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200kW Marine Fuel Cell Integration Manual



1. Disclaimer

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

This manual includes certain safety guidelines and recommendations. However, this manual is not intended to cover all situations.

This manual attempt to specify the requirements for most applications, but for applications which may require operation outside of the stated specifications, please contact Ballard Power Systems Europe.

The integrator is responsible for being aware of, and complying with, all applicable laws and regulations.

The integrator is responsible for determining the suitability of the FCwave™ for the particular application and ensuring the safe operation, maintenance, and storage of the device and any systems into which it is integrated.

Ballard Power Systems Europe, Inc. ("Ballard") cannot be responsible for the use of the device in ways, or as part of systems, that deviate from the intended use according to this manual.

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.

Procedures described in any part of the manual can only be attempted once the customer has read this entire manual.

There are inherent risks in the operation of a fuel cell module that can result in death or bodily injury or loss or damage to property.

- It is necessary for the customer to take all prudent safety precautions in the installation, use, and maintenance of this device.
- Persons who install, operate, and service the device are required to be technically qualified and experienced in working with electrical equipment, hot and/or pressurized fluids, and hydrogen.

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. See abbreviation list.

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4. Abbreviations

Acronym	Definition
BOL	Beginning of Life
BOP	Balance of Plant
BPSE	Ballard Power Systems Europe
CAN	Controller Area Network
DI	Deionized
EOL	End Of Life
FC	Fuel Cell
FCM	Fuel Cell Module
FCwave	Product name 200kW Marine Fuel Cell module
H2	Hydrogen (Gaseous)
H2E	Hydrogen Enclosure
IEC	International Electrotechnical Commission
IMO	International Maritime Organization
IP	Ingress Protection Rating
LEL	Lower Explosive Limit (18% vol mix with atmospheric air)
LFL	Lower Flammability Limit (4% vol mix with atmospheric air)
LVC	Low Voltage Connector
MCU	Module Control Unit
PEM	Proton Exchange Membrane (Fuel Cell Technology)
RDU	Remote Data Unit
SVN	Subversion, internal source code repository
UPS	Uninterruptable Power Supply
VCS	Vessel Control System

Table 1 – List of Abbreviations

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5. Reference Documents

Document	Title
7001000-01	FCwave™ 200kW Arrangement Plan
CMS010	Schematic description of Input and Output Circuits
CMS013	Customer CAN Matrix
CMS014	Control System Alarm List
CMS006	Electrical Datasheet

Table 2 – List of Reference Documents

6. General Information

6.1. Scope of Manual

This Integration Manual provides the necessary system requirements for integrating and operating the FCwave™ 200 kW Marine Fuel Cell Module (hereafter referred to as the "module").

It covers topics such as

Expected product performance,
Required system inputs/outputs,
Mechanical/electrical interfaces and control details.

7. FCwave™ Fuel Cell Module Datasheet

Too see the latest revision of the electrical datasheet (CMS006), go to Customer Portal, or contact Ballard Power Systems Europe.

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7.1. Fuel cell module

The major components and features of the module sub-systems are listed below:

- Liquid cooled PEM (Proton Exchange Membrane) fuel cell stacks.
- Built-in control system, control power supplies and control power distribution.
- Independent Safety Controller with separate power supply and safety instrumentation.
- Sensors for voltage, current, pressure and temperature measurements.
- Safety devices, including ventilation system (fans and ventilation exhaust line), fuel pressure relief device, fire detection and hydrogen sensors.
- High voltage contactors for electrically isolating the fuel cell stack from the high voltage output terminals.
- High voltage system pre-charging and reverse current protection during start-up.

Hydrogen (Anode) Sub-system

- Complete hydrogen subsystem, which delivers and conditions the fuel supply to the fuel cell stacks.
- Valve block with integrated hydrogen shutoff, pressure regulation and safety pressure relief device.
- Hydrogen recirculation with purge.

Air (Cathode) Sub-system

- Air compressors and inverter assemblies for supplying process air to the fuel cell module.
- Air mass flow sensor for air flow rate measurement and control.
- Intercooler and humidifier for conditioning the incoming air stream.

Coolant Sub-system

- Internal high-temperature coolant loop, with coolant pump and controller assembly for supplying coolant to the fuel cell stacks.
- Liquid to liquid stainless-steel heat exchanger between internal high-temperature coolant loop and customer coolant loop, able to handle a wide range of coolant media (fresh water, water-glycol mix).
- Electronically actuated control valves used for stack coolant inlet temperature control.
- Separate low-temperature coolant loop to cool motors and motor controllers.

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8. Safety

8.1. Hazard Symbols



WARNING *in this manual indicates 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 *in this manual indicates 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*- Obey ALL warnings, cautions, and safety instruction related to electricity. Failure to do so may result in electrical shock leading to personal injury or death.*

8.2. General Safety



The modules are to be installed in a dedicated fuel cell installation room.

The system integrator is responsible for providing means to lockout energy sources on the system prior to any service activity being performed, and a written procedure to Ballard service personnel detailing the equipment and steps required to sufficiently lock out all necessary energy sources.

- Keep module doors and electrical enclosures closed when the system is operating.
- The module and its auxiliary systems are intended to be serviced only by personnel technically qualified and experienced in handling electrical equipment and compressed/flammable gases
- Remove jewelry, watches, rings, and metal objects on clothing that can potentially cause short circuits when working on the fuel cell module.

8.3. High Temperature Safety



Integrator shall ensure that process exhaust piping is leak tight and touch proof.

- Surfaces on coolant interfaces and the process exhaust can reach up to 80 °C during normal operation.
- Components within the fuel cell module can reach temperatures up to 120 °C during normal operation.

8.4. High-Pressure Safety



The module uses pressurized gases which can be hazardous.

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- Use caution and ensure circuits are de-pressurized before opening any lines or fittings.
- Some sub-systems may remain pressurized even when the fuel cell module is powered off.

8.5. High Voltage Safety



Ballard recommends that the electrical integration of the fuel cell module must be designed under the supervision of a qualified professional electrical engineer.

It is the integrator's responsibility to design the integration of the fuel cell module such that the integration complies with all applicable legislation and requirements.

After shutdown, high voltages may remain on the fuel cell stacks for a duration of time. No maintenance activities are to be performed during this time as the stacks present a shock hazard. Also, residual reactants (oxygen and hydrogen) within the fuel cell module can cause the fuel cell output voltage to rise unexpectedly.

Allow the fuel cell voltage to drop to below 30 VDC prior to servicing the fuel cell module. Certain circumstances can lead to voltage persisting on the fuel cell stack indefinitely.

Always check for residual voltage before any service activity.

Operate the fuel cell module high voltage as a "floating electrical system". Ensure that neither the fuel cell high voltage positive terminal nor the fuel cell high voltage negative terminal is connected to the application ground, earth or chassis.

Before working on the fuel cell module and its auxiliary systems in a floating DC system, it's important to make sure the system is de-energized. This involves checking for near-zero volts in three key areas: between the fuel cell's high voltage positive and negative terminals, between the high voltage positive terminal and the chassis, and between the high voltage negative terminal and the chassis.

Measurements are to be made on both AC volts and DC volts scales.

The monitoring of the isolation resistance of the overall high voltage system shall be done with a device capable of detecting both single and double pole isolation failures.

The system integrator is responsible for ensuring that a suitable ground fault monitoring system is installed and functioning during operation of the fuel cell power system. If the level of electrical isolation is ever deemed unsafe according to regulatory standards, the integrator must provide means for the fuel cell power system to be shut down in case of a ground fault.

Select fuel cell module power output cables that appropriately suit the application.

Ensure that cable specifications meet voltage, current, environmental temperature limits, chemical and mechanical resistance and flexure requirements of the application.

Avoid hazardous and unsafe situations that could result from conditions such as, but not limited to, the following:

Improper grounding
Handling electrical leads or devices with wet hands or on wet ground
Frayed electrical leads

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Incorrect or improper connection of the terminal leads
Short circuits
Back-feed from energized normal and emergency power sources

8.6. High Voltage Isolation Failures



Under normal circumstances both high voltage output terminals (positive and negative) are isolated from the fuel cell module enclosure and low voltage system.

If isolation is lost on one high voltage pole, a person working on the module could sustain a fatal current flow by touching the other high voltage pole and ground.

If two simultaneous faults occur and isolation is lost on both high voltage poles, a high voltage short circuit can occur resulting in extremely high currents. High currents can generate a large amount of heat which will subsequently damage electrical and fuel cell systems and cause bodily harm.

It is the responsibility of the system integrator to ensure that the electrical isolation between the high voltage and low voltage systems (Ground) is accurately and continuously measured and that appropriate action is taken before a hazardous condition develops.

Normal System

Under normal operation, the fuel cell system will operate as shown in Figure 1 where both high voltage poles are isolated from ground.

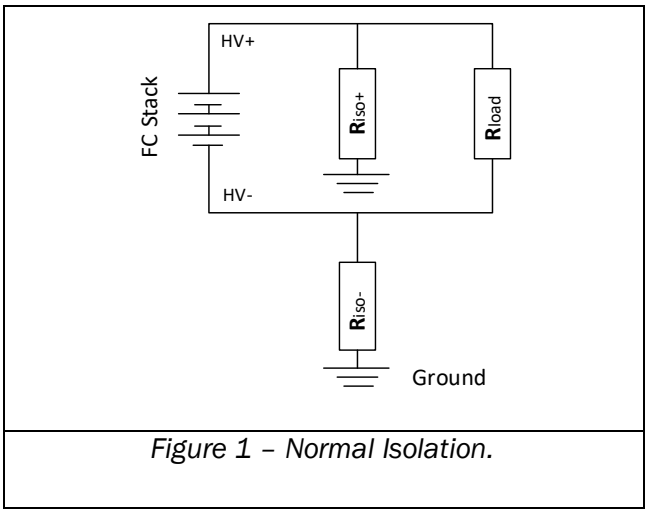


Figure 1 – Normal Isolation.

Single Pole Isolation Failure

In a single pole isolation failure, one point on the high voltage circuit is no longer isolated from ground as shown in Figure 2. An isolation resistance measurement or ground fault detection system can typically detect this failure if utilized. A single pole isolation failure will not cause a short-circuit, nor will

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it prevent fuel cell operation, however, it significantly increases the risk of electrical shock for personnel working on or around the fuel cell system.

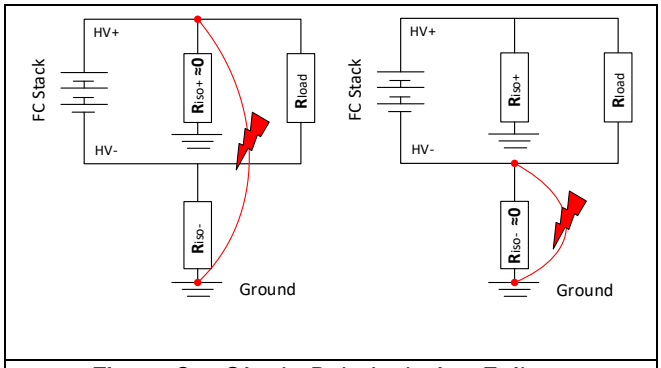


Figure 2 – Single Pole Isolation Failure.

Double Pole Isolation Failure

A double pole isolation failure, where the high voltage system is no longer isolated from ground in two different locations, may result in a high voltage short-circuit as shown in Figure 3. An isolation resistance measurement or ground fault detection system can typically detect this failure if utilized.

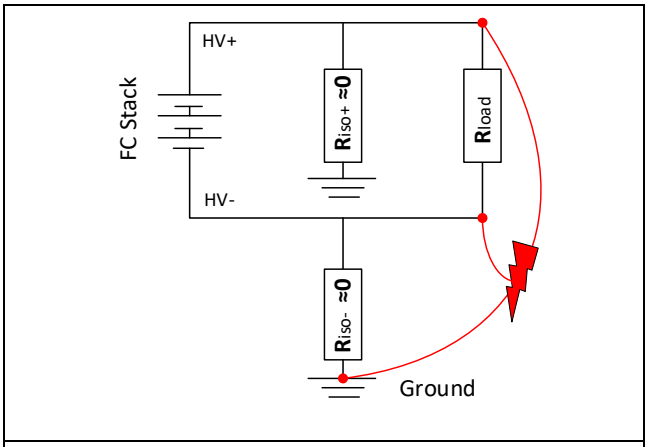


Figure 3 – Double Pole Isolation Failure.



If an isolation failure is detected and found to be located in the module, do not operate the fuel cell module until the root cause is determined and remedied.

Distributed Capacitance and Effects on HV Safety

The Distributed capacitance is the total amount of capacitance that exists between each pole of an isolated high voltage system and the chassis (fuel cell enclosure). This capacitance is a concern as it can hold charge which can be discharged into a person that simultaneously touches the high voltage system and chassis.

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In normal operation, this is not an issue as all high voltage conductors are covered and insulated but could be a concern if a system is being serviced.

HV safety due to residual reactants

Within the module, the fuel cell stack will also maintain voltage if hydrogen and air are present within the system. Voltage could also be generated when a fuel or air source is introduced, and reactants are moved to an active point in the fuel cell stack. This voltage will normally bleed down to safe levels within minutes, but this should always be verified using the RDU interface first, and then testing with digital multi-meter prior to accessing the module.

Confirm that the voltage is zero

Between pole to pole (positive to negative)
Between each pole to chassis before service.

Built in service procedures involve running the air compressors and hydrogen recirculation blower to inert the fuel cell prior to servicing the system Is necessary.

Refer to section “31.2 State: Prepare for Service” for pre-maintenance procedures. Untrained service personnel should not perform maintenance procedures on fuel cell modules.

One other effect of the distributed capacitance will be a delay in the ground fault detection system measurement.

8.7. Hydrogen Safety

⚠WARNING

Install and handle the hydrogen in accordance with applicable regulations and the gas supplier’s recommendations.

- Hydrogen is a colorless, odorless, and highly flammable gas so there will be no warning signals before unconsciousness results.
- Hydrogen is lighter than air and will escape upwards. This also allows it to diffuse through many materials considered airtight.
- Hydrogen is non-toxic, but it can cause asphyxiation by displacing the oxygen in the air, so do not operate the module in enclosed or non-ventilated areas.

Furthermore, hydrogen’s small molecular size results in high buoyancy and diffusivity, so any leaked hydrogen will be diluted readily by the surrounding air.

Present potential leakage or permeation sites

- Fuel lines,
- Non-welded connections,
- Non-metal seals such as gaskets, O-rings,
- Pipe thread compounds and packings

Hydrogen leaks which develop within the fuel cell module will be detected by a hydrogen sensor located inside the fuel cell module hydrogen enclosure ventilation duct. Detection of a high hydrogen concentration will trigger an alarm causing the closing of the fuel cell module hydrogen supply valve

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(integrator's scope) before an unsafe condition can exist. For more information see section "14.5 Module H2 Supply Valve and H2_ENABLE"

It is possible for a hydrogen sensor to degrade to the point where it will no longer trigger an alarm if the hydrogen content exceeds safety limits. For this reason, the H2 sensor is part of the maintenance plan.

Exposure to Volatile Organic Compounds (VOC's) is known to cause hydrogen sensor degradation, care should be taken to avoid exposure whenever possible. High levels of VOCs are often encountered during vessel painting and solvent degreasing; therefore, it is recommended that the module or hydrogen sensors to be removed during these processes. Efforts have been made to isolate the sensor from contamination; however, degradation can still occur.

Some failure modes can result in hydrogen gas being present in the cooling system header tank. The risk can be mitigated by following the design considerations, maintenance procedures and filling instructions specified in Section 18.8.

The hydrogen supply to the module will remain pressurized when the module is shut down. Verify that there is no pressure in this line prior to disconnecting the hydrogen supply.

The hydrogen lines inside the module may contain hydrogen, even after the module has been removed from the system. Safely vent the remaining hydrogen pressure prior to removing the fuel cell module.

The responsibility for leak detection external of the fuel cell module rests with the system integrator.

It is strongly recommended that the integrator implement hydrogen detection in any enclosure where the fuel cell module is installed, including the fuel cell room, or similar enclosed space. Interlock the hydrogen detection system with a hydrogen supply valve installed directly upstream of the fuel cell module.

If an excessive hydrogen leak is detected, cease operation of the FCM and do not restart the FCM until safe operation conditions are reestablished.

⚠WARNING **The module hydrogen sensor may degrade if exposed to various contaminants and become less sensitive when degraded. Scheduled checks, as per the module service schedule, ensure that the sensors have sufficient sensitivity for safe operation. Failure to perform scheduled hydrogen sensor checks can result in unsafe operation of the module, as the module may not shut down in the presence of ventilation outlet emissions if the hydrogen sensor is severely degraded.**

8.8. Chemical Hazards

The fuel cell HT coolant loop contains ethylene glycol.

Ethylene glycol is toxic if ingested or if its vapors are inhaled.

All personnel handling ethylene glycol or working on the fuel cell stack HT coolant loop are required to adhere to the precautionary measures identified in the Safety Data Sheet of the specific coolant being used.

Such precautionary measures include Personal Protective Equipment (PPE), for instance wearing safety glasses and chemically protective gloves.

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Dispose ethylene glycol in accordance with applicable local regulations.

8.9. Acoustical Noise

The acoustical noise of the FCwave™ during standby has an A-weighted equivalent Sound Pressure Level (SPL) of 69 dB(A) $L_{Aeq,2min}$ 1 meter from module front. During normal operation (steady at 200kW) the A-weighted equivalent SPL is 88 dB(A) $L_{Aeq,2min}$ at the same location. During ramping up, the maximum noise level reaches 92 dB(A) $L_{Aeq,1sec}$ (1m from module front).

To reduce the likelihood of hearing impairment, all personnel are advised to wear hearing protection devices entering the fuel cell engine room while FCwave(s) are operational.

8.10. FCwave™ hazard mitigation approach

The potential hazards related to the FCwave, posing the highest risks are:

- Unacceptable hydrogen concentrations (in the ventilation or process air exhaust) leading to fuel-fed combustion.
- Electrical short-circuits and possible shock hazards caused by reduced electrical isolation of the high voltage system.

The control system is coupled with sensors (Such as Pressure, temperature, H2 concentration et.al.) intended to identify conditions (which can lead to a hazardous situation) and shut down the operation of the FCwave™ and related functions, before an unsafe condition develops. The safety control functions are managed in a dedicated controller unit.

9. FCwave™ Performance

The performance and lifetime of the FCwave™ module is, among others, depending on good quality reactants (fuel = hydrogen, oxidant = air). Make sure the quality of the reactants meets or exceeds requirements outlined in this document.

The FCwave™ can be configured in either Single or Dual Output modes. The preferred configuration has to be planned before commissioning.

Table 3 shows the module output to the DC/DC or DC/AC converter (in general connected to a DC/DC).

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Power	Configuration	Voltage	Current
50 – 200kW	Dual Output	350 – 720 VDC	(2x) 50 - 300A
50 – 195kW	Single Output	350 – 720 VDC	(1x) 100 - 550A

Table 3 – Module power, voltage, and current limits

Figure 4, Figure 5, Figure 6 and Figure 7 show the expected performance envelope of the FCwave™ module. The net power output represents the output to the module DC/DC converter and accounts for the power generated by the fuel cell stacks and the power draw of the BOP components. The net power output is the total power available to the vessel.

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9.1. System Output Voltage and Current

The voltage from the module is dependent on the load drawn from the system, the correlation between power and voltage is shown in Figure 4. Output current in relation to system output power is shown in Figure 5.

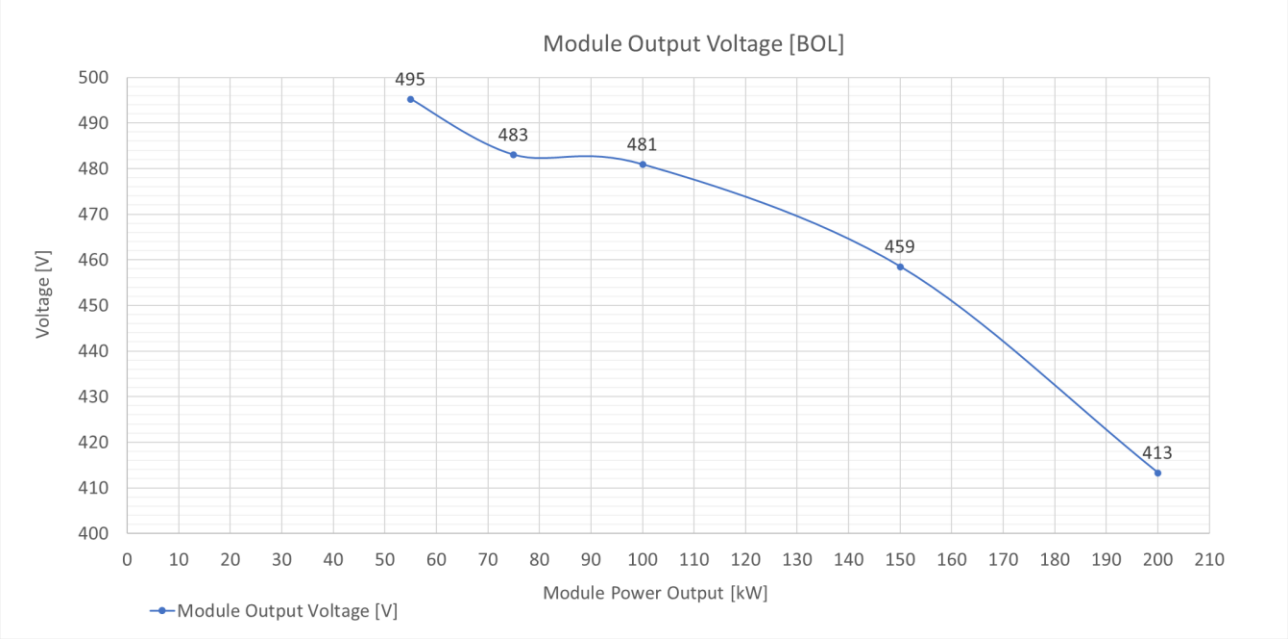


Figure 4 – Module output Voltage at Beginning of Life.

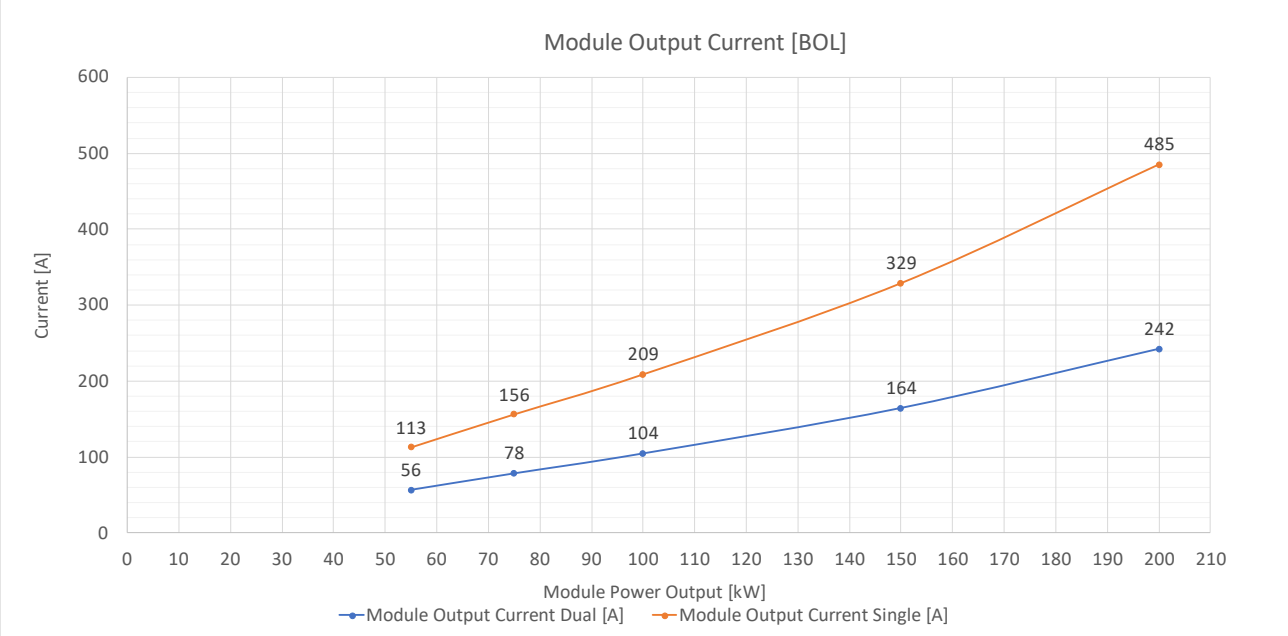


Figure 5 – Module Output Current at BOL.

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9.2. System Efficiency

The module electrical net efficiency in Figure 6 is defined as the fraction of electrical energy produced.

The lower heating value of hydrogen used for the calculation is 119,91 MJ/kg (ISO 6976:1995).

