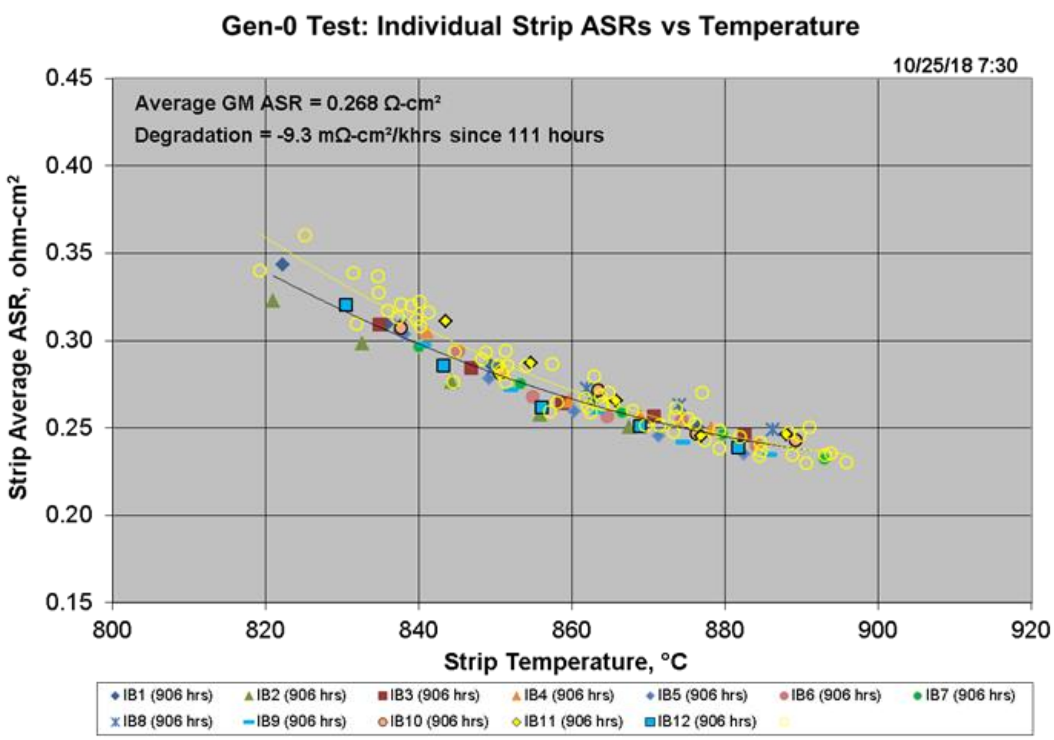



**Figure 49 Early Strip ASR vs. Temperature**

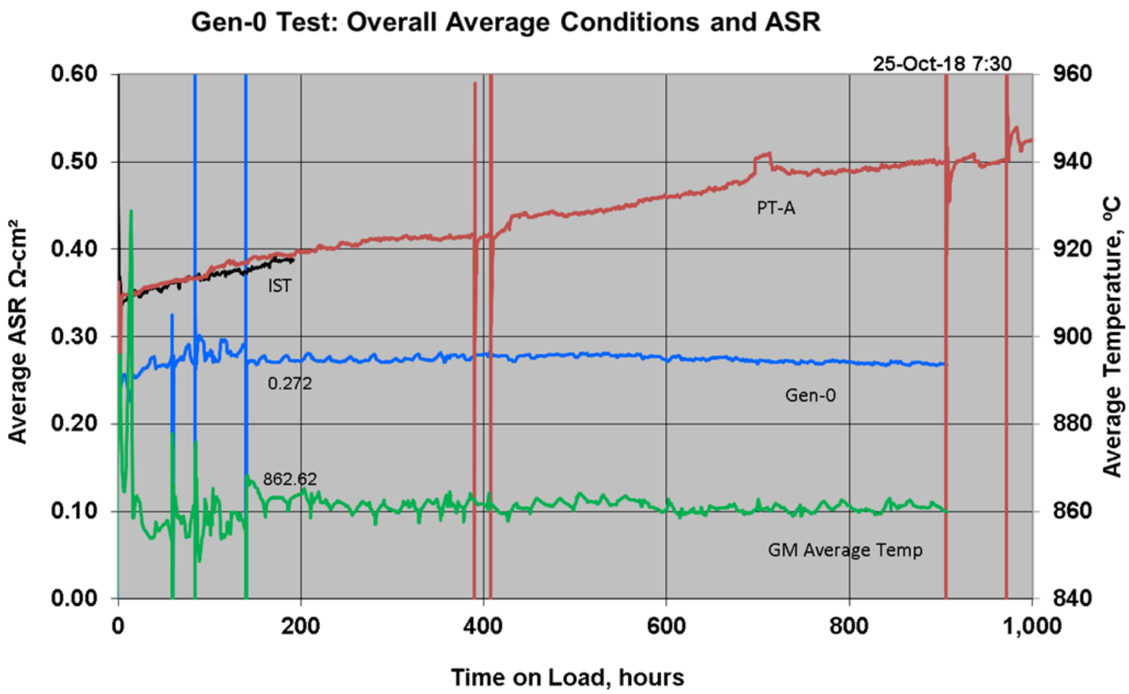



**Figure 50 Comparison of Gen-0 with Previous System Tests**

**Longer Term Performance:** Figure 51 shows the power generated by the Gen0 system over the 1800-hour demonstration period. The plot shows that the DC power generated was 262 kW-electrical while the AC power pushed out to the utility's electric grid was 251 kW-electrical. This surpassed the 250-kW target. Also shown is the DC efficiency. This is ratio of electrical energy generated by the fuels to the input from the Natural gas. The DC efficiency was 61% and surpassed the 60% target. Finally, the plot shows the fuel utilization. This is the percent of the fuel input that is converted into electricity (79%). The balance of fuel (21%) not converted into electrical energy is converted into thermal energy that is used to keep the system at the proper operating temperature. The overall ASR shown in Figure 52 is 0.279 Ω-cm² at a stack average temperature of 864°C with good uniformity and a tight distribution as shown in Figure 53.

