Mark1020 ACS™ Fuel Cell Stack

Product Manual and Integration Guide

Model Name: Mark1020 ACS™
Part Number: 5114510 through 5114580

Document Number: MAN5100192-0F
Date: 25-Feb-09

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NOTE: YOU MUST READ THIS BEFORE ATTEMPTING ANY PROCEDURE DESCRIBED IN THIS MANUAL

There are inherent risks in the operation of a fuel cell stack that could result in death or bodily injury or loss or damage to property. It is therefore necessary for the customer to take all prudent safety precautions in the installation, use, and maintenance of this device. Those who install, operate, and service the device must be technically qualified and experienced in working with electrical equipment, compressed gases, and hydrogen. This manual includes certain safety guidelines and recommendations; however, this manual is not intended to cover all situations. The customer is responsible for determining the suitability of the customer's particular design or application, and for ensuring the safe operation, maintenance, and storage of the device and any systems into which it is integrated. Ballard Power Systems, Inc. ("Ballard") cannot be responsible for the use of the device in ways, or as part of systems, that deviate from the operating recommendations in the manual. The customer is responsible for being aware of, and complying with, all applicable laws and regulations. Ballard has limited its liability for damages incurred by the customer or its personnel in the contract documents pursuant to which the device is provided to the customer. Please refer to those documents for additional information.

The customer must read this entire manual before attempting any procedure described in any part of the manual. Failure to follow any instruction or recommendation could result in death or bodily injury or loss or damage to property.

Ballard intends for the device to be installed, operated, and serviced only by technically qualified and experienced people who understand the principles of fuel cell technology, are aware of the safe operating limits of fuel cells, and are familiar with the risks posed operating a fuel cell stack. Ballard relies on customers to use their own knowledge and experience when installing, operating, and servicing the device. Ballard also relies on the people using this manual to be familiar with common terms and abbreviations used in the manual.

BALLARD

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(i) Warnings, Cautions and Symbols Used

WARNING *WARNINGS in this manual indicate actions that may result in an accident, which could cause immediate bodily injury or loss of life or could cause damage to equipment or other property.*

CAUTION *CAUTIONS in this manual indicate actions that may result in an accident, which could cause damage to equipment or other property and which could cause bodily injury if not promptly detected and remedied.*

ELECTRICAL HAZARD *ELECTRICAL HAZARDS in this manual indicate actions that pose a risk of high voltage or electrical shock that may result in an accident, which could cause bodily injury or loss of life or could cause damage to equipment or other property.*

✸ *NOTE: general notes*

(ii) Disclaimer

It is anticipated that the customers will find many different ways to integrate the Mark1020 ACS Fuel Cell Stack. This manual does not attempt to address all possible options. The customer is responsible for determining the suitability of the various integration options for the customer's particular needs, and for ensuring the safe operation, maintenance, and storage of the device and any systems into which it is integrated. It is the responsibility of the customer to ensure that his or her design is free from claims of patent infringement. Ballard cannot be responsible for any injury or damage caused by the use of its products in ways, or as part of systems, not expressly approved by Ballard.

(iii) Glossary

Term	Description
ASL	Above Sea Level
A	Ampere
BOL	Beginning of Life
ºC	degree Celsius
cc	cubic centimeter
CVM	Cell Voltage Monitoring
EOL	End of Life
kW	kiloWatt
kPa	kiloPascal (absolute unless otherwise specified)
IEC	International Electrotechnical Commission
mm	millimeter
ms	millisecond
mV	milliVolt
NOPL	Non-Operating Performance Loss
OCV	Open Circuit Voltage
PEM	Proton-Exchange Membrane
PM2.5	Particles up to 2.5 micrometers in diameter
PM10	Particles up to 10 micrometers in diameter
ppm	parts per million
slpm	standard liter per minute, evaluated at 1 atmosphere and 0°C
stack	Fuel cell stack, generally referring to the Mark1020 ACS fuel cell stack
V	Volt

(iv) Scope of Manual

This manual is a guide for the customer to use in integrating the Mark1020 ACS into their system and successfully operating it. Product specifications, expected product performance, required system inputs, electrical interfaces and acceptable operating conditions are included in the manual. This manual will provide guidance for operation within the bounds of the specification. Please contact Ballard Power Systems for questions relating to the operation outside the stated specification.

1.0 Safety

ELECTRICAL HAZARD: Fuel cell stacks generate high voltage. Obey ALL warnings, cautions, and safety instructions. Failure to do so may result in electrical shock leading to personal injury or death.

The installer and operator of the fuel cell stack must be technically qualified and experienced in handling electrical equipment, compressed gases and hydrogen.

1.1. General Safety

- The fuel cell stack may contain residual voltage when not operating.
- Keep all guards, screens, and electrical enclosures in place when the system is operating.
- The fuel cell stack should not be used or stored in wet or damp conditions.
- Remove jewelry, watches, rings, and metal objects on clothing that can cause short circuits when working with the fuel cell stack or system.

1.2. High Temperature and High Pressure Safety

- The fuel cell stack can reach a temperature of 70° C or higher if operated outside the specification. Avoid touching exposed components during or shortly after operation.
- The fuel cell stack and associated system use pressurized gases, which can be hazardous. Use caution and ensure circuits are de-pressurized before opening any lines or fittings.
- The fuel cell stack is assembled under high compression. Do not attempt to disassemble the stack.

1.3. High Voltage Safety

- The fuel cell stack generates up to 80 VDC (open circuit voltage) for a 80-cell stack (maximum ~1V/cell). Always ensure that the Stack Power HV+ and HV-terminals are connected to an appropriate load prior to operation.
- Current leakage from the stack can also occur if there is inadequate isolation elsewhere in the electrical system and the stack is not fully isolated from that portion of the electrical system. The inadequate isolation could occur elsewhere in the fuel cell module or external to the fuel cell module. This leak path can be minimized by ensuring all electrical equipment and wiring in the fuel cell module is adequately isolated and by ensuring that the fuel cell module electrical buses are isolated from the application electrical system.
- The fuel cell stack has a potential for current leakage across clearances and creepage distances. The fuel cell stack installation should be designed with adequate clearances and creepage distances as listed in applicable standards.
- Stack Power connection cables must be appropriately sized to suit the application for voltage, current and insulation temperature limits. Cables must have suitable voltage rating, current carrying capacity, and insulation temperature rating, depending on the end-users' specific application and operating environment.
- Exercise caution when routing the Stack Power Cables. In particular, ensure that no other electrical cables are routed in between the physical loop formed by the Fuel Cell Stack power terminals, the HV+ and HV- and the load power terminals.
- Exercise caution when working with the stack. Residual reactants within the stack can rapidly develop a charge, even when there is no fuel flow and the stack has been short-circuited. A reading of zero volts across the entire stack does not guarantee that all cells are uncharged.
- All metal parts on the stack must be either electrically bonded or live. A means should be provided to prevent people or objects from touching the live parts.
- Be sure that all electrical connections and connectors are properly installed and connected with proper torque. Do not over-torque, as this can damage the stack.

- Avoid hazardous voltage situations that could result from unsafe conditions such as, but not limited to, the following:
  - Improper grounding
  - Accumulation of foreign material or debris between live stack parts and hardware that could lead to loss of isolation or reduction in creepage/clearance.
  - Handling electrical leads or devices with wet hands or on wet ground
  - Frayed electrical leads
  - Improper connection or re-connection of the terminal leads
  - Short circuits
  - Back-feed from energized normal and emergency power sources.

1.4. Hydrogen Safety

WARNING

- Hydrogen is a colorless, odorless, highly flammable gas.
- Hydrogen must be sited and handled in accordance with applicable regulations and the gas supplier's recommendations.
- Hydrogen is non-toxic but can cause asphyxiation by displacing the oxygen in the air. There are no warning symptoms before unconsciousness results.

Hydrogen molecules are smaller than any other gas, making hydrogen more difficult to contain. It can diffuse through many materials considered airtight. Fuel lines, non-welded connections, and non-metal seals such as gaskets, O-rings, pipe thread compounds and packings present potential leakage or permeation sites. Furthermore, hydrogen's small molecule size results in high buoyancy and diffusivity, so leaked hydrogen will diffuse and become diluted quickly. Stack hydrogen leak rates will generally increase with stack lifetime.

The responsibility for leak detection and the mitigation of combustible leaks rests with the customer. Hydrogen leaks emanating from the fuel cell stack can be readily detected by means of a hydrogen detector, which can trigger warnings well before the hydrogen/air mixture reaches a flammable concentration.

1.5. Stack Fire Safety

Operation of the fuel cell stack in a manner that is significantly outside specification may result in open flame at the stack. Specifically, the following conditions may result in fire:

- Operation with significant fuel starvation (insufficient purge, long periods of over-cooled operation)
- Operation above maximum stack temperature rating

To prevent this condition, stack operation should be automatically stopped in the event of loss of fuel or coolant flow using either a voltage or stack temperature signal.

The cells in the stack contain platinum catalyst, which may react if exposed to certain chemicals. The stack should not be exposed to any chemicals not mentioned in this application guide, and used stacks should be returned to Ballard for proper disposal.

1.6. Asphyxiation Safety

The fuel cell stack consumes O2 while operating. If operating the stack in poorly ventilated, small enclosures, care must be taken that O2 concentrations do not drop below safe levels.

2.0 Mark1020 ACS Stack Physical Characteristics

The Mark1020 ACS fuel cell stack is a cathode-cooled proton exchange membrane (PEM) fuel cell stack designed to provide stable electrical power while operating on air and dry hydrogen over a wide range of operating and environmental conditions. Figure 1, Figure 2, and Figure 3 show the main physical features of the Mark1020 ACS stack.

Figure 1 Mark1020 ACS Stack

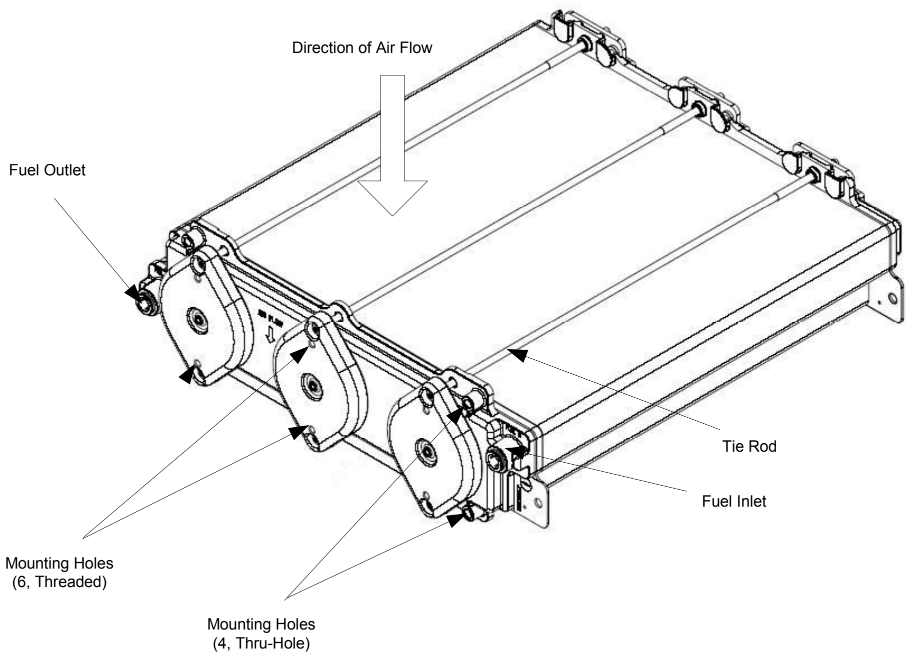


Figure 2 Isometric View from Anode End

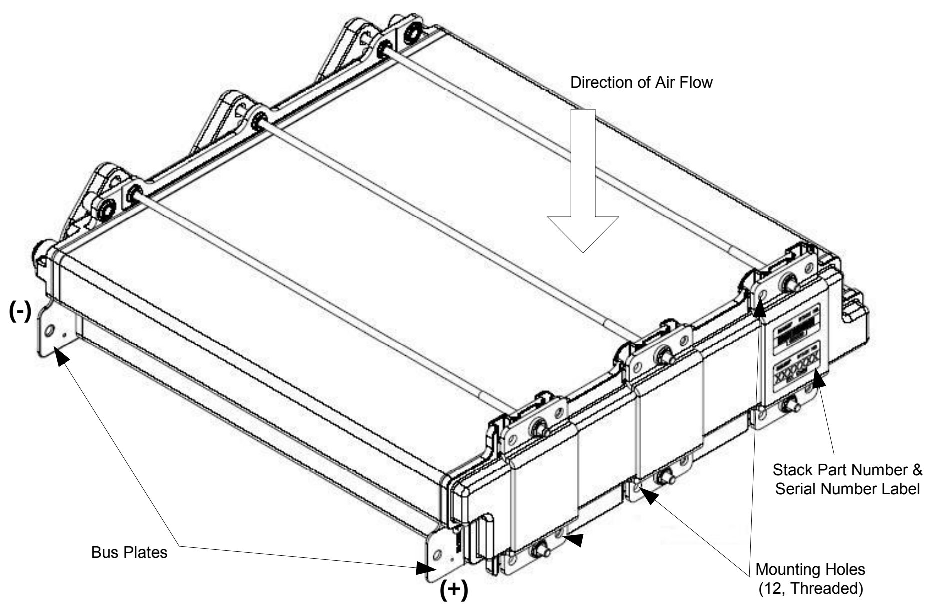


Figure 3 Isometric View from Cathode End

3.0 MARK1020 ACS Stack Specifications

The Mark1020 ACS stack is available in sizes ranging from 10 cells up to 80 cells.

3.1. Stack Performance

Table 1 Stack Performance at Beginning of Life

Performance Parameter		Stack Current (A)						
		0	7.8	14.5	29.0	51.7	65.3	77.0[1]
Average Power	W/cell	0	6.5	11.7	22.1	35.9	41.9	44.8
Average Voltage	mV/cell	1000	839	807	763	694	642	582
Standard Deviation[2]	mV	-	8	8	7	9	10	12

[1]A nominal operating current of 65A, and a maximum operating current of 75A is recommended. See Section 5.1.
[2]Standard Deviation defines the expected variability in performance from stack to stack at Beginning of Life due to manufacturing variability. Stack performance is normally distributed within the population.

3.2. Operating Conditions

Ballard recommends that system integrators design their systems to operate the Mark1020 ACS stack at the optimal conditions listed in Table 2. Operation at these conditions will maximize stack lifetime while ensuring stable operation.

Table 2 Stack Operating Conditions

Stack Current (A)		**0**	**7.8**	**14.5**	**29.0**	**51.7**	**65.3**	**77.0**
Optimal Stack Temperature, Steady-State (T_{opt})	°C	38	42	45	51	59	63	66
Range of Allowable Stack Temperatures, Steady-State and Transient	See Section 5.2.							
Cooling / Oxidant (Air)								
Optimal Inlet Flow	Depends on stack current and air inlet temperature; see Section 5.3.1.							
Minimum Inlet Stoichiometry, Steady-State	20							
Inlet Pressure/Altitude	Optimal: Sea Level to 1000m without de-rate Allowable range: -400m to +7600m with de-rate at high altitude							
Inlet Temperature	Optimal: 10°C to 40°C Allowable range: –20°C to +52°C with de-rate at high temperature/low RH							
Inlet Humidity	Allowable range: 0 to 100% RH non-condensing with de-rate at low RH/high temperature no added humidification required							
Fuel (Pure Hydrogen)								
Inlet Stoichiometry (Dead-Ended Operation)	~1.07 optimum							
Optimal Inlet Pressure (Operating)	136 kPa absolute (0.36barg)							
Inlet Pressure Range (Operating)	116 to 156 kPa absolute (0.16 to 0.56 barg)							
Maximum Allowable Inlet Pressure (Safety Limit)	200 kPa absolute (1.0 barg)							
Range of Allowable Inlet Temperatures	–15°C to +65°C							
Humidity	Dry fuel preferred No added humidification required							

3.3. Ambient Environment Specifications

Table 3 Ambient Environmental Conditions

Ambient Conditions	
Operating Pressure/Altitude	-400m to 7600m
Ambient Temperature, Operation	-20°C to +52°C
Ambient Temperature, Standby and Startup	-10°C to +52°C
Total Allowable Freeze-Thaw Cycles	36*
Relative Humidity	0 to 100% RH non-condensing**
Shock/Vibration	Tested to: • NEBS GR-63-CORE o Transportation Vibration Test o Zone 4 Earthquake Test o Office Vibration Test • Vibration: UL2267 • Shock: 15g, 11ms, 1000 cycles (based on IEC-68-2-27, Ea and IEC-68-2-29, Eb)

*This limit reflects the maximum cycles tested at Ballard – there are some indications that a much higher limit may be possible without performance & lifetime impacts.
**Storage below ~5%RH will not result in stack damage; however, stack startup time may be impacted significantly, see Section 6.4.