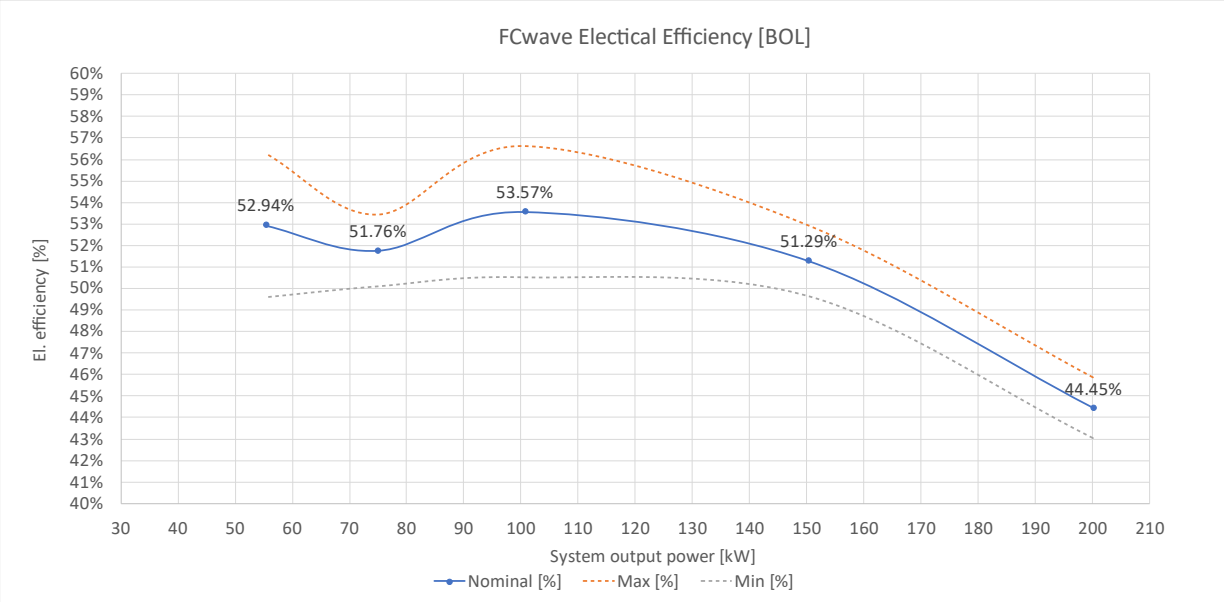


Figure 6 – Module Net Efficiency BOL.
(Test done according to IEC62282-3-200:2016 using 95 confidence interval)

9.3. System Hydrogen mass flow

The hydrogen consumed by the module at different load points are shown in Figure 7 – Hydrogen mass flow.

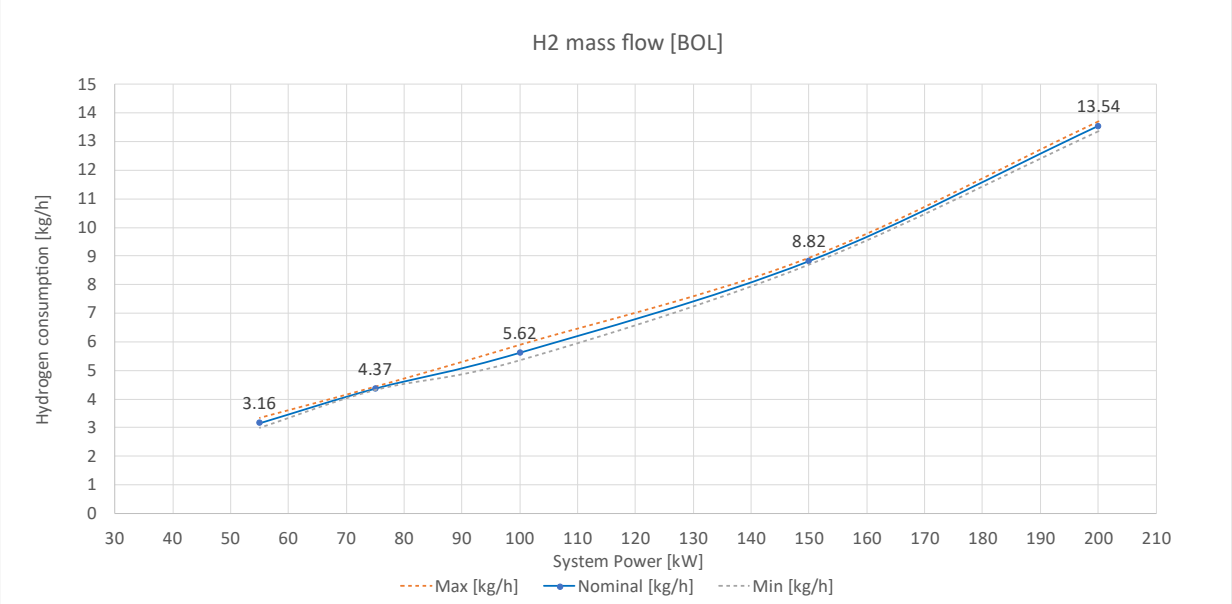


Figure 7 – Hydrogen mass flow BOL.
(Test done according to IEC62282-3-200:2016 using 95 confidence interval)

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10. Mechanical Integration

Measurements and figures in this section are for reference only and should not be used for design purposes. Ballard can supply 3D models and integration drawings upon request.

10.1. Reference Drawings

For a list of the mechanical reference drawings contained in the **7001000-01**, refer to Table 4 – Mechanical Reference Drawings.

Mechanical Reference Drawings	
Drawing Number	Drawing Title
7001000-01, Sheet 1	General Arrangement Plan
7001000-01, Sheet 2	Interface Panel Connection Locations
7001000-01, Sheet 3	Process Exhaust and H2E Ventilation Locations

Table 4 – Mechanical Reference Drawings contained in 7001000-01.

10.2. Module Installation

This section describes the major physical properties of the FCwave™ fuel cell module.

Modules require front access, refer to section 10.4 “Space Claim for Service Access”. Modules do not require side or rear access and can be placed side by side, back-to-back or a combination thereof.

Refer to the isometric view of the module in Figure 8, below.

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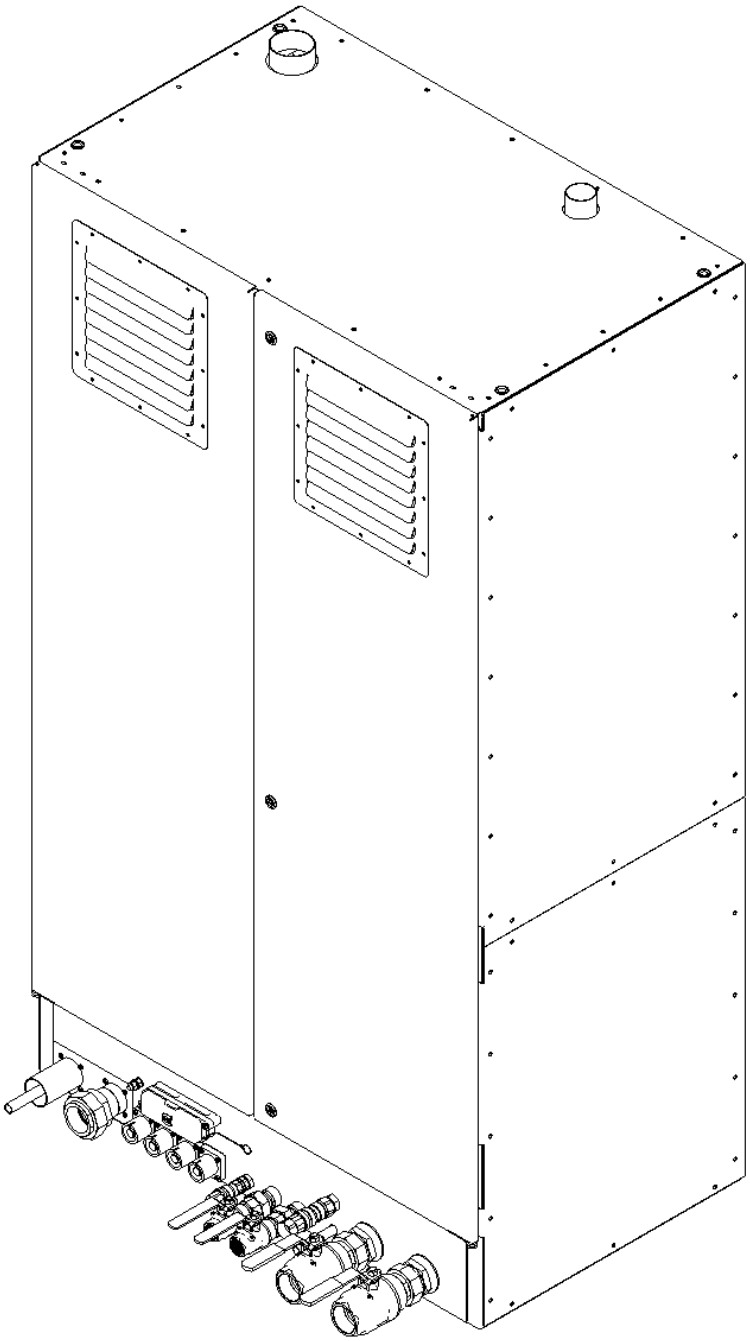


Figure 8 – Isometric view of FCwave™ module.

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10.3. False Floor

The module is designed to be installed in a Fuel Cell Installation Room, with a false floor.

As shown in Figure 9 and Figure 10, the module is designed to mount on a solid floor, with the false floor installed 200mm above (the false floor is not included, it is responsibility of the integrator). The

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200mm space is used to connect process and electrical connections to the module. The false floor will serve as protection for these connections.

The false floor panels should be removable for service access.

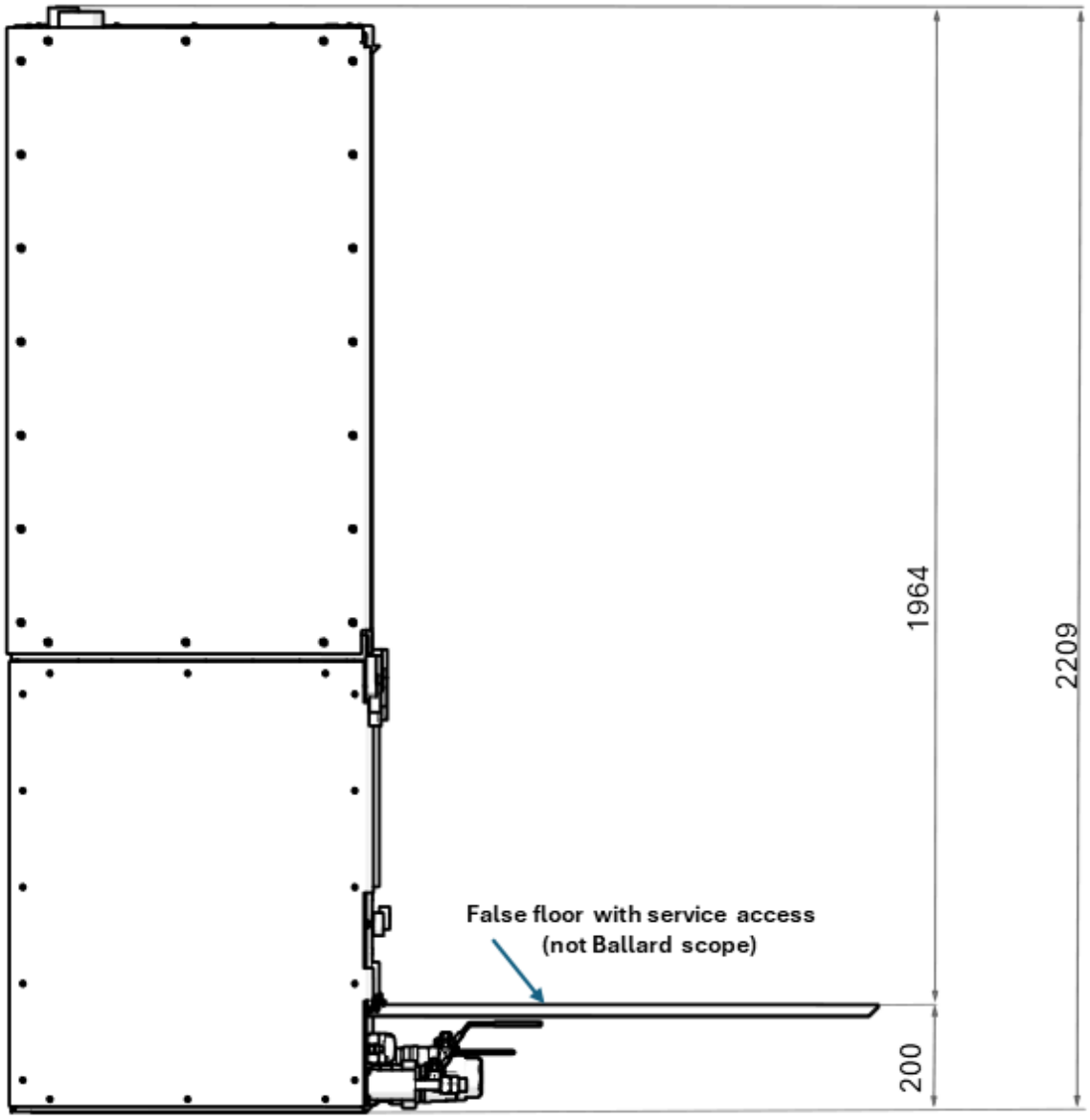


Figure 9 – Module Side View, showing details of False Floor with service access.

[Dimensions in mm]

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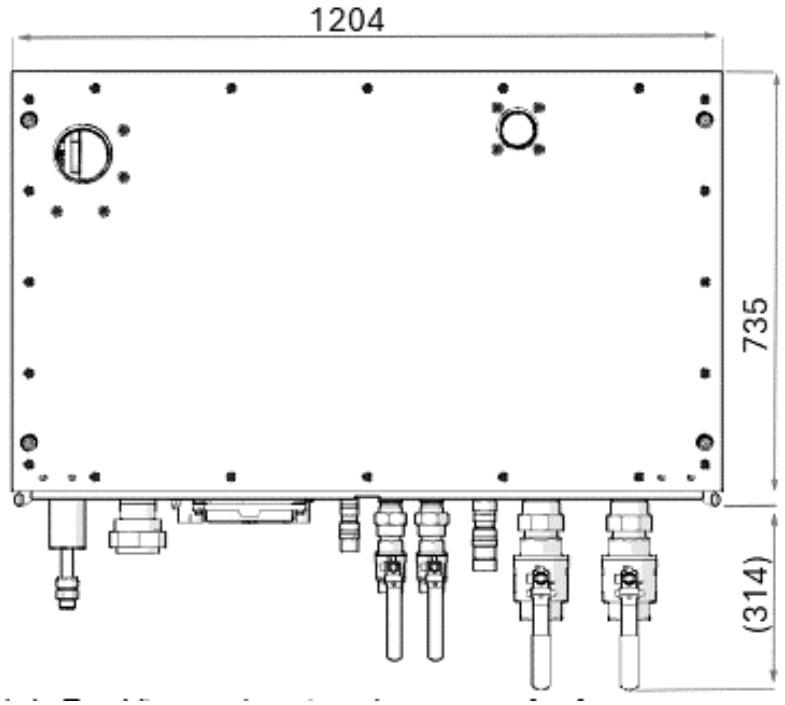


Figure 10 – Module Top View, showing clearances for front process and electrical connectors. [Dimensions in mm].

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10.4. Space Claim for Service Access

The space in front of the module shall be available for service activities. See Table 5 and Figure 11.

Cabinet doors can be wide-opened to 120°. If necessary, demount the cabinet doors for additional service access during maintenance procedures.

The false floor must be designed to carry the weight during service and component replacements, see Table 5.

Specification	
Width	1500 mm
Depth	1100 mm
Height	2300 mm
False floor load capacity	>845 kg

Table 5 – Space Claim for Service Access

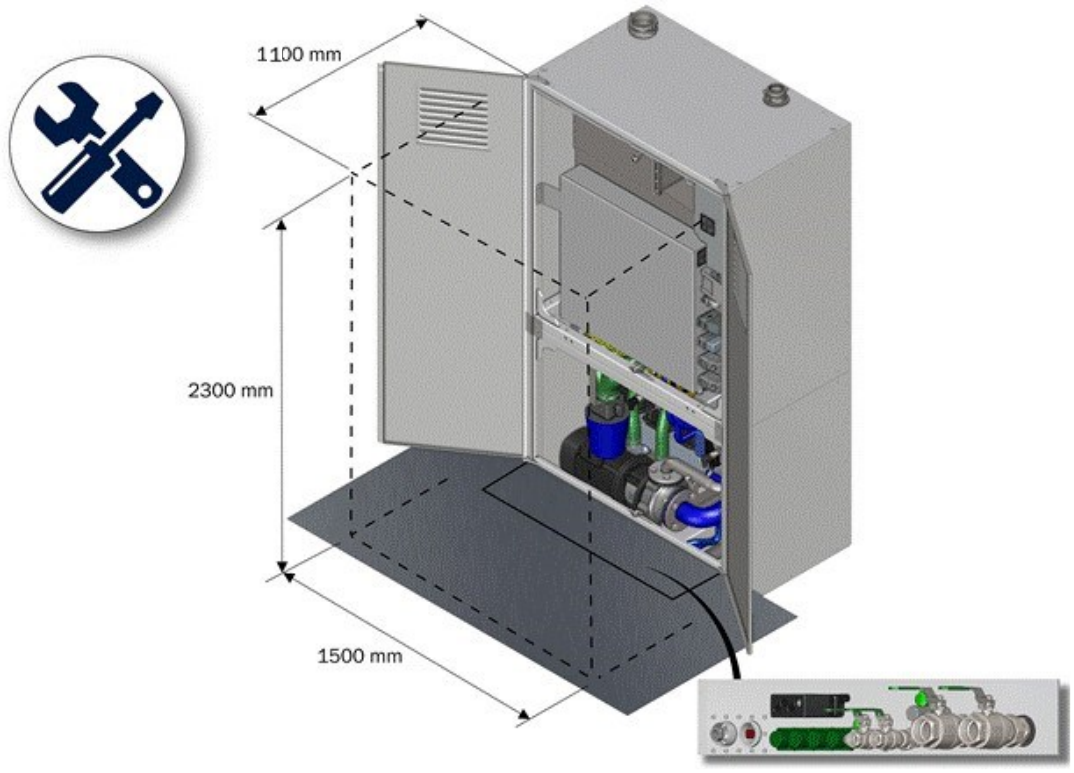


Figure 11 – Space Claim for service access to module.

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10.5. Mounting points and Center of Gravity

Please refer to Ballard document 7001000-01. This document specifies mounting points and center of gravity for a complete FCwave™ module.

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10.6. Module Lifting

When lifting the FCwave™ module during shipping and installation, only use a suitable lifting beam, or equipment design to connect to all four lifting points on the top. Lifting beam and eyebolts are not provided by Ballard.

WARNING **Local regulation for lifting and handling the equipment have to be followed, failure to follow guidelines can cause lifting accident, which leads to personnel injury and damage to equipment.**



Figure 12 – FCwave™ cabinet with lifting beam and eyebolts.

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10.7. Module Split Cabinet

The FCwave™ module can be split in two halves (top and bottom). This separation in halves eases the installation of the module in the Fuel Cell Room (if necessary) and also makes a “top swap” of the Fuel Cell section possible, see Figure 13. This procedure is only to be undertaken by Ballard personnel or people trained by Ballard.

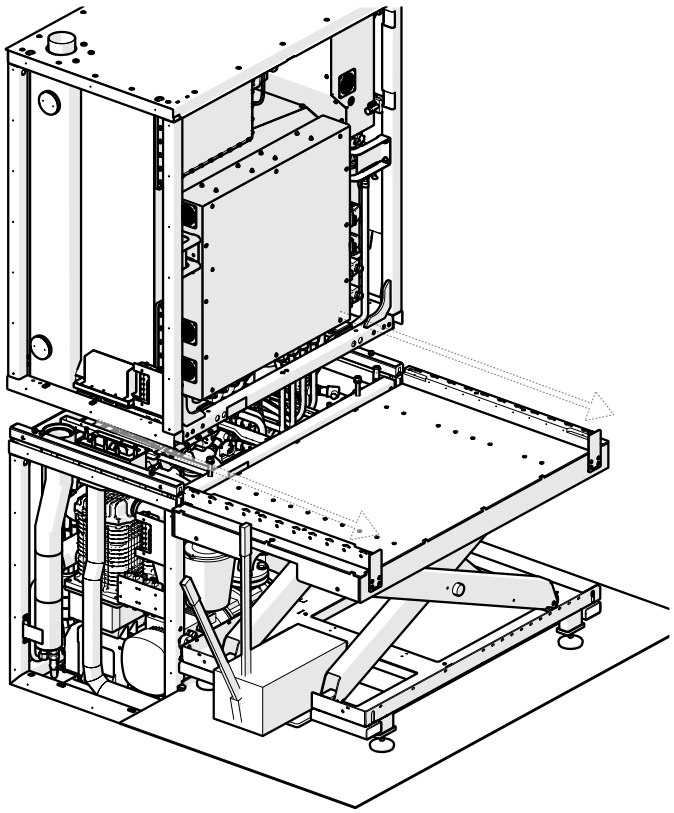


Figure 13 – The module cabinet split into upper and lower sections with lifting cart.

10.8. Lifting on sight

On sight, it is recommended to have a crane in front of the module that can lift the top part of the module and the cart, in case of top module swap. The crane has to be able to go from the module to the exit of the installation room. An example of this crane can be seen in Figure 14.

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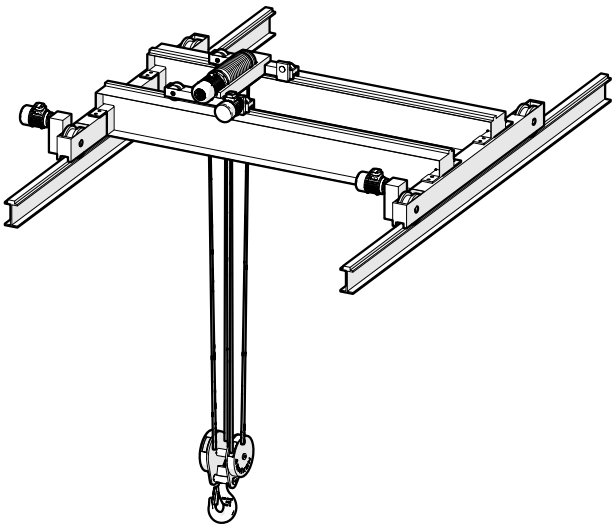


Figure 14 Crane used to move the Top module and the cart.

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11. Fuel Cell Installation Room Requirements

For type approved FCwave™ modules it is required that the fuel cell is installed within a Fuel Cell Installation Room, which must fulfill all requirements from the classification society and IMO.

The compartment in which the fuel cell modules are to be installed are termed the “Fuel Cell Installation Room”, and requirements are presented below in the following sections.

11.1. Structural Requirements for the Installation

This section describes the structural requirements for the Fuel Cell Installation Room, where one or more fuel cell modules are installed. The FCwave™ module shall always be installed in a shelter to protect against weather conditions such as but not limited to, heavy rain, direct sun, extreme heat & cold, dust etc.

1. The FCwave™ must be securely fastened at bottom, back and top.
2. The FCwave™ is designed to be accommodated in a Fuel Cell Installation Room with a false floor, with the hydrogen and electrical supply placed below the floor.
3. Requirements for service access in front of the FCwave™ must be followed, see Figure 11.
4. The Fuel Cell Installation Room free volume should not be less than 10m^3.

11.2. Hydrogen connection

The hydrogen supply connection to the module must fulfill the following requirements:

1. A hydrogen supply shutoff valve with a reaction time less than 2 seconds is required to be installed for each module.
2. The hydrogen flow must be restricted by suitable means such that hydrogen mass flowrate shall not exceed 4.9 g/s.
3. The amount of hydrogen in the fuel cell module must be minimized when not in operation. The physical volume of the pipe between hydrogen shutoff valve and module interface plate is not to exceed 5 liters.
4. For maritime installations, it is a requirement that the pipe between the hydrogen shutoff valve and module interface plate is double-walled, with detection measures for the annular space.

11.3. Process exhaust connection

This section describes the options for process exhaust connections from a FCwave™ module in a Fuel Cell Installation Room:

In all cases, the following apply:

1. Process exhaust must be let to the outside.
2. FCwave™ process exhaust can be fully water saturated and with negligible hydrogen (below <2% of the LFL) content.

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3. The process exhaust must have provision for a drain at the lowest point of the connection, as there will be condensation inside the process piping.[1]

11.4. Module Ventilation exhaust connection

Module ventilation exhaust should be led to a safe exterior location free of any spark or ignition source. The integrator must prevent ingress of water droplets or other debris running backwards into the system through the ventilation exhaust.

The material of the exhaust systems shall withstand the environment, and not be of risk of corrosion clogging due to sediments in the exhaust system. Recommended material is EN 1.4301 / AISI 304 or EN 1.4401 / AISI 316 stainless steel. It is important that no debris or lose sediments enter the FCwave™ .

The exhaust and the ventilation is two separate systems, and should not be joined.

The integrator's side of the ventilation exhaust connection should be done of 1.4404/AISI 316L or 1.401/AISI 304 stainless steel, to minimize the amount of corrosion and other particles accumulating in their walls and the possibility of them falling into the FCwave™.

11.5. Installation Room ventilation

The air handling system in the fuel cell installation room must be sufficient to supply the FCwave™ process air (as specified in section 11.1). Addition ventilation of the fuel cell installation room to be determined by Classification Society or Vessel Integrator.

Ballard recommends performing a calculation according to IEC 60079-10 to establish the required ventilation rate for the fuel cell installation room. In normal operation, all probable leakage scenarios internal to the FCwave™ are managed inside the module.

11.6. Drain connections

It is required that integrator implements backflow prevention from module to module and/or from external source to module(s).

11.7. Safety system

The vessel control and safety system must include visual and audible signaling to crew in appropriate locations.

Recommendation is to clearly indicate which FC module is in operation inside the fuel cell room.

The FCwave™ does not provide an emergency stop button, only an input for one. It is the responsibility of the integrator to install adequate and accessible safety stop buttons or similar, as well as ensure the integration of FCwave™ in the emergency stop circuit (Figure 36).

An uninterruptible power supply must provide a 24VDC output with a maximum voltage deviation of ±10% (applicable to both normal and safety supply) for a duration exceeding 10 minutes, as indicated in Table 25.

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[1] Draining the process exhaust though the FCwave™ module process water drain is not permissible.

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11.8. Fuel Cell Installation Room Access

Access to the fuel cell installation room during operation shall be limited to trained service technicians and personnel that have received Ballard fuel cell training.

Unrestricted access to the fuel cell installation room can be permitted by the vessel authorities when all fuel cell modules are powered off and otherwise deemed permissible.

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12. Process Connections

Process connections for the module are located on the lower part of the front panel, as shown in Figure 15. Annotation references are shown in Table 6.