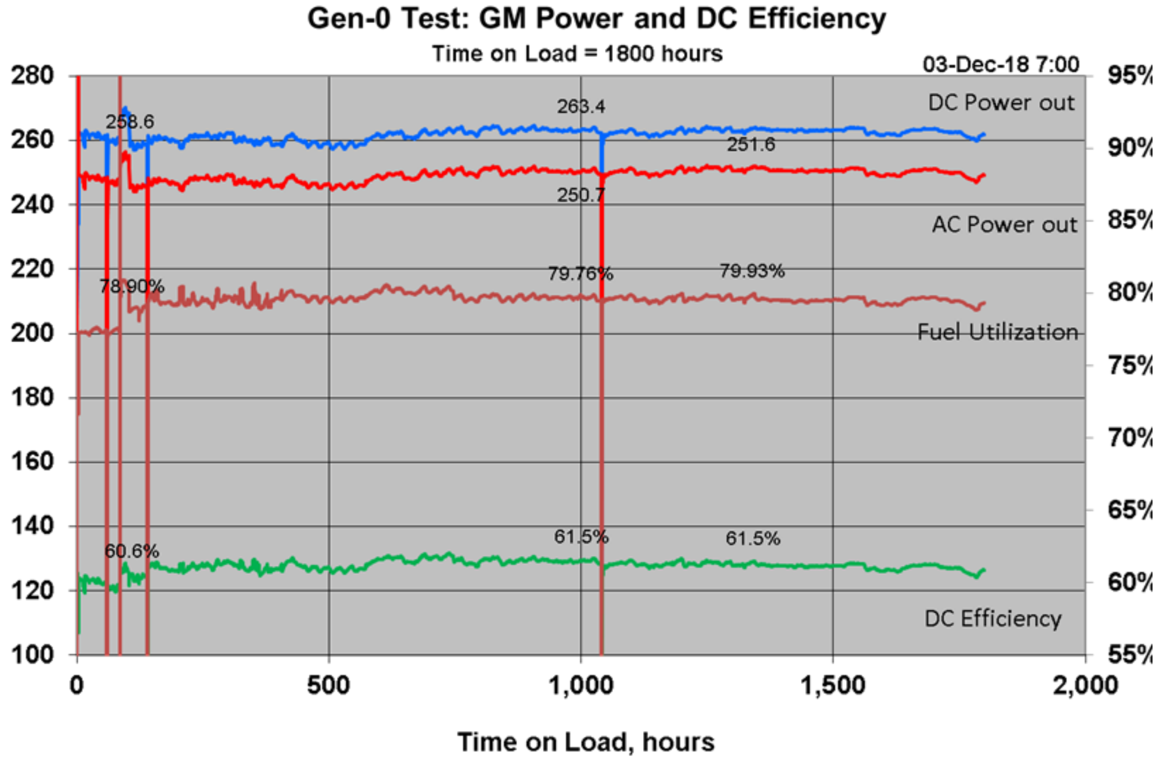



**Figure 51 Longer Term Power and DC Efficiency**

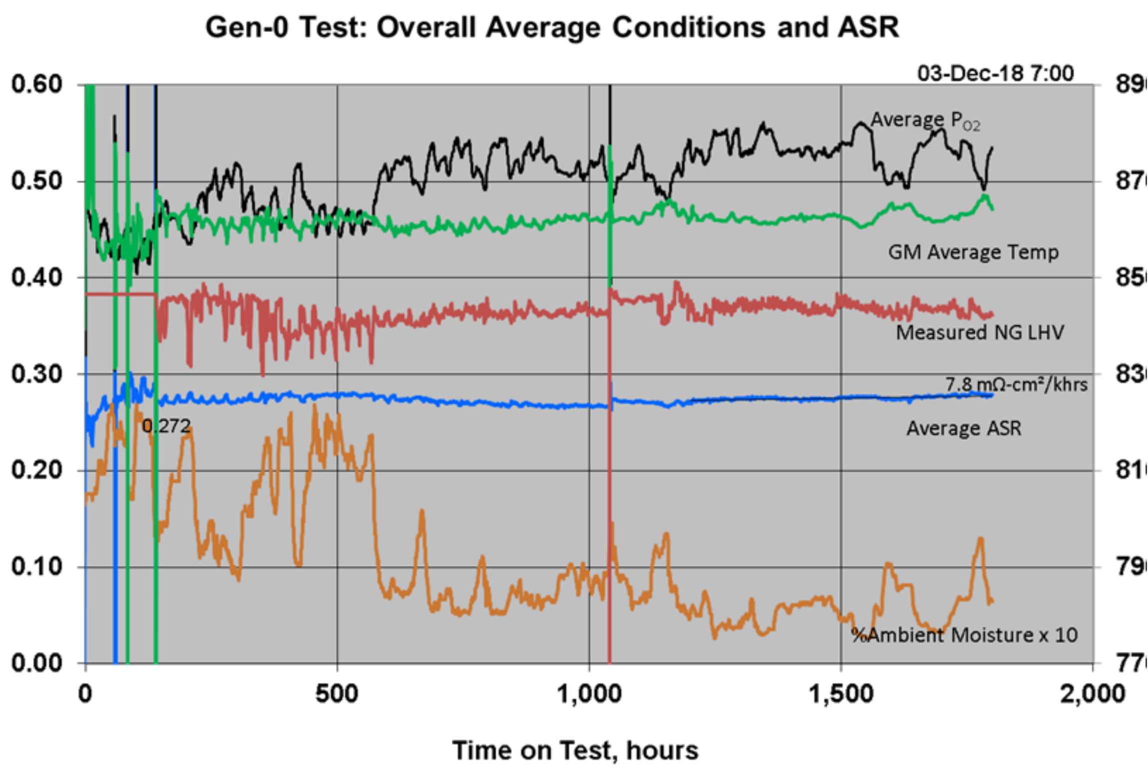



**Figure 52 Longer Term Test Condition and ASR**

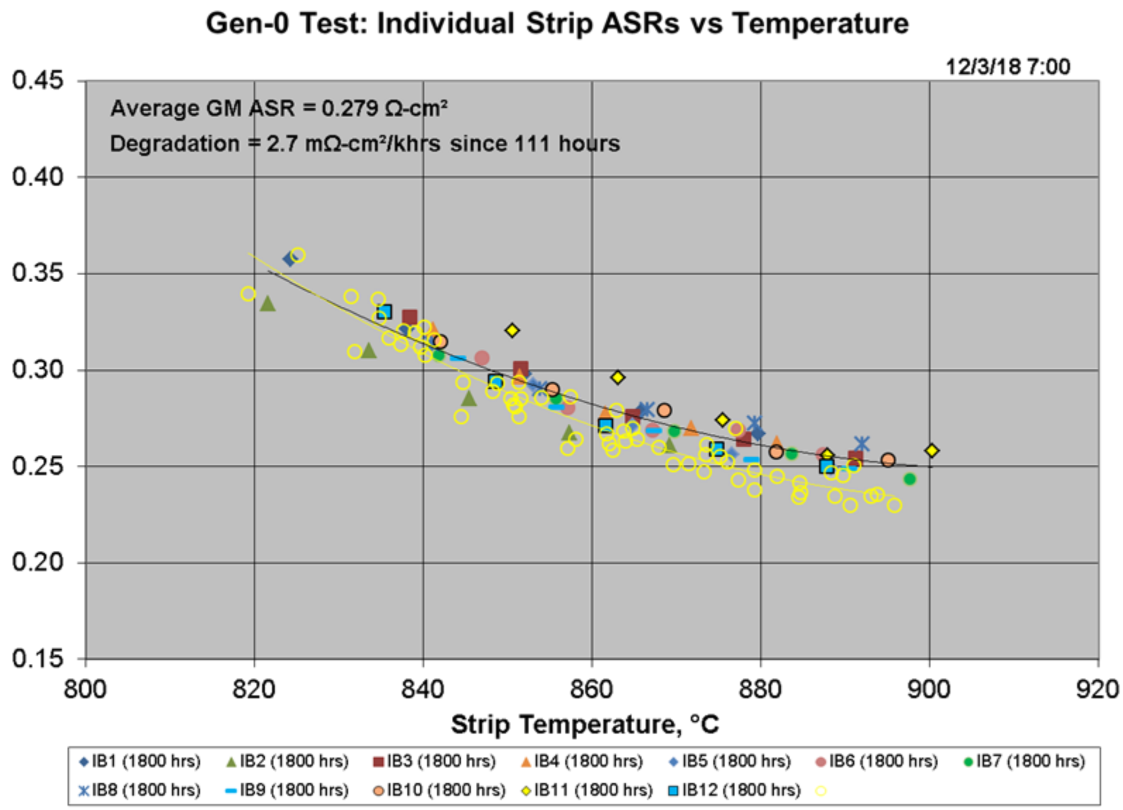



**Figure 53 Longer Term Strip ASR vs. Temperature**

**Degradation Rate:** The power generated by Gen0 and the system efficiency for Gen0 were very steady throughout the demonstration period. This is an indication of a low degradation rate for the fuel cells. The calculated degradation rate for the test period between 111 hours and 1800 hours of operation was 2.7 milliohms-centimeter squared per thousand hours. This was a better result than the target value (3.0) which corresponds to a power degradation rate 0f 0.4 %/1000 hours of operation. The table shown in

Table **14** gives details for the 12 integrated blocks (IBs) located inside the Gen0 generator module. Operating temperature and power generated per block were very consistent between all the IBs.