Note – Shock and Vibration:

The spring-cap mounting option is recommended for applications that are expected to see significant shock and/or vibration environments. The stack should be rigidly mounted; rubber mounts or other vibration isolation features are not recommended. See Section 7.1.3.3 for more detail.

3.4. Reactant Specifications

Table 4 Oxidant Specification (Ambient Air)

Description	Specification
Chemical	
Sulfur Dioxide (SO_2)	0.01 ppm
Nitrogen Monoxide (NO)	0.025 ppm
Nitrogen Dioxide (NO_2)	0.05 ppm
Volatile Organic Compounds (e.g. Benzene C6H6, Toluene C7H8)	0.008 ppm
Hydrogen Sulfide	0.04 ppm
Ammonia	0.01 ppm
Ozone	1 ppm
Carbon Monoxide	5 ppm
Carbon Dioxide	1% vol
Particulate	
Airborne Particles	
Coarse Particles (PM 10)	90 $\mu g/m^3$
Fine Particles (PM 2.5)	15 $\mu g/m^3$

Note: see Section 5.5.4 for more detail on oxidant contaminants

Table 5 Fuel Specification

Description	Specification
Composition	Hydrogen Gas
Total inert gases	500 ppm (99.95% H2)
Water	5 ppm
Totally hydrocarbons	2 ppm
Oxygen	5 ppm
Helium	300 ppm
Nitrogen, Argon	200 ppm
Carbon dioxide	2 ppm
Carbon monoxide[1]	0.2 ppm
Total sulfur compounds	0.004 ppm
Formaldehyde	0.01 ppm
Formic acid	0.2 ppm
Ammonia	0.1 ppm
Total halogenated compounds	0.05 ppm

1. Exposure to 0.2ppm of CO in the fuel may lead to some recoverable performance loss between shutdowns.

3.5. Emissions (BOL)

Table 6 Beginning of Life (BOL) Emissions

Fuel (H_2)	
External Fuel Leak*	< ~5 cc/min H2 per cell @ 136 kPa inlet pressure
Startup Purge	Recommend 20cc/cell in 200ms (~6slpm)
Operating Purge	Recommend 20 cc/cell per purge
Water	
Liquid Water or Condensate	Minimal, some liquid water may collect at fuel outlet

*External fuel leak is expected to increase over stack lifetime.

3.6. Stack Weight and Dimensions

Table 7 Weight and Dimensions

Stack Length (mm)	Height (mm)	Width (mm)	Dry Mass (kg)	Thermal Mass (J/°C/cell)
55.4 + (# Cells X 5.5)	103	351	2.1 + (# Cells X 0.16)	100

*All dimensions are nominal. Refer to the stack interface drawing (DRW5109909) for details.

3.7. Shipping/Storage Conditions

Table 8 Shipping and Storage Environmental Conditions

Environmental Condition Limits	
Temperature Range	-40°C to +70°C with duration limits; see Section 8.2.1
Total Allowable Freeze-Thaw Cycles	36*
Relative Humidity Range	0% RH to 100% RH non-condensing*
Shock and Vibration	Designed to withstand normal shipping shock and vibration in standard Ballard packaging.

*See Table 3 for more detail.

4.0 NOMINAL OPERATING CHARACTERISTICS

4.1. Nominal Polarization Characteristics

Figure 4 below shows the polarization curve for a Beginning-of-Life (BOL), fully conditioned Mark1020 ACS stack operating at nominal conditions, with confidence bands defining the expected 99% confidence interval on stack-to-stack variability. Table 1 above also lists nominal cell voltage at selected currents. Nominal operating conditions are as follows:

- Steady-state operation (decreasing current)
- Stack operating at optimum temperature for each current (as listed in Table 2 above and described in Section 5.2 below)
- Oxidant stoichiometry $\geq$ 100
- Stack oxidant supply from the Ballard lab environment (18-24°C, 25-35% RH, low levels of common urban pollutants such as nitrogen oxides and sulphur oxides).
- Anode dead-ended with adequate purge (per Section 5.4.1.2)
- 136 kPa fuel inlet pressure

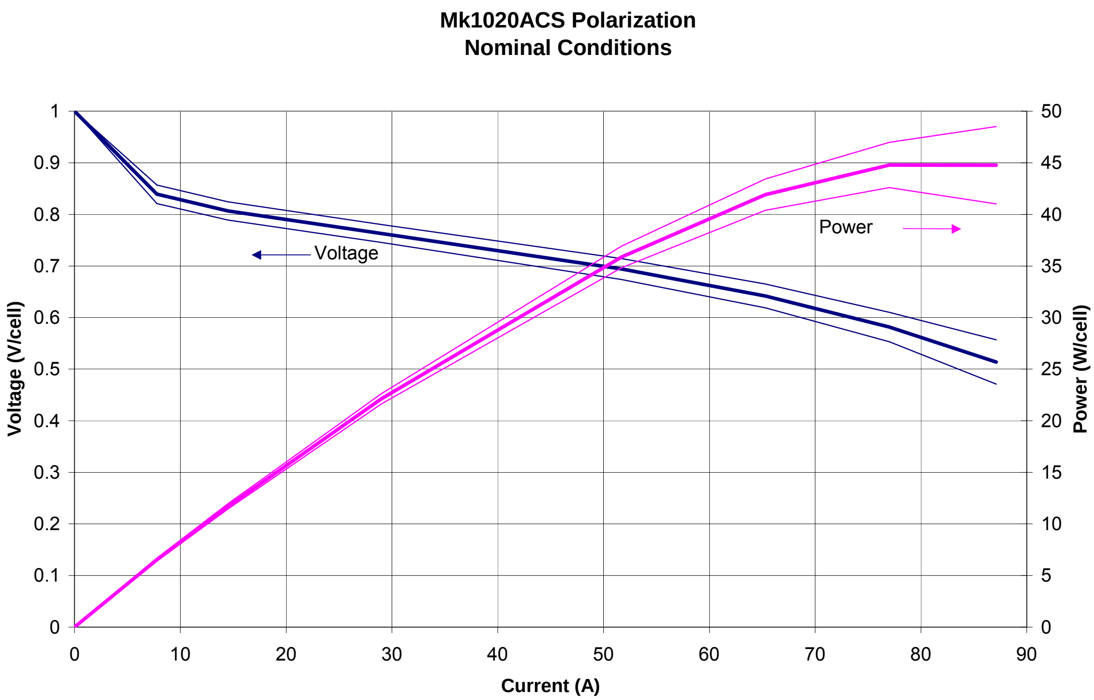


Figure 4 Nominal Polarization

The following equation models the nominal BOL polarization of the Mark1020 ACS fuel cell stack over its working current range.

Equation 4-1 Estimated Nominal Polarization Characteristic

$$CV = -0.0019 \times i^3 + 0.268 \times i^2 - 14.34 \times i + 973.6$$

$$\begin{aligned} &\mathrm{CV} = \text{average cell voltage, mV} \\ &\mathrm{i} = \text{stack current, A} \end{aligned}$$

4.1.1. Polarization Hysteresis

Measured average cell voltage for a given current may be slightly higher than nominal just after a decrease in current. This "boost", or hysteresis, is a characteristic of the Mark1020 ACS fuel cell stack and is temporary. After a short time the stack will return to steady-state conditions. The amount of the temporary boost varies from about 20 mV at low stack currents to about 40 mV at higher stack currents.

4.2. Cell-to-Cell Voltage Deviation

The standard deviation of average cell voltage between Mark1020 ACS stacks at rated power (65A), BOL nominal conditions is 12mV.

The usual standard deviation of voltages between the individual cells in a Mark1020 ACS stack at BOL is ~10mV. A standard deviation up to 20mV is acceptable as long as no individual cell voltage is more than ~50mV from the average. A greater standard deviation may indicate a fuel supply problem, or other issue with the stack.

4.3. Stack Degradation Rate and Lifetime

The original design target for the lifetime of a Mark1020 ACS stack was 500 hours and 500 on/off cycles with air on the anode before reaching End-of-Life (EOL).

There are generally two key life-limiting failure modes that will prevent the stack from performing as required in a given application: voltage loss and fuel leakage. Voltage loss is seen as a steady degradation in maximum power. Fuel leakage will lead to both an increase in fuel consumption, and H2 emissions in the coolant air exhaust stream.

While the definition of specific failure criteria will differ depending on the application, Ballard has used the following End-of-Life (EOL) criteria to measure Mark1020 ACS stack lifetime:

Average cell voltage at 65.3 A drops to less than 564 mV

OR

Anode leak rate increases to more than 6.5 cc/min per cell (tested with nitrogen at 0.5 barg)

Testing has demonstrated that the Mark1020 ACS stack has a mean lifetime of approximately 1000 on/off cycles under a worst-case duty cycle typical of a backup power application, and using the failure criteria described above. Lifetime depends primarily on the number of on/off cycles that occur with an air-filled anode. Other factors, such as the number of operating hours, are less significant.

If lower voltage or higher leakage are acceptable in the application, of if a more benign duty cycle is used, the Mark1020 ACS stack will be able to be operate beyond these limits.

In general, to maximize stack life, avoid the following conditions:

- Non-optimal startup procedure (inadequate startup purge or high cell voltage during H2 fill, as described in Sections 6.1.1 and 5.4.1.1)
- Fuel starvation (for example, due to inadequate operating purge, or operating for significant periods of time below optimal operating temperature)

沒有適當的Purge造成電池堆內部積水，因此氫氣反應量不夠。

- Leakage in the anode loop or fuel system that allows either:
  a) Slow ingress of fuel into an air-filled stack after shutdown
  b) Slow ingress of air into a fuel-filled stack after shutdown
- High operating temperatures (operating for significant periods of time above optimal operating temperature)
- Contaminants in the coolant/oxidant air
- Contaminants in the fuel
- Ripple currents from the Balance-of-Plant (BOP) power conversion subsystem

從BOP系統回饋的不穩定電流，有可能造成STACK損壞，因此需要隔離。

✸ *NOTE: Stack lifetime is highly dependant on the application. Please contact an Applications Engineer at Ballard for assistance in determining achievable lifetimes in your application.*

5.0 OPTIMAL PROCESS INTERFACE AND OPERATING CONDITIONS

The following sections explain the optimal process interface and operating conditions for the Mark1020 ACS stack as well as the range of allowable conditions. The integrator should follow these recommendations to get best performance, maximum lifetime and stable operation from the Mark1020 ACS fuel cell stack.

5.1. Working Current Range

The working current range for a new, fully conditioned Mark1020 ACS stack is 0 A to 87 A. A maximum operating current of 75A is recommended.

Operating the stack above the peak gross power point should be avoided. Figure 4 shows the peak gross stack power for a new, fully conditioned stack occurs close to 87 A. Since higher current results in lower power, there is no benefit in operating at higher currents. Also, the stack operating point will be unstable at currents higher than peak gross power.

Furthermore, it is advisable to allow for some buffer between the maximum operating current and the expected peak power point:

- Increasing current when operating near the peak power point results in relatively little gain in available power, while significantly increasing the risk of stack instability.
- The peak power point will shift whenever there is a drop in stack performance from nominal (e.g. due to degradation over lifetime, operation at off spec. conditions, extreme ambient conditions, or extended storage times). The peak power point shifts slightly to the left (lower current) as the stack performance degrades; typically the peak power point occurs at an average cell voltage around 0.5V.

Stack lifetime testing was performed at a maximum operating current of 65A.

5.2. Optimal Operating Temperature

The Mark1020 ACS stack operating temperature is the temperature measured by the stack temperature sensor(s) located at the coolant/oxidant outlet. The Mark1020 ACS stack is provided with the temperature sensors installed. The Mark1020 ACS stack operating temperature is not the same as coolant outlet temperature.

The optimal operating temperature (Topt) of the Mark1020 ACS stack is the operating temperature at which the optimum combination of stack performance and cell stability is achieved. At this temperature, the stack is operating near its optimum humidity point. The optimum temperature varies depending on stack current, from about 42°C at 7.5 A to about 66°C at 78 A; this is shown in Figure 5. Equation 5-1 can be used to estimate the optimal operating temperature as a function of current.

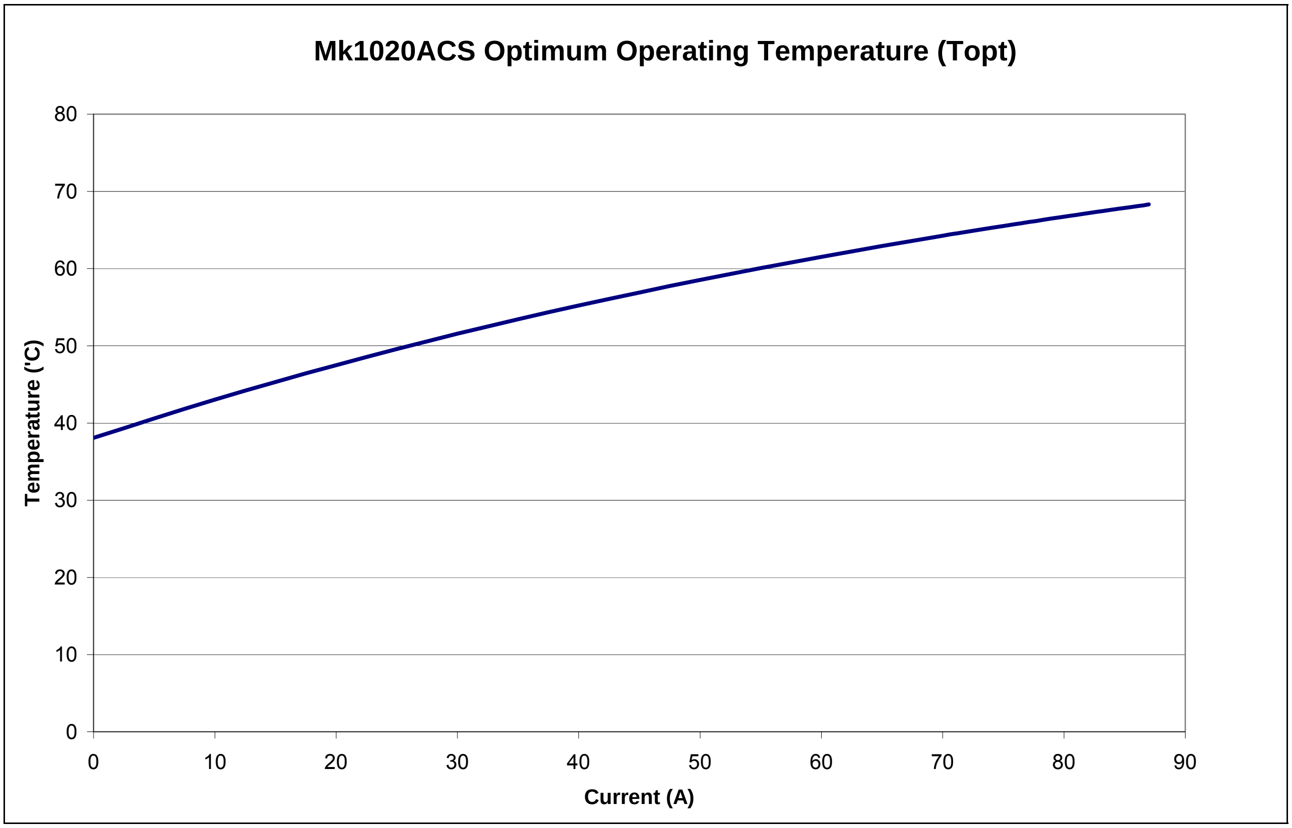


Figure 5 Optimal Operating Temperature

Equation 5-1 Estimated Optimal Operating Temperature

$$T_{opt} = 52.204 \times (1 - e^{-0.010i}) + 38.095$$

$$\mathrm{T_{opt}} = \text{optimal operating temperature, } {}^{\mathrm{o}}\mathrm{C}$$
$$\mathrm{i} = \text{stack current, A}$$

The curve and equation above are valid across the range of coolant/oxidant inlet temperatures. Optimal operating temperature will vary slightly from stack to stack, and will be slightly dependant on the ambient relative humidity. Both of these effects are minor and should not require a change in the definition of Topt. However, for applications where stack performance is very critical and maximum stack voltage is required at all times, it may be possible to define the optimum operating temperature more precisely depending on stack characteristics and ambient environment conditions. Contact Ballard if more information is required on these effects.