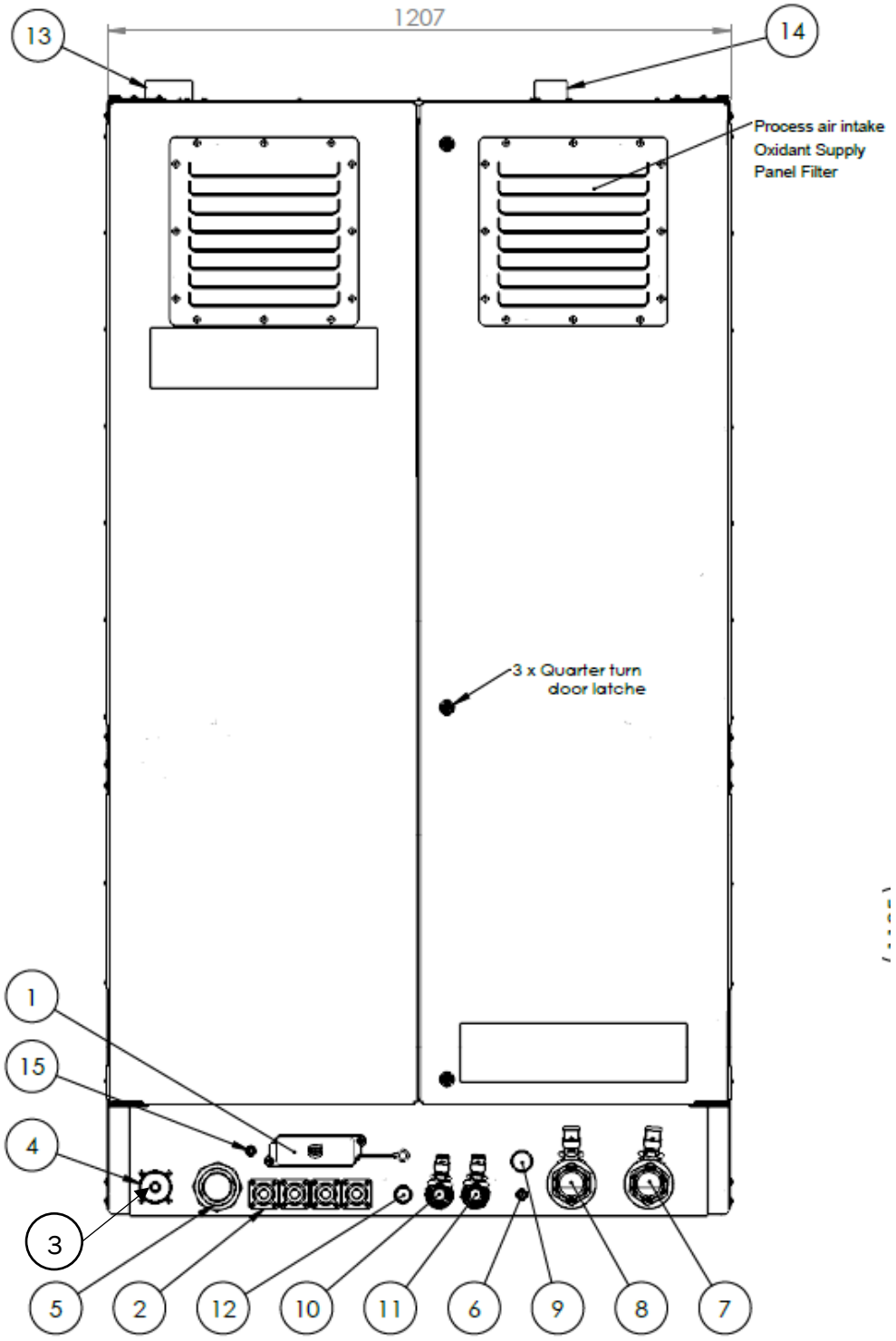


Figure 15 – Detail View of module process connections.

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Process Connections					
Position	Description	Connection	Media	Temperature	Pressure
1	Control and Communication Connector	Harting Male 24HPR	24V DC, Hardwired, CAN bus, Ethernet	n/a	n/a
2	High Voltage Connectors	Amphe-Phase, SLS Panel Source	330-720 VDC, 2*300A or 1*550A	n/a	n/a
3	H2 Supply – Primary Barrier	Ø20 x 1,8mm	Gaseous H2, <4,9 g/s	0 – 80 °C	3,5 – 6,5 barg
4	H2 Supply – Secondary Barrier	Ø60,3 x 2mm	n/a	n/a	n/a
5	H2 Enclosure Ventilation Inlet	DN50 – ISO7/1 R2”	Air, Salt-filtered	<45 °C	Ambient
6	Process Water Drain	Ø18 mm	DI Water	10-70 °C	n/a
7	High Temperature Coolant Out	DN50 – ISO7/1 Rp 2”	Coolant, see section 18.5	dT = 25 °C max 65°C	dP < 0,3 bar
8	High Temperature Coolant In	DN50 – ISO7/1 Rp 2”	Coolant, see section 18.5	5 – 45 °C	<30 barg
9	High Temperature Coolant Fill/Drain	Non-drip coupling G3/4” DN14	Internal Coolant fluid, see section 18.3	10 – 70 °C	<100 mbarg
10	Low Temperature Coolant In/Out	DN25 – ISO7/1 – Rp1”	LT Coolant, see section 19	5 – 50 °C	< 1,5 barg
11	Low Temperature Coolant In/Out	DN25 – ISO7/1 – Rp1”	LT Coolant, see section 19	5 – 50 °C	< 1,5 barg
12	Low Temperature Coolant Fill/Drain	Non-drip coupling G1/2” DN9	LT Coolant, see section 19	5 – 50 °C	< 1,5 barg
13	Process Exhaust	Ø88,9 x 2,0mm	Oxygen-depleted air, DI water droplets. See section 16.5	50 – 80 °C	Backpressure <15mbar @ 12700 lpm
14	H2 Enclosure Ventilation Exhaust	Ø60,3 x 2,0 mm	Air, trace H2 amounts	< 55 °C	Backpressure < 200 Pa @ 750 lpm
15	Grounding stud	M10 Zinc coated copper stud	Grounding point	n/A	n/a

Table 6 – Process Connections, refer to Figure 15.

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12.1. Process Air

The installation section describes the intake and exhaust for process air.

Process air intake is through the air filters on the module door panels, as shown on Figure 8. Integrator shall supply conditioned air to the Fuel Cell Installation Room as described in section 16.2 - Process Air Intake Quality.

The module air exhaust should be connected to an outlet with a drain downstream of the process air outlet to capture liquid that will condensate in the pipe.

Note that the pressure-drop presented by the exhaust piping and any installed equipment must be considered. See section 16.4 and 16.5 for more details.

12.2. Ventilation Air

The module is equipped with active ventilation of the hydrogen carrying sections of the module (Hydrogen Enclosure / “H2E”). The air intake for the ventilation is in the cabinet base of the module, incorporating the hydrogen pipe.

The ventilation fans inside the module are only designed to ventilate the module itself. The fans are not designed to ventilate any double-wall piping arrangement outside the module. The annular space around the primary fuel pipe is welded closed at the interface panel

The integration shall ensure the exhaust from FC modules (ventilation air) is led to a safe location free of any spark or ignition source.

The ventilation inlet and outlet must be equipped with automated fire dampers. The dampers must be closed in case of fire, and before releasing a fire extinguishing system.

12.3. Hydrogen Fuel

The gaseous hydrogen fuel process interface connections are a double wall design, detailed in Figure 16:

Primary Barrier:
Ø20 x 1,8 mm
Welded connection
Secondary Barrier:
Ø60,3mm
Welded connection surrounding the primary barrier.

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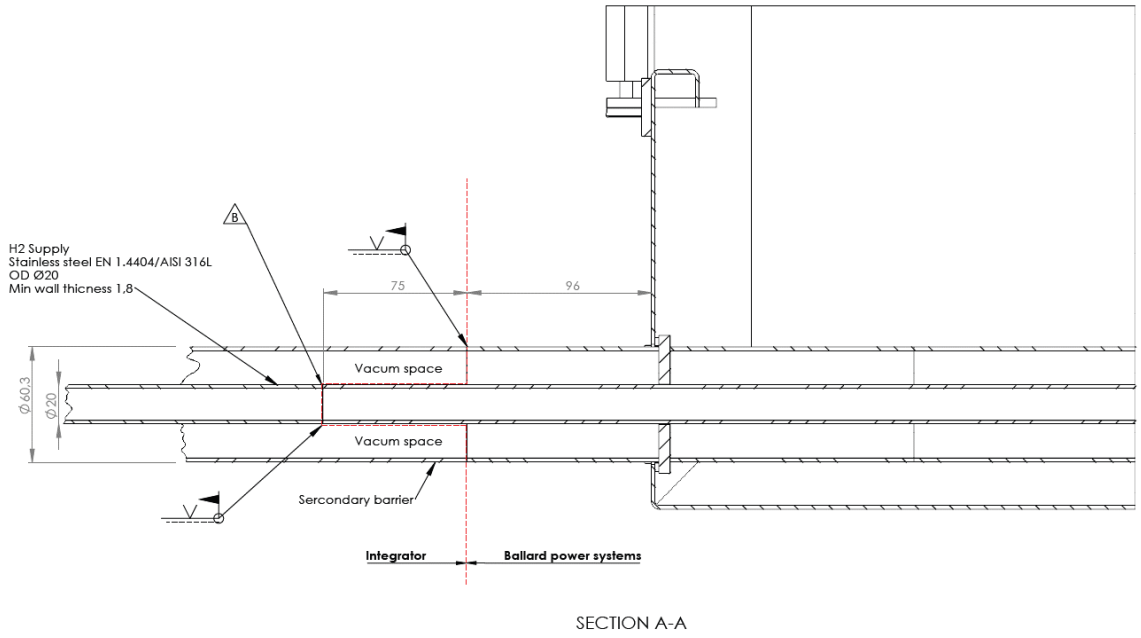


Figure 16 – H2 Supply Connection Detail View.

The space between primary and secondary barrier inside the FC module carries the H2E ventilation air. The space between inner and outer tubes must be ventilated by the integrator in a marine application. For stationary applications no ventilation is needed.

12.4. Welding of Hydrogen pipe

In marine applications, the welding of the double walled pipe has to be performed in accordance with requirements from Classification Societies and Vessel Integrator.

After welding the Hydrogen pipe in on the interface of the FCwave™ system, the welding shall go through a cleaning and pressure test.

Contact Ballard support for details

Cleaning recommendations

When welding of the double walled pipe is completed and approved, cleaning of the hydrogen pipe is required, due to removal of any impurities in the pipe. Cleaning can be performed by blowing with air or Nitrogen.

⚠ CAUTION Contact Ballard service for details regarding this procedure or check the service documentation

Pressure testing recommendations

After cleaning of H2 supply pipe, a pressure test must be carried out.

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12.5. Coolant

The integrator is to supply module coolant to both the High Temperature and Low Temperature coolant loop inside the module.

High Temperature Coolant Loop:
Transfers the excess heat produced by the reaction inside the fuel cells to the integrator. See section 18 - High temperature Coolant Subsystem.

Low Temperature Coolant Loop:
Transfers the excess heat produced by the liquid cooled balance of plant components inside the module to the integrator. See 19 - Low Temperature Cooling .

12.6. Process Drain

The integrator is to connect a drain to the Process water drain. This drain separates and leads away the liquid water produced in the reaction and not carried away in the process exhaust.

12.7. Electrical connections

Locate the fuel cell module such that there is enough clearance to access:

The Low Voltage Connector, which provides 24V power to the Control and Safety systems alongside hardwired and bus data connections.
High Voltage DC output connectors, which provide the electrical power produced by the system.

13. Environmental Protection

The module is constructed with the ingress protection rating IP44 for the module (excluding connectors) and IP67 for front panel electrical connectors only.

~~Do not use a direct high pressure water spray on the FC module.~~

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14. Anode Subsystem

This section contains information about the anode (hydrogen) system inside the FCwave™ (Ballard scope) and the upstream hydrogen delivery system (customer scope).

The purpose of the internal hydrogen system is providing hydrogen for the fuel cell stacks. A simplified hydrogen system is shown in Figure 17 – Simplified Hydrogen System.

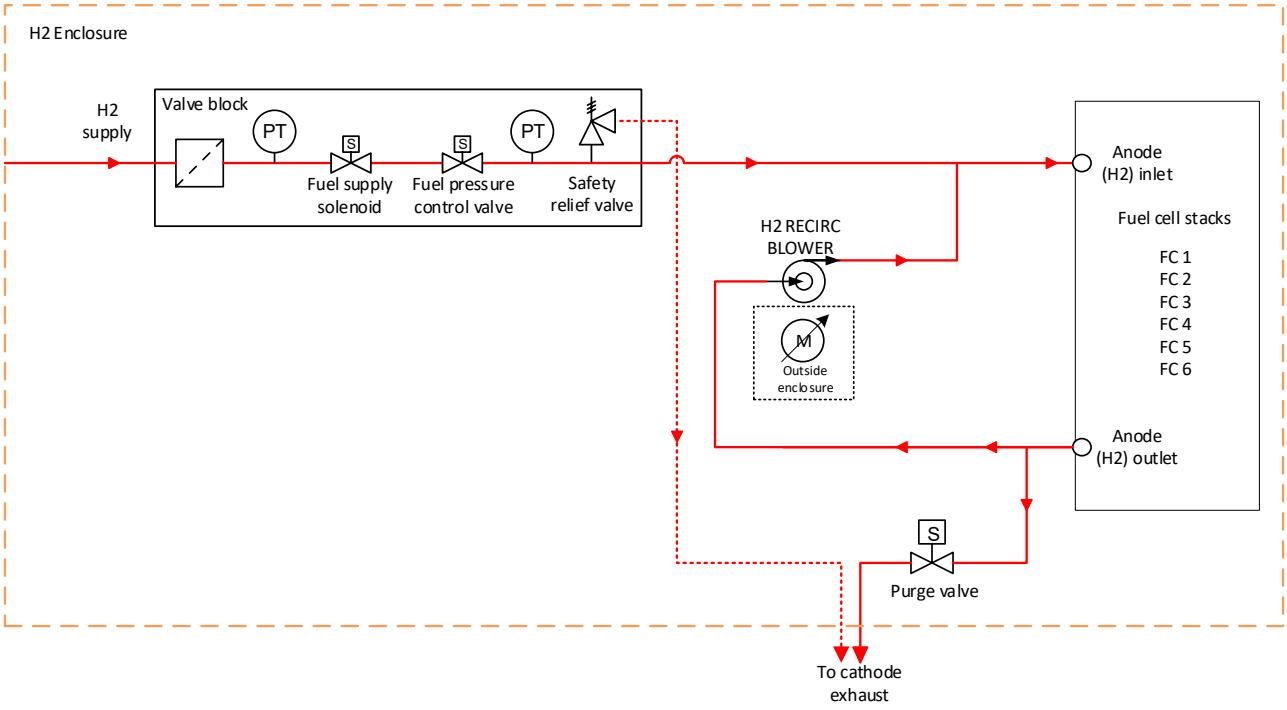


Figure 17 – Simplified Hydrogen System.

14.1. Requirements for upstream H2 delivery system

This section describes the requirements that the integrator must fulfill in the H2 supply system before the module boundary.

Integrator must provide sufficient hydrogen of a quality, pressure and temperature as specified in:

Table 7 – Hydrogen Supply Quality Specification.
Table 8 – Hydrogen Supply Temperature and Pressure Specification.
Table 9 – Hydrogen Supply Flow Rate Specification.

The source of hydrogen may be compressed gas storage, vaporization of liquid hydrogen or reforming of other fuels, if quality, pressure and temperature requirements are met.

Integrator must in accordance with classification society fulfill the requirement of H2 supply pipe leading to module.

Integrator must provide a block and bleed capability upstream of the module. A schematic of this can be seen in Figure 18.

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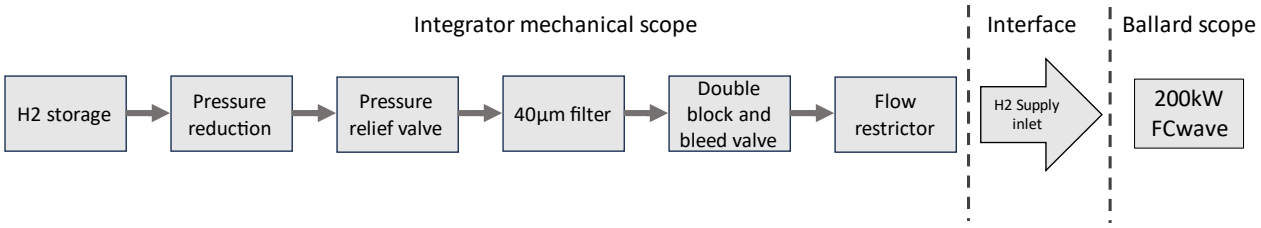


Figure 18-- Installation diagram of the H2 system with integrator and Ballard's parts differentiated.

14.2. Anode System Overview

The fuel cell module anode system is primarily comprised of an internal fuel supply shutoff valve and devices for regulating and conditioning the fuel pressure and water content. A Hydrogen Recirculation Blower (HRB) circulates the hydrogen inside the fuel loop.

A small amount of gas in the hydrogen circuit is purged to maintain acceptable hydrogen concentrations at the stack and remove N2 and water. This purged gas is directed to the process exhaust where it is diluted to a safe concentration by mixing with the process exhaust.

In the unlikely event that the hydrogen loop is over-pressurized, a mechanical pressure relief valve installed on the fuel valve block is in place to safely relieve the pressure (see section 14.3).

Perform a leak check after any service work is done to hydrogen supply fittings and associated piping

Follow the hydrogen supply quality requirements specified in Table 7 – Hydrogen Supply Quality Specification. Both hydrogen quality specifications are acceptable.

Specification	
Hydrogen Quality	SAE J2719:MAR2020
OR	
Hydrogen Quality	ISO 14687:2019 Type I, Type II – Grade D

Table 7 – Hydrogen Supply Quality Specification.

Hydrogen can be sourced from compressed gaseous storage or vaporization of liquid hydrogen if quality and temperature requirements are met.

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Before commissioning and after service on the hydrogen supply system (external to module), a sequence of fill and drain cycles will be needed to ensure the correct hydrogen purity.

For the vessel tank system several fill and drain cycles (especially with new hydrogen storage tanks) will be required as they often come pre-filled with nitrogen or air. Contact the tank manufacturer for the recommended purge procedure.

If the resultant hydrogen purity is questionable, then it is recommended that a sample of the gas be analyzed by a laboratory for its composition. If these purity levels are not achieved, then there can be adverse effects to the performance of the fuel cell stack.

A 40µm filter should be installed directly upstream of the fuel cell module fuel supply inlet to ensure the particulate size requirement is met.

Note: Incomplete purging of the vessels hydrogen tank is often a source of impurity. Ensuring that hydrogen tanks are purged as per the manufacturer's specification is crucial to remove residual inert gases. After purging, it is recommended to have a gas sample analyzed ensure all inert gases are removed from the hydrogen storage system

⚠ CAUTION **Improper purging can often result in conditions leading to irreversible fuel cell damage and may have warranty implications.**

14.3. Hydrogen Supply Temperature and Pressure

When selecting a pressure regulator to install upstream of the fuel cell module, regulator droop[2] and hysteresis should be considered to ensure that the supply pressure is always within the range specified in Table 8.

Specification	
Nominal Inlet Pressure	4,5 barg
Minimum Inlet Pressure	3,5 barg
Maximum Inlet Pressure	6,5 barg
Maximum Inlet Temperature	80 °C
Minimum Inlet Temperature	0 °C

Table 8 – Hydrogen Supply Temperature and Pressure Specification.

Locating a pressure transducer and/or pressure gauge immediately upstream of the fuel cell module can be a valuable tool for troubleshooting hydrogen supply issues.

NOTE: A low pressure relief valve (internal to the module) is vented into the cathode exhaust. Implement overpressure protection in case of a fuel delivery system regulator malfunction. It is recommended that the integrator provide two levels of protection:

Electronic: If a regulating device from a storage is installed upstream ensure following:

Allow for electrical disabling of the fuel delivery system (e.g., remove power from the normally closed solenoid valves using a pressure switch) if the regulator outlet pressure exceeds 10 barg. Set up the system such that the hydrogen

[2] Sometimes referred to as the 'Proportional Band' or 'Offset', droop is an inherent characteristic in all self-operated and pilot-operated regulators. Droop is a decrease in outlet pressure from the set value due to an increase in media flow rate.

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supply will not be switched on automatically when the downstream pressure drops.

Mechanical: Install a pressure relief valve, sized to maintain the pressure less than **10 barg** at maximum flow.

WARNING **Fuel supply overpressure can result in an unsafe situation since it can cause the fuel cell module hydrogen components to fail. It is very important that these components are adequately protected in the event of a hydrogen supply pressure regulator malfunction or failure which results in an overpressure.**

14.4. Hydrogen Supply Flow Rate

Always provide enough hydrogen flow to the fuel cell module. The maximum expected hydrogen flow rates are specified in Table 9.

At this maximum flow rate, the hydrogen supply pressure should remain within the range specified in Table 8.

Integrator **shall** install an orifice restriction such that hydrogen mass flowrate shall not exceed 4,9 g/s.

Specification	
Max H2 Flow (Design)	4,9 g/s
Minimum Flow Operational Flow Full Load [BOL]	3,76 g/s

Table 9 – Hydrogen Supply Flow Rate Specification.

14.5. Module H2 Supply Valve and H2_ENABLE

The integrator is required to install a fuel shutoff solenoid valve directly upstream of the fuel cell module. This valve should be situated as close as possible to the fuel cell module fuel supply inlet to minimize the volume of hydrogen which will remain in the supply line during a shutdown.
The fuel cell module has a hydrogen supply shutoff valve inside the fuel cell module. This valve is meant to stop the flow of fuel into the fuel cell when the fuel cell module transitions from Running to Standby state. It is not designed to be a fuel system isolation/shutoff valve and does not replace the integrator's main fuel shutoff valve.

WARNING **The integrator is to ensure the H2 Supply valve is not used a shutoff method or that this valve is not closed during operation or though the shutdown sequence (see section "25 Control System – State Machine"). Failure to abide by this may result in stack fuel starvation or an alarm condition that will allow the high voltage contactors to open under load.**

WARNING **When shutdown, pressurized hydrogen is trapped in the supply line connected to the fuel cell module. The integrator must provide a means to isolate the supply line and vent any hydrogen remaining in the supply line prior to disconnecting the fuel cell module from the system for service**

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The module provides an output to the integrator (H2_ENABLE), which signals to the vessel that the module requests opening of the H2 Supply Valve. H2_ENABLE is switched to the negative of the 24V supply when active, see Figure 19.
Please note that the H2 Supply Valve is separate from the internal shut-off valve inside the module.

This low-side output switching arrangement allows both module and integrator to control the open/close status of the H2 supply valve for the module.

The integrators H2 supply valve must be of the Normally Closed type.

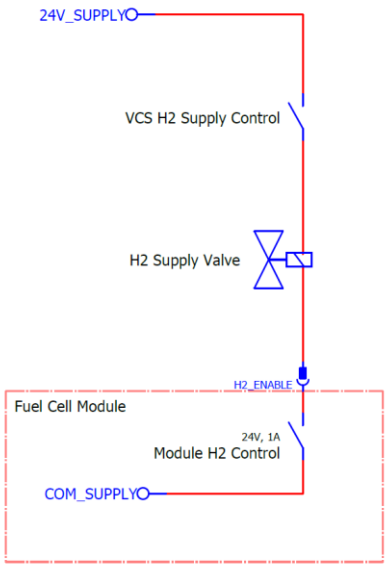


Figure 19 – H_2 Supply Valve Control.

15. Hydrogen Enclosure Ventilation

The module is equipped with active ventilation of the hydrogen carrying sections of the module (Hydrogen Enclosure / “H2E”).

> Integrator is responsible for salt and water droplet filtration from H2E Ventilation air.
> This includes prevention of water droplets running backwards into the system through the ventilation exhaust.

The air intake for the ventilation is in the cabinet base of the module. The ventilation air is in customer scope. Module ventilation shown in Figure 20 – Simplified P&ID for the Module Ventilation system.

The maximum allowable fuel cell module and auxiliary systems ambient temperature is specified in Table 10.

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Specification	
Maximum Fuel Cell Module Ambient Temperature	45°C
Minimum Fuel Cell Module Ambient Temperature	>0°C

Table 10 – Ambient Temperature Specification.

Specification	
Module Ventilation Air Salt Content maximum allowable content	< 20µg/m³

Table 11 – Ventilation Air Salt Content Specification.

The ventilation duct acts as the secondary barrier in the double barrier protection principle.

Two ventilation fans are installed in the ventilation exhaust. The ventilation fans draw air from the inlet through the H2 Enclosure to the ventilation exhaust outlet.

The ventilation air is exhausted out of the upper-most part of the module, and shall be routed to a zone, with no ignition sources within a safe distance.
There is an option for rear facing ventilation exhaust, see section **Error! Reference source not found.**.

Note that the pressure-drop presented by the ventilation exhaust piping and any installed equipment must be considered. See Table 12.

Specification	
Ventilation Exhaust Backpressure (Maximum allowable pressure-drop between at Ventilation air outlet port and atmosphere)	≤2 mBar at 750 lpm
Ventilation inlet pressure drop (Maximum allowable pressure-drop between atmosphere and Ventilation air inlet port)	≤2 mBar at 750 lpm

Table 12 – Air Ventilation Exhaust Backpressure Specification.

The ventilation system is a key safety component, and is under close surveillance, with multiple monitored functions:

Redundancy of fans,
Fan rotation monitoring
Flow monitoring in inlet duct.
Pressure monitoring in hydrogen enclosure
Redundancy on Hydrogen sensors, which will detect any unacceptable levels of hydrogen in the outlet.

NOTE: The hydrogen sensors will need to be accessed periodically as part of preventive maintenance activities.