**Table 14 Gen0 Summary Performance at 1800 Hours**

| | Temp, ºC | | | | Voltage | Current | Power | DC Eff | ASR | Util. | Deg Rate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Int. Block** | **Inlet** | **Outlet** | **Avg.** | **Delta** | **(V)** | **(Amps)** | **(kW)** | **(%)** | **ohm-cm2** | **%** | **mΩ-cm²/khrs** |
| **IB1** | 817 | 873 | 845 | 55 | 570 | 38.6 | 22.0 | 59.6% | 0.308 | 78.4 | 4.1 |
| **IB2** | 816 | 875 | 845 | 60 | 573 | 38.6 | 22.1 | 60.9% | 0.290 | 79.8 | 3.0 |
| **IB3** | 832 | 898 | 865 | 66 | 576 | 37.8 | 21.8 | 61.0% | 0.285 | 79.5 | 4.2 |
| **IB4** | 836 | 900 | 868 | 64 | 576 | 37.8 | 21.8 | 60.2% | 0.282 | 78.4 | 7.9 |
| **IB5** | 835 | 894 | 865 | 59 | 577 | 37.8 | 21.8 | 60.7% | 0.278 | 78.9 | 3.8 |
| **IB6** | 842 | 905 | 874 | 63 | 576 | 37.9 | 21.8 | 60.9% | 0.271 | 79.2 | 3.3 |
| **IB7** | 835 | 905 | 870 | 70 | 579 | 37.8 | 21.9 | 61.0% | 0.265 | 79.1 | -1.3 |
| **IB8** | 835 | 898 | 867 | 64 | 576 | 37.8 | 21.8 | 61.1% | 0.279 | 79.5 | -2.7 |
| **IB9** | 838 | 896 | 867 | 58 | 577 | 37.9 | 21.8 | 61.2% | 0.268 | 79.6 | 1.4 |
| **IB10** | 835 | 902 | 869 | 66 | 574 | 37.8 | 21.7 | 61.3% | 0.277 | 80.1 | 5.9 |
| **IB11** | 844 | 907 | 876 | 62 | 574 | 37.8 | 21.7 | 61.1% | 0.274 | 79.8 | 0.2 |
| **IB12** | 829 | 894 | 862 | 66 | 578 | 37.8 | 21.9 | 61.5% | 0.277 | 79.7 | 2.4 |
| **Average** | **833** | **896** | **864** | **64** | **576** | **37.9** | **21.8** | **60.9%** | **0.279** | **79.3** | **2.7** |

**Gaseous Emissions:** The gaseous emissions for NOx (nitrogen oxides) from the exhaust stack of Gen0 were very low. They were measured as 0.0003 lbs/MW-hr at the full load condition. This was much less than the target < 0.01 lbs/MW-hr. The gaseous emissions for carbon monoxide (CO) from the exhaust stack of Gen0 were higher than expected. They were measured as 1.13 lbs/MW-hr at the full load condition. This was much more than the target <0.13 lbs/MW-hr. To reduce the carbon monoxide emissions to an acceptable level, a catalytic oxidizer like those used on automobile exhausts could be added to minimize the CO emissions.

**Key Performance Indicators:** The key performance indicators are shown in Table 15. Overall the following was achieved:

- After early anomalies were resolved, GEN0 system operated very well
- Initial performance met pre-test expectations
- DC performance and efficiency were on target
- AC performance and efficiency were on target
- ASR performance and degradation consistent with expectations and a 3-year stack life
- Performance far exceeded previous system testing (IST/PT-A)
- The LGFCS SOFC Prototype System (GEN0) was demonstrated in an operational environment and therefore achieving Technical Readiness Level 7