Figure 6 shows that the sensitivity of stack performance to operating temperatures increases as the current increases. Stack performance is relatively stable within the band shown, and will begin to drop outside of this range. This results in the requirement for more precise control of cooling flow at higher currents.

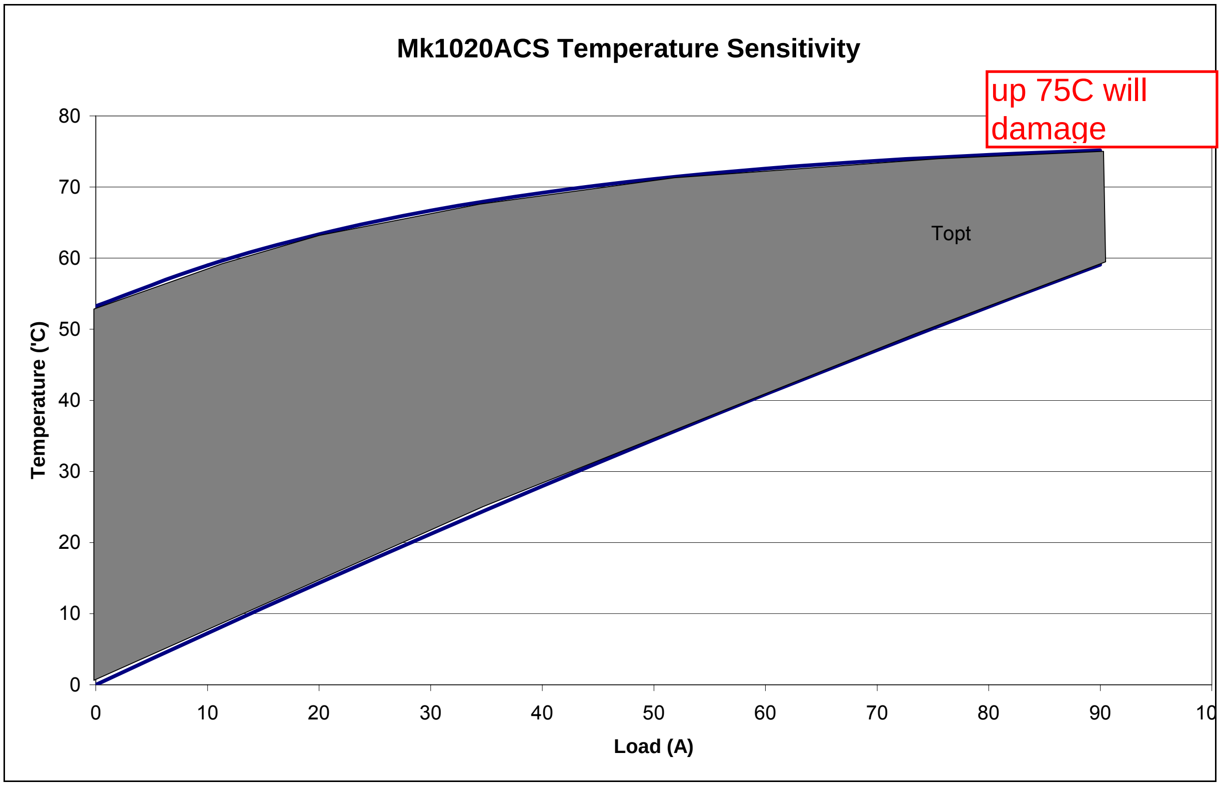


Figure 6 Performance Sensitivity to Operating Temperature

WARNING

The fuel cell stack can reach a temperature of 70° C or higher if operated outside the specification. Avoid touching exposed components during or shortly after operation

WARNING

Operating at temperatures above 75°C or higher may result in stack damage and/or cell reversals due to cell dehydration. Stack current should be reduced before the stack reaches this critical temperature, and operation of the fuel cell stack should be stopped if stack temperature exceeds 75°C.

Operation at higher or lower than optimal operating temperature will result in reduced performance as shown in Figure 7. The reduction in performance can be estimated using Equation 5-2 and Equation 5-3.

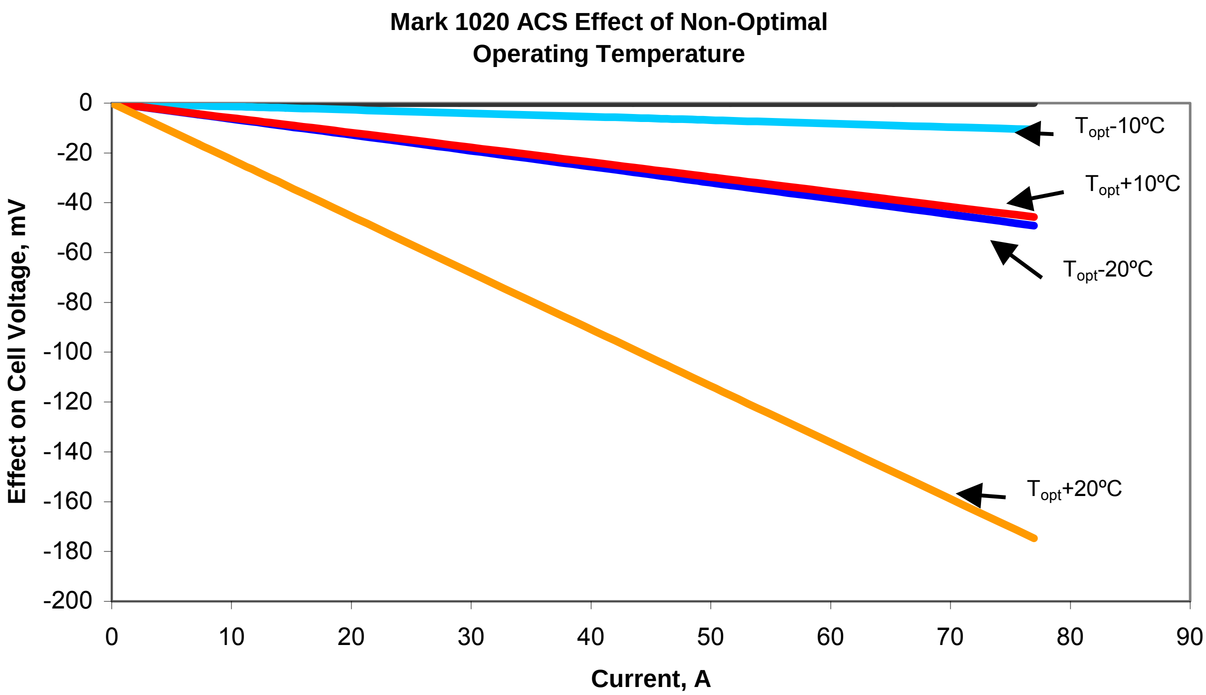


Figure 7 Effect of Operating Temperature on Performance

Equation 5-2 Estimated Reduction in Performance When Operated at Temperature Higher Than Optimal

$$\Delta CV = \left[0.13575 \times (T_{act} - T_{opt})^2 + 0.13032 \times (T_{act} - T_{opt})\right] \times -0.03990 \times i_{stack}$$

$\Delta\mathrm{CV}$ = difference in cell voltage from nominal, mV

= CV_{act} - CV_{nom}

$\mathrm{CV}_{\mathrm{nom}}$ = nominal cell voltage, mV

$\mathrm{CV}_{\mathrm{act}}$ = actual cell voltage, mV

$\mathrm{i}_{\mathrm{stack}}$ = stack current, A

$\mathrm{T}_{\mathrm{opt}}$ = optimal operating temperature, $^{\circ}$C

$\mathrm{T}_{\mathrm{act}}$ = actual operating temperature, $^{\circ}$C

Equation 5-3 Estimated Reduction in Performance When Operated at Temperature Lower Than Optimal

$$\Delta CV = \left[-2.954\times10^{-3}\times(T_{opt}-T_{act})^2+7.315\times10^{-3}\times(T_{opt}-T_{act})\right]\times0.61711\times i_{stack}$$

ΔCV = *difference in cell voltage from nominal, mV*

= CV_{act} - CV_{nom}

CV_{nom} = *nominal cell voltage, mV*

CV_{act} = *actual cell voltage, mV*

i_{stack} = *stack current, A*

T_{opt} = *optimal operating temperature, ^oC*

T_{act} = *actual operating temperature, ^oC*

As general guidance, the stack should be operated as close to Topt as possible, and no more than 5-10°C above or below Topt for any significant period of time. Operation above 75°C can lead to stack damage.

Note that it can take several minutes to reach steady-state performance once the stack temperature is changed. The equations above may not apply after either very short or very long run times. For example, stack voltage is normally better than expected while the stack is cold during startup. Also, *worse* performance than expected can occur during long runs:

- Operating above Topt will lead to stack dehydration, causing stack performance to gradually drop over time. This may also reduce stack life, because the higher temperature will accelerate development of leaks. For example, operating the stack at 75°C instead of the recommended 60°C at 51.7 A will reduce stack lifetime by about 50%.

- Operating below Topt may lead to liquid water accumulation in the anode flow-fields ('flooding'), and resulting cell voltage instability. The flooded cells may also have areas of anode fuel starvation, resulting in cell damage and non-reversible performance loss. Extreme fuel starvation causes cell voltage reversal, which can lead to significant stack damage. Obviously, during certain operating states such as during cold start-up and following a large load increase, the stack will be operating below optimum temperature. To minimize the risk of fuel starvation, the stack should not be operated more than 1000 Amp-seconds per °C below Topt. Testing has shown that, for steady state operation, no cell instability will occur until approximately 150,000Amp-seconds below Topt (independent of number of °C below Topt); however, for operation that is expected to include significant power transients or sub-freezing operation, the former value of 1000 Amp-seconds per °C below Topt is more conservative.

長時間處於最佳工作溫度下，STACK壽命會變短，甚至造成積水。

5.3. Coolant / Oxidant

The cooling and oxidant flows are combined into a single stream in the Mark1020 ACS stack.

5.3.1. Flow Requirement

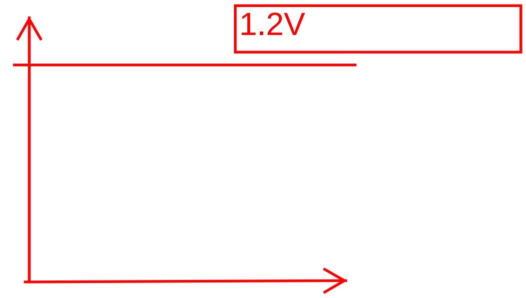
The Mark1020 ACS stack must receive enough cathode air flow to satisfy both the cooling flow and the oxidant flow requirements. For most operating conditions the flow requirement for cooling is higher so the cooling requirement fixes the flow rate. However, the requirement for oxidant flow determines the air flow requirement in the following conditions:

- Operation at low power settings with very cold coolant/oxidant inlet air.
- During startup or upward transients. The optimal stack operating temperature increases with current and the stack has some thermal capacitance, so the increase in cooling flow will lag the increase in current.

5.3.1.1 Cooling Flow

The amount of flow required to cool the Mark1020 ACS stack depends on the number of cells, the operating point (voltage and current), the stack operating temperature, and the coolant/oxidant inlet air temperature. The required flow can be predicted using Equation 5-4 below.

Equation 5-4 Estimated Cooling Flow Requirement



$$Q_{stack} = Q_{cell} \times n_{cell}$$

$$Q_{cell} = 82.161 \times \left[\frac{q_{cell}}{T_{stack} - T_{in}} \right]^{1.35}$$

$$q_{cell} = (E - v_{cell}) \times i_{stack}$$

$\mathrm{Q_{stack}}$ = total cooling air for stack, $\mathrm{slpm_0}$

$\mathrm{Q_{cell}}$ = cooling air flow per cell, $\mathrm{slpm_0}$

$\mathrm{n_{cell}}$ = number of cells in stack

$\mathrm{q_{cell}}$ = heat produced per cell, W

$\mathrm{T_{stack}}$ = stack operating temperature, °C

$\mathrm{T_{in}}$ = cooling / oxidant flow inlet temperature, °C

E = maximum EMF of the cell when product water is produced as vapor

= 1.2545V at 50°C

$\mathrm{v_{cell}}$ = cell voltage, V

$\mathrm{i_{stack}}$ = stack current, A

Note: The required coolant flow as predicted by Equation 5-4 is an estimate only, and should be validated for extremely high or low ambient temperature cases. Stack cooling characteristics may change; leading to a requirement for higher flows than predicted under extreme high temperature conditions, and lower flows than predicted under extreme low temperature conditions.

In an operating system, the controls should adjust the amount of coolant/oxidant flow to control the stack temperature, measured by the included temperature sensor, to its optimal operating temperature (per Section 5.2 above).

5.3.1.2 Oxidant Flow

The Mark1020 ACS stack provides maximum performance with an oxidant stoichiometry between 50 and 200. There is some performance loss for stoichiometries less than 50. The loss becomes more significant if the oxidant stoichiometry is less than 20. The stack must have a minimum oxidant stoichiometry of 10 to function.

Equation 5-5 Oxidant Stoichiometry

Stoichiometry = $\mathrm{Q_{stack}}$ / (C * I * $\mathrm{n_{cell}}$)
$\mathrm{Q_{stack}}$ = total cooling air for stack, slpm
C = Air Consumption, 0.0167slpm/A/cell
$\mathrm{n_{cell}}$ = number of cells in stack

Figure 8 shows the effect of oxidant stoichiometry on stack performance. The predicted performance loss can be estimated using Equation 5-6.