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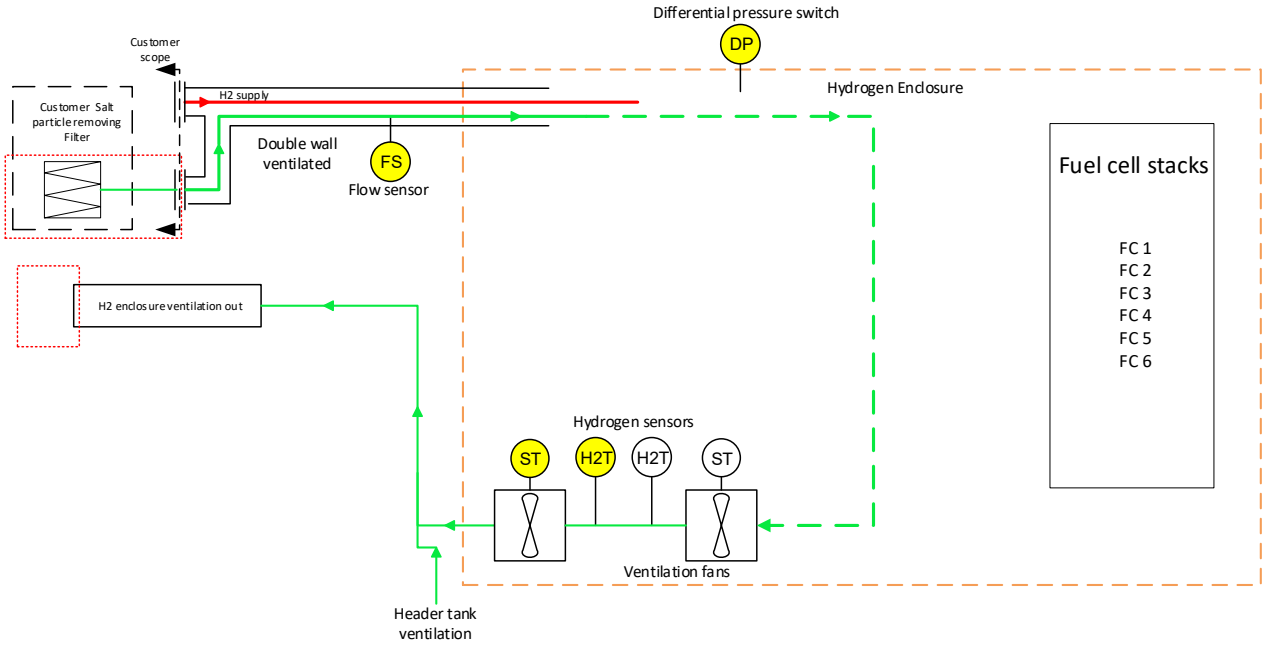


Figure 20 – Simplified P&ID for the Module Ventilation system.

16. Cathode Subsystem

The purpose of the cathode subsystem is to provide oxygen from atmospheric air to the fuel cell stacks. Process air is taken from the fuel cell installation room. It is the integrators responsibility to ensure sufficient air supply to the fuel cell modules as well as the required air quality.

Table 13 Ambient air characteristics necessary for the cathode subsystem.

Specification.	
Air inlet minimum temperature	0°C
Air inlet maximum temperature	+45°C
Maximum allowable salt concentration	< 20µg/m³
Process air pr FCwave™ module[3]	12.700 l/min

16.1. Process Air Subsystem Overview

The process air delivery system will automatically supply the necessary air to the fuel cell module. The amount of process air will depend on the current being drawn from the fuel cell.

[3] Minimum amount of air available at all times while the FC module is running

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The process air delivery subsystem is primarily composed of an intake filter, twin compressors, and air conditioning elements (humidifiers) before air enters the stacks. After the stacks, air exits from the module through the process air exhaust. A simplified process air system is shown in Figure 21.

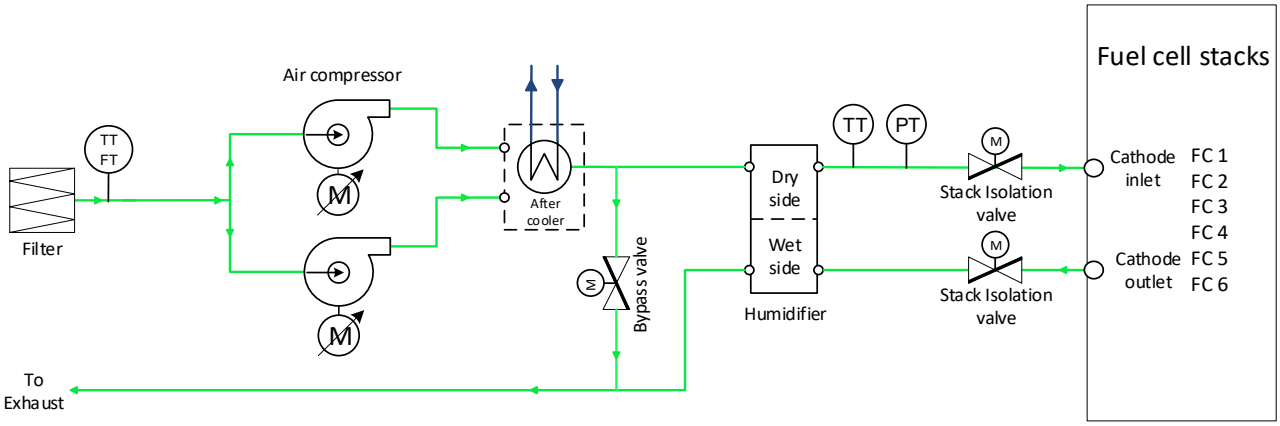


Figure 21 – Simplified Process Air System.

16.2. Process Air Intake Quality

The air filter in the cabinet doors of the module will ensure the purity of the air delivered to the fuel cell stack meets acceptable levels. To increase filter life and improve their performance, the fuel cell room shall be treated to minimize quantity of salts, SOx, NOx and ammonia, as they are quite harmful to the FCwave™ module. The air filter is a service item and part of the preventative maintenance schedule.

Consult Ballard during the integration design for feedback on this topic.

16.3. Process Air Intake

The process air intake is in the top of the two cabinet doors in the module. The air intake must have enough clearance and not be restricted . See Figure 8 – Isometric view of FCwave™ module. The air in the fuel cell room shall be of good quality (as explained above) and come from a non-hazardous zone. There shall be enough free space around the module to ensure sufficient air intake (as explained in section 11.1).

16.4. Process Air Exhaust Backpressure

The process air flow rate capacity of the air delivery system is sensitive to the backpressure exerted at the process air exhaust of the fuel cell module. In vessel integration, the integrator should work to minimize the pressure drop through the exhaust piping and any additional components such as a water separator in the exhaust. The backpressure at this exhaust should not exceed the value in Table 14

Specification	
Item	Value
Process air Exhaust Backpressure (Maximum allowable pressure-drop between the process air outlet port and atmosphere)	≤15 mbar
Average exhaust flow	12.700 lpm

Table 14 – Air Exhaust Backpressure Specification.

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Consult Ballard during the integration design for feedback on this topic.

16.5. Process Air Exhaust Composition

Specification	
Item	Value
Temperature	50-80 °C
Mass flow	100 – 260 g/s (dry basis)
Nitrogen	78 – 92% (dry vol)
Oxygen	7 – 21% (dry vol)
Relative Humidity	~100% RH
Liquid Water	Stack current and coolant temperature specific
Hydrogen	Startup: <1 % (dry vol) Operation: <1 % (dry vol)

Table 15 – Air Exhaust Composition Specification.

The expected composition of the process air exhaust stream is detailed in Table 15.

The process air exhaust will contain oxygen-depleted air, water in liquid and vapor form, and a small amount of hydrogen. The hydrogen component in the process air exhaust is the result of purged gas from the hydrogen circuit.

WARNING Special note should be taken of the reduced oxygen content in the exhaust stream. Personnel is not permitted inside exhaust ducting or other spaces containing fuel cell exhaust with fuel cell operating. All such spaces shall be thoroughly ventilated before personnel is permitted to enter.

16.6. Process Air Exhaust Integrator Requirements

This section describes the requirements to the integrator when designing the process air exhaust from the fuel cell module.

The exhaust piping must be suitable for the temperatures and composition as outlined in Table 15. Note that the air stream contains significant amounts of de-ionized water droplets and vapor. The surface temperatures of the exhaust can be up to 80 °C hot.

The liquid water from the exhaust must be handled by the integrator. As the condensed water will collect in the lowest sections of the exhaust piping, experience has shown that this settlement of liquid could lead to corrosion, freezing during periods of non-operation and intermittent spraying of liquid water out the exhaust pipe. It is recommended that the integrator incorporate a water drain on low sections of the piping.

Note: The drain in the FCwave™ is not intended for draining customer part of the exhaust system.

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17. Process Water Drain

The fuel cell reaction produces DI water, which must be drained from the module from the Process Water Drain.

Refer to section 12 “Process Connections”, in Figure 15, the Process Water Drain is number “6”.

The process water drain piping must be constructed of materials resistant to DI water. Contact Ballard if there are questions regarding material selection.

The Integrator shall ensure the drain does not freeze and block the flow of liquid.

The produced water at 200 kW is ≤ 3 L/min. This is mostly water vapor mixed with the process exhaust.

Only a small percentage of this water will come out the process water drain as liquid.

Specification	
Item	**Value**
Media	De-Ionized Water
Temperature	20 – 70°C
Volume	0 – 3 L/min
Potable Water	No

Table 16 – Process Water Properties and Composition.

18. High temperature Coolant Subsystem

As part of the fuel cell stack operation, heat is developed. The liquid cooled stacks reject heat proportional to the power output. The amount of rejected heat is increased in proportion to stack aging/degradation and load. A simplified coolant circuit is shown in Figure 22 – Simplified HT Coolant Circuit.

18.1. HT Coolant System Overview

The FCwave™ module coolant delivery subsystem contains a coolant pump and motor set with a liquid cooled controller which delivers the required coolant flow to the fuel cell module. The coolant inside the module passes through an internal heat exchanger, where heat is transferred to the external coolant loop, provided by the integrator.

Coolant loop and composition:

Internal Coolant
Allowed cooling medium: High-purity De-ionized water / ethylene glycol 50/50 mix (further options see Table 17 and Table 59)

External Coolant (High Temperature loop) – **Integrator supply**
De-ionized water, fresh water, or glycol mixture. Integrator is responsible for cooling medium and pump.

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A pair of electronically controlled valves are regulating the stack coolant inlet temperature. The valves either throttles the flow of coolant to the heat exchanger or bypass the heat exchanger.

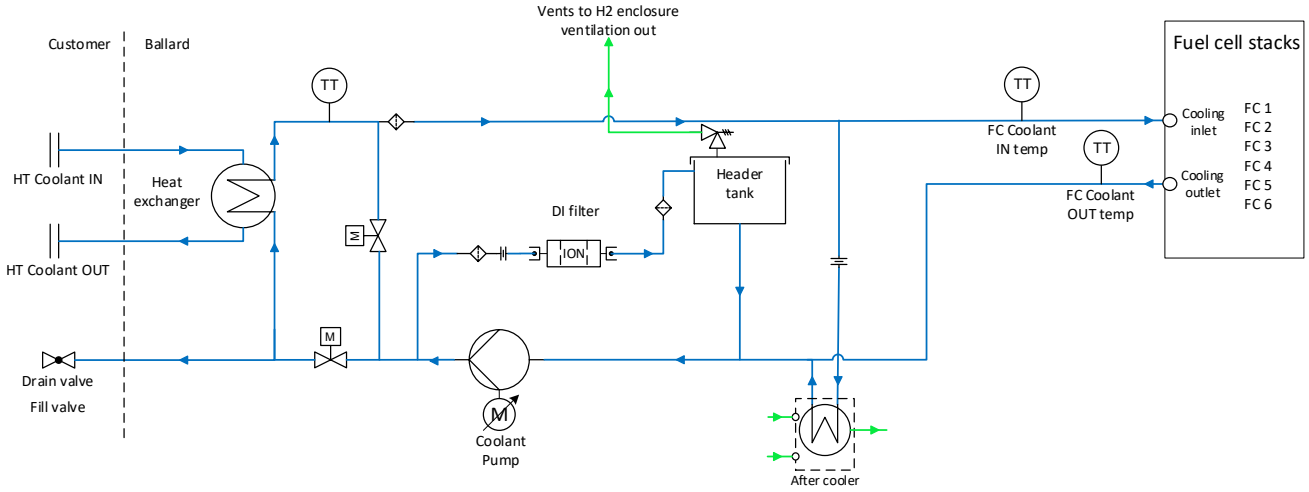


Figure 22 – Simplified HT Coolant Circuit.

During start-up, the coolant valves is positioned to bypass the heat exchanger, allowing coolant to recirculate though the stack, reducing the warm-up time. The internal cooling system also contains a particulate filter to remove any particulate matter present.

18.2. Coolant Chemical Hazard

⚠ CAUTION

The fuel cell coolant loop will contain ethylene glycol. For safety see chapter 8.8

18.3. Internal Coolant Specification

Follow the requirements specified in Table 17 – Module Coolant Specification, ensure that:

- The cooling system can maintain the conductivity below the maximum specified value.
- Adequate clean maintenance practices are in place.
- Any material used in the cooling system is compatible with the coolant type.

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Specification	
Item	Value
Conductivity	≤ 5µS/cm @ 25 °C
Ethylene Glycol Concentration	≤ 50% volume Balance DI Water or 60% volume Balance DI Water[4]
Particulate Size	<100 µm
Chloride Concentration	≤2 ppm
Iron Concentration	≤2 ppm

Table 17 – Module Coolant Specification.

NOTE: High coolant conductivity will result in loss of electrical isolation between the fuel cell high voltage and the system chassis since the coolant circuit can provide a conductive path. The coolant conductivity specified in Table 17 should be suitable for most applications; however, the conductivity required for a specific application may need to be lower to achieve an overall system isolation which satisfies regulatory standards. The integrator should ensure that the conductivity limit chosen is suitable for their application.

To maintain the stack coolant conductivity below the maximum level, a DI filter is installed in the coolant circuit. Part of the overall coolant flow is diverted to the DI filter to continuously remove ions in the water.

Table 18 lists the recommended suppliers for fuel cell grade ethylene glycol mixture. Pure ethylene glycol mixed with deionized water is acceptable (providing the conductivity is <5µs) and deionized water (under **non-freezing** operation). Do not use other coolant types. Pure deionized water (<5µS conductivity) is permissible if the module is used for laboratory operation and is kept above freezing temperatures.

Specification		
Supplier	**Part Number**	**Notes**
BASF	Glysantin J21725	50/50 Ethylene Glycol / DI Water Pre-mixed
BASF / Valvoline	Glysantin FC G 20-00/50	50/50 Ethylene Glycol / DI Water Pre-mixed
Merck	100949	Ethylene Glycol Extra Pure
Univar	610583	50/50 Ethylene Glycol / DI Water Pre-mixed
Univar	1126085	Pure Ethylene Glycol
Univar UK	4338	Pure Monoethylene Glycol
Dynalene	LC-EG	Ethylene Glycol / DI Water Pre-mixed

Table 18 – Coolant Suppliers. Some of these coolants come pre-mixed others need to be diluted. The maximum 50% Ethylene Glycol concentration as mentioned in the specification must be followed.

[4] If the storage temperature after operation is expected to be <-37°C then use 60/40 glycol/DI water mix. The module is pre-flushed with 60/40 glycol/DI before shipping.

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NOTE: It is not recommended to store modules filled with deionized water for more than 7 days, due to its reactivity. Stagnant deionized water has shown an ability to create a corrosion reaction in some components of the module. For extended storage it is recommended to flush the coolant circuit with a water/ethylene glycol mix. Use only coolants shown in Table 18 or consult Ballard Power Systems.

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18.4. Internal Coolant Volume

The coolant volume of the fuel cell module and coolant delivery system is specified in Table 19.

Specification	
Item	Value
Internal coolant system volume	45 L

Table 19 – Module Coolant Volume Specification.

For filling and draining the internal coolant system, see section "18.8 Filling and Draining the Internal Coolant Loop"

The coolant header tank contains no more than 10 liters of volume.

CAUTION **Overpressure of the coolant circuit during filling can cause permanent damage to the fuel cell.**

18.5. External Coolant Specification

The list of permitted coolant compositions for the external primary coolant loop is listed in Table 20.

Specification	
Item	Value
Coolant Medium	DI Water, Water/Glycol mixture
Maximum particulate size	1,2 mm
Maximum pressure	30 barg
Maximum inlet temperature	45 °C

Table 20 – Module External Coolant Specification.

18.6. Coolant Inlet Temperature and Heat Rejection

Maintain the temperature specified in Table 21 for a nominal fuel cell module coolant inlet temperature.

Some comments and considerations for coolant heat rejection and inlet temperature control:

The expected module coolant heat rejection and flow rates at End Of Life (EOL) are specified in Table 21 – HT coolant loop specifications. These values can be used as a guideline for sizing the coolant radiator.

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Specification		
Parameter	**Value**	**Unit**
Coolant inlet temperature nominal	40	°C
Coolant inlet temperature minimum	5	°C
Coolant outlet temperature maximum	65	°C
Coolant loop ΔT	25	°C
Maximum heat dissipation full load EOL	350	kW
Expected mass flowrate cold side [@40°C inlet]	14.015	kg/h
Connections	DN50, 2" ISO7/1	
Pressure drop, Heat exchanger customer side [@ 11.000 kg/h]	< 100	mbar

Table 21 – HT coolant loop specifications.

The expected module coolant heat rejection and flow rates at End Of Life.

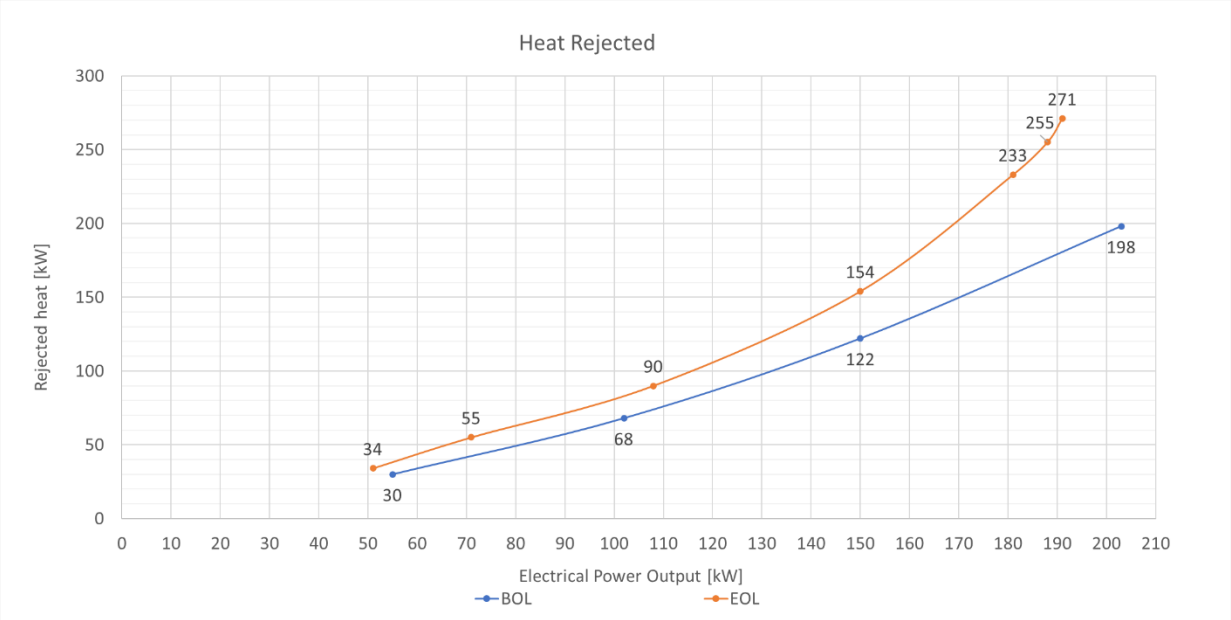


Figure 23 - System Heat Rejection through the heat exchanger vs. Power.

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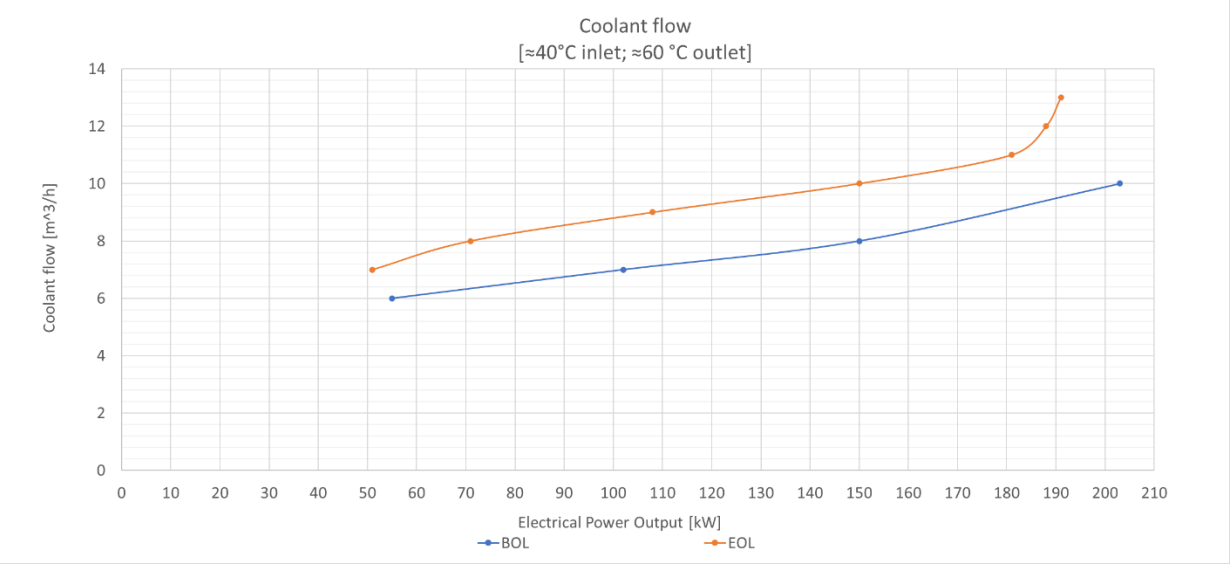


Figure 24 - System Coolant Flow vs. Power (HT customer coolant flow)

18.7. Header Tank of the Coolant System, Air Bleed and Pump Make Up

The module contains an internal header tank for the HT coolant loop, which provides a reservoir of coolant and accommodates thermal expansion of the coolant. There is a low level switch in the header tank to provide warning for low coolant levels.

When filling or draining the module's HT coolant loop, use the makeup connector outlined in Table 6 position 9. Connect an external pump to the connector and use the pump to fill the module with coolant.

When handling coolant, wear personal protective equipment in accordance with the Safety Data Sheet and local regulations. Hydrogen gas may accumulate in the coolant tank. Purge the header tank of said hydrogen prior to servicing. Always wear safety eyewear and eliminate sources of ignition (flames, sparks, electrical tools, etc.) when servicing the header tank.

18.8. Filling and Draining the Internal Coolant Loop

The Internal Coolant loop can be filled and drained by a fill/drain connection on the interface plate of the module. An external pump is connected to this port and used to fill or drain the module.

During filling operations, **do not** overfill the coolant header tank, but continually observe the reading in the sight glass on the header tank. Flowrates and pressure during filling are specified in Table 22.

To perform a filling and draining of the system Service Tier 1 training completion is required.

Specification	
Make-up pressure	Between 200 mbarg and 1 Barg

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Make-up flowrate	< 10 lpm

Table 22 – Module Coolant make up pressure and flowrate.

When changing the coolant inside the module, use the provided fill/drain port (see Figure 15).

It is strongly recommended that the coolant is pumped into the lowest part of the circuit with the use of a small off-board coolant fill pump. When filling the internal coolant circuit, keep an eye on the sight glass on the header tank, where the coolant level is visible.

Care should be taken as to not overpressure the coolant circuit during filling. This can occur if the flow of the coolant being pumped in exceeds the capacity of the header tank vent to relieve the displaced air. It is recommended to install a mechanical pressure relief device at the outlet of the coolant fill pump cart that is set to 1.0 Barg.

19. Low Temperature Cooling System

The fuel cell module also contains a low temperature cooling system. The low temperature cooling system is an independent system used for cooling of:

- Inverter for Cooling Pump motor
- Inverter for Hydrogen Recirculation Blower electrical motor
- Air compressors (2 pcs)
- Inverters for air compressors

The low temperature cooling system is considered as an auxiliary coolant circuit internal to the fuel cell module. Unlike the main cooling system, there is no coolant pump in the auxiliary circuit. The coolant and flow for this system is supplied by the integrator and should comply to the data given in Table 23. Integrator connection to the low temperature cooling system is in the base of the cabinet.

Diagram over the low temperature coolant circuit is shown in Figure 25. Interface connectors are shown in Figure 15.

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Specification		
Parameter	**Value**	**Unit**
Maximum inlet temperature	50	°C
Minimum inlet temperature	5	°C
Maximum inlet pressure	1,5	barg
Maximum heat dissipation	5	kW
Pressure drop	1	barg
Typical flow *[@Δt 10°C; inlet 40°C & outlet 50°C]*	8	L/min
Coolant mix	50/50 Water Glycol mix.[5]	
Connections	DN25 – ISO7/1 – Rp1”	

Table 23 – LT coolant loop specifications.