**Table 15 Key Performance Indicators**

| Specification | GEN-0 Target | Measure | Actual result |
|---|---|---|---|
| Baseload Power Output | ≥ 225 kWac | Average (during 1,000hours) net AC kW rating | **250 kWac** |
| Total System Efficiency, AC, DC | ≥ 53% ac<br>≥ 60% dc | AC net (NG to Grid), DC net (NG to Fuel Cell DC) | **55% ac<br>61% dc** |
| Stack Life (Degradation Rate) | ≥ 3 years (0.4 %/1k hours) | Degradation Rate (ASR difference over time) | **3<br>(0.4%)** |
| Duration | ≥ 5000 hours | Accumulated time of operation on load | **1800 hours** |
| Reliability | ≥ 85% | (1 - Unscheduled time offline/Duration) * 100%<br>No loss of functionality at Emergency Shut Down | **<90%** |
| Emissions | < 0.01 lbs/MWh | NOx lbs/MWh | **0.0003** |
| | < 0.15 lbs/MWh | CO lbs/MWh | **1.13** |
| Noise | ≤ 76dBA | dBA@7 meters | **68** |
| Footprint | ≤ 40m^2 | Total Area of System | **46** |
| Unmanned Operation | ≥ 30 days | Continuous days of operation | **37** |
| ANSI/CSA FC1.2014 | Compliant | Stationary Fuel Cell Power Systems | **Yes** |
| IEEE 1754 | Certified | Standard for Interconnecting Distributed Resources with Electric power Systems Grid Connection | **AEP approved** |

# 2.0 SUMMARY

The objective of this program was to test a 250kWe thermally self-sustaining modular solid oxide fuel cell (SOFC) Power System (GEN0 Demonstrator) while advancing this commercial prototype product demonstrator to a Technical Readiness Level (TRL) 7.

The scope of work included:

- The assembly of the Fuel Cell Vessel (FCV)
- Assembly and packaging of the Generator Module and Balance of Plant (BOP)

- Installation and interconnection of the power system packages and connection to the fuel supply and power grid
- Commissioning and shakedown testing to validate assembly and safe operation
- Operation at a base load power rating to the grid

The GEN0 Demonstrator underwent testing on a site provided by Stark State College in North Canton, Ohio. System performance and degradation as well as cost estimates were compared to established SOFC Program performance metrics to assess progress.

The major achievements were:

- Assemble and QA qualified 70 fuel cell strips for 12 integrated blocks and 2 spare integrated blocks
- Assemble and QA qualified 12 integrated blocks and 2 spare integrated blocks and installed in fuel cell vessel
- Delivered fuel cell vessel to test site and installed in generator module
- Installed fuel and power electronics modules on test site
- Interconnected generator, fuel and power electronics modules on test site
- Commissioned and started the LGFCS SOFC Prototype System
- Performance to date:
    - Over 1800 Hours on Load
    - Power to Grid = 250 KW-AC
    - Efficiency = 61% DC / 55% AC
    - Power Degradation = 0.3% per 1000 hours
    - Emissions meet NOx standards
- The LGFCS SOFC Prototype System (GEN0) was demonstrated in an operational environment and therefore achieving Technical Readiness Level 7

# 3.0 ABBREVIATIONS

| | |
|---|---|
| AF | Auxiliary Fuel |
| ASR | Area Specific Resistance |
| BOP | Balance of Plant |
| BPC | Block Power Controller |
| DC | Direct Current |
| DNG | Desulfurizer Natural Gas |
| EIS | Entry into Service |
| ESD | Emergency Shutdown |
| FCV | Fuel Cell vessel |
| FP | Fuel Processor |
| GM | Generator Module |
| HMS | Health Monitoring System |
| IB | Integrated Block |
| IBR | In Block Reforming |
| IGFC | Integrated Gasification Fuel Cell |
| IST | Integrated String Test |
| KPI | Key Performance Indicators |
| KW | Kilo Watt |
| LGFCS | LG Fuel Cell Systems |
| LHV | Lower Heating Value |
| MMA | Magnesia Magnesium Aluminate |
| MW | Mega Watt |
| NGFC | Natural Gas Fuel Cell |
| PCS | Power Control System |
| PE | Power Electronics |
| QA | Quality Assurance |
| sccm | Standard Cubic Centimeter per Minute |
| SIC | Secondary Interconnect |
| SOFC | Solid Oxide Fuel Cell |
| slpm | Standard Liter per Minute |
| TG | Turbogenerator |
| TGA | Turbogenerator Assembly |
| TRL | Technology Readiness Level |