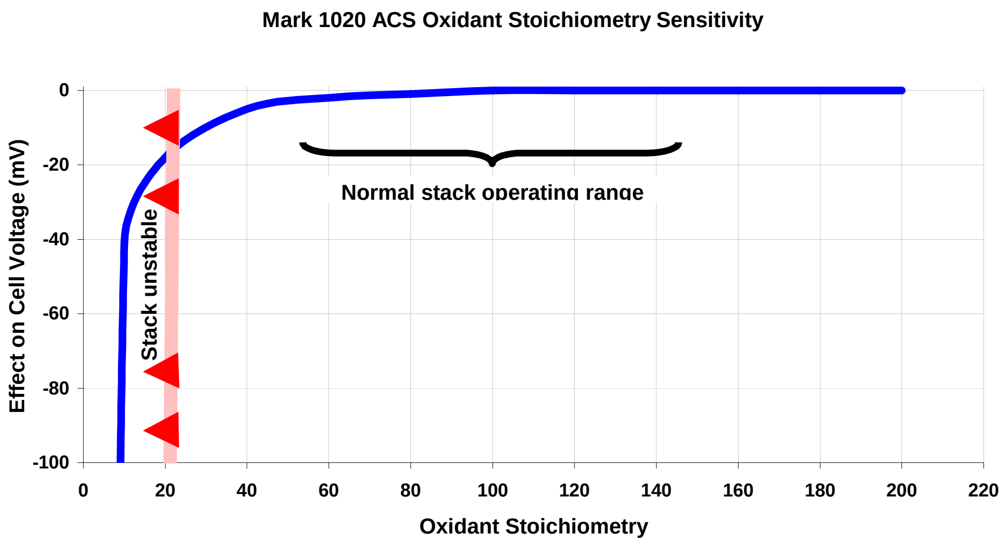


Figure 8 Effect of Oxidant Stoichiometry on Mark1020 ACS Stack Performance

Equation 5-6 Estimated Reduction in Performance When Operated at Low Oxidant Stoichiometry

$$\Delta \mathrm{CV} = -\frac{0.4363}{\lambda - 5} \qquad (\text{for } \lambda > 5)$$

$$\Delta \mathrm{CV} = \text{difference in cell voltage from nominal, \%}$$

$$= \frac{\mathrm{CV}_{act} - \mathrm{CV}_{nom}}{\mathrm{CV}_{nom}}$$

$$\mathrm{CV}_{nom} = \text{nominal cell voltage, mV}$$

$$\mathrm{CV}_{act} = \text{actual cell voltage, mV}$$

$$\lambda = \text{air stoich}$$

5.3.1.3 Uniformity of Flow

The coolant/oxidant air inlet flow rate should be uniform across the air inlet face of the Mark1020 ACS stack. This can normally be achieved by using fans to pull air through the stack, rather than mounting fans at the air inlet and blowing air through the stack. The negative pressure zone created at the air outlet will act to distribute airflow evenly through the stack.

The best indication of even coolant flow is the temperature distribution across the stack air inlet or air outlet face. A temperature difference of up to ~8°C from the end cells to the middle of the stack, and ~6°C along the length of one cell is typical for full-power operation in normal room temperature ambient conditions. For reference, a typical temperature distribution is shown in Figure 9. Temperature deviations significantly larger than this may be an indicator of uneven air flow distribution.

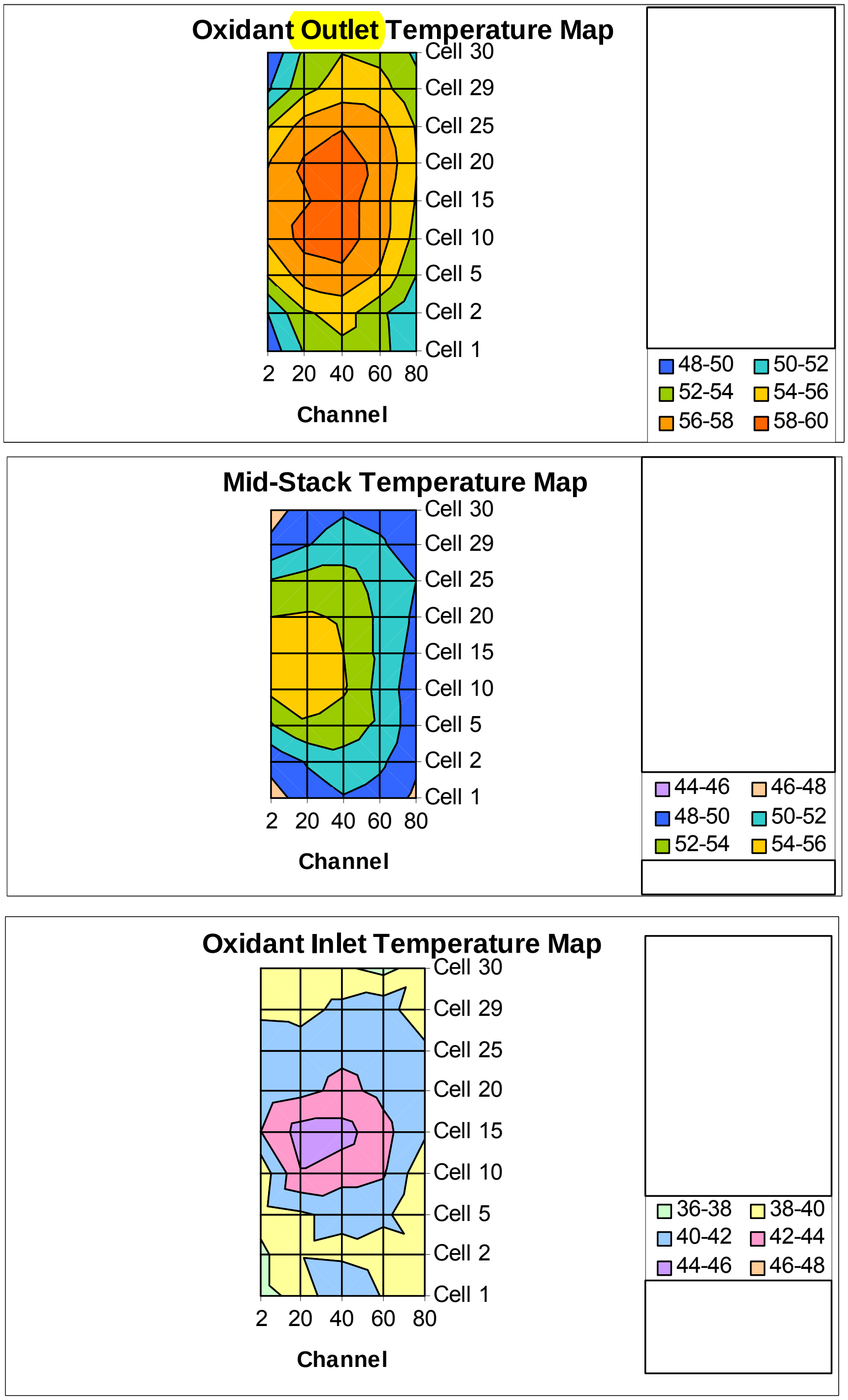


Figure 9 Mark1020 ACS Stack Typical Temperature Map at 52A, 20°C Ambient

5.3.1.4 Passive Operation

The Mark1020 ACS fuel cell stack is able to provide about 2-7 watts per cell with no active coolant/oxidant flow through the cathode. As long as the cathode inlet and outlet are not blocked, diffusion and convection provide some cooling and oxidant.

This ability may be useful as failure mitigation, or as a means of attaining sufficient fan turndown under very low ambient temperature conditions. Operating the Mark1020 ACS stack without active cooling as a normal operation is not recommended.

5.3.2. Pressure/Altitude

The effect of reduced coolant/oxidant inlet pressure on stack performance will be the same whether the reduced pressure is a result of altitude or a result of restriction in the air supply ducting. This section gives pressures as equivalent altitudes because effect of reduced coolant/oxidant inlet pressure on Mark1020 ACS stack performance was measured by operating the stack in an altitude chamber.

The Mark1020 ACS stack is designed for coolant/oxidant inlet pressures/altitudes of sea level to 1500 m. Within this range, inlet pressure/altitude has a slight effect on stack performance. The Mark1020 ACS stack has proven to be able to produce power with coolant/oxidant inlet pressures/altitudes up to 7600 m. Reduced stack performance was observed at inlet pressures/altitudes above 1500 m in a test of the stack installed in a module.

Figure 10 illustrates the effect of coolant/oxidant air inlet pressure on Mark1020 ACS stack performance. The effect can be estimated using Equation 5-7.

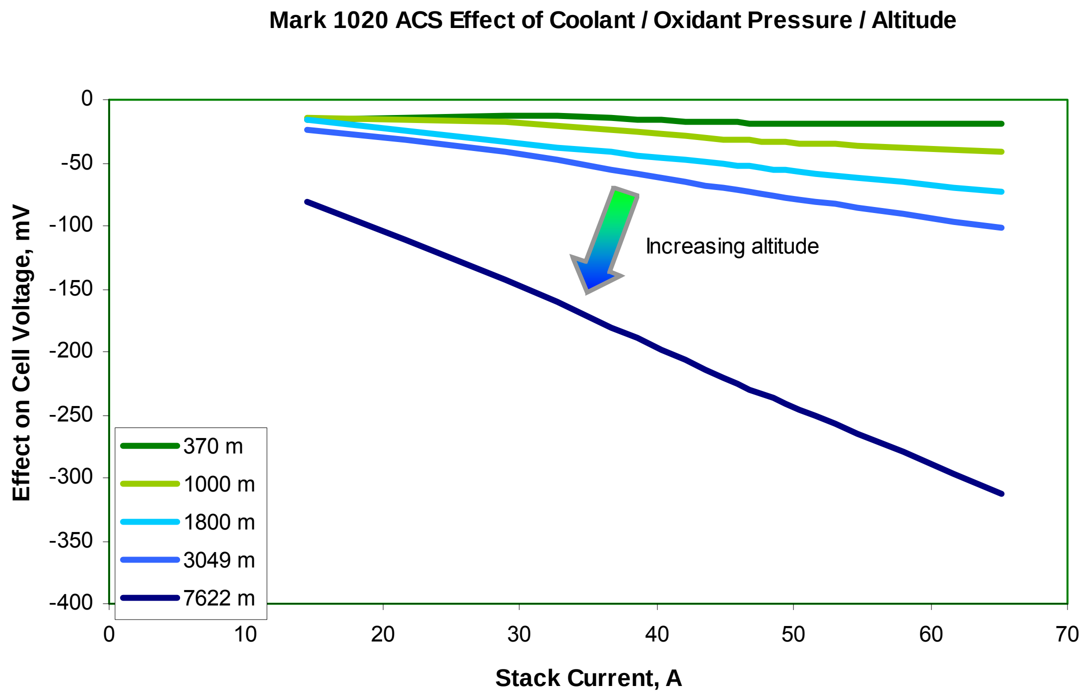


Figure 10 Effect of Coolant / Oxidant Inlet Pressures / Altitudes on Stack Performance

Equation 5-7 Estimated Effect of Coolant / Oxidant Inlet Pressures / Altitudes on Stack Performance

$$\Delta CV = -58.89 \times \frac{[i_{stack} \times alt]}{100{,}000}$$

$$\Delta \mathrm{CV} = \text{difference in cell voltage from nominal, mV}$$
$$= CV_{act} - CV_{nom}$$
$$\mathrm{CV_{nom}} = \text{nominal cell voltage, mV}$$
$$\mathrm{CV_{act}} = \text{actual cell voltage, mV}$$
$$\mathrm{i_{stack}} = \text{stack current, A}$$
$$\mathrm{alt} = \text{altitude, m ASL}$$

5.3.3. *Temperature and Humidity*

The Mark1020 ACS stack provides the best performance when the coolant/oxidant air inlet temperature is between 10°C and 40°C. As shown in Figure 11 below, stack performance is only slightly sensitive to air inlet temperature in this range. The Mark1020 ACS stack was designed to operate with coolant/oxidant inlet air temperatures ranging from 3°C to 51°C.

5.3.3.1 Low Temperature Operation

Operation has been demonstrated with inlet air temperatures of –20°C without performance loss. Operation has been demonstrated at temperatures as low as –45°C; however, performance drops by about 40% at these low temperatures, and it becomes very difficult to prevent over-cooling the stack, especially at low currents. This performance loss is fully recoverable when ambient temperature rises.

5.3.3.2 High Temperature Operation

Air inlet temperatures above about 40°C result in some performance loss as shown in Figure 11. Operation with coolant/oxidant air inlet humidity from 0% RH to 90% RH has been demonstrated - for a given inlet air temperature, stack performance increases with increased inlet humidity. Also, there is an interaction between the effects of coolant/oxidant inlet air temperature and coolant/oxidant inlet air humidity. Figure 11 shows that higher inlet humidity mitigates the performance loss normally seen with inlet temperatures above 40°C.

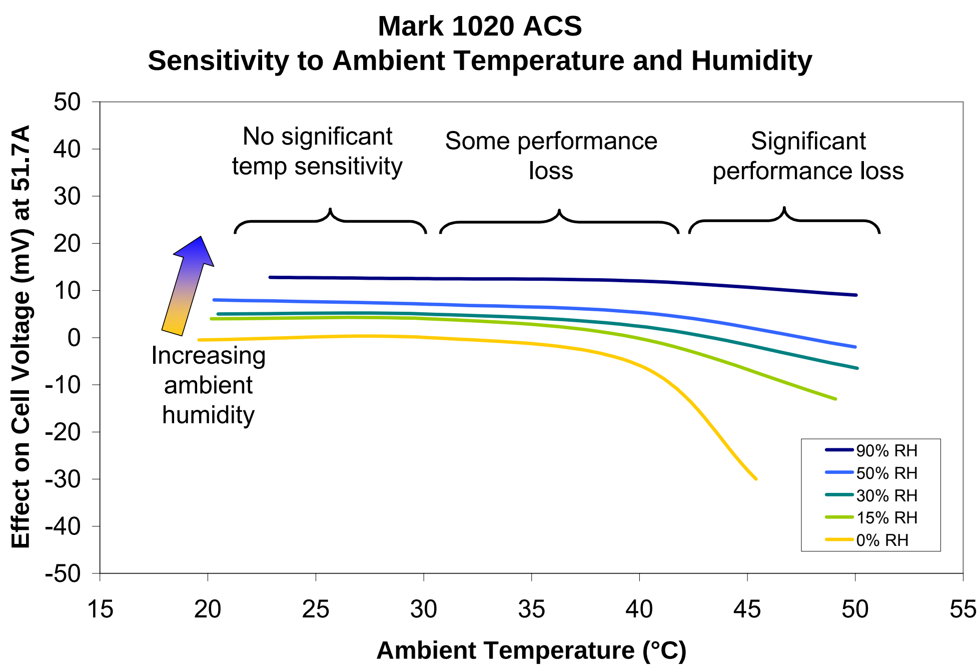


Figure 11 Effect on Coolant/Oxidant Air Inlet Temperature and Humidity on Performance at 51.7 A

The effects of coolant/oxidant inlet air temperature and relative humidity on Mark1020 ACS stack performance shown above can be estimated using the equation below. In general, the stack experiences greater voltage drop under hot/dry conditions at extreme high or low operating currents, with less voltage drop experienced at intermediate current (see Figure 12). The effect of ambient RH and temperature above 40°C is approximately linear. Note that the equation results may not exactly match the data shown in Figure 11 and Figure 12, since these equations are based on a larger data set than shown.

Equation 5-8 Estimated Combined Effects of Coolant/Oxidant Inlet Air Temperature and Humidity

$$\text{for } I > 0,\ T_{in} > 40:$$

$$\Delta CV = \left(-73.40 + 2.974 \cdot I - 0.03935 \cdot I^2\right) \cdot \left(\frac{T_{in} - 40}{12}\right) \cdot \left(\frac{0.95 - RH}{0.85}\right)$$

$$\text{for } I = 0 \text{ or } T < 40$$

$$\Delta CV = 0$$

where:

ΔCV = difference in cell voltage from nominal, mV

$= CV_{act} - CV_{nom}$

CV_{nom} = nominal cell voltage, mV

CV_{act} = actual cell voltage, mV

I = stack current, A

T_{in} = inlet air temperature, ^{o}C

RH = relative humidity, decimal percent

Mark1020 ACS stack performance also becomes more sensitive to deviations from optimal *stack* operating temperature as the coolant/oxidant air inlet temperature increases above 40°C. Higher inlet humidity mitigates this effect.