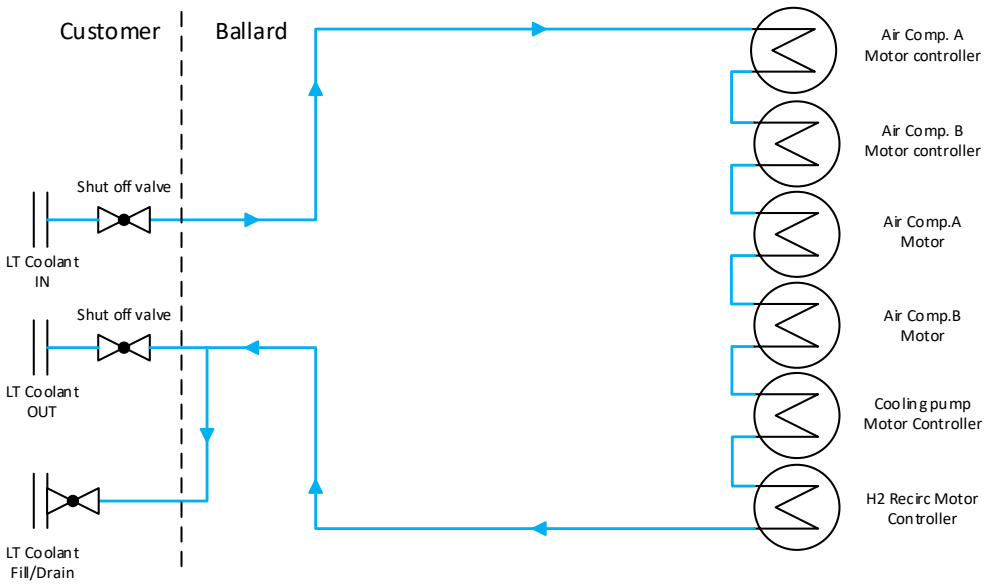


Figure 25 – Low Temperature cooling loop (LT Cooling).

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[5] DI water is not permitted as coolant medium

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20. Gas Freeing and Inerting Procedures

Before performing service on the FCwave™ module, the following must be verified:

- Hydrogen supply line has been depleted
- No dangerous voltages are present in the system

The FCwave™ system includes an automated procedure that must be executed before beginning maintenance procedures, which depletes hydrogen from the supply line and system.

WARNING **Before accessing High Voltage Panel or components inside the Hydrogen Enclosure, all procedures must be followed**

20.1. Inerting procedure – Prepare for Service

This automatic procedure is carried out by request of the Vessel Control System, which activates an automatic subroutine in the FCwave™ fuel cell module which performs the inerting procedure. The function “Prepare for Service” uses the module blowers and compressors to ensure the module is ready for maintenance.

There is no requirement for the integrator to supply inert gas such as Nitrogen.

After completion of the automated procedure, manual verification of voltage must be performed before any maintenance actions.

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21. Control and Electrical Introduction

The purpose of this section is to provide the integrator a high-level overview of the control and electrical systems that comprises the FCwave™ module.

The fuel cell module contains four main control and electrical systems:

- Low voltage electrical (24 VDC)
  - Responsible for supplying all process instrumentation and controllers with power. Contains internal EMC filters and fuses
- High voltage electrical (350-720 VDC)
  - Responsible for supplying power from the fuel cell stacks to the integrator and balance of plant components. Power to start the system is provided by the integrator during the start-up sequence.
- Control System
  - Responsible for monitoring and controlling the processes inside the fuel cell module, communicating with the integrator, datalogging and service functionality
- Safety System
  - Responsible for monitoring the safety and integrity of the fuel cell module. This includes hydrogen concentration measurements, ventilation air flow verification and fire detection.

The following overview includes references to the different aspects of the operation of the FCwave™ module and the sections where they are described. Use Ctrl+Click to jump to the references.

Control System
- Supply
7 FCwave™ Fuel Cell Module Datasheet
22.1 Low Voltage Supply
- Functionality
25 Control System – State Machine
30 Start-up sequence for the FCwave™ module
32 Normal Operation Example
- CAN bus
37.3 CAN Communication
37.4 CAN Customization Key
35.5 Low Voltage Connector Pin Assignment
- Physical connections
34.2 Digital Supply and Signal Definitions
35 Low Voltage Connector Construction
35.5 Low Voltage Connector Pin Assignment
Safety System
- Supply
22.1 Low Voltage Supply
- Functionality
38 Safety System – Functional description
- Physical connections
34.2 Digital Supply and Signal Definitions
35 Low Voltage Connector Construction

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35.5 Low Voltage Connector Pin Assignment
Operating the module
- Establishing communications
37.3 CAN Communication
37.4 CAN Customization Key
37.5 Controller Heartbeat
- Error codes
37.1 Fault Severities
37.2 Resetting a fault
- DCDC Converters
27 Integration with external DCDC Converters
28 DCDC Control Indicators
29 Important limits during operation
30 Start-up sequence for the FCwave™ module
- Operational Sequence
30 Start-up sequence for the FCwave™ module
31 Special Operating States
32 Normal Operation Example
- Precharge
30.3 Pre-charge
- Startup sequence
32.1 Startup Sequence
- Module running
29 Important limits during operation
- Shutdown and after-run process
30.7 Shutdown procedure of the DCDCs
32.4 Shutdown sequence
32.5 Pressure Decay self-test
33 Overnight storage of FCwave

CAUTION **Before operating the FCwave™ module, carefully read through all above points and refer any questions to your Ballard representative. Improper use and handling of the fuel cell may lead to dangerous situations and permanent or temporary damage and performance degradation of the fuel cell module.**

22. Low Voltage Electrical Overview

The control system of the FCwave™ is powered by two 24V DC supply voltages, as specified in CMS006.

The normal 24V supply powers the module controller, module sensors and control voltage for the motor controllers.

The safety 24V supply powers the safety system, safety controller and safety sensors.

The 24V supply voltages are passed through EMI filters before being separated out to the different sub-systems in the module.

The module controllers are powered from the 24V supply and runs continuously while 24V is supplied to the module. Ventilation fans, internal to the module, are also running while 24V is supplied.

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The 24V system is internally fused with resettable electronic circuit breakers.

22.1. Low Voltage Supply

The system is supplied by 24V DC. Please note the voltage tolerance on the 24V supply is narrower than normal 24V marine supply. The Low voltage supply shall be equipped with a UPS system with at least 10 minutes of backup duration. When the UPS system is active, Ballard strongly recommends that the module is brought to a controlled **shutdown** without delay.

Specification	
Control and Safety system supply voltage	24 V DC
Maximum Allowable voltage deviation	±10%

*Table 24 – **Control and Safety system** supply specification.*

Specification	
Control and Safety system supply backup	Uninterruptible Power Supply required
Backup duration	10 minutes

Table 25 – Control and Safety system UPS specification.

22.2. Design Standard and Exceptions

The module control system is designed to comply with EN-60204-1:2018.

The system does not have a bonding between 0 Vdc and chassis/ground.

23. High Voltage Electrical Overview

The FCwave™ module PEM fuel cell stacks are a DC current source, with an output voltage which varies depending on the current drawn from the system. This relationship is shown in Figure 4 – Module output Voltage and Figure 5 – Module Output Current.

The HV DC system must be operated as a floating electrical system, see section 40.1.

During operation, the stacks supply power to the BOP components, internal to the module, making it self-sufficient. As described in section 27.2, external high voltage DC power must be provided during startup. During operation, the fuel cell stacks convert chemical energy from hydrogen to electrical and thermal energy, the rate of which is dependent on the load imposed on the fuel cell module by the external DCDC converters. The fuel cell operates as a load follower, such that the managing of the load is the responsibility of the integrator. To assist in this, the module communicates its operational limits to the integrator over the CAN bus.

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23.1. Pre-charge of the Electrical HV system

The input stages of the motor inverters in the module contain capacitors, which may lead to surges in current draw if directly connected to a high voltage supply without current limiting measures in place.

The FCwave™ module contain equipment and control sequences for gradually charging the internal capacitances such that current surges are avoided.

The pre-charge sequence is detailed in section “30.3 Pre-charge”

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24. Control and Safety System Overview

The control and safety system of the Module is comprised of the following, illustrated in Figure 26:

- **Module Control Unit**
  - Responsible for control of the fuel cell and balance of plant components.
  - Monitors and controls the state of reactants and power flowing to and from the module.
  - Monitors and reacts to system conditions, including hydrogen concentration measurements.
  - Transfers data logs to Ballard when able to establish communication with the Internet (via encrypted connection)
- **Safety Control Unit**
  - Responsible for monitoring safety of the module via independent sensors and inputs. Provides hardwire signals to and from the vessel.
  - Independent from Module Control Unit, triggers emergency shutdown of module when it detects an emergency.

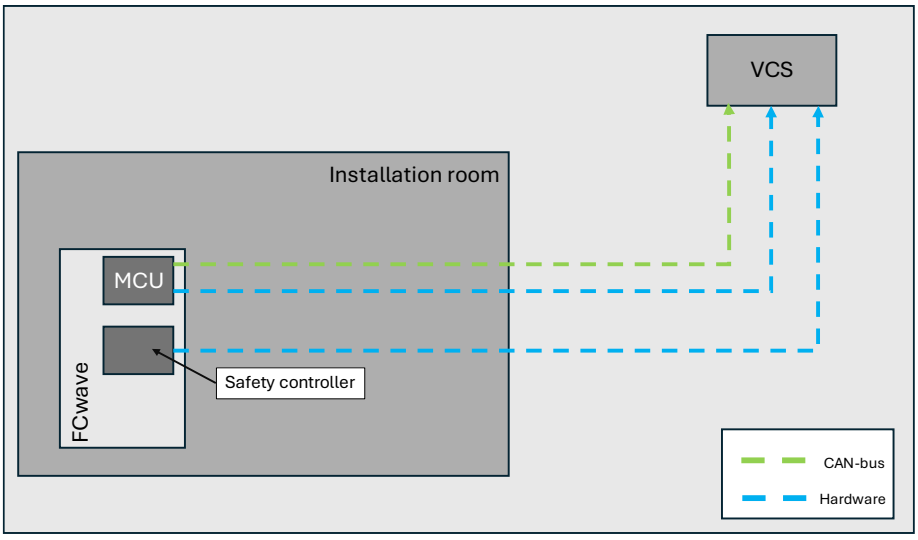


Figure 26 – Control System Architecture.

25. Control System – State Machine

The module control is based on a state machine, in which states correspond to the operating mode of the fuel cell. These states are communicated to the integrator over the CAN bus.

25.1. Introduction

In normal operation, inputs from the integrator causes the state machine to transition from the initial "Locked" state towards the "Running" state, in which the fuel cell is in operation.

The states are enumerated in Table 26. Please note that some states contain internal sub-states.

The normal high-level sequence of states for the fuel cell module, as well as the customer signals, required to initiate the various state changes, is shown in Figure 27 – High Level State Sequence.

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Estimates of power flow, to and from the fuel cell, during the state sequence and the approximate timing of **Startup** and **Shutdown** sequences, are also shown.

The integrator should follow the diagram for the control signal sequence to ensure safe operation of the module.

State	Description
Locked	The module controller is active, after receiving the **SAFE_IN** signal (see Table 41) but will remain in **Locked** state until the correct CAN customization key is received.
Unlocked	Correct CAN customization key received from the drive system (see Section 37.4). High Voltage circuits are depowered.
Pre-charge	The module pre-charge internal HV circuit. When pre-charge is complete, module enters **Standby.**
Standby	The module is waiting for the **MODULE_RUN** CAN signal to start the fuel cell. Module HV bus is connected to Vessel. Stack contactors are open.
Prepare for maintenance	This state provides a function for depleting the module of hydrogen to prepare for maintenance.
Startup	A sequence of steps that power up the fuel cell stacks and prepare the module to provide power. Air and hydrogen start flowing to the fuel cell module. Fuel cell stack voltage will rise. High voltage output contactors are closed. Note: This state contains sub-states internally.
Running	The module will set I_ALLOW > 0 Amps and current can be drawn from the fuel cell (see Section 32.1).
Shutdown	Water is purged from the reactant gas circuits and a controlled bleed down of voltage from the stack is performed. Module state will return to Unlocked. Note: This state contains sub-states internally.

Table 26 – System Operating States and Descriptions.

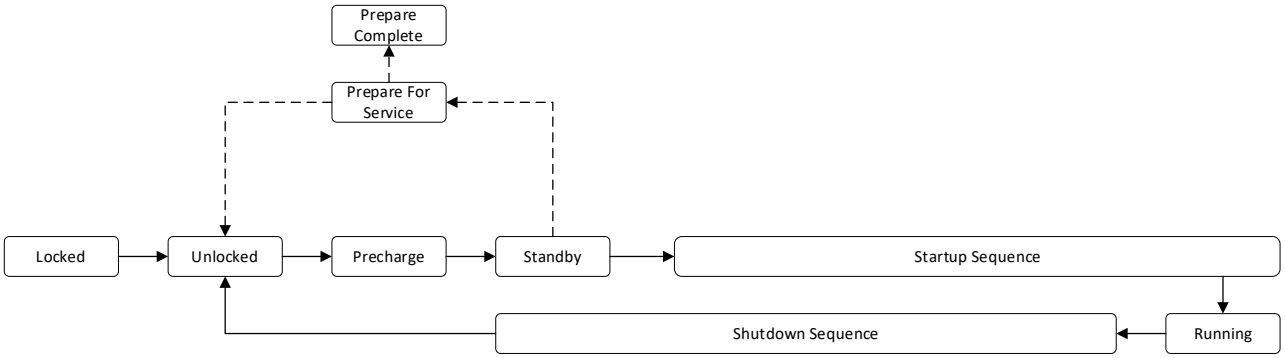


Figure 27 – High Level State Sequence for FCwave.

A more detailed overview of the module state machine is available in section 28 " DCDC Control Indicators", Figure 29 – FCwave™ State machine with DCDC Indicators.

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26. Ballard Master Control Unit

The module can be operated from a Vessel Control System directly, or if several FCwave™ modules are present, they can be controlled from a Ballard Master Control Unit.

For questions regarding the master control unit, contact Ballard.

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27. Integration with external DCDC Converters

The fuel cell module is a DC power source and operates as a load follower, with the external DCDC operating as load controller. This makes it extremely important to have the right understanding of the fuel cell module operation when designing the DCDC control.

27.1. Requirements for external DCDC converters

This section describes the functional requirements for the DCDC converters connected to the high voltage DC outputs.

These requirements are valid for bi-directional DCDC converters, which can provide power to the module during startup. For other configurations, please contact Ballard Europe.

For control specification for the DCDC converter(s), see section 30.6 “Startup procedure of DCDCs” and section 30.7 “Shutdown procedure of the DCDCs”.

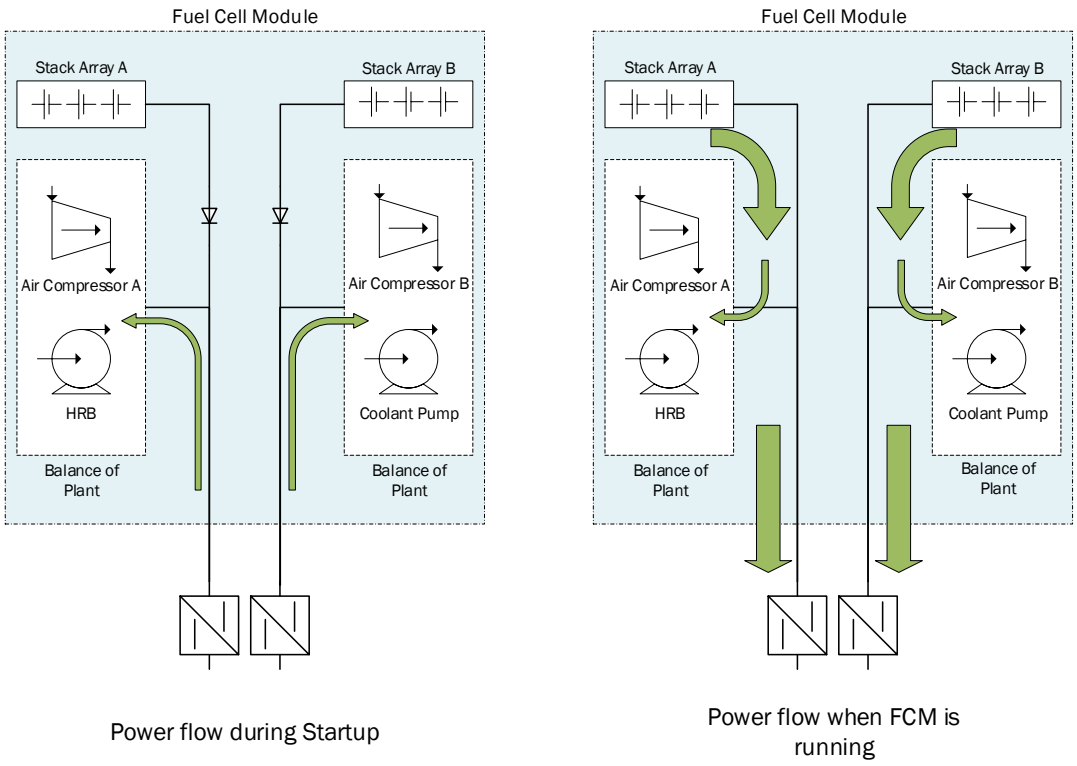


Figure 28 – Power flow to and from FCM during startup and run mode.

Dual Output configuration shown.

27.2. Role of the DCDC converters

The role of the DCDC converters is twofold:

During module startup, DCDC(s) must source power to the Balance of Plant (BOP) components of the module. After startup, the BOP components are powered by the stacks, directly.

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During normal operation, regulate the current drawn from the module, within the specified limits of I_Allow and the vessel operator.

Proper integration between the DCDC and the module is essential, as the module is a load-follower with dynamic and static limitations that the module cannot enforce by itself.

These limitations are communicated to the integrator via CAN bus (see section 37.2), and the integrator is responsible for respecting them when supplying power to the vessel.

27.3. Functional Requirements

Two converters are to be connected to the module for the dual output configuration.
Single converter is to be connected to the module for the single output configuration.
Converters must be able to handle voltages and currents as specified in CMS006 “FCwave™ Fuel Cell Module Datasheet”.
When the converter is drawing power from module to the vessel DC bus (power supplied from module to vessel):
The converter must be able to operate in constant-current (CC) mode, or a functionally identical mode. The setpoint must be on the input side.
The converter must have input side high and low voltage limits.
Stack voltage measurement is provided by the module controller and provided to integrator over CAN bus.
Output voltage and current limits are solely the responsibility of the integrator.
When the converter is drawing power form the vessel DC bus and supplying to the module (sourcing from vessel to module):
The converter must be able to operate in constant-voltage (CV) mode. The setpoint must be set on the input side.
The setpoint for the CV operation is received over CAN bus from the module and will in the range from 300 to 500 VDC.
During CV operation, the voltage must be within ±5% of setpoint. Below 2% deviation is preferred.
The CV operational mode shall implement a current-limiting function on the input side, which ensures the safety of the system.
The current draw from the module will start high and fall to 0 as BOP load transitions from external DCDCs to the internal stacks. The DCDC must allow the voltage to increase above the setpoint without exporting power from the module. Power needs during startup is detailed in section 32.2 “Startup Energy Consumption”.
Voltage ripple during operation shall not exceed 5% nominal voltage during the full range of operation. Voltage ripple of less than 2% is preferred.

27.4. DCDC Converters during start up

When the customer wishes to operate the fuel cell module, external power must be supplied.
As the stacks require both oxygen and hydrogen, the air compressor and hydrogen recirculation system must operate before the stacks can supply power.

To operate the module successfully, the DCDC must adhere to the procedures, described below and illustrated in Figure 28:

During module startup, DCDC(s) must source power to the Balance of Plant (BOP) components of the module. After startup, the BOP components are powered by the stacks, directly.

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During normal operation, regulate the current drawn from the module, within the specified limits of I_Allow and the vessel operator.
See the section 28 “DCDC Control Indicators” which describe when the DCDC converters are to operate in which direction and mode.

The voltage and current requirements are detailed in section 30.6 “Startup procedure of DCDCs”.

27.5. DCDC Converters during operation

During the “Running” state of the module, the DCDC converters are required to operate in constant current mode, with the setpoint set at the input side (towards module).

27.6. Definitions

- All voltages and currents are Direct Current.
- Power flow **from** Fuel Cell Module **to** rest of vessel is defined as positive direction.
  - Current flowing from module is denoted I > 0.
  - Current flowing from vessel to module (e.g., during startup) is I < 0.
- Input of the DCDC converter is defined to be towards the fuel cell module.
- Output of the DCDC converter is defined to be towards the vessel drivetrain.
- In dual output configuration, the DCDC converter connected to stack string A is referred to as “Converter A” or “CNV A” in abbreviated terms. “Converter B” or “CNV B” is similarly connected to stack string B.
- $I_{OutputA}$ is the current flowing from module to Converter A
- $I_{OutputB}$ is the current flowing from module to Converter B

27.7. DCDC Technical Requirements

This section describes the validated specifications for the external DCDC converters.

Product validation and EMC testing has been performed with DCDC converter switching frequency of 4kHz and 5kHz. If the integrator wishes to use switching frequencies outside the validated range, contact Ballard. If there are questions about using bigger DCDC converters, ask Ballard.

Specification		
External DCDC Converter switching frequency	Minimum	4 kHz
	Maximum	5 kHz
Voltage Ripple	Maximum	5% peak-peak
	Preferred	2% peak-peak
Maximum DCDC size	< 400kW	

Table 27 – DCDC Converter requirements.

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28. DCDC Control Indicators

This section describes the function of several indicator bits, transmitted over the CAN bus to the integrator. These bits indicate the desired operating mode of the connect DCDC converters.

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The bits are transmitted in the CAN Message "FCM_REQUEST_1" and are defined as follows:

- **DCDC_STOP**
  - This bit, if active, signals that the Fuel Cell does not require the DCDC converter to be active and it should not be actively modulating.
- **DCDC_IMPORT**
  - This bit, if active, signals that the Fuel Cell requests that the DCDC converter is active and operates in constant voltage mode towards the fuel cell module. Desired voltage setpoints and current limits are transmitted in the "FCM_REQUEST_2" CAN message.
- **DCDC_EXPORT**
  - This bit, if active, signals that the Fuel Cell is ready to provide power to the vessel and the DCDC converter should be active and operating in constant current mode towards the vessel. Current limitations are described in the following sections:
    - Section 29 - Important limits during operation.
    - Section 29.5 - Ramp rates

The DCDC Control Indicators are illustrated in Figure 29 – FCwave™ State machine with DCDC Indicators.

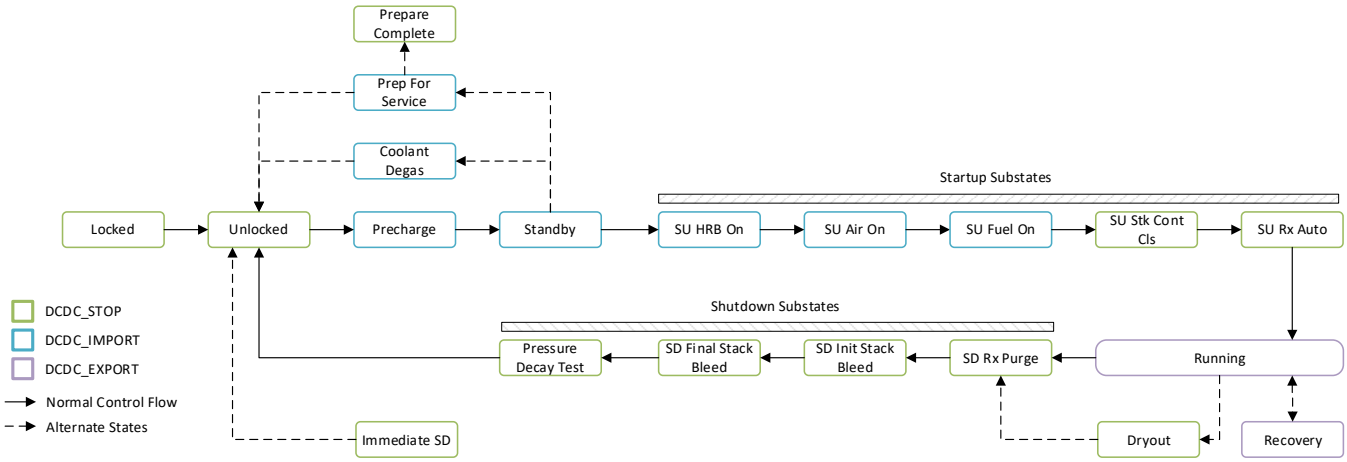


Figure 29 – FCwave™ State machine with DCDC Indicators.

28.1. DCDC_STOP Control Indicator

In case the DCDC_STOP control indicator is active, the module requests no action from the connected DCDC converters. They can be in standby mode, but no active modulation.

The DCDC_STOP control indicator is active during the following states:

- When the module is in Locked and Unlocked states
- When the module is in the shutdown sequence after operating
- When the module is in the later part of the **Startup** sequence
- When the module is in the **Dry-out** or **Prepare for Service Complete** state (see section 31 "Special Operating States")

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28.2. DCDC_IMPORT Control Indicator

In case the DCDC_IMPORT control indicator is active, the module requests that the connected DCDC converter is active, operating in Constant Voltage mode with constant voltage towards the fuel cell module.

The DCDC_IMPORT Control Indicator is active during the following states:

When the module is in **Pre-charge** and **Standby** states.
When the module is in the early part of the **Startup** sequence
Please note that the module becomes self-powering after the SU Fuel On state, as both hydrogen and oxygen is present in the stacks, therefore the DCDC is stopped until the module reaches Running state
When the module is in the **Coolant Degas** or **Prepare for Service** state (see section 31 “Special Operating States”)

28.3. DCDC_EXPORT Control Indicator

In case the DCDC_EXPORT control indicator is active, the module requests that the connected DCDC converter is active, operating in Constant Current mode, exporting power from the fuel cell module to the DC-bus.