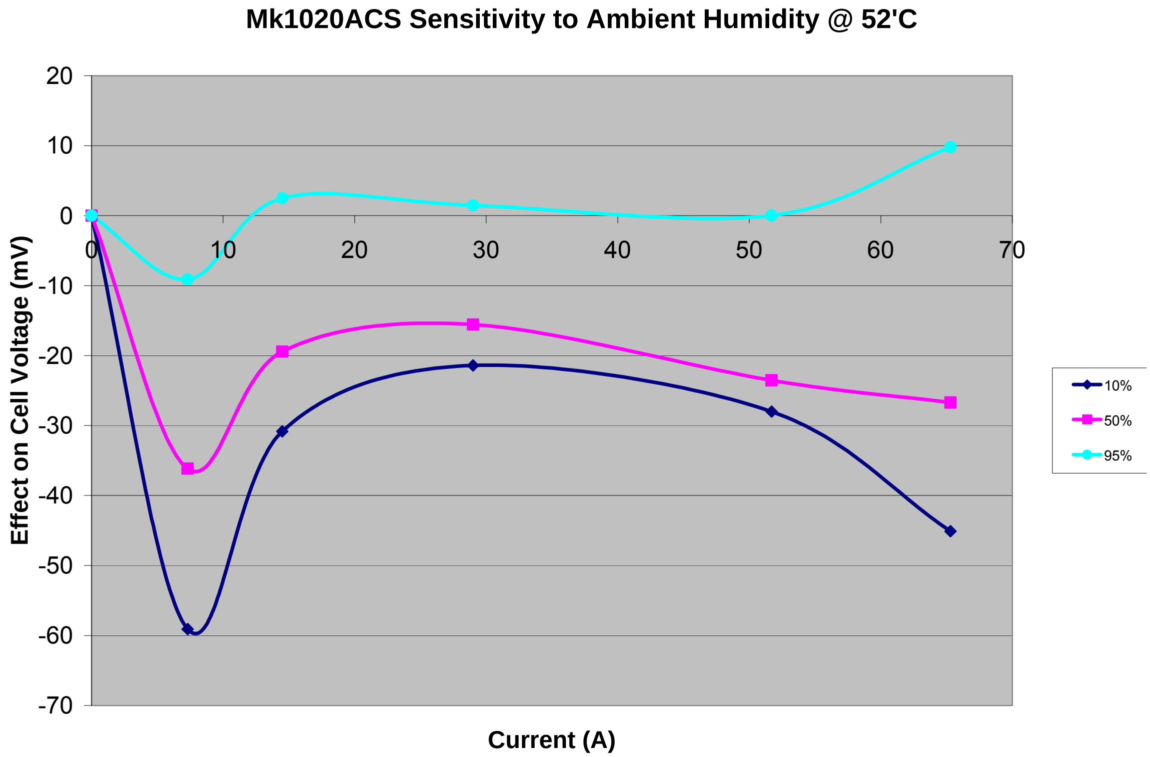


Figure 12 Effect of Ambient Relative Humidity at 52°C Air Inlet Temperature

Operation under hot/dry air inlet conditions may also result in a gradual decrease in stack performance over extended operating times. Figure 13 shows that cell performance drops by about 0.4W/cell/hour under 52°C, 30% RH conditions at 59A load.

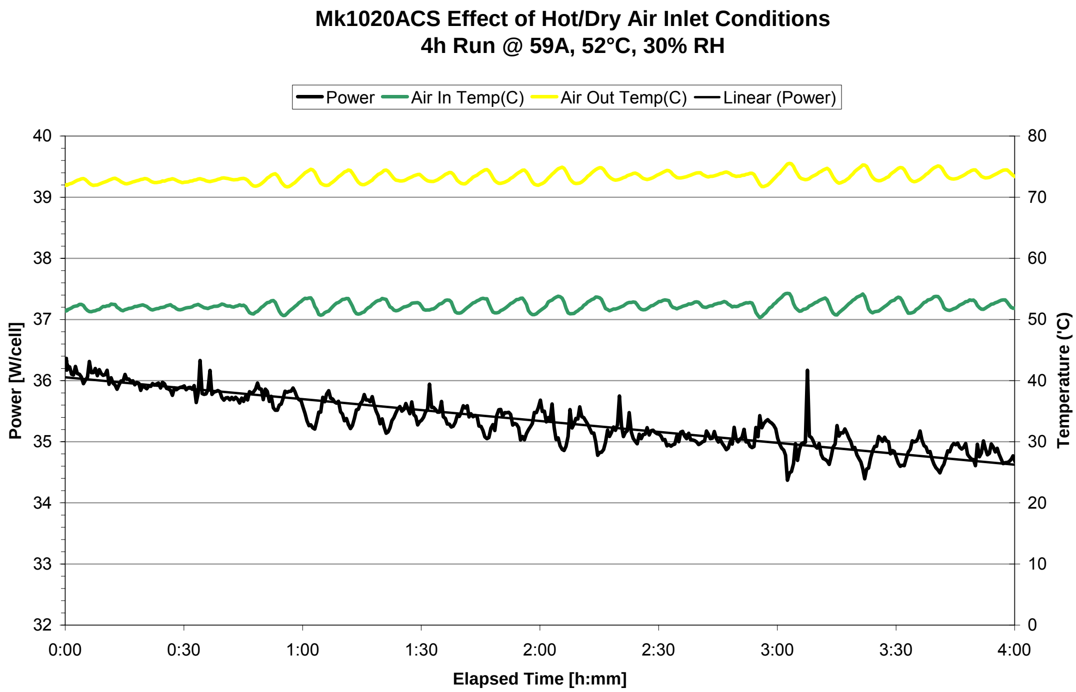


Figure 13 Effect of Hot / Dry Ambient Conditions over Extended Run Times

5.3.4. Cathode Pressure Drop Characteristic

The Mark1020 ACS stack cathode pressure drop can be calculated using Equation 5-9. Typical air pressure drop and flowrates required to maintain optimum stack operating temperature are shown in Figure 14.

Equation 5-9 Estimated Cathode Pressure Drop Characteristic

$$DP/P_{in} = \frac{0.000267 \times S^2 + 0.037625 \times S}{1000}$$

$$S = Q_{cell}\frac{\sqrt{T_{in}}}{P_{in}}$$

Q_{cell} = *inlet air flow rate per cell, slpm*$_0$

S = *corrected inlet air flow rate, slpm*$_0 \cdot \sqrt{K}/kPa$

T_{in} = *inlet temperature, K*

P_{in} = *inlet pressure, kPa for corrected flow equation*

DP = *pressure drop*

[Note that DP/P$_{in}$ *is dimensionless; however, both DP and P*$_{in}$ *should be in the same units in this expression.]*

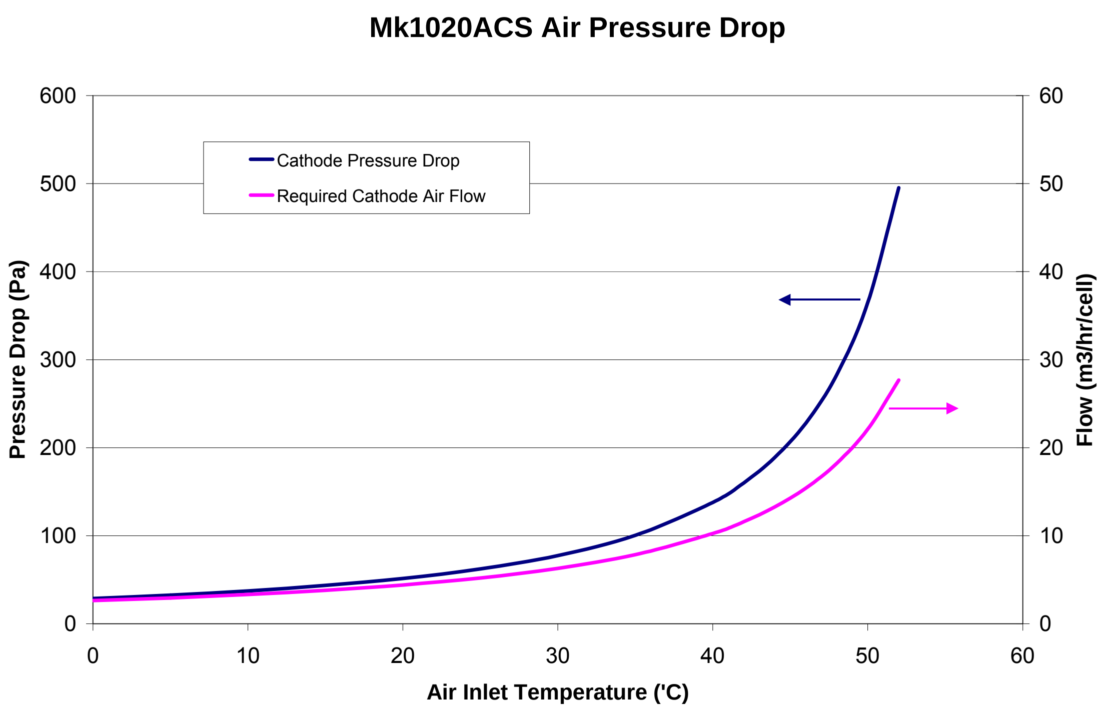


Figure 14 Mark1020 ACS Stack Air Pressure Drop at 65A

5.3.5. Exhaust

The Mark1020 ACS stack coolant/oxidant exhaust is a stream of slightly oxygen-depleted, humidified air. Except under unusual conditions (see Section 5.3.3) the exhaust should contain no liquid water.

The coolant/oxidant exhaust air temperature is not the same as the stack temperature.

5.4. Fuel

5.4.1. Flow and Purge Requirements

5.4.1.1 Startup Purge

The anode side of Mark1020 ACS stack should be purged with fuel as quickly as possible on each startup to avoid premature performance degradation.

After coolant/oxidant flow is started, ~20mL/cell of anode gas must be exchanged in no longer than 200 ms. This requires a flow rate of about 6 slpm per cell during the purge.

If maximum stack cycling life is needed, the startup purge should be completed in 100 ms; this requires a flow rate of about 12 slpm per cell during the purge.

5.4.1.2 Normal (Dead-ended) Operation

The Mark1020 ACS stack was designed for dead-ended operation; that is, all the fuel that enters the anode is used up. In theory there is no anode exhaust and the fuel stoichiometry is one. In practice, water vapor, nitrogen, and other inert gases collect in the anode so the anode must be purged periodically. A small percentage of the fuel is exhausted in the purge so the actual stoichiometry is slightly greater than one.

WARNING

Hydrogen is a colorless, odorless, highly flammable gas. Hydrogen purged from the fuel cell must be managed in a safe manner. It is recommended to direct the purged hydrogen into the inlet of the ventilation fan.

Hydrogen is non-toxic but can cause asphyxiation by displacing the oxygen in the air. There are no warning symptoms before unconsciousness results.

Although reducing the purge frequency or duration can reduce hydrogen emissions and improve fuel consumption, Ballard strongly recommends that if integrators want maximum stack life, they should design their systems to provide frequent and ample anode purges.

WARNING

Failure to provide an adequate purge may lead to fuel starvation, cell reversals, and possibly stack fire.

The Mark1020 ACS stack is designed to have fuel supplied to the anode inlet at constant pressure, usually using a pressure regulator. The anode is purged through an on-off valve at the anode exhaust. The valve is periodically toggled open to exhaust the water vapor and inerts.

Anode purge during operation can be characterized by 3 parameters:

- **Purge Volume**: the total volume of H2 removed from anode during each purge event.
- **Purge Duration**: the time over which each purge event occurs (a shorter purge duration for a given volume = higher purge flow rate)
- **Purge Interval**: the time between individual purges

A **purge volume** of at least 20mL/cell or greater is recommended. Smaller purge volumes may not remove all of the inert gases in the anode. The best sign of an insufficient purge volume is a significant stack voltage drop between purges (or a 'sawtooth' shape in stack voltage over time). With a sufficient purge, stack voltage between purges will remain relatively constant (expect <1-2% change in stack voltage).

The **duration** of the operational purge is not as critical as the duration of the startup purge; however, shorter purge durations will generally result in a more effective purge because of the higher gas velocity. The maximum operational purge duration should be about 500 milliseconds. If the fuel supply pressure is constant across all power settings, the flow rate during the purge will remain constant and purge volume will depend only on the time that the purge valve is left open. Therefore, the purge duration can be kept constant across all power settings.

The optimum **purge interval** is a tradeoff between fuel consumption and stack lifetime. A purge interval of between 2300 and 3800 Amp-seconds (integrated) is optimal for stack lifetime; however, fuel efficiency at rated power is optimized around 5500 Amp-seconds between purges (at even greater purge intervals the drop in stack voltage begins to impact efficiency). Purging less frequently results in greater cell-to-cell voltage variation, which is indicative of some fuel starvation. Fuel starvation can accelerate performance degradation. Ballard lifetime testing was performed with a purge interval of 2300 Amp-seconds.

Figure 15 shows how the Mark1020 ACS stack average cell voltage drops with time as the stack operates without an anode purge, given an adequate purge beforehand. The Mark1020 ACS stack can operate at 51.7 A for up to five minutes between fuel purges without a significant change in stack performance, and for up to 20 minutes without purge before failing because of anode fuel starvation.

1.Nexa Purge 的依據為cell voltage 下降時，啟動purge 功能。
2. 1020ACS 是根據2300Amp-s or 5400Amp-s 來啟動purge 功能，不能使用Nexa的方式來Purge，因為啟動Purge的時間會太慢。

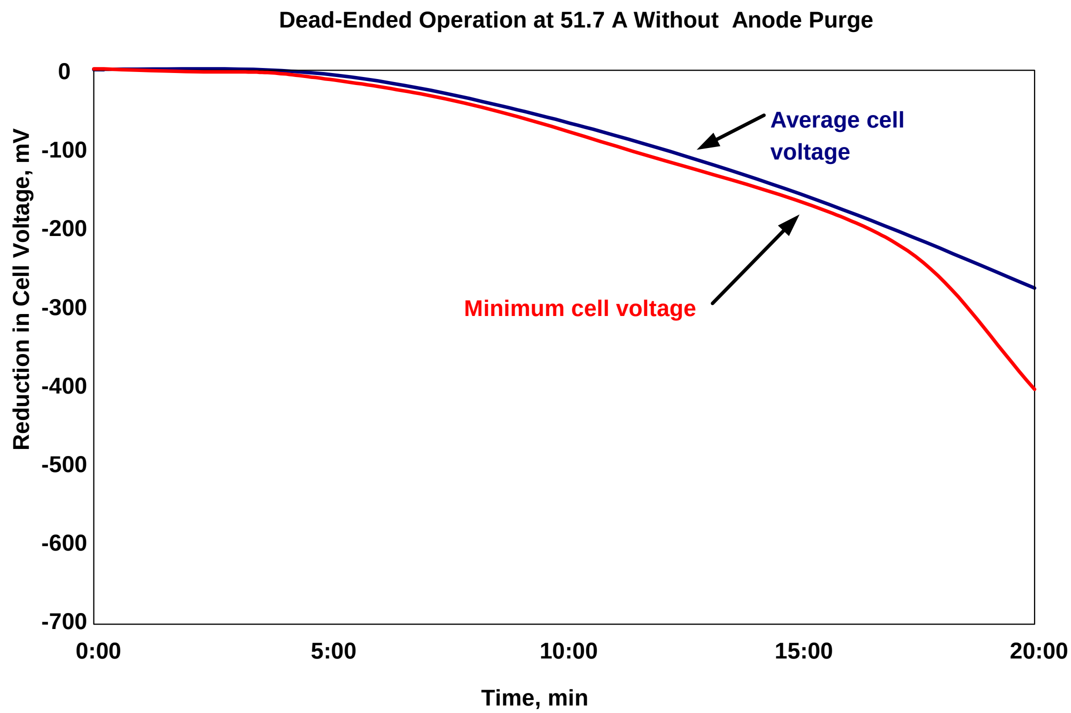


Figure 15 Operation at 51.7 A without Anode Purge

A useful method of measuring the purge volume is to collect the anode purge gas over a series of purges and measure the gas volume. This can be performed by purging into an inverted water-filled graduated cylinder, or some other variable-volume container, as shown in Figure 16.