Current limitations are described in the following sections:

- Section 29 - Important limits during operation
- Section 29.5 - Ramp rates

The DCDC_EXPORT Control Indicator is active during the following states:

When the module is in the Running state
When the module is in the Recovery state (see section 31 “Special Operating States”)

29. Important limits during operation

29.1. Minimum and Startup Current Draw

The fuel cell module has a minimum current draw of 50A for each stack string at BOL (Equivalent to approx. 55 kW) from the module. Operating at a power level below this, for an extended period, will reduce stack lifetime. If the customer current draw is below the minimum level, for more than 10-20 seconds, the module will shut down in a controlled fashion and report an error code to the operator. For a single output module, the value is doubled (100A minimum current draw)

During startup, it is recommended that the initial current is 10A (20A for single output configuration), (see Table 28 – Initial Current Draw Specification) and then ramped to minimum current draw with the ramp rate specified in section 29.5 “Ramp rates”

Specification	
Single Output Configuration – Initial Current Draw	20 A
Dual Output Configuration – Initial Current Draw	10 A

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Table 28 – Initial Current Draw Specification.

29.2. I_Allow and I_Offset

The fuel cell controller will report a maximum allowable instantaneous current draw for the stacks (*I_Allow*) as part of the CAN message transmitted by the Fuel Cell – the message is transmitted with a 100 ms interval.

The Module Control Unit will also report a desired offset between the stack strings, which serves to balance load between components and extend lifetime of the stacks. This parameter is not used in single output systems

- Single Output Configuration:
  - The I_Allow parameter is the maximum allowable current draw from the system. Current draw is never to exceed this value
  - The I_Offset parameter is disregarded.

- Dual Output Configuration:
  - The I_Allow parameter is the maximum allowable current that can be drawn from each string. Current draw for each string is never to exceed this value.
  - The module transmits the I_Offset parameter, which should be added to the current draw from string A and subtracted to the current draw from string B
  - The I_Offset parameter is signed, and a positive value indicates that a higher current should be drawn from string A than string B
  - I_Offset is capped at ±7,5A.

$$I_{OutputA} < I_{Allow}$$

$$I_{OutputB} < I_{Allow}$$

$$I_{OutputA} = I_{Output} + I_{Offset}$$

$$I_{OutputB} = I_{Output} - I_{Offset}$$

Where:

I_{Output} is the current as desired by the customer
$I_{OutputA}$ is the current setpoint for the DCDC converter attached to Output A
$I_{OutputB}$ is the current setpoint for the DCDC converter attached to Output B
I_{Allow} is the maximum instantaneous current draw, transmitted from the Module Control Unit via CAN bus
I_{Offset} is the desired offset between $I_{OutputA}$ and $I_{OutputB}$.

Example:

- Dual Output Configuration

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- I_{Output} is 200A
- I_{Allow} is 250A
- I_{Offset} is +2A
- In this example, the current draw from the DCDC converters ($I_{OutputA}$ and $I_{OutputB}$) must be below 250A and $I_{OutputA}$ should be 202A and $I_{OutputB}$ should be 198A.

29.3. Origin of the I_Allow parameter

The default current limit is set based on maintaining a minimum air stoichiometric ratio, with a maximum allowable current. Computations are then made to determine whether any other factors should be limiting the stack current below its default value. If any of these computations lead to a lower maximum allowable current than the default, module output is de-rated.

Exceeding I_Allow for more than 3 sec will result in an immediate shutdown procedure, to protect the module.

In order to obtain best long-term performance from the module, it is recommended to follow the current-ramp, described in section 29.5.

29.4. Reverse current protection during start-up operation

During startup, the following precautions are taken to prevent reverse polarization of the stacks:

HV system is isolated from stacks via diodes.
HV system is pre-charged gradually, to prevent sudden voltage and current spikes.
The permissible voltage range is transmitted to the integrator over CAN bus.
Voltage is measured inside the module and compared to the acceptable range.
Current limitations are transmitted to integrator over CAN bus. Integrator is responsible for ensuring that the DCDC(s) operate within this range.

If any parameters deviate from allowed ranges, start-up is aborted, and module returns to the 'unlocked' state. Module may open HV contactors to isolate itself if parameters are outside acceptable range. This is done in all alarm severity 3 and safety severity 4 situations.

⚠WARNING Reverse polarization of the stacks must be prevented. This occurs when a voltage, higher than the stack voltage, is applied to the system. A direct consequence of this is rapid heating, hydrogen development and irreversible damage to the stacks.

In worst-case, rapid heating and hydrogen development can lead to detonation or deflagration of present or developed hydrogen, inside the module.

29.5. Ramp rates

As described in section 29 "Important limits", the ability of the fuel cell module to respond to dynamic changes in current draw is bounded.

For longevity of the stacks and balance of plant components, it is recommended to avoid rapid cycling of the current draw, as this will lead to excessive wear on stacks and BOP components.

Ballard recommends that current draw, during normal operation, follows the current vs. time graph shown in Figure 30 – Current/Time ramp for operation of external DCDCs.

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Specification	
Single Output Configuration - Maximum increase/decrease in current draw	40 A/s
Dual Output Configuration - Maximum increase/decrease in current draw (each output)	20 A/s

Table 29 – Current Draw Delta Specification.

Please note that in some shutdown conditions, the I_Allow parameter will decrease more rapidly than specified in Table 29.

Current draw must never exceed I_Allow, which may decrease (or become 0) more rapidly than specified ramp rates. In this case, converter current draw must be immediately reduced to I_Allow or less.

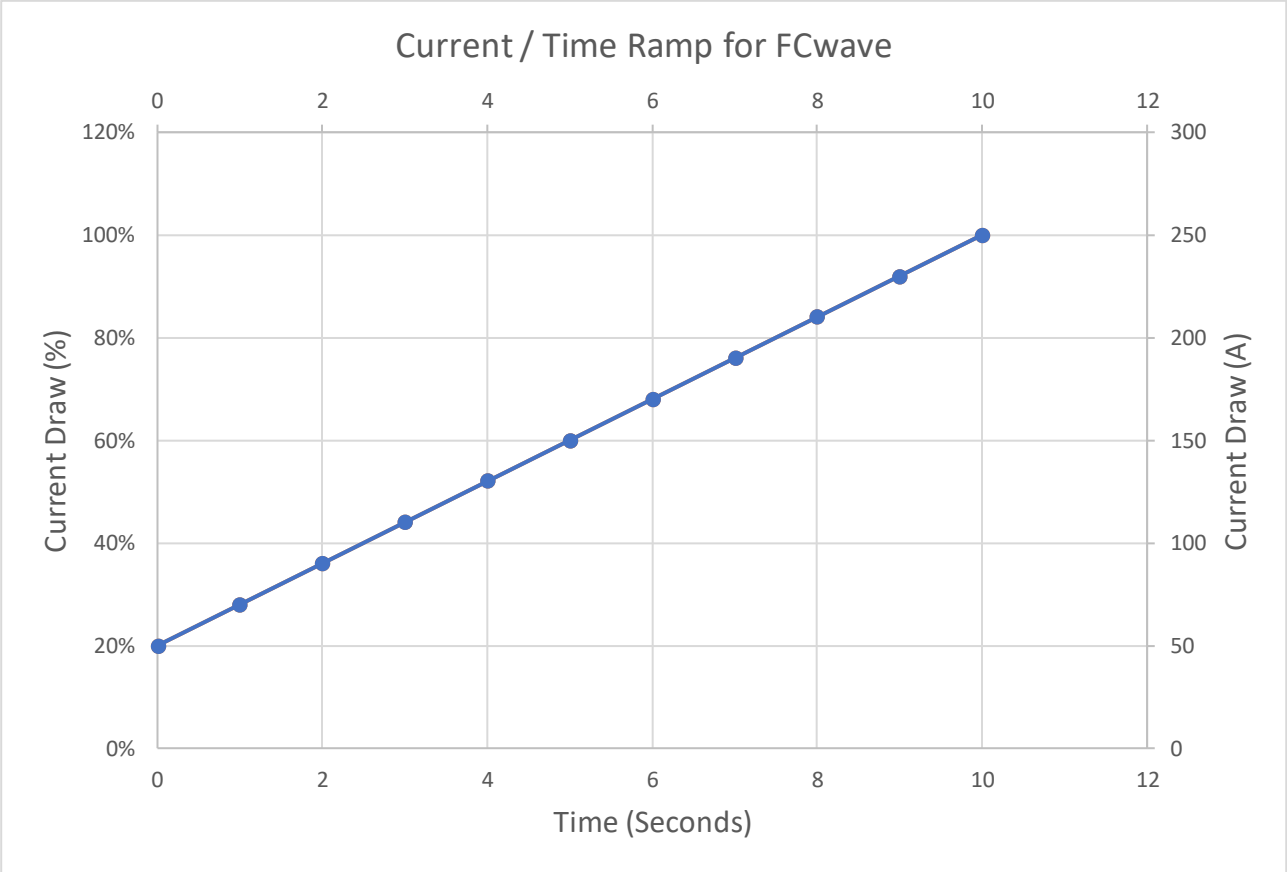


Figure 30 – Current/Time ramp for operation of external DCDCs. Dual Output Configuration shown.

The integrator must always ensure that the current draw remains below the I_Allow parameter, as transmitted over the CAN bus.

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30. Start-up sequence for the FCwave™ module

This section describes the sequence to start operation of the FCwave™ module.

30.1. Standby to Running Cycles

Lifetime of the system is based on the maximum number of **Standby** to **Running** cycles specified in Table 30. This is to preserve the performance of the fuel cell stack and BOP for the entire life cycle of the module. Ballard recommends this is not exceeded in daily use.

Recommendation	
Average Standby to Running Cycles	4 cycles per day (based on 18-hour days)

Table 30 – Maximum Standby-Running Cycles Recommended.

30.2. Vessel Requirements

When integrator desires to operate the Fuel Cell Module (FCM), the integrator must first ensure the following systems are ready to perform as outlined in the datasheet:

- H_2 supply system is ready to provide hydrogen.
- Coolant system is ready to transport heat away from module.
- DCDC converters are ready to operate.
- FCM is in the **Unlocked** state.

The integrator sets the “MD_Enable” hardwire connection to the FCM. This causes the module to enter the **Precharge** state.

30.3. Pre-charge

The module can enter the **Precharge** state from the Unlocked state. In the pre-charge state, the module connects the internal HVDC bus to the external HVDC supply and gradually charges the internal capacitors.

In Pre-charge state, the module awaits HVDC from Integrator. The module will send a severity 1 warning if HV is not measured after 5 seconds. It will stay in Pre-charge indefinitely until either HV is present and pre-charge process is complete or MD_Enable is not active.

- The module low side DC bus is directly coupled to the external DC bus.
- The module high side DC bus is coupled to the external DC bus over a pair of 500Ω resistors.
- This limits the current to 1A or less.
- Internally the voltage is measured:

When the voltage has exceeded a minimum level **AND**
Rate of change on the internal voltage is below a threshold.

- The module high side DC bus is coupled directly to the external DC bus.
- The resistors are decoupled.
- **Precharge** is complete.

When pre-charge is complete, module transitions to the **Standby** state.

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30.4. Standby state

From the **Standby** state, the module provides power to the motor controllers and prepares for operation. H_2 supply valves are closed.

When the integrator transmits the "MD_Run" signal over the CAN bus, the module will transition to the **Startup** state.

The DCDCs must provide a constant voltage to the HV system.

The module can be kept in **Standby** state indefinitely. High voltage DC power is present, but consumption is very low in **Standby** state, unless maintenance is being performed.

30.5. Startup sequence

In the **Startup** state, which comprises several sub-states, the module readies all systems for operation, requests H_2 valves open from the Integrator, and performs the stack power-up sequence.

In this mode, the constant voltage provided by the DCDCs must be kept operating, in order to provide power for the **Startup** sequence, see section 28.

> The air compressors are brought to minimum power levels and start providing oxidizer to the stacks.
> When the HRB is running, the module will flush the H_2 loop, to quickly fill the fuel cells with hydrogen.
> As oxygen and hydrogen are circulated in the stacks, the voltage increases, and rises above the voltage provided by the DCDCs. BOP supply is transitioned from external supply to the stacks.

Integrator shall stop providing a constant voltage when module state (as reported in the FCM_STATUS_1 CAN telegram, see **CMS013 CAN Matrix**) is "**Startup Stk Cont Cls**" or **Startup RX Auto**

The MCU signals the DCDCs to stop and air compressors are spooled up and the module will be able to provide power as the MCU transitions to Running state

During startup, the power supplied from the DCDCs to the module is below 4kW.

30.6. Startup procedure of DCDCs

When controlling the DCDC converters, attention must be paid to the CAN messages from the module, which describe when to provide or draw power.

The DCDC(s) must react according to the following CAN-messages, see **CMS013 - CAN Matrix**:

From message "FCM_STATUS_1"

- DCDC_STOP
- DCDC_IMPORT
- DCDC_EXPORT

From message "FCM_REQUEST_2"

- String A Maximum Import Current (I_BOP_A)
- String B Maximum Import Current (I_BOP_B)
- String A Minimum Voltage (UFC_MIN_A)

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- String B Minimum Voltage (UFC_MIN_B)

The module must not receive nor draw any current through the DCDCs in states *Locked* and *Unlocked*. (DCDC disabled or in stopped state). In these states the contactors are open and the module is disconnected from the DCDC.

In the states **Precharge** until[6] **Startup *Stk Cont Close***, the DCDCs must keep a voltage above the minimum voltages, by supplying adequate current. Preferred voltages are 350 to 450 V, and maximum voltages are 550 V. This is signaled by the flag "DCDC_IMPORT" being true.

There must never be supplied more current than the Maximum Import Current, even if the voltage would drop to less than the minimum voltage.

Going from the beginning of the **Startup** sequence to **Startup Stk Cont Close** takes 30 seconds typically.

In the state **Startup Stk Cont Close**, the DCDC shall stop providing constant voltage (Flag DCDC_STOP is true).

In the state **Running** the DCDC converter shall be in voltage-following constant current mode. In this state I_ALLOW will be ramped up to above the minimum current, described in section 29, within 1 second. The DCDC then has 10 seconds to increase the current draw to above the minimum current.

If the DCDC fails to draw more than the minimum current, the module will first provide a warning over the CAN bus, and if the current draw still does not exceed minimum levels, will signal a fault and perform a controlled shutdown.

30.7. Shutdown procedure of the DCDCs

Before a shutdown, it is required to reduce the current draw to the minimum current, described in section 32.4 "Shutdown sequence".

When a shutdown is initiated, the module will enter the state *Shutdown Rx Purge.* The maximum current the DCDCs must draw is now 0 A. I_ALLOW will within 1 second fall to below 10 A. This state will last between 10 and 60 seconds.

After reducing DCDC power to 0A and module has transitioned to *Shutdown Rx Purge*, the DCDC converters are not needed until next restart of the module and can be switched to standby.

The module will then deplete internal reactant remains and perform a pressure decay test to verify the tightness of the hydrogen system (see section 32.5). After this test is complete the module transitions to unlocked state. If MD_Enable is still present, the module will again enter the **Precharge** state.

[6] Following the normal startup procedure. The states are *Standby, Startup HRB on, Startup Air On, and Startup Fuel On*

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31. Special Operating States

This section describes the special operating states that the system can operate in when requested.

These states are not a part of normal operating sequence but are necessary for maintenance activities and pre-storage preparations.

31.1. State: Coolant Degas

The purpose of this state is to remove air bubbles from the Internal HT coolant loop. This state is typically used after coolant fill/drain cycles, or maintenance involving the HT coolant loop

Parameter:	Value:	Comment:
Preceding state	Standby	
HV Supply	Yes, <3kW	Power to operate coolant pump
Customer HT Coolant	No	
Customer LT Coolant	Yes	Coolant for inverter, expected <500W
H2 Supply	No	
Exit condition	Manual	Returns to Unlocked state

Table 31 – Coolant Degas State.

To use this state, bring module to **Standby** and activate the DEGAS_REQ bit. When completed, disable the bit. This state takes typically 5-10 minutes to degas the coolant loop after a complete drain/fill cycle.

In this state, the coolant pump circulates the coolant while the internal valves actuate in order to flush all air bubbles in the internal coolant loop.

The state is active as long as requested by customer/maintenance personnel.

This state does not affect the external HT coolant supply.

31.2. State: Prepare for Service

The purpose of this state is to remove all residual hydrogen from the fuel circuit, such that maintenance activities can be performed in a safe manner. The hydrogen is reacted with oxygen from the air and either used by the motor inverters or dissipated in the bleed resistors.

This is achieved by circulating the contents in the fuel system by operating the HRB and supplying oxygen by operating the compressors at low speed.

Parameter:	Value:	Comment:
Preceding state	Standby	
HV Supply	Yes, <4kW	Power to operate HRB, Air compressors
Customer HT Coolant	No	
Customer LT Coolant	Yes	Coolant for inverters, expected <500W
H2 Supply	No	
Exit condition	When finished	Next state: “Prepare Complete”

Table 32 – Prepare for Service State.

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When **Prepare for Service** is complete, all hydrogen in the fuel system is exhausted and the stack voltage is reduced to below 10V. The system transitions to **Prepare Complete**.

31.3. State: Prepare Complete

The purpose of this state is to indicate for maintenance personnel that the system has completed the procedures to exhaust available hydrogen and stack voltage is below dangerous levels.

This state has no exit condition, and a power cycle is required to exit it.

Parameter:	Value:	Comment:
Preceding state	Prepare for Service	
HV Supply	No	
Customer HT Coolant	No	
LT Coolant	No	
H2 Supply	No	
Exit condition	None	Requires power cycle to exit state.

Table 33 – Prepare Complete State.

Please note that the prepare for maintenance procedure it not intended for daily use, as excessive use of this functionality may degrade stack performance.

31.4. State: Dry-out

The purpose of this state is to remove liquid water from the module, such that stacks are in a “dry” condition after completing this procedure. This is intended to be the final part of the last operation cycle before long term storage or transportation of the module, where temperatures may reach freezing conditions.

Parameter:	Value:	Comment:
Preceding state	Running	I_Allow ramps to 0A, then disconnects HV system.
HV Supply	Disconnected	
Customer HT Coolant	Yes	Reduced cooling requirements
LT Coolant	Yes	
H2 Supply	Yes	
Exit condition	Timed, Conditional	Exits to module shutdown. Duration 6 min or less

Table 34 – Dry-out State.

Initiating Dry-out

The prerequisites for the dry-out sequence are as follows:

- The module must be in the “Running” state.
- No alarms

To start the dry-out sequence, enable the “DRYOUT REQUEST” bit from over the CAN bus.

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Dry-out Sequence

When requested to begin a dry-out, the module ramps I_Allow to 0A. When the customer current is reduced to <5A, the module begins the dry-out process.

The integrator will observe that the fuel cell module opens its HV connectors and disconnects from the vessel HV system. When disconnected, the module ramps up temperature and airflow to accomplish the dry-out process. During this state, the air compressors are operating at high power levels.

Dry-out Completion

When the module has completed the dry-out process or 6 minutes has elapsed, the module will perform a controlled shutdown process, identical to a normal operational shutdown. After the shutdown, the module is prepared for long term storage.

Restarting module after Dry-out and Storage

When the module is to be operated again after the dry-out procedure, integrator must operate the module in a low power regime (50-75kW) for at least 20 minutes before increasing power. This allows the stack to return to proper humidification conditions.

Expect that performance is impacted until stacks are re-humidified. This is temporary and can be helped by performing a conditioning cycle, contact Ballard for details.

31.5. State: Recovery

The Recovery state is intended to recover temporary performance degradations.

Please consult with Ballard before utilizing the recovery functionality.

Parameter:	Value:	Comment:
Preceding state	Running	Certain conditions apply.
HV Supply	Operating	
HT Coolant	Yes	
LT Coolant	Yes	
H2 Supply	Yes	
Exit condition	Manual	Returns to Running.

Table 35 – Recovery State.

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32. Normal Operation Example

During normal operation, the stack converts hydrogen to power, dependent on the current drawn and at a voltage primarily dependent on the stack operating point. The voltage vs. current relationship is described by the system polarization curve.

Operation Example					
Sequence	**Description**	**Module State or Transition**	**DCDC Indicators**		**Typical duration**
1	Integrator enables 24V supplies to module and SAFE_IN safety input. Integrator sends Module key over CAN bus	Module transitions from Off to Locked to Unlocked	STOP	False	1-2 minute
			IMPORT	False	
			EXPORT	False	
	Module is in Unlocked state	Module state is Unlocked	STOP	True	Can stay in Unlocked indefinitely.
			IMPORT	False	
			EXPORT	False	
2	Integrator enables MD_Enable input	Module transitions from Unlocked to Precharge	STOP	True	<1 second
			IMPORT	False	
			EXPORT	False	
	Module pre-charges HV Circuit	Module transitions from Precharge to Standby	STOP	False	2 seconds
			IMPORT	True	
			EXPORT	False	
	Module is in Standby	Module State is Standby	STOP	False	Can stay in Standby indefinitely
			IMPORT	True	
			EXPORT	False	
3	Integrator wishes to operate FCwave™ module and sends MD_Run over CAN bus	Module transitions from Standby to Startup sequence	STOP	False	<1 second
			IMPORT	True	
			EXPORT	False	
4	Module has begun drawing power on HV bus to spin compressors, module requests H2 valves open. Hydrogen flows to stacks	Startup sequence	STOP	False	30 seconds
			IMPORT	True	
			EXPORT	False	
5	Module is self-powered from stacks, start-up sequence continues	Startup sequence	STOP	True	<15 seconds
			IMPORT	False	
			EXPORT	False	

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6	Module completes the startup sequence and enters Running. Module transmits I_Allow > 0 on CAN bus and begins producing power	Running	STOP	False	<5 seconds
			IMPORT	False	
			EXPORT	True	
7	Module is in Running state and produces power to vessel. Integrator follows current ramp and does not exceed I_Allow	Running	STOP	False	Module can operate indefinitely
			IMPORT	False	
			EXPORT	True	
8	Integrator wishes to stop operating the module. Ramp current draw to <10A as described in section 32.4 and stop sending MD_Run	Running	STOP	False	<10 seconds
			IMPORT	False	
			EXPORT	True	
9	Module begins shutdown sequence	Module transitions from Running to Shutdown	STOP	True	<1 second
			IMPORT	False	
			EXPORT	False	
10	Module executes shutdown sequence. After complete shutdown sequence module transitions to Unlocked	Shutdown to Pressure Decay	STOP	True	30 seconds
			IMPORT	False	
			EXPORT	False	
11	Module performs pressure decay self-test of hydrogen system.	Pressure Decay to Unlocked	STOP	True	30 seconds
			IMPORT	False	
			EXPORT	False	
12	After 15 minutes inactivity, it is permissible to power off module	Unlocked to Off			15 mins

Table 36 – Operation Example Events. See Figure 31.

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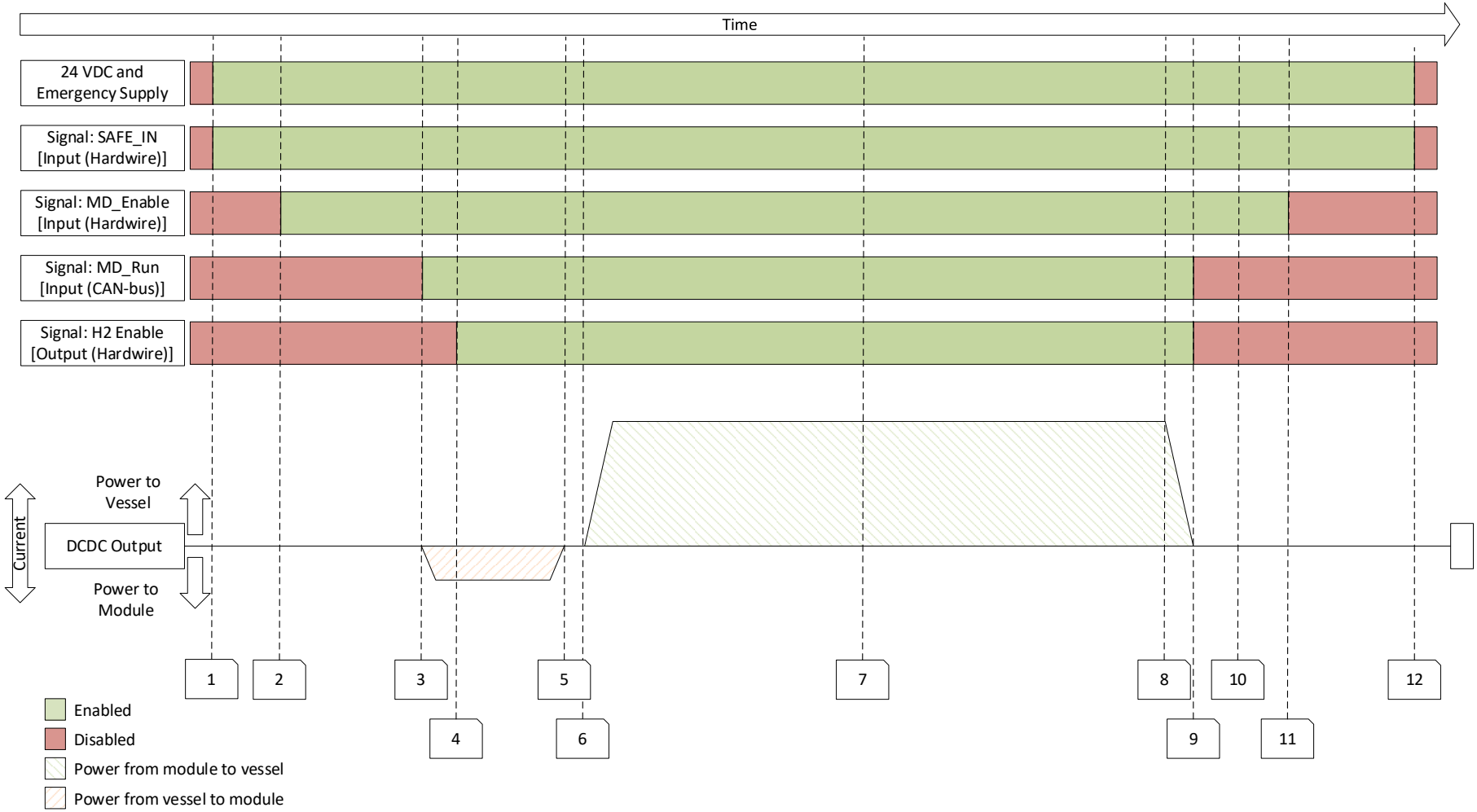


Figure 31 – Control Sequence during startup and operation of FCwave. See Table 36.