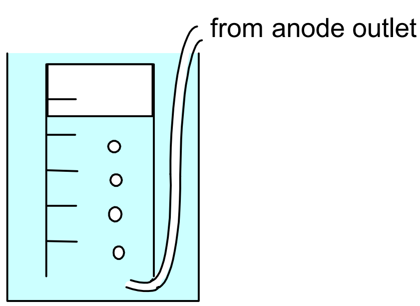


Figure 16 Method of Measuring Anode Exhaust Flow to Develop Purge Duration

5.4.1.3 Flow-through Operation

While the Mark1020 ACS stack was designed for dead-ended operation, it is also able to operate in anode flow-through configuration.

The performance of the Mark1020 ACS stack in flow-through configuration is best when its fuel stoichiometry is greater than 2.5. Figure 17 shows the Mark1020 ACS stack sensitivity to fuel stoichiometry during flow-through operation with humidified fuel.

Integrators should be cautious about operation at high fuel stoichiometries. High fuel stoichiometries may result in reduced performance because the anode may become dry. Ballard has not tested the Mark1020 ACS stack to the fuel stoichiometry at which anode drying starts to occur.

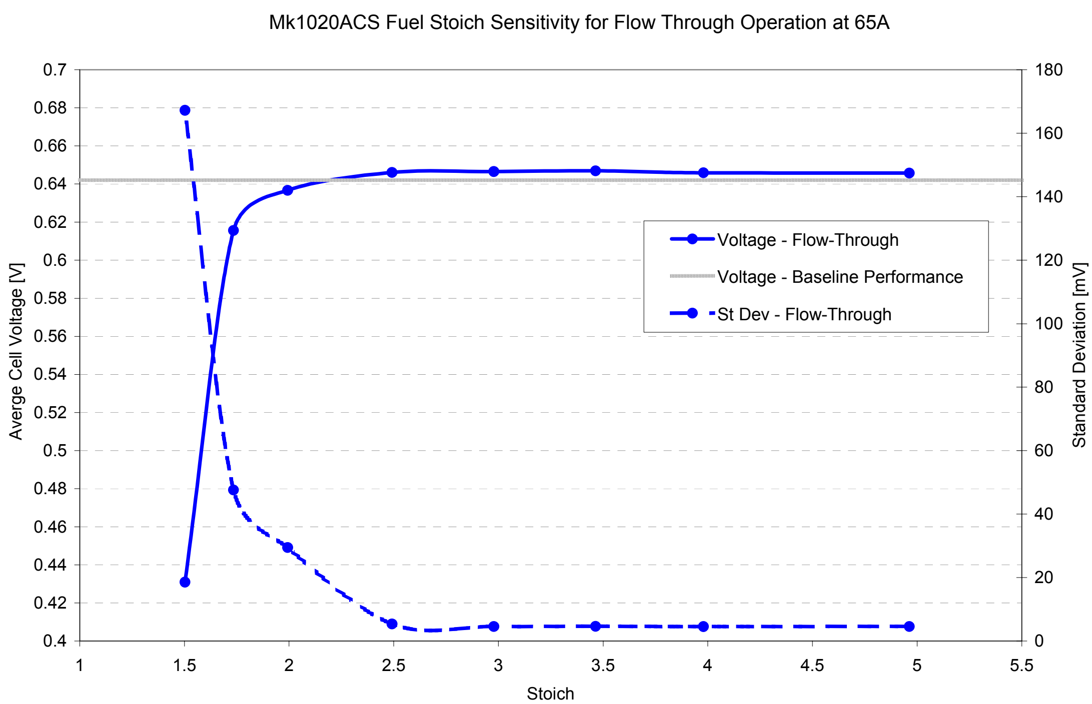


Figure 17 Effect of Fuel Stoichiometry on Performance at 65.3A During Flow-Through Operation

In some flow-through system designs the anode exhaust is re-circulated to the anode inlet, where it mixes with fresh fuel. Ballard has not tested the Mark1020 ACS stack in an anode recirculation configuration. Anode recirculation usually results in increased levels of both inert gases (mainly nitrogen) and water vapor in the anode inlet stream. The effect of the increased inert gas concentration is not known, although the Mark1020 ACS stack can probably tolerate a low concentration. However, high anode inlet humidity can cause reduced performance, unstable operation, and long-term damage (see Section 5.4.4 below).

5.4.2. Pressure

The nominal fuel pressure for the Mark1020 ACS stack is 136 kPa (absolute). The stack is able to operate in dead-ended configuration with fuel inlet pressures ranging from 116 kPa to 156 kPa. Stack damage is expected above 200kPa (see Table 2). The use of a pressure relief device or other fail-safe mechanism to avoid stack overpressure is recommended.

WARNING

The fuel cell stack and associated system uses pressurized gases, which can be hazardous. Use caution and ensure circuits are de-pressurized before opening any lines or fittings.

Do not exceed the maximum allowable operating pressure of the stack (200kPa).

The Mark1020 ACS stack is only slightly sensitive to variations in fuel pressure within the allowable range. Figure 18 shows that there is a slight performance improvement with increasing fuel pressure (without changing purge duration - the performance improvement is primarily attributable to the increased fuel purge at higher pressures). The effect of fuel pressure on Mark1020 ACS stack performance can be calculated using Equation 5-10.

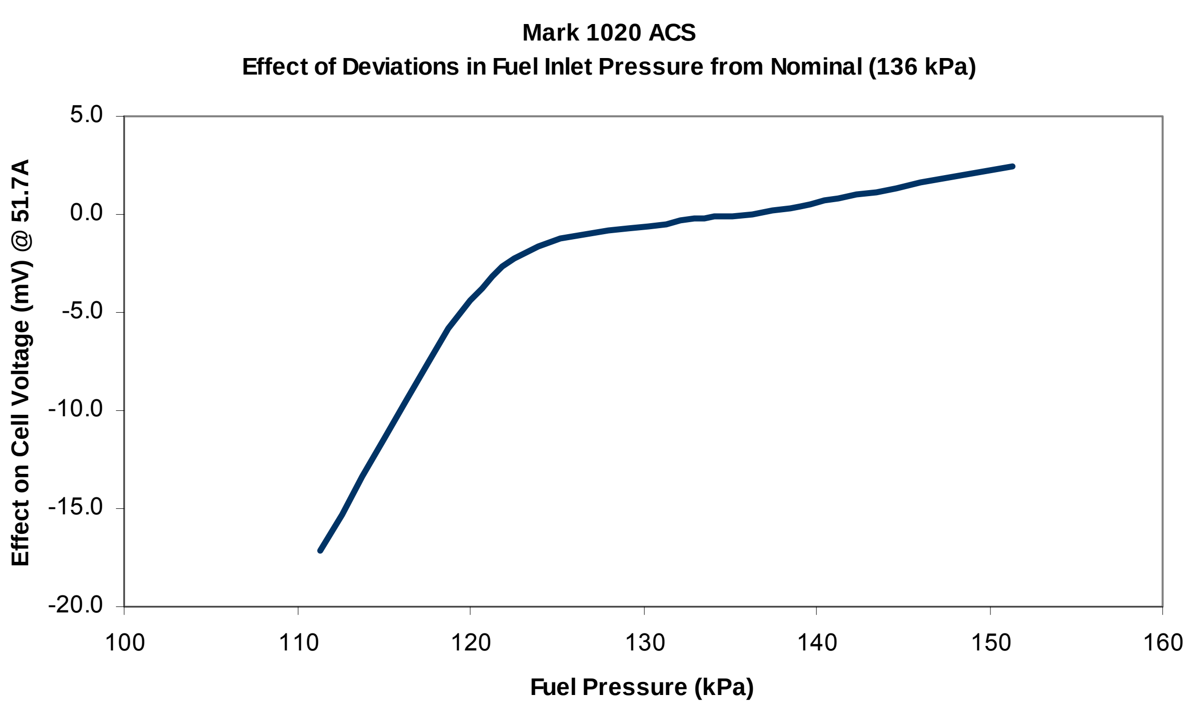


Figure 18 Effect of Fuel Inlet Pressure on Stack Performance at 51.7 A

Equation 5-10 Estimated Effect of Fuel Pressure on Mark1020 ACS Stack Performance at 51.7 A

$$\Delta CV = -3.6580 \times 10^{-5} \times P^4 + 2.0174 \times 10^{-2} \times P^3 - 4.16504 \times P^2 + 381.6851 \times P - 13104.6545$$

$$\Delta CV = \textit{difference in cell voltage from nominal, mV}$$
$$= CV_{act} - CV_{nom}$$
$$P = \textit{Fuel inlet pressure, kPa}$$

The Mark1020 ACS stack anode leak test is performed with air or N_2 at 150kPa (0.5 barg).

5.4.3. Temperature

The Mark1020 ACS stack was designed to operate with fuel inlet temperatures of -15ºC to 65ºC (see Table 2).

5.4.4. Humidity

The Mark1020 ACS stack is designed for use with dry hydrogen; no external humidification is required.

While the Mark1020 ACS stack can probably tolerate some inlet humidity, the anode is not designed for liquid water removal. High fuel inlet humidity will cause cell flooding. When liquid water blocks the flow of fuel in the anode, fuel starvation occurs and the cell voltage will drop. This can cause unstable operation. In the longer term, fuel starvation accelerates performance degradation.

Ballard has not tested the Mark1020 ACS stack to characterize the fuel inlet humidity conditions at which anode flooding will occur.

5.4.5. Quality

The Mark1020 ACS stack has been designed to withstand 500 hours of operation and 500 on-off cycles using commercial Grade 3.5 hydrogen (99.95% H_2 concentration), as specified in Section 3.4. Stack performance meets the specification in Table 1 when using Grade 3.5 fuel with the standard recommended purge parameters.

Operation using Grade 2.6 hydrogen (99.6% H_2) at the standard purge conditions results in a significant performance loss, and is expected to result in significant non-recoverable degradation in performance. Operating with lower grade fuel requires optimizing purge frequency to improve stack performance.

Stack durability testing was performed using 99.999% pure (Industrial Grade 5) hydrogen. The impact on stack lifetime of using Grade 3.5 hydrogen is unknown.

5.4.6. Anode Pressure Drop Characteristic

The anode side of the Mark1020 ACS stack has a very low resistance to flow. When the stack is installed in a system, the stack anode pressure drop will probably be small compared with the pressure drop of the fuel piping and valves.

The Mark1020 ACS anode pressure drop can be calculated using Equation 5-11. This equation is for pure hydrogen as described in Table 4. If the anode flow is a mixture of gases (if the system uses anode recirculation), the pressure drop will be higher. Note that the data used to derive this equation was gathered on a 10-cell stack at flows <1slpm/cell, and may not be accurate for larger stacks or higher flows.

Equation 5-11 Estimated Mark1020 ACS Stack Anode Pressure Drop Characteristic

$$DP = 8.96 \times Q_{cell}$$

$$\mathrm{DP} = \text{pressure drop (mbar)}$$

$$\mathrm{Q_{cell}} = \text{inlet hydrogen flow rate per cell, slpm}$$

5.4.7. Exhaust

When the Mark1020 ACS stack operates in a dead-ended configuration using dry hydrogen fuel, the anode exhaust consists mainly of water vapor and inert gases, plus a small amount of hydrogen. The anode exhaust does not normally contain liquid water until after the flow stream pressure has dropped (by passing through the purge valve, for instance) or the flow stream has cooled. Liquid water may form in the anode exhaust line after system shutdown as water vapor cools and condenses.

When the Mark1020 ACS stack operates in a flow-through configuration, the anode exhaust will contain water, inert gases, and hydrogen. The amount of hydrogen will depend on the fuel inlet stoichiometry. If the inlet fuel is dry, the water will be in vapor form. If the inlet fuel contains water vapor, there may be liquid water in the exhaust. (See Section 5.4.4 above.)

5.5. Ambient Environment

For the Mark1020 ACS stack, coolant/oxidant air inlet conditions are usually the same as ambient conditions. If the coolant/oxidant air is supplied from somewhere other than the immediate stack environment, the coolant/oxidant supply conditions may be different from the ambient conditions. In such installations it is more important to control the coolant/oxidant air inlet conditions than the ambient air conditions.

5.5.1. Pressure/Altitude

The Mark1020 ACS stack is designed for standby, startup, and operation at ambient pressures/ altitudes of sea level to 1500 m. Standby, startup, and operation at pressures/altitudes up to 7600 m have been demonstrated.

5.5.2. Startup and Operating Temperatures

The Mark1020 ACS stack was designed to operate in ambient temperatures ranging from 3°C to 51°C and to stand by and start up in ambient temperatures up to 50°C. Startup from ambient temperatures of –10°C to +52°C has been demonstrated, and stable operation is possible at ambient temperatures from –20°C to +52°C.

5.5.3. Humidity

The Mark1020 ACS stack was designed for standby, startup, and operation at an ambient humidity of 0%RH to 100%RH (non-condensing). Standby in environments with less than ~5%RH may significantly impact stack startup time.

5.5.4. Contaminants

Operating with contaminant levels below those specified in Table 4 will guarantee stack performance over the full product lifetime. Exposure to higher contaminant levels is possible, but will generally result in some performance drop; this performance loss may or may not be recoverable.

If the operating environment is expected to be very dusty, filtration of the oxidant air may be required.

For most applications, pollution-based lifetime performance degradation will not be significant, so chemical filtration should not be required. In general, the worst case pollutants are Sulphur-containing compounds such as SO_2 or H_2S; these can cause irreversible damage to the cell. NO_x are commonly-occurring pollutants that can also cause significant performance degradation; however, testing has shown that NO_x contamination is reversible.

Figure 19 shows the results of testing at various concentrations of SO_2 and NO over a 4-hour, 65A steady state run. In this testing, the voltage loss caused by NO contamination was fully recoverable, while the SO_2 contamination was non-recoverable.