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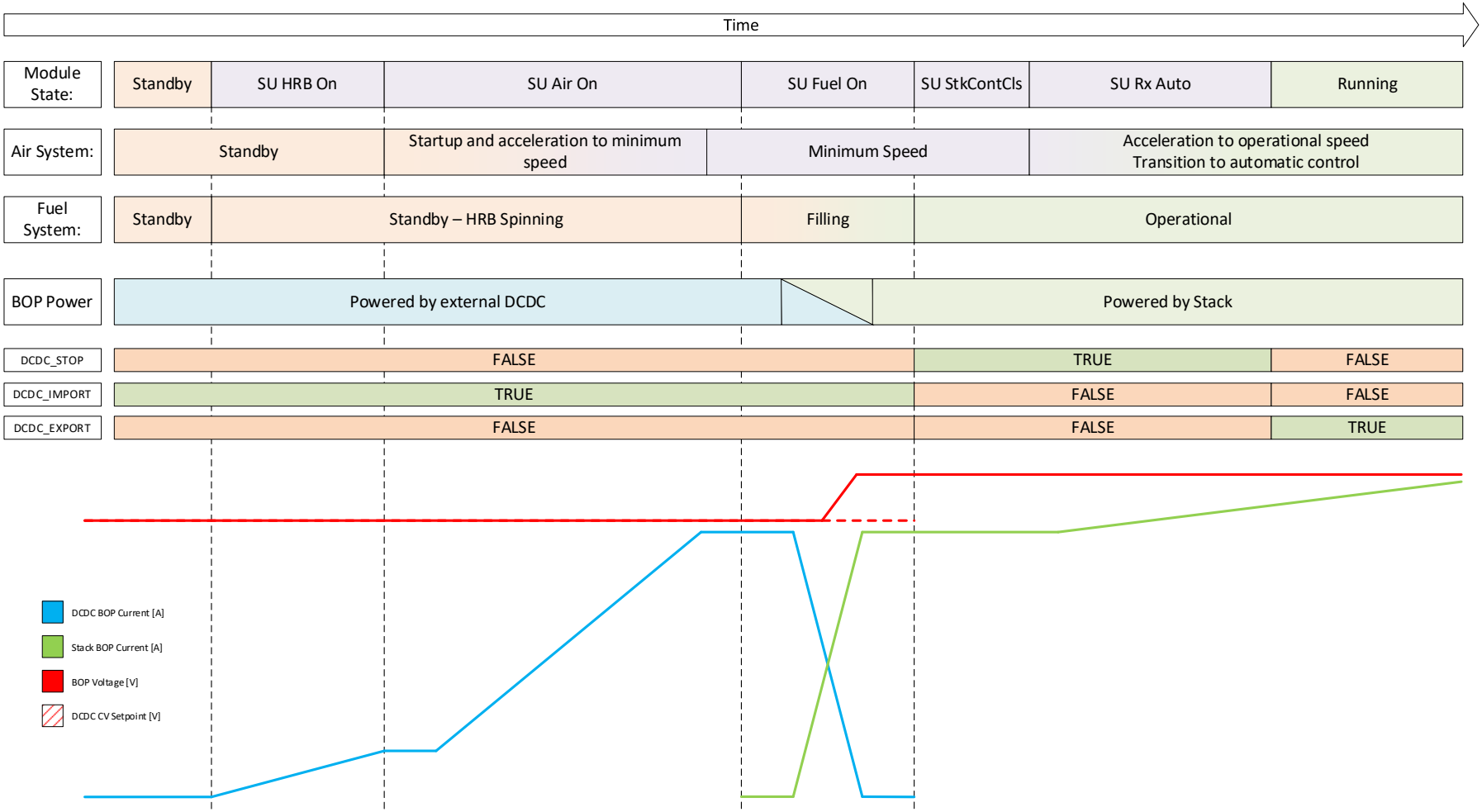


Figure 32 – FCwave™ Startup Sequence and DCDC Integration.

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32.1. Startup Sequence

The detailed **Startup** sequence for the FCwave™ module is outlined in Table 37 and shown in Figure 32.

FCwave™ Module Startup - Detailed			
Module State	**Description**	**Module State or Transition**	**Typical duration**
Standby	Module has completed pre-charge. DCDC is providing constant voltage to BOP components. Current draw is ~0	Standby	Indefinite
Standby	Integrator transmits MD_RUN over CAN bus	Transition to SU HRB On	n/a
SU HRB On	HRB Motor spins up. DCDC maintains voltage, current draw increases.	SU HRB On	~5 sec
	HRB is at speed	Transition to SU Air On	n/a
SU Air On	Air compressors initialize and spin to startup speed. DCDC load increases as compressors draw power.	SU Air On	~10 sec
SU Air On	Air compressors stable at startup speed. DCDC load stable.	Transition to SU Fuel On	n/a
SU Fuel On	Fuel subsystem opens valves and flood stacks with hydrogen. Stack voltage increase to ~600V. Load on DCDCs fall to nearly 0, as BOP is powered by stacks through diodes.	SU HRB On	~15 sec
SU Fuel On	Fuel pressure is stable at nominal levels	Transition to SU StkContCls	n/a
SU StkContCls	Main stack contactors close, bypassing startup diodes.	Transition to SU Rx Auto	<1 sec
SU Rx Auto	BOP Components switch from minimum setpoints to operational control	SU Rx Auto	~5 sec
SU Rx Auto	BOP Components are stable at operational control	Transition to Running	n/a
Running	Module is ready to provide power	Running	n/a

Table 37 – Detailed Startup sequence, See Figure 32.

32.2. Startup Energy Consumption

The energy consumption during **Startup** is detailed in Table 38.

Type	Duration	Amount	Total Energy
24VDC auxiliary power input	Continuously	352W	10 kJ
HV DC	0-27s	4000W	52
Hydrogen	4-6s	0,11 g/s	66 kJ
Combined	-	-	128 kJ

Table 38 – Startup energy consumption.

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32.3. Running state

Transition from start-up to running state

When module transitions from **Startup** to **Running** state, "I_ALLOW" will rise above 0 Amps and the integrator can begin drawing current from the module.

The interval between the transition to **Running** mode and for the integrator to begin drawing current should not exceed 5 seconds, under normal operating conditions.

If the integrator does not draw more than the minimum current, the module will first signal a severity 1 warning. If the current draw remains below minimum level for more than 20 seconds, the module will perform a controlled shutdown and signal a severity 2 alarm.

Running state limitations

In the running state, the system is providing electrical power, and acting as a load follower for the DCDCs. The system has limited dynamic capabilities and will signal its ability to provide current as described in section 29.

Note: During operation, the integrator must respect the limits imposed by "I_ALLOW".

Note: During operation, the integrator shall not reduce current draw below minimum levels (50A), except during shutdown. Brief (<5 seconds) reductions below 50A can be permitted but should be avoided.

Note: The recommended current ramp is specified in section 29.5

32.4. Shutdown sequence

When the integrator wishes to stop operating the FCM, the proper procedure is as follows:

1. Reduce current draw from DCDCs to 10A.
2. Reduce to 0 A, within 5 seconds disable the MD_Run CAN signal.
3. The module preforms the shutdown sequence. Expected duration is 45 seconds.
4. During the shutdown, the module performs a pressure decay self-test, see section 32.5.
5. After shutdown is complete, module returns to Unlocked state.
6. Integrator decides if module is expected to operate soon:
    a. If module is not expected to operate in < 1h, disable MD_Enable and module transitions to **Unlocked** state.
    b. If module is expected to operate in < 1h, maintain MD_Enable and module will return to **Standby** state
    In order to return to Standby, external HVDC supply must be active as described in section "30.3 Pre-charge"
7. When the module switches to **Standby** state, integrator can re-enable MD_Run to restart module or disable MD_Enable if an imminent restart is not expected.
8. If integrator disables MD_Enable, module switches to **Unlocked** state

Module may be powered off 15 minutes after entering **Unlocked** state[7]. The module will during this time consume the remaining hydrogen in the supply system, as it may not be turned off with excess

[7] Duration to be revised after system testing, in order to verify the duration it takes to dissipate H2 inside the module

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hydrogen in the supply line. It is recommended to turn off the 24V supply if the module is not used for the next several hours.

During this time, the module will also upload log files to Ballard if internet is available.

32.5. Pressure Decay self-test

This section describes the pressure decay self-test performed by the module as a part of the shutdown sequence.

Conditions for performing the self-test is as follows:

- Shutdown is caused by customer disabling MD_Run CAN signal
- No alarms active

During the test, the module uses hydrogen to partially pressurize the internal hydrogen loop and then close supply valve. Then the pressure decay over time is monitored and evaluated. The pressure decay self-test typically lasts 30 seconds.

Failed Pressure Decay self-test

If the module fails the pressure decay self-test, it will signal a severity 2 alarm and require a specific acknowledgement of the alarm before allowing restart. The causes of a failed self-test can be:

- Unable to pressurize internal hydrogen loop.
  - Internal pressure does not reach setpoint within time limit. Ensure module has available hydrogen to perform self-test
- Pressure decays too rapidly
  - This indicates a leakage inside the hydrogen loop. Contact Ballard service
- Pressure test aborted
  - The test is aborted if MD_Enable becomes high or any alarms are active.

If a pressure decay test failure occurs, it is required to perform an investigation into the cause of the failure. This investigation should include all relevant data, including ventilation exhaust hydrogen content and inlet pressure. When the cause has been identified and the system is deemed safe, the pressure decay failure can be reset by setting the “Pressure Decay Failure Reset” bit in the VCS_REQUEST CAN message. For further instruction on pressure decay testing follow the maintenance instructions.

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33. Overnight storage of FCwave

This section describes the options for an installed FCwave™ module during overnight (unattended) options on the vessel.

33.1. Environmental Concerns

If the module is left overnight or for longer periods, for example weekend and holidays, the environment surrounding the module must stay within the environmental specifications as listed in Table 10 – Ambient Temperature Specification.

NOTE: Do not permit the hydrogen enclosure ventilation intake to circulate air <0°C into the module

33.2. Power off

When finished with the daily operation of the module, allow the module to remain 15 minutes in non-operating state (Unlocked or Standby), such that H2E ventilation may continue to operate and allow the module to cool down.

After the 15 minutes has elapsed, shut off 24V power to the FCwave™ module.

In the unpowered state, no part of the control or safety system is operational and there is no activity inside the module.

It is not possible to turn off the control system only, as one of the ventilation fans operate off the control system supply.

33.3. Unlocked

If it is desired to maintain the hydrogen enclosure ventilation and monitoring system of the module, allow the module to remain in the “Unlocked” state, where the alarm system is operational, and the hydrogen enclosure is continually ventilated by the fans.

In this state, the module draws 350W continuously, which must be provided by the vessel.

NOTE: Do not permit the hydrogen enclosure ventilation intake to circulate air <0°C into the module

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34. Low Voltage Electrical Connections

This section describes in detail the connections between the FCwave™ module and the vessel. For the recommended wiring diagram, refer to document CMS010 “Schematic description of Input and Output Circuits”, with focus on appendix CMS101-A.

34.1. Switching types

Figure 33, Figure 34 and Figure 35 illustrate the different types of inputs and outputs from the module.

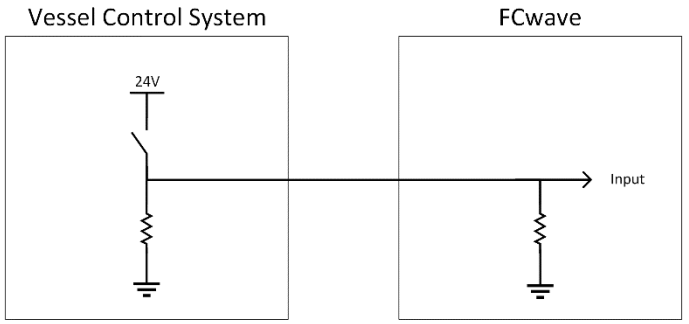


Figure 33 – High-Side Switching Input.

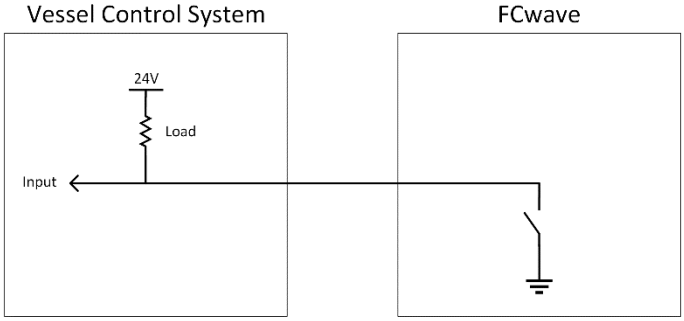


Figure 34 – Low-Side Switching Output.

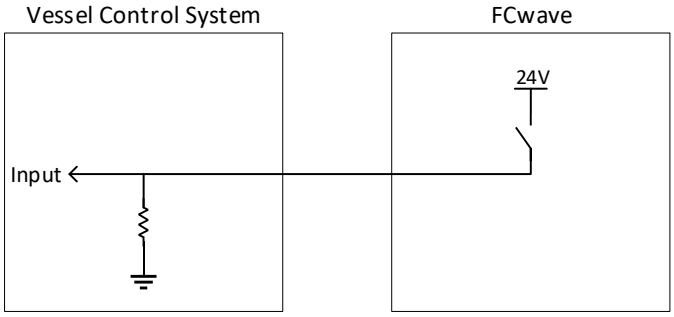


Figure 35 – High-Side Switching Output.

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34.2. Digital Supply and Signal Definitions

Hardwired inputs and outputs between the drive system and module are defined in Table 39, Table 40, and Table 41. These include the type of signal and a description of their purpose.

Module Supply Definitions

Interface Specification				
Interface name long	**Interface name**	**Interface type**	**Input / Output**	**Description**
24V DC supply	24V_SUPPLY	Supply	Input	Max 750W power draw
DC common	COM_SUPPLY	Supply	Input	DC Common. Not connected to GND.
Module grounding stud	GND_01	Grounding stud	Grounding	Grounding of module frame

Table 39 – Connection Definitions for Module Control Supply.

Fuel Cell Controller Signal Definitions

Signals in this category are referenced to 24V_SUPPPLY. CAN bus communications are specified in **CMS013 CAN Matrix**.

Interface Specification						
Interface name long	**Interface name**	**Interface type**	**Input / output**	**Switching type**	**Description**	**Active High/Low**
Module enable	MD_Enable	24V Hardline	Input	High side input	Signal to transition module from **Unlocked** to **Standby** state – Used prior to module activation	Active High
H2 enable	H2_ENABLE	24V Hardline	Output	Low side output	Signal to hydrogen supply system to open upstream H2 valves and provide hydrogen for module activation. Switched to COM_SUPPLY when active. See section 14.5.	Switched to COM_SUPPLY when active.
FUEL CELL MODULE STATUS OK	FCM_OK	24V Hardline	Output	High side output	Signal to customer if module is operational (I.e., has no fault of severity 2 or 3). (*Please note that this is separate from a Safety system emergency).*	Active low. High = FCM OK Low = FCM Error
Customer CAN bus	CAN_02	CAN bus	Bidirectional	n/a	Customer interface to fuel cell module.	n/a
Ethernet	ETH_01	Ethernet	Bidirectional	n/a	Service and Datalogging interface.	n/a

Table 40 – Signal Definitions for Module Controller and Display Panel.

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Safety System Supply and Signal Definitions

Signals in this category are referenced to 24V_SAFE.

Interface Specification						
Interface name long	**Interface name**	**Interface type**	**Input / output**	**Switching type**	**Description**	**Active High/Low**
24V DC supply safety	24V_SAFE	Supply	Input	n/a	Max 250W power draw, Ship Emergency Supply	n/a
DC common safety	COM_SAFE	Supply	Input	n/a	DC Emergency Supply Common. Not connected to GND.	n/a
Main safety in	SAFE_IN	24V Hardline	Input	High side input	Safety input from Vessel control system. Disable this signal to trip emergency system externally.	Active High
Main safety out	SAFE_MAIN	24V Hardline	Output	High side output	Main output from safety control system. This output will, together with the following sub-system specific output signal give the condition of the emergency system.	Active High
Safety – fire detection	SAFE_FIRE	24V Hardline	Output	High side output	Output indicating the status of the fire detection system.	Active High
Safety – hydrogen concentration	SAFE_H2CONC	24V Hardline	Output	High side output	Output indicating the status of the hydrogen concentration in the H2 enclosure being too high.	Active High
Safety – ventilation status	SAFE_VENT	24V Hardline	Output	High side output	Output indicating the status of the ventilation system.	Active High
Safety - watchdog	SAFE_WD	24V Hardline	Output	High side output	Output indicating the status of the safety system internal monitoring.	Active High
Estop – wire 1	ESTOP_W1	24V Hardline	Input	High side Input	Input to safety system from external 2-wire ESTOP button, Integrator responsibility.	Active High
Estop – wire 2	ESTOP_W2	24V Hardline	Input	High side Input	Input to safety system from external 2-wire ESTOP button, Integrator responsibility.	Active High
Estop – out 1	ESTOP_OUT1	24V Hardline	Output	n/a	ESTOP output for external 2-wire ESTOP button. Connected internally to “24V-SAFE”.	n/a
Estop – out 2	ESTOP_OUT2	24V Hardline	Output	n/a	ESTOP output for external 2-wire ESTOP button. Connected internally to “24V-SAFE”.	n/a
Safety – External ESTOP	SAFE_EXTERN	24V Hardline	Output	High side output	Output indicating the status of the external safety inputs	Active High

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Safety – Fire Detection System Malfunction	SAFE_FIREMALF	24V Hardline	Output	High side output	Output indicating the status of the fire detection apparatus. When inactive, indicates a malfunction in the fire detection system	Active High

Table 41 – Signal Definitions for Safety System.

34.3. ESTOP Connections and wiring

The ESTOP connections on the FCwave™ module, as detailed in Table 41 should be wired according to applicable standards and rules for the application.

Ballard recommends the ESTOP connection and button connected to the FCwave™ should fulfill the following requirements:

Construction compliant to EN/ISO 13850
Contacts should be of the type "Positive forced opening normally closed contact", two contact sets
Wiring performed in accordance with diagram CMS010-A and section 35 2133586288.429.

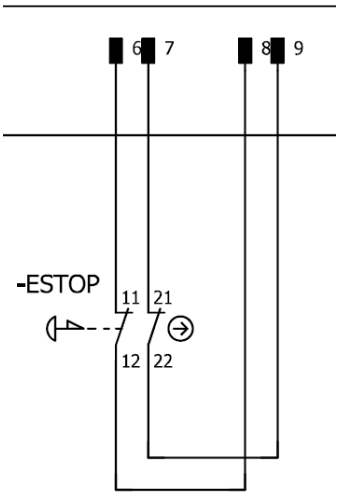


Figure 36 – ESTOP Wiring diagram, reproduced from CMS010-A.

35. Low Voltage Connector Construction

The Low Voltage Connector ("LVC") is constructed with a housing and a frame containing six modular elements, each with a distinct function and connection pattern.

35.1. Signal Wiring

Ballard strongly suggests shielded wiring for low voltage power, bus and signals. Shielding is absolutely required for CAN bus communications (Slot D).

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35.2. Connector Elements

The Ballard scope of the Low Voltage Connector (LVC) is constructed by the following elements:

Component	Tag	Manufacturer	MFG Part name	MFG Part #
Housing	X_E01	Harting	Han 24HPR Base Panel Screw locking	09 40 024 0311
Frame	X_E01	Harting	Han hinged frame plus, for 6 modules a-f	09 14 024 0371
Slot A	X_E01-A	Harting	Han 40A axial module, female 2,5-8 mm²	09 14 002 2701
Slot B	X_E01-B	Harting	Han DD Quick-Lock module, female	09 14 012 2732
Slot C	X_E01-C	Harting	Han Gigabit Module, Female	09 14 008 3111
Slot D	X_E01-D	Harting	Han D-Sub module, crimp female	09 14 009 3101
Slot E	X_E01-E	Harting	Han 40A axial module, female 2,5-8 mm²	09 14 002 2701
Slot F	X_E01-F	Harting	Han DD Quick-Lock module, female	09 14 012 2732

Table 42 – Low Voltage Connector Construction.

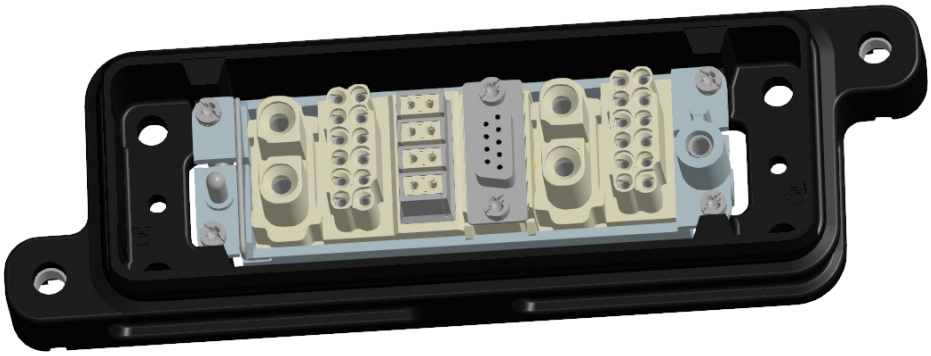


Figure 37 – Rendering of Low Voltage Connector. Slots A to F are shown from left to right.

As shown in Figure 37, the LVC is comprised of the frame with the 6 modules slotted into the frame. The Modules are designated A to F, viewing the image from left to right.

35.3. Protection of the Low Voltage Connector

When the Control and Communication Connector is not mated to a suitable plug, it should be protected against ingress of dust, grime and fluids by an appropriate protective cover.

Ballard will provide a screw locking cover for the connector during shipping and handling. If this cover is lost, replacement can be purchased from Ballard or Harting, quoting Harting Stock # 9400245411.

When mated to a suitable connector or protective cover, the Ingress Protection rating of the connector is IP65 and IP68 in both cases.

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35.4. Low Voltage Connector kit

Ballard can supply a kit containing a suitable set of parts to construct a connector. Contact Ballard Europe and request “7500168 Integrator LVDC Connector Kit”.

35.5. Low Voltage Connector Pin Assignment

This section describes the pin assignment for the low voltage connector.

Slot A

This slot in the connector is the connection point for the module 24VDC supply. Voltages and tolerances are described in CMS006.

Pin	Tag	Function	Interface name
1	=X_E01-A:1	+24VDC	24V_SUPPLY
2	=X_E01-A:2	0VDC	COM_SUPPLY

Table 43 – Slot A Signal Definitions and Assignments.

Slot B

This slot in the connector is the connection point for the fuel cell controller signals. These signals are referenced to the potentials in Slot A

Pin	Tag	Function	Interface name
1	=X_E01-B:1	Digital Out	FCM_OK
2	=X_E01-B:2	Digital Out	H2_ENABLE
3	=X_E01-B:3	Digital In	MD_Enable
4-12	Various	Not Connected	Not Applicable

Table 44 – Slot B Signal Definitions and Assignments.

Slot C

This slot in the connector is the connection point for the Module Control Unit Ethernet Interface.

The module is wired according to TIA **T568B**.

Pin	Color	Function	Interface name
1	Orange / White	Ethernet	MCU Network
2	Orange	Ethernet	
3	Green / White	Ethernet	
4	Blue	Ethernet	
5	Blue / White	Ethernet	
6	Green	Ethernet	
7	Brown / White	Ethernet	
8	Brown	Ethernet	

Table 45 – Slot C Signal Definitions and Assignments.

See section 37.6 “Module Default IP and CAN Address” for details on the ethernet connection.

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Slot D

This slot in the connector is the connection point for the Module Control Unit CAN bus module control interface. The connector accepts a standard D-SUB 9 pin plug, male.

For functional details, please refer to **CMS013 CAN Matrix.**

Pin	Tag	Function	Interface name
2	=X_E01-D:2	CAN LOW	CAN02, Low
7	=X_E01-D:7	CAN HIGH	CAN02, High
3	=X_E01-D:3	CAN GND	CAN02, Ground
SH	=X_E01-D:SH	CAN Shield	CAN02, Shield
<others>	Various	Not Connected	Not Applicable

Table 46 – Slot D Signal Definitions and Assignments.

Slot E

This slot in the connector is the connection point for the module 24VDC supply for the Safety System. Voltages, Power Draw and tolerances are described in CMS006.

This should be connected to the Vessel Emergency Supply.

Pin	Tag	Function	Interface name
1	=X_E01-E:1	+24VDC	24V_SAFE
2	=X_E01-E:2	0VDC	COM_SAFE

Table 47 – Slot E Signal Definitions and Assignments.

Slot F

This slot in the connector is the connection point for the safety system signals. These signals are referenced to the potentials in Slot E.

Please refer to Table 41 – Signal Definitions for Safety System for functional description.

Pin	Tag	Function	Interface name
1	=X_E01-F:1	Digital Out	SAFE_MAIN
2	=X_E01-F:2	Digital Out	SAFE_FIRE
3	=X_E01-F:3	Digital Out	SAFE_H2CONC
4	=X_E01-F:4	Digital Out	SAFE_VENT
5	=X_E01-F:5	Digital Out	SAFE_WD
6	=X_E01-F:6	+24VDC, Max 0,25A	ESTOP_OUT1
7	=X_E01-F:7	+24VDC, Max 0,25A	ESTOP_OUT2
8	=X_E01-F:8	Digital In	ESTOP_IN1
9	=X_E01-F:9	Digital In	ESTOP_IN2
10	=X_E01-F:10	Digital In	SAFE_IN
11	=X_E01-F:11	Digital Out	SAFE_FIREMALF
12	=X_E01-F:12	Digital Out	SAFE_EXTERN

Table 48 – Slot F Signal Definitions and Assignments.