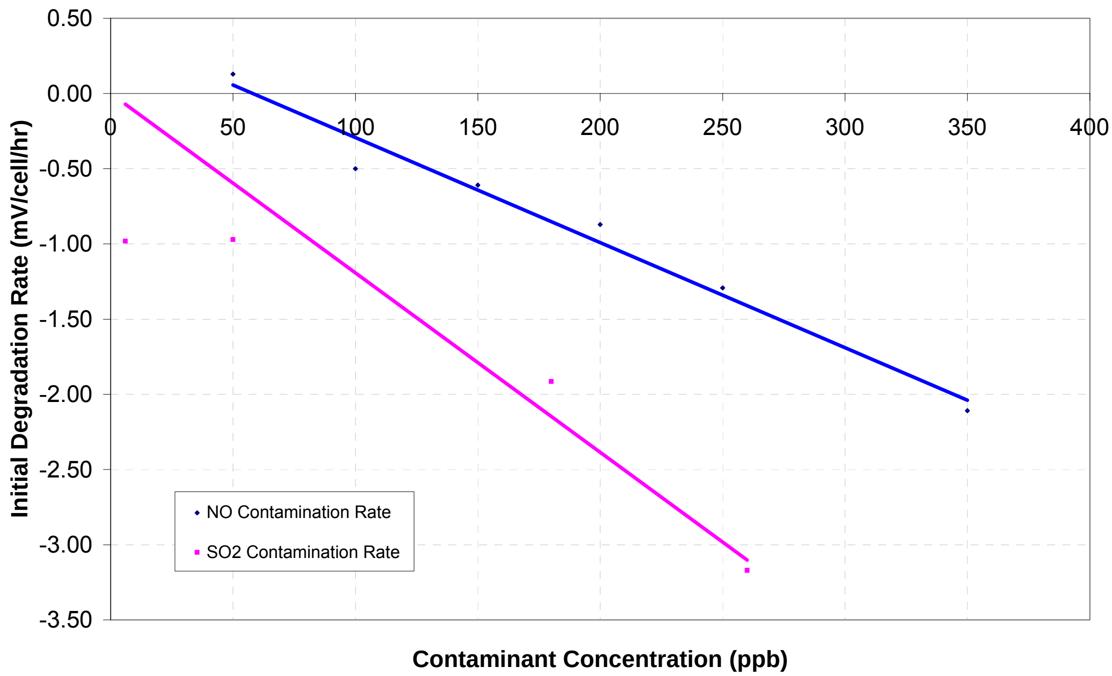


Figure 19 Initial Degradation Rate due to NO & SO_2 Contamination at 65A Steady State

Note that for longer-term exposures to airborne contaminants (>>4 hours), the degradation rate is not expected to be linear. The voltage loss caused by a given concentration of contaminant will reach a lower limit. Figure 20 shows the expected voltage loss, based on modeling, for 300-hour steady-state exposures to various concentrations of SO_2.

When selecting chemical filters for a given application, the long-term voltage loss over lifetime may be a more critical parameter. This design choice is complicated by the fact that some or all of the voltage loss may be recovered by standard shut-down/startup cycles that includes air on the anode and air-starvation procedures such as current pulsing (per Section 6.3).

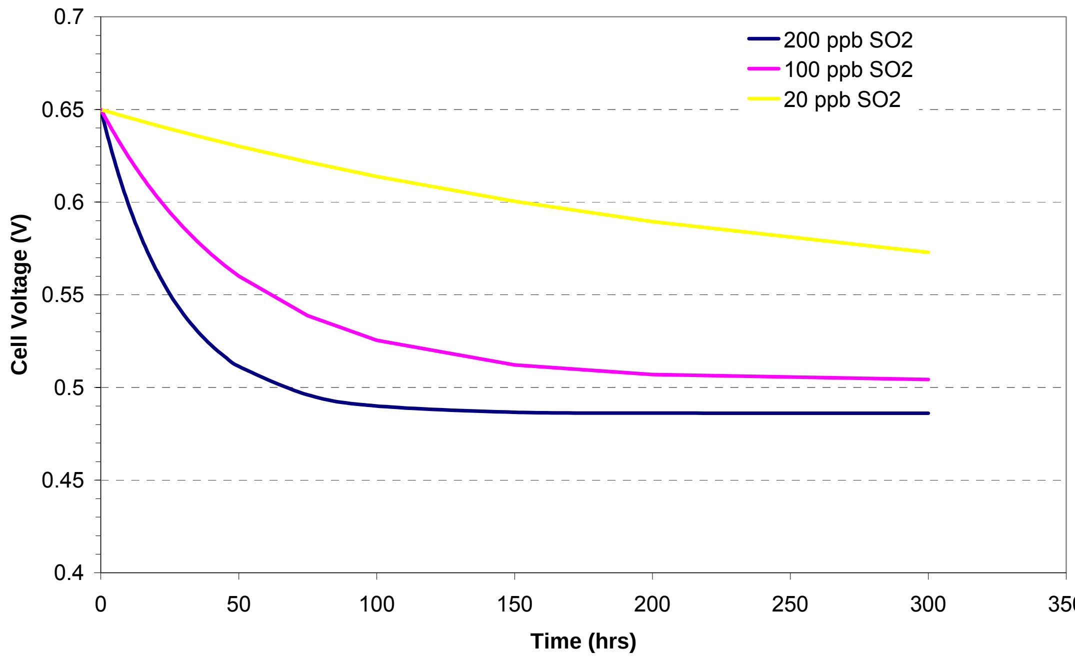


Figure 20 Model Results of Expected Long-Term Degradation due to Contaminant Exposure at 65A Steady State

Similarly to chemical contaminants, operating at particulate contamination levels below those specified in Table 4 will guarantee stack performance over the full product lifetime. However, testing has demonstrated that the Mk1020 ACS stack is quite robust to particulate contamination.

Particulates smaller than 5μm or larger than 30μm are unlikely to impact stack performance, so any filtration should focus on particle sizes from 5-30μm. Smaller particulate sizes appear to pass through the stack without falling out of suspension. Larger particulate sizes drop out of suspension before entering the stack.

Particulate contamination at a concentration of up to 90mg/m³ can be expected to result in a performance loss of only ~3% at 65A over a 1500 hour lifetime. This is based on an observed experimental performance loss of ~20 mV/cell (3%) at 65.3 A after 120 hours of particulate exposure at a concentration of 1 mg/m³. Voltage loss due to particulate contamination becomes worse at higher currents.

6.0 STACK OPERATION

6.1. Transients

6.1.1. Startup

WARNING

The fuel cell stack may contain residual voltage when not operating. Exercise caution when working with the stack. Residual reactants within the stack can rapidly develop a charge, even when there is no fuel flow and the stack has been short-circuited. A reading of zero volts across the entire stack does not guarantee that all cells are uncharged.

The startup procedure for the Mark1020 ACS stack is as follows.

1. Start coolant/oxidant airflow.
2. Apply startup load.
3. Complete the startup fuel purge (see Section 5.4.1.1).
4. Remove startup load.
5. Begin normal operation.

The startup load in step 2 should be used for applications where maximum stack lifetime is required. The intent is to ensure there are no high cell potentials during the startup fuel purge, as these will reduce stack cycling life. The load should be high enough to bring the average cell voltage down to around 500 mV per cell, and should be controlled to ensure there are no cell reversals; typically a load of around 15A will be appropriate. Large startup loads, or shorting the stack during the H2 fill, will cause some cells to go into reversal. Ballard recommends determining the effectiveness of the startup load by testing on a development unit that has individual Cell Voltage measurement.

Mark1020 ACS stack startup time depends on the temperature and relative humidity during standby, the storage time, the load, and the characteristics of the BOP. Table 9 lists estimated startup times based on constant-load (65A) startups at the minimum air stoic of 20. Bridging energy is an estimate of the amount of energy required to substitute for power from the stack during the startup under these conditions.

Table 9 Estimated Mark1020 ACS Stack Startup Time

Soak Temperature (°C)	Time to 80% stack power (min:sec)	Time to 100% stack power (min:sec)	Required Bridging Energy (J/cell)
20	0:20	1:35	340
0	1:00	2:51	1080
-10	1:20	3:47	1660

The time required for the Mark1020 ACS stack to reach steady-state power depends mainly on the time that is required for the stack to reach the optimal operating temperature for the target current. The following can help accelerate the startup:

- Minimize stack voltage as stack is warming up (draw as much load as possible). High current/low voltage operation will produce more heat, accelerating warm-up time.
- Keep coolant flow to a minimum (by ensuring sufficient fan turn-down).
- Perform an air starve for a few seconds after the fuel purge is complete; that is, reduce the air flow to an oxidant stoichiometry of less than 20 or pulse the air flow on and off (see Section 6.3).
- Perform several current pulses following startup (see Section 6.3). Current pulses are better than air-starve procedures for minimizing bridging energy requirements for startup.

Temporarily air-starving the Mark1020 ACS stack on startup may also help to recover Non-Operating Performance Loss (NOPL). See Section 6.3 for a discussion of NOPL mitigation.

It is not clear whether current pulsing or shorting during the startup is an effective way to reduce the Mark1020 ACS stack startup time. Excessive current pulsing or shorting may lead to a reduction in stack life.

6.1.2. Shutdown

Shutdown of the Mark1020 ACS stack is straightforward.

- Remove load.
- Turn off the coolant/oxidant airflow and stop the fuel flow.

The Mark1020 ACS stack typically cools down to ambient temperatures in about 30 minutes. Cell voltage bleeds down within about 15 minutes as the anode consumes residual hydrogen. Anode pressure typically falls below ambient (to about 15 kPa to 50 kPa) as the hydrogen is consumed. The anode pressure returns to ambient within about 30 minutes as air diffuses back into the anode. The pressure recovery will be faster if there are leaks in the membrane, seals, or stack hardware connections such as the fuel purge valve. Leaks will also reduce the peak vacuum after shutdown. Both of these measurements can be used to estimate stack leakage.

Ballard does not recommend the use of a bleed resistor to accelerate removal of the voltage from the Mark1020 ACS stack after shutdown. Continuing airflow for several minutes after shutdown should not significantly impact performance for the following startup.

6.1.3. Power transients

The Mark1020 ACS stack responds faster to downward transients than to upward transients. When the load drops the stack responds instantaneously. When the load increases there is a time lag before the stack responds. The Mark1020 ACS stack will immediately provide the increased current but average cell voltage dips below the new steady-state polarization value. Typically the cell voltage will return to its steady-state polarization value within 5 to 30 seconds.

The temporary drop in cell voltage occurs mainly because of the change in optimal operating temperature, and reduced air stoichiometry as the stack is warming up. When the stack current is suddenly increased, the stack is not operating at the optimal temperature for the new current. It takes several seconds for the stack temperature to reach its new optimal value. It may be possible to increase the temperature faster by temporarily reducing coolant/oxidant flow, but the oxidant stoichiometry should not drop below its minimum value (see Section 5.3.1.2).

Ballard recommends an extra fuel purge during or just after each upward transient to improve the transient response. The extra fuel purge ensures there is plenty of reactant available in the anode to provide the new, higher current.

6.2. Cell Voltage Monitoring

Ballard recommends use of a Cell Voltage Monitoring (CVM) device during system development to ensure the system parameters are set to provide optimal stack operating conditions. It is not necessary to measure each individual cell voltage; the cells can be measured in pairs or larger groups. In a final commercial application, the intent is that measuring only the overall stack voltage (from the stack bus plates) will be adequate to ensure safe stack operation.

Note: Ballard does not provide the CVM or the voltage pickup fingers.

Ballard recommends against using the CVM data as a means of controlling system parameters during operation. Theoretically, reactant flows and hydrogen emissions released in the purge could be minimized by monitoring cell voltages and adjusting system parameters as the cell voltages change. In practice, controlling system parameters to CVM feedback usually results in an unstable system, which can lead to frequent shutdowns and reduced stack life.

See Section 4.2 for a discussion of normal cell-to-cell voltage deviation.

6.3. Non-Operating Performance Loss

The Mark1020 ACS stack will experience reversible performance loss during storage. The loss increases with increased storage time and increased storage temperature, but should reach a maximum of no more than 70mV loss per cell. Testing over 13 weeks at worst-case storage conditions resulted in a voltage loss of about 1.5mV/cell/week at 65A.

reversal happen:1.short
2.H2 O2 not enough
3. fire

The performance loss is due to the growth of a reduction resistant oxidation layer on the cathode catalyst, which impedes performance. The degree of Non-Operating Performance Loss (NOPL) can be limited by minimizing the storage time and avoiding high storage temperatures.

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The performance loss is most easily recovered by lowering the cathode potential, causing a reduction reaction on the surface of the cathode catalyst. This serves to remove the catalyst oxide layer and "reactivate" the catalyst. This lowering of the cathode potential can be practically performed in two ways:

1) Operating the fuel cell normally at some high current density. This has been shown to recover NOPL, although typically a significant run time is required (depending on the amount of performance loss). If the Mark1020 ACS stack is exercised regularly, a 15- to 20-minute run is typically enough. If it has reached maximum recoverable performance degradation, from 24 up to 48 hours of operation may be required for full recovery.

2) Briefly starving the cathode of oxygen. This can be done by either removing or reducing air flow while continuing to draw load from the stack (air starvation); or by drawing a brief, very high load that momentarily starves the reaction sites of O2 (current pulse). These procedures are recommended if the application includes significant periods of storage/ stand-by, combined with a requirement for full stack performance in the first few minutes of operation.

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Recommended air starvation procedure:

1. Operate the stack for a few seconds or minutes to ensure adequate membrane hydration
2. Turn reactant air flow supply off, continuing to supply fuel and drawing load from the stack. Generally, a load greater than 15-20A is required to completely starve the cathode of O2, since the open-cathode design of the Mk1020 ACS will always result in some O2 being available for the reaction due to diffusion.
3. Cell voltage should drop to ~0V/cell. Hold this condition for 5-10 seconds, then restart reactant air flow.

Note that the interfacing load must be able to draw current at very low or zero stack voltage for this procedure to be effective.

Recommended current pulsing procedure:

1. Operate the stack for a few seconds or minutes to ensure adequate membrane hydration
2. Apply a brief high-load or short across the stack power terminals. In practice, this is best achieved using a specific shorting device (normally FET based), or using components in the power electronics system. Ballard has most experience with current pulses meeting the specifications outlined in Table 10. A sample current pulse profile is shown in Figure 21.

Table 10 Mark1020 ACS Stack Current Pulsing Specification

Parameter	Specification
Peak Pulse Current	~1000 A
Steady-State Pulse Current	~150 A
Max. Resistance During Pulse	10 mΩ
Max. Pulse Duration	300 ms
Min. Interpulse Period	5 seconds
Min. Fuel Cell Voltage During Pulse	~0.5 Volts
Max. Rise and Fall Time	10 ms

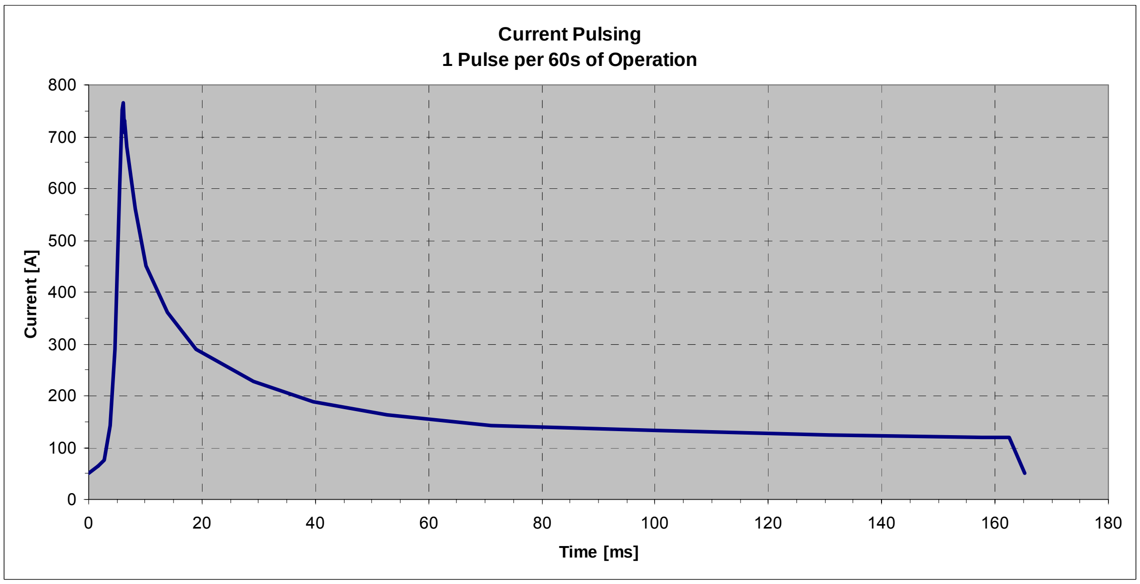

Figure 21 Example Current Profile for Stack Current Pulsing

The stack will generally return to rated power following storage after about 3-5 current pulses; the first current pulse normally recovers about 70-80% of the loss.

Note that current-pulsing or air-starvation can also have the effect of improving stack performance under normal operation. Oxides can build-up on the cathode during steady-state operation (not just storage). Continuing to pulse the stack periodically following startup results in overall improved performance of the stack compared to normal steady-state performance; however, there is a possibility that this operating mode will impact stack durability. There is a small risk that current pulsing causes a small amount of fuel starvation on the anode, leading to MEA damage (oxygen starvation does not cause MEA damage). The risk of damaging the stack from a few current pulses during startup is considered to be quite small; however, lifetime risk of operational current pulsing has not been quantified.

6.4. Dehydration Performance Loss

Initial stack performance during the first few seconds or minutes of startup can also be affected by dehydration of the membrane. Under normal ambient storage conditions, this performance loss typically recovers very quickly (within a few seconds) as the membrane self-hydrates while producing power. This slight difference in performance in the first few seconds of startup between a normally humidified stack and a slightly dehydrated stack is generally not noticeable in terms of bridging energy requirements. However, under some storage/standby conditions, the membrane can become very dry and “deactivate”, leading to considerably longer startup times to full rated power.

Current predictions estimate that at storage conditions below about 5% RH, startup performance can be significantly worse than baseline. The stack may take as long as 3 minutes to reach full power when starting from this dehydrated condition, compared to a normal startup time to full power of 10-20 seconds. This can have significant implications on the amount of energy storage required to start up a fuel cell system.

The best strategy investigated to date for starting up a stack that has been stored under extremely dry conditions is to pull maximum load as early as possible in the startup (down to a voltage of 300-400mV/cell). This high load/low voltage operation will produce the maximum amount of water in the fuel cell to re-hydrate the membrane.

7.0 PHYSICAL INTERFACE CHARACTERISTICS

7.1. Physical Interfaces

7.1.1. Coolant/Oxidant

The Mark1020 ACS stack cooling and oxidant flows are combined into a single stream that flows directly into and out of the cathode channels of the stack.

To maximize efficiency, seal the Mark1020 ACS stack inlet or outlet against the fan or blower ducting by installing a strip of foam (e.g. weather-stripping-type material) between the stack and the duct. Figure 22 shows one example of some typical foam strip locations for air flow sealing. Sealing materials that contact the stack plates must be nonconductive to avoid electrical shorting.

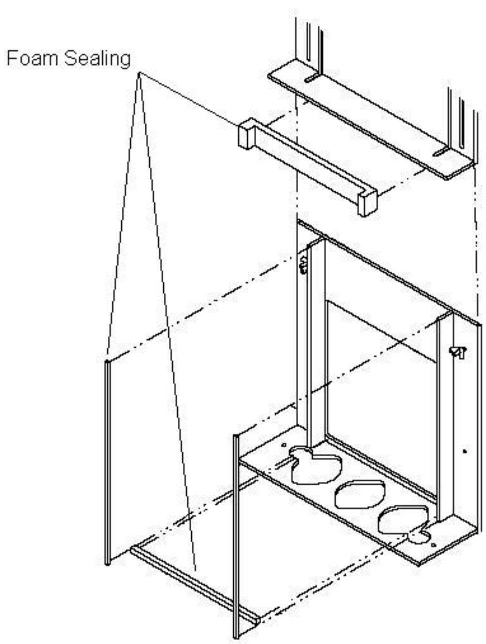

Figure 22 Air Flow Sealing Example

Mark1020 ACS stack product water is normally exhausted as vapor so no water drain is needed at the cathode outlet.

7.1.2. Fuel

The Mark1020 ACS fuel inlet and outlet ports are both located on the anode (-) end of the stack, at opposite corners of the anode. The fuel inlet is on the same side of the stack as the oxidant inlet while the fuel outlet is on the same side of the stack as the oxidant outlet. See Figure 2.

Table 11 Fuel Interface Connection Specification

Type	John Guest PCM2808S "Push-In" tube fitting
Size	5/16" (8mm) OD

The fuel inlet and outlet fittings are John Guest Part # PCM2808S. These are push-fit connectors that accept 5/16" polymer tubing (Teflon recommended); the fittings are also compatible with 8mm tubing. Metal tubing should not be used due to electrical isolation considerations. The fittings contain two O-rings that seal around the outer circumference of the tubing, so the ends of the tubes should not have sharp edges that could damage the O-rings when the tubing is inserted. The tubing must be inserted at least 17mm into the fitting to ensure that the tube clears both o-rings up to the tube stop. The tube should be inspected for any surface damage prior to insertion.

Straight pipe lengths upstream of the inlet connector are not required. Piping from the downstream connector should point to the side or downwards to ensure that any liquid water drains away from the stack. It should not have any low points that could collect liquid water.

Side-load or pull forces on the tube should not exceed 20N.

7.1.3. Stack Mounting

WARNING

Handling the stack has the potential to damage the MEA. Care should be taken to avoid contact with the cathode side of the MEA since it is exposed to the environment.

7.1.3.1 Mounting Orientation

The Mark1020 ACS stack can be mounted in almost any orientation. To ensure that any liquid water in the anode system drains away from the stack:

- The anode inlet fitting should be physically higher than the anode outlet fitting; and
- The anode outlet fitting should be level or point downwards.

7.1.3.2 Mounting Points

Figure 2 and Figure 3 show the general locations of the Mark1020 ACS mounting points, refer to the interface drawing (DRW5109909) for details.

7.1.3.3 Other Mounting Considerations

Mark1020 ACS stack mounting should compensate for thermal expansion or creep over stack lifetime along the mounting length of the stack (see below). This can be done by fixing the anode end plate and allowing the cathode end plate to float, or by using the fixed spring cap on the anode end to mount the stack.

Thermal Expansion (70°C temperature change): +/-0.015mm/cell

Creep over Stack Life: -0.05mm/cell

Do not allow the mounting system to put any bending or twisting moments on the Mark1020 ACS stack.

Note that the anode end of the stack has two mounting options (see Figure 2). The thru-holes can be used with a non-threaded sliding rod to allow for a floating cathode end plate. The threaded holes in the spring cap allow for rigid mounting of the stack, as the spring caps will not move relative to the cathode-end mounting holes. The spring-cap mounting holes are preferred for environments where significant shock or vibration is expected.

7.1.4. Current Collection

The Mark1020 ACS stack delivers electricity from its bus plates; their locations are shown in Figure 1. The bus plate at the anode end of the stack is the negative terminal.

Attach lugs to the conductive inboard surfaces of the bus plates using M6 bolts and nuts, torque 5Nm. Recommended interfacing lugs:

Panduit: LCD6-14A-L (straight), LCD6-14AH-L (45°), LCD6-14AF-L (90°)

Thomas & Betts: 54205 (straight), 54205UF (45°), 54205UB (90°)

7.1.5. Stack Temperature Measurement

The Mark1020 ACS stack is equipped with thermistors (Betatherm P/N 100K6MBD1) with Molex connectors. The required Molex mating connectors are as follows:

Table 12 Stack Thermister Interface Specification

Connector Housing	Molex P/N 43645-0200
Connector Terminal	Molex P/N 43030-0002

The number of thermistors installed on the stack depends on the size of the stack. The thermistor resistance vs temperature table can be found in Appendix A.

7.2. Electrical Integration

7.2.1. Electrical Isolation

Ballard recommends installing the Mark1020 ACS stack as a floating electrical system. Under some circumstances it may be acceptable to connect one of the buses to earth. Contact Ballard for details.

Since the stack will normally be integrated as a floating electrical system, a means should be provided of draining any potential static discharge from the stack. This can be practically achieved by either adding a high-impedance resistance to earth on either the negative or positive stack voltage terminals, or by using a fuel inlet/exhaust tube that has some conductivity.

All metal parts on the stack must be either electrically bonded or live. A means should be provided to prevent people or objects from touching the live parts.

The maximum stack voltage for electrical isolation design of the system is the stack Open Circuit Voltage (OCV) listed in Table 1. The Mark1020 ACS stack is designed with sufficient internal isolation to satisfy a voltage withstand test at 1600 V in a clean, low humidity, sea level environment. (This satisfies the requirements of IEC 62282-2 for a working voltage of up to 250 V.)

The primary current leakage paths for the Mark1020 ACS stack are those typical of any high-voltage electrical equipment. Theoretically, there is also a potential for carbon tracking at the reactant outlets- that is, creation of a potential current leakage path through carbon that sheds from stack anode or cathode and deposits on anode or cathode exhaust lines. While carbon deposits have been noted on the anode exhaust line of the Mark1020 ACS stack operating in the dead-ended configuration, carbon tracking has not been observed. Nonetheless, Ballard recommends that the integrator ensure there is enough creepage distance between the anode exhaust fitting and the purge valve.

The fuel cell stack has a potential for current leakage across clearances and creepage distances. The fuel cell stack installation should be designed with adequate clearances and creepage distances as listed in applicable standards

There is a greater possibility of a carbon track forming at the anode outlet if the stack is operated in an anode flow-through configuration with humidified anode inlet gas. (The anode inlet gas is humidified if anode recirculation is used.)

If Mark1020 ACS stacks are to be installed electrically in series, the integrator must ensure that the total resulting voltage is compatible with the stack withstand voltage noted above. Compliance with most electrical standards requires that:

2 x total voltage of the series + 1000 < stack withstand voltage

The stack withstand voltage may need to be derated if the Mark1020 ACS stack is to operate in a polluted environment or at higher altitudes.

Care should be taken by the integrator to ensure that no conductive foreign material can enter the stack enclosure and become trapped between the stack and any grounded components.

7.2.2. Interactions with Balance-of-Plant

The Balance-of-Plant must not impose a ripple current on the Mark1020 ACS stack that is greater than 10% of the average stack current. Ripple currents below about 400 Hz may cause the stack to be starved of reactants at each current peak.[1] Ripple currents above about 100 kHz may cause the stack to radiate EMI.

The Balance-of-Plant must never apply a voltage or impose a reverse polarity on the Mark1020 ACS stack.

7.3. Material Compatibility

7.3.1. Materials for Wet and Dry Gases

The following materials can be used for any process gas lines, interface fittings or connections:

- Teflon
- PVDF
- Neoprene
- Glass
- Low sulfur content EPDM
- Viton
- Aluminum

7.3.2. Materials for Dry Gases

The following materials may be used for dry gas lines. Do not use these materials for humid gas lines, interface fittings or connections:

- Brass

[1] The value given is for a generic PEM fuel cell stack. A Mark1020 ACS Stack operating in dead-ended mode is probably less susceptible to reactant starvation caused by low frequency ripple currents, because the stack normally operates with very high oxidant stoichiometry and with fuel supplied on demand. Lifetime implications of significant ripple currents on the Mark1020 ACS have not been quantified.

- Copper
- Stainless steel
- Carbon steel
- Zinc
- Buna N

7.3.3. Materials to Avoid

Do not use the following materials for process gas lines, interface fittings or connections:

- Materials that off-gas (usually indicated by an odor)
- Materials containing Fenton's catalysts

Do not use stainless steel near the anode inlet or outlet, where it could become wetted by anode exhaust or by condensed water dripping out of the anode inlet after stack shutdown.

Contact Ballard Power Systems before using materials not specifically mentioned above.

7.4. Other Packaging Considerations

The Mark1020 ACS stack should be protected from contamination from environmental dust, oils, and other pollutants.

8.0 SHIPPING AND STORAGE

8.1. Preparation For Storage

The Mark1020 ACS stack does not require any special operational procedure to prepare it for storage. Use the standard shipping container to protect it against dust and contaminants.

8.2. Shipping and Storage Ambient Environment

8.2.1. Ambient Temperature and Humidity Range

The Mark1020 ACS stack was designed for a shipping and storage temperature range of –40°C to +70°C.

The Mark1020 ACS stack is designed for, and has demonstrated, the ability to withstand up to 36 freeze-thaw cycles with only slight increase in leak rate and no performance degradation. More freeze-thaw cycles may increase fuel leak rates and may cause performance degradation.

Storage at high temperatures will accelerate Non-Operating Performance Loss (NOPL) (See Section 6.3.). If the Mark1020 ACS stack is stored at higher temperatures for longer than the durations shown in Table 13 below, special startup procedures will be required.

Table 13 High Temperature Storage Limits

Storage Temperature Range (°C)	Maximum Storage Duration
3 to 30	2 years
30 to 50	1 month
50 to 70	3 days

The Mark1020 ACS stack was designed for a shipping and storage ambient humidity range of 0%RH to 100%RH non-condensing.

8.2.2. Shock and Vibration

See Table 8.

APPENDIX A

Thermistor Data Sheet

100K6MBD1 100,000 Ohms @ 25°C Tolerance = ±0.2°C from 0°C to 70°C							
Temp (°C)	RValue (Ohms)	Temp (°C)	RValue (Ohms)	Temp (°C)	RValue (Ohms)	Temp (°C)	RValue (Ohms)
-50	8,337,869	-10	612,366	30	79,428	70	15,502
-49	7,743,400	-9	578,321	31	75,912	71	14,944
-48	7,194,826	-8	546,376	32	72,567	72	14,410
-47	6,688,364	-7	516,372	33	69,389	73	13,897
-46	6,220,553	-6	488,178	34	66,365	74	13,405
-45	5,788,455	-5	461,683	35	63,489	75	12,932
-44	5,388,878	-4	436,773	36	60,752	76	12,479
-43	5,019,313	-3	413,344	37	58,149	77	12,043
-42	4,677,268	-2	391,294	38	55,668	78	11,625
-41	4,360,636	-1	370,547	39	53,307	79	11,223
-40	4,067,212	0	351,017	40	51,058	80	10,837
-39	3,795,342	1	32,619	41	48,915	81	10,466
-38	3,543,286	2	315,288	42	46,873	82	10,110
-37	3,309,422	3	298,959	43	44,927	83	9,767.60
-36	3,092,416	4	283,558	44	43,071	84	9,438.10
-35	2,890,843	5	269,041	45	41,301	85	9,121.40
-34	2,703,671	6	255,337	46	39,613	86	8,816.90
-33	2,529,672	7	242,414	47	38,003	87	8,523.80
-32	2,367,900	8	230,210	48	36,465	88	8,241.90
-31	2,217,423	9	218,688	49	34,999	89	7,970.70
-30	2,077,394	10	207,807	50	33,598	90	7,709.70
-29	1,947,006	11	197,521	51	32,260	91	7,458.30
-28	1,825,568	12	187,803	52	30,983	92	7,216.30
-27	1,712,400	13	178,613	53	29,761	93	6,983.40
-26	1,606,911	14	169,924	54	28,595	94	6,758.90
-25	1,508,530	15	161,702	55	27,479	95	6,542.70
-24	1,416,745	16	153,923	56	26,413	96	6,334.50
-23	1,331,059	17	146,560	57	25,394	97	6,133.80
-22	1,251,079	18	139,588	58	24,419	98	5,940.50
-21	1,176,328	19	132,984	59	23,486	99	5,754.00
-20	1,106,485	20	126,729	60	22,593	100	5,574.30
-19	1,041,173	21	120,799	61	21,739	101	5,401.10
-18	980,100	22	115,179	62	20,921	102	5,234.10
-17	922,956	23	109,850	63	20,138	103	5,072.90
-16	869,458	24	104,796	64	19,388	104	4,917.30
-15	819,378	25	**100,000**	65	18,669	105	4,767.30
-14	772,463	26	95,449	66	17,981	106	4,622.60
-13	728,492	27	91,128	67	17,321	107	4,482.90
-12	687,276	28	87,026	68	16,689	108	4,348.10
-11	648,624	29	83,129	69	16,083	109	4,217.80