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36. High Voltage Connections

The purpose of this section is to describe the HVDC connectors on the front plate of the module.

The module has 4 connection points from the stack strings, two from each.

36.1. Connector - HVDC

The HVDC connectors are produced by Amphenol Industrial, within the product line Amphe-Power.



Figure 38 – Amphe-Power panel mount connector – Module connectors are red or black.

The four front panel mount connectors are color coded and keyed to prevent connection errors.

TAG	Electrical Connection	MFG	MFG#	Ballard Part #	Color	Keying
X_HV01	String A Positive	Amphenol Industrial	APSPS-1-R-T5	7000819	Red	1
X_HV02	String B Positive	Amphenol Industrial	APSPS-2-R-T5	7000820	Red	2
X_HV03	String A Negative	Amphenol Industrial	APSPS-1-BK-T5	7000821	Black	1
X_HV04	String B Negative	Amphenol Industrial	APSPS-2-BK-T5	7000822	Black	2

Table 49 – HVDC Connector Tags.

Amphe-Power Range – Key Specification	
No of Contacts	1
Maximum Continuous Current Rating	Up to 800A
Surge Current	75kA
Short Circuit Rating	Up to 35.5kA
Cables Cross Sectional Area C.S.A	24mm2 to 300mm2
Contact Termination	Screw or Crimp
Mating Method	Bayonet Lock
Operating Voltage	1000VAC
Max Rated Voltage to Earth	2kV AC/ 3kV DC

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Minimum Flashover	9.5kV DC or AC Peak
Insulation Resistance	>5M ohms @ 500V DC
Ingress Protection	IP67
Protection against Electrical Shock	IP2X
Flammability	UL94-V0
Mating Cycles	>500
Shell Material	High Temperature Thermoplastic
Contact Plating	Silver

Table 50 Amphe-Power key specifications

36.2. Mating Part - HVDC

This section describes the recommended mating Parts to be used with the power connectors.

TAG	Electrical Connection	MFG	MFG#	Ballard Part #	Color	Keying
Customer Scope	String A Positive	Amphenol Industrial	APSLD-1-R-S120-M40S	7000823	Red	1
Customer Scope	String B Positive	Amphenol Industrial	APSLD-2-R-S120-M40S	7000825	Red	2
Customer Scope	String A Negative	Amphenol Industrial	APSLD-1-BK-S120-M40S	7000824	Black	1
Customer Scope	String B Negative	Amphenol Industrial	APSLD-2-BK-S120-M40S	7000826	Black	2

Table 51 – HVDC Connector Mating parts.

Ballard Europe can supply a set of matching connectors suitable for 120mm2 cables. Contact Ballard Europe and request “7500169 Integrator HVDC Connector Kit”.

36.3. Protection of the High Voltage Connector

When the High Voltage Connectors are not mated to a suitable plug, they should be protected against ingress of dust, grime and fluids by an appropriate protective cover.

When mated to a suitable connector or protective cover, the Ingress Protection rating of the connectors is IP67.

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37. Control System – Fault Severities and Reporting

This section details the reporting of severities and fault handling by the module. A sample alarm is listed, but the full list of possible alarms is too long to present here. Integrators are referred to **CMS014 Control System Alarm List**.

The module has 1 level of informational message and 3 levels of warnings and alarms of increasing severity, internal to the control system.
A further level is handled separately by the safety control system and is included for completeness.

37.1. Fault Severities

Table 52 – Module Fault Severities and Descriptions lists the five types of module fault severities.

> Severity 0 through 3 is handled by the control system and does not involve the independent safety system.
> Severity 4 is handled by the safety system and overrides the module control system.

There are several ways the module can notify the Vessel Control System of a fault condition. The module provides a hardwired output (**FCM_OK**) to indicate when it has entered an alarm state. The module also broadcasts its Operating State via CAN, along with the fault codes detailed in the CAN Matrix Customer Specification (**CMS013 CAN Matrix**) document. The list of fault codes, their description and details are available in document **CMS014 Control System Alarm List**.

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Alarm Severities	
Severity	**Description**
0: information	No fault reporting to drive system. May derate **I_ALLOW**, otherwise for information only. Severity 0 events are logged by the modules on-board data acquisition system.
1: Warning	A system parameter has deviated from normal range. The fault category is reported to the drive system over CAN, along with its severity. The hardwired **FCM_OK** output remains unchanged. The module should be inspected and/or process data reviewed. Does not result in a shutdown.
2: Alarm	A system parameter has exceeded acceptable operating range, and the fuel cell module will undergo a **controlled shutdown**. The fault is reported to the drive system over CAN and the hardwired signal **FCM_OK** output will go to **0V.** **I_ALLOW** will be set to 0A. Do not exceed **I_ALLOW**. After a severity 2 fault, **do not** attempt a restart until action has been taken to identify and resolve the cause of the fault. To clear this fault, cycle the hardwired **MD_EN** signal.
3: Severe Alarm	• A system parameter has exceeded a safe operating range, and the fuel cell module will undergo an **immediate shut down**. • The fault is reported to the drive system over CAN and the hardwired signal **FCM_OK** output will go **0V**. • **I_ALLOW** will be set to 0A **immediately**. Cease current draw from the fuel cell module immediately. This severity will cause the high voltage contactors to open under load. • After a severity 3 fault, the fuel cell module must not be restarted until the cause of the fault has been determined and resolved. In addition, the module should be inspected for safe operation and Ballard must be consulted before a restart is performed.
4: Safety System Activation	• The module safety system has tripped and disabled all outputs from the module controller. This causes contactors to open under load and closes all hydrogen valves. The module performs an **immediate uncontrolled shutdown.** • The type of emergency is reported over the safety hardline connections (see section Safety System Supply and Signal Definitions2133586288.429). The hardwired signal **FCM_OK** output will go **0V**. • **I_ALLOW** will be set to 0A **immediately**. Cease current draw from the fuel cell module immediately. This severity will cause the high voltage contactors to open under load. • After a severity 4 fault, the fuel cell module must not be restarted until the cause of the fault has been determined and resolved. In addition, the module should be inspected for safe operation and Ballard must be consulted before any further actions are taken.

Table 52 – Module Fault Severities and Descriptions.

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37.2. Resetting a fault

To reset an alarm from the module, after remedying the fault and verifying that the underlying cause cannot reoccur, the integrator can toggle the **MD_Enable** signal.

The module controller clears alarms on the rising edge of **MD_Enable**, refer to section 2133586288.429 “Fuel Cell Controller Signal Definitions”.

Alternatively, the integrator can attempt to reset faults over the CAN bus. This can be done in the “Unlocked” state by sending the “Alarm Acknowledge” bit in the **VCS_REQUEST** can message.

37.3. CAN Communication

The individual CAN messages to and from the fuel cell module are detailed in the CAN Matrix Customer Specification **CMS013**. Contact Ballard Power Systems for the latest version of the customer-specific CAN matrix. The CAN network operates at a fixed baud rate of 250 kbps and a watchdog is in place to verify CAN activity.

As CAN networks are susceptible to noise, it is strongly recommended to follow best practice and use shielded cables for all CAN wiring. Special care should be taken for the placement of the two terminating resistors on the CAN bus.

Include a 120Ω terminating resistor on the module CAN interface. It is the responsibility of the integrator to add the terminating resistors on the customer interface harness. The module contains one 120 Ω resistor at the MCU CAN bus connection point. After complete assembly, the measured resistance between CAN high and Low should be 60±5 Ω.

Note: The module will shut down (Severity 2) if CAN communication is lost during operation. It is strongly recommended to have a proper wiring, shield each CAN cable and to be EMI proof.

37.4. CAN Customization Key

Ballard will supply each integrator with a unique customization key, which can be found on the CAN Matrix Customer Specification (**CMS013**) document. Send this specific CAN message to allow the module to exit **Locked** state (refer to Figure 27 – High Level State Sequence). It is also used to ensure the correct software is in place for the integrator.

37.5. Controller Heartbeat

The module controller sends a heartbeat over CAN, for the integrator to use as an input for their watchdog. This heartbeat should be synchronized with the drive side watchdog as a method to ensure the module controller is powered up and active. The CAN message **FCM_REQUEST_1** transmits as soon as low voltage power is provided, and the controller is booted-up. As per the CAN matrix (**CMS013**), it is an 8-bit counter that increments every 100 milliseconds and will wrap around after 25.5 seconds (255 heartbeats).

37.6. Module Default IP and CAN Address

Modules are delivered, unless explicitly requested otherwise by customer/Integrator, according to a default IP and CAN address schedule provided in Table 54 – Single Module IP and CAN address. For multiple modules in a deployment, the range of IP, CAN source addresses and CAN destination addresses (called “PDU Specific”) are given in Table 55 – Multiple Module IP and CAN .

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37.7. Single Module and Vessel CAN Address

For deployments of a single module, default IP and CAN addresses are as follows:

Vessel Name	IP Address	CAN bus Source Address
<no fixed name>	<no fixed address>	0x27

Table 53 – Vessel Control System CAN address.

Module Name	IP Address	CAN bus Source Address
“Vesselname 1”	10.10.10.10	0x12

Table 54 – Single Module IP and CAN address.

37.8. Multiple modules

There is a practical limit to how many modules can co-exist on a single CAN bus. This limit is currently unconfirmed but is expected to be around 8 modules without exceeding CAN bus traffic recommendations. This pre supposes no other traffic on the CAN bus.

For deployments of multiple modules, the default IP and CAN addresses are as Table 55. The vessel control system CAN source address is unchanged.

Module Name	MCU IP Address	MCU CAN bus Source Address	VCS CAN bus PDU Specific Offset
“Vesselname 1”	10.10.10.10	0x12	0x00
“Vesselname 2”	10.10.10.11	0x13	0x01
“Vesselname 3”	10.10.10.12	0x14	0x02
“Vesselname 4”	10.10.10.13	0x15	0x03
“Vesselname 5”	10.10.10.14	0x16	0x04
“Vesselname 6”	10.10.10.15	0x17	0x05
“Vesselname 7”	10.10.10.16	0x18	0x06
“Vesselname 8”	10.10.10.17	0x19	0x07
<etc>	<etc>	<etc>	<etc>

Table 55 – Multiple Module IP and CAN addresses.

The FCwave™ CAN matrix is designed with inspiration from SAE standard J1939, thus the FCwave™ CAN Matrix specifies a PDU Specific for all CAN messages from Vessel to Module controller. The CAN bus PDU Specific Offset must be added to the value specified in that document, in effect modifying the message ID of the relevant CAN messages.

Example

Table 56 below shows how the IP and CAN addresses should be set up for a vessel named “Ballard” with four FCwave™ modules installed.

Module Name	MCU IP Address	VCS_REQUEST Msg ID	VCS_STATUS Msg ID	VCS_REQUEST_FAST Msg ID	MCU CAN Source Address
“Ballard 1”	10.10.10.10	0x10FF0027	0x18FF0027	0x00FFA027	0x12
“Ballard 2”	10.10.10.11	0x10FF0127	0x18FF0127	0x00FFA127	0x13
“Ballard 3”	10.10.10.12	0x10FF0227	0x18FF0227	0x00FFA227	0x14

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"Ballard 4"	10.10.10.13	0x10FF0327	0x18FF0327	0x00FFA327	0x15

Table 56 - IP and CAN address example for deployment of four FCwave™ modules.

37.9. EMC / EMI

The system integrator is responsible for ensuring EMC/EMI conformity to regulatory standards for the integration with DCDC equipment and vessel communication system.

Steps can be taken when routing the high voltage output cables in order to minimize emissions from a switching load during operation. The positive and negative conductor going to each individual load should be bundled closely and routed together. If possible, the conductors should be shielded as well.

37.10. Hydrogen Alarm Lockout

The module is equipped with two hydrogen sensors to monitor the hydrogen concentration in the hydrogen enclosure outlet ventilation.
The sensor associated with the control alarms are discussed below.

Alarm: A2_ AZT_J50_H

In an event where the ventilation air hydrogen sensor trips, a severity 2 alarm ***A2_AZT_J50_H*** will shut the module down and **FCM_OK** signal will be set to 0V. This alarm will trigger an additional alarm called ***A2_ AZT_J50_HLOCK*** (high lock) which will lock the module and prevent further attempts of restarting until the Hydrogen level is below the acceptable limit. Once the H2 is no longer in alarm, ***A2_ AZT_J50_H*** may be cleared by cycling ***MD_Enable*** but ***A2_ AZT_J50_HLOCK*** will remain latched.

A2_ AZT_J50_HLOCK

To *clear* ***AZT_J50_HLOCK, AZT_J50_HLOCK_RESET*** must be enabled from the Service Interface or over customer CAN link. Only trained personnel should perform the reset function after it is deemed safe to do so.

Note: if an attempt is made to set the *RESET* flag without a hydrogen lockout present, another severity 2 alarm ***A2_ AZT_J50_RESETERR*** will be set to ensure the system is not forced to run in an unsafe condition. To reset the reset error the reset flag needs to be cleared followed by cycling ***MD_Enable***. For details, please refer to the CAN Matrix Customer Specification (CMS013) document.

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38. Safety System – Functional description

The Safety Controllers purpose in the module is to ensure that all foreseable dangerous situations are detected, signaled to the vessel, and that the module is brought to a safe state.

The safety controller takes input from the following safety subsystems:

- Hydrogen detection
- Ventilation monitoring
- Fire detection
- External emergency notification
- Controller Watchdog

38.1. Warning and Alarm notification

It is the responsibility of the integrator to display an audible and a visual alarm if the emergency system notifies the vessel control system. The module does not include audible or visual indicators for the alarms.

38.2. Hydrogen detection

The safety controller takes input from a hydrogen volumetric concentration sensor, which gives an alarm at 40% LFL. Activation of this alarm leads to immediate shutdown of the module and signals to the vessel that an H_2 alarm has been tripped, this signaling is done over the SAFE_H2 hardwire connection, see 2133586288.429 “Safety System Supply and Signal Definitions”.

Failure of the sensor is treated as a high-level detection.

Detection of H_2 above 40% LFL or failure of the sensor causes a Severity 4 Safety System Activation.

38.3. Ventilation monitoring

The safety controller takes input from the devices and sensors ensuring the flow of ventilation air though the H_2 enclosure. If any of these fails, the safety system triggers an immediate shutdown and signals the vessel that a ventilation failure has occurred.

The ventilation subsystem monitors the following parameters:

- Ventilation intake airflow speed.
- H2 enclosure differential pressure monitoring.
- Fan and secondary fan rotational speed (Tacho).

Failure of any sensor is treated as a failure of the ventilation monitoring and causes a Severity 4 Safety System Activation.

Restriction of the ventilation airflow

If the air flow through the module ventilation is restricted, due to accident or buildup of debris, the airflow flow switch will trip. Ensure that the ventilation intake and outlet are routed correctly, and no debris may collect in the ventilation intake.

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38.4. Fire detection

The safety system has fire detection via a linear heat detection cable. This cable passes over the electric motors, motor controllers, high voltage panel and fuel cell stacks, where heat from a fire would be detected if present.

In case of a fire, the heat will melt the insulation on the internal conductors in the fire wire cable and cause a change in ohmic resistance of the fire wire. The monitoring system detects this change and triggers a Severity 4 Alarm (Safety System Activation). The signal will be sent to vessel firefighting system.

The system also contains a smoke detector, which will trigger the Safety System activation if it detects smoke inside the module.

The monitoring system can discriminate between a fire detection and the cable failing open circuit. The open circuit triggers a shutdown and lockout of the controller, until certified personnel can perform trouble shooting and maintenance. No signal will be sent to vessel firefighting system.

38.5. External emergency

The safety controller has two external inputs to the module.

- Vessel Safety Status
- Emergency Pushbutton (two-wire)

The vessel safety status is an input from the vessel control system to the module, where the vessel signals to the module that the vessel is in a safe state. If an emergency, external to the module, occurs (from the Vessel control system, such as flooding, fire in other compartments, hydrogen detection, etc.), this input allows the vessel control system to trigger an emergency shutdown of the module.

The emergency pushbutton input is connected to a two-wire emergency “mushroom-style” pushbutton, placed in the fuel cell room **Note: Integrator scope**. This allows personnel in the fuel cell room to trigger an emergency shutdown.

38.6. Reset of the Safety Controller

A reset of the Safety Controller requires a full power cycle of the 24V power supply to the module.

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39. Datalogging function

The MCU stores operational date from the module. This information is then transmitted to Ballard over a secure connection via the vessel internet connection when the connection is enabled by bridge control.

This data allows Ballard personnel to troubleshoot and diagnose issues with the module and is essential to rapid response and resolving issues.

Before requesting assistance from Ballard, allow remote data unit to upload data to Ballard.

39.1. Remote connection details

Network Communication Specification	
Parameter	**Value**
Network Access	Ethernet/IP 100/1000 Mbit/s
WAN	Dynamic, private, internet routable IP address.
Availability	When possible, required at least once each 24-hr. period.
Internet Connection Throughput	>256 Kbps upload.
Data Logging Rate	10 MB/Hr/Module
Internet connection details	Provided during commissioning of module. Dedicated IP address and gateway needs to be aligned with integrator

Table 23 - Datalogging Connection Requirements.

39.2. Location of Stored Data

Data is stored on the module control unit (MCU) locally before being transmitted securely to Ballard.

39.3. Maintenance access

During commissioning and service, Ballard service personnel will require a wired ethernet connection which is routable to the module ethernet interface.

Service access is also possible via a service interface on the low voltage panel.

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40. High Voltage Electrical

This section describes the High Voltage interface between the FCwave™ and the DC/DC converters on the integrator's side. It also covers electrical safety both for the service personnel and the module.

40.1. High Voltage Interface

Operate the fuel cell module as a "floating electrical system" by ensuring that neither the fuel cell high voltage positive terminal nor the fuel cell high voltage negative terminal is connected to the application ground, earth or chassis.

The peak total current output at the fuel cell module high voltage connections is not to exceed 300 amps, but higher currents are possible if the limit is exceeded by the vessel system. Note that the module is **unfused**. Load cables must be sized properly for the maximum load that the vessel is expected to draw.

WARNING **To ensure a floating DC system is de-energized prior to servicing the fuel cell module, it is critical to measure zero volts between the fuel cell high voltage positive and high voltage negative terminals, between the fuel cell high voltage positive terminal and chassis, and between the fuel cell high voltage negative terminal and chassis. Measurements need to be made on both AC volts and DC volts scales.**

The system integrator is responsible for providing a means to lockout all necessary energy sources on the system prior to any service activity being performed. Furthermore, the integrator must provide a written procedure to Ballard personnel, detailing the equipment and steps required to sufficiently lock out all energy sources, such as a high voltage or high-power electrical sources.

40.2. Voltage Measurement

The fuel cell module has on-board measurements of the fuel cell stack DC voltages. While these measurements are sent by the module over CAN, it is strongly recommended that integrators do not only rely on the internal module voltage measurement.

40.3. High Voltage Disconnection

The module is disconnected from the Vessel by decoupling the HV DC connectors on the interface panel. See item #2 on Figure 15 – Detail View of module process connections.

40.4. Bonding

A stud is provided on the module for bonding. The bonding point is located left of the Control and Communication Connector (item #1 in Figure 15). The integrator must ensure that the bonding points are bonded to the vessel chassis or earth ground by a cable rated for the full current output of the fuel cell module, see (CMS006). The required maximum resistance between the fuel cell module bonding stud and chassis or earth ground is shown in Table 57.

Specification	
Maximum Resistance to Chassis	0.005Ω

Table 57 – Bonding Resistance Specification

Template 210818-1 Rev. A

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40.5. Ground Fault Monitor

The system integrator must ensure that a suitable ground fault monitoring system is installed and is functional. For a DC dual-output floating electrical system, the ground fault monitoring system must monitor all High-voltage DC outputs. Refer to section 8.6 for safety related issues to ground faults.

40.6. Electrical Isolation

Following the directives in DS/EN 60204-1-2018, two isolating devices are required.

1. For each **incoming** supply to a machine
2. For each **onboard** power supply

The isolation of the **incoming** supply is the customer's responsibility.

For the **onboard** power supply, the precautions taken are:

- The Ampherol plugs have retaining means to prevent accidental disconnection.
- There is a clear warning notice stating "Do not disconnect under load".

Use the isolation resistance in Table 58 as a reference. The isolation resistance of the FCwave will depend on the filter used. The filter each module have will depend on whether the module was produced before or after the 2nd of August of 2024.

Typical Resistance (HV) to Chassis:	
Modules from before 02/07/2024	240kΩ
Modules from after 02/07/2024	400kΩ

Table 58 – Module Electrical Isolation.

40.7. High Voltage Power During Maintenance

During service by Ballard certified personnel, the module may request HV power to perform diagnostic tasks.

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41. Multiple Module Installation

The purpose of this section is to describe the requirements and additional action points needed for an installation of multiple FCwave™ modules in a single installation onboard a vessel or installation room.

The compartment in which the fuel cell modules are to be installed is termed the “Fuel Cell Installation Room”, and requirements are presented below in the following sections.

41.1. Structural Requirements for the Installation

Follow instructions from section 11 Fuel Cell Installation Room Requirements.

41.2. Hydrogen connection

The hydrogen supply connection to the module must fulfill the following requirements:

5. A hydrogen supply shutoff valve with a reaction time less than 2 seconds is required to be installed for each module.
6. The hydrogen flow must be restricted by suitable means such that hydrogen mass flowrate shall not exceed 4.9 g/s.
7. The amount of hydrogen in the fuel cell module must be minimized when not in operation. The physical volume of the pipe between hydrogen shutoff valve and module interface plate is not to exceed 5 liters.
8. It is a requirement that the pipe between the hydrogen shutoff valve and module interface plate is double-walled, with detection measures for the annular space.

41.3. Process exhaust connection

This section describes the options for process exhaust connections from multiple FCwave™ modules in a Fuel Cell Installation Room:

Permitted options are:

1. Individual process exhausts from each module led to the outside without combining them
   1.1. The process exhaust should not exceed the backpressure specifications in Table 14
2. Combined process exhaust from multiple modules led to the outside
   2.1. This requires a separate isolation damper for each module, which will close when modules are not operating to prevent backflow from running modules to non-running modules.
   2.2. The combined process exhaust should not exceed the backpressure specifications in Table 14 in any operational scenario
   2.3. The design of the combined process exhaust should in all operational cases prevent backflow from modules running at differing output levels (e.g. full power and partial power)

Option 1 and 2 are illustrated in Figure 39.

In all cases, the following apply:

- Process exhaust must be let to the outside.
- FCwave™ process exhaust is fully water saturated and with negligible hydrogen content.

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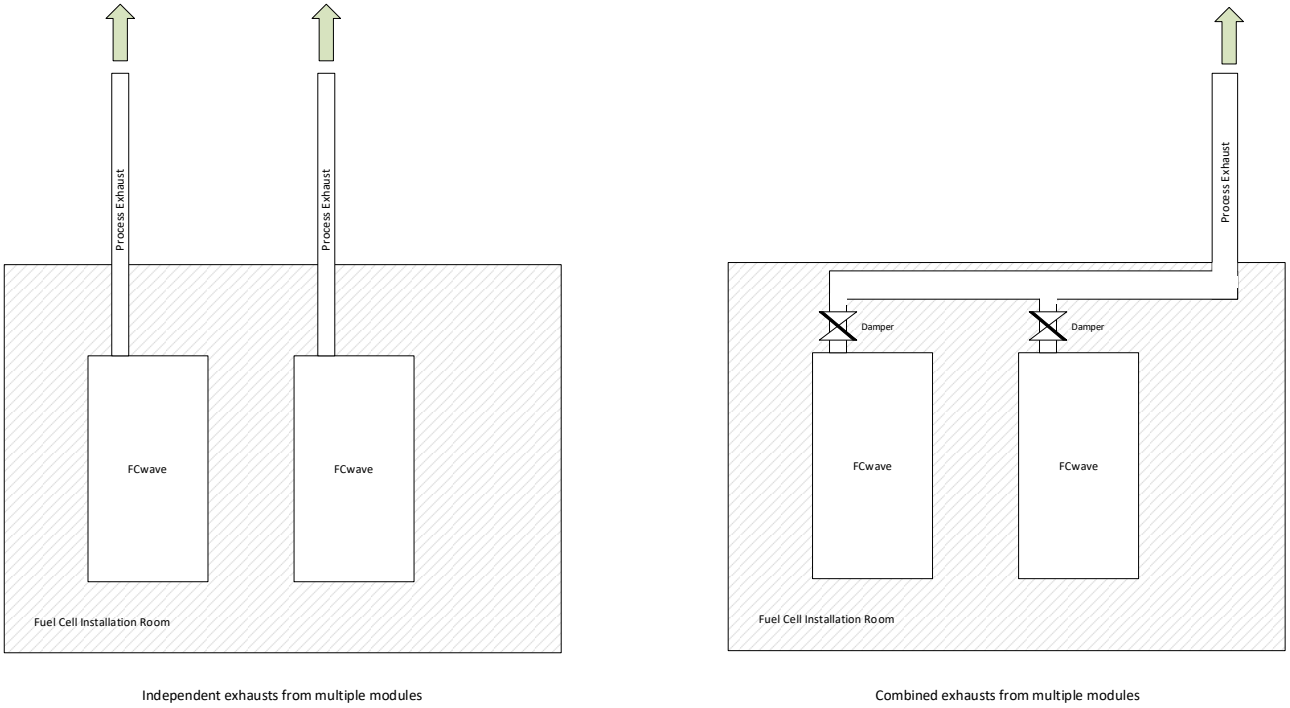


Figure 39 – Options for process exhaust of multiple FCwave™ modules.

41.4. Module Ventilation exhaust connection

If ventilation exhausts are combined from multiple systems, they must be equipped with separate isolation dampers, which must close if the module are not operating.

H2 Enclosure ventilation must be let to the outside.

The integration to the vessel shall ensure the exhaust from FC modules (ventilation air) is led to a safe location free of any spark or ignition source.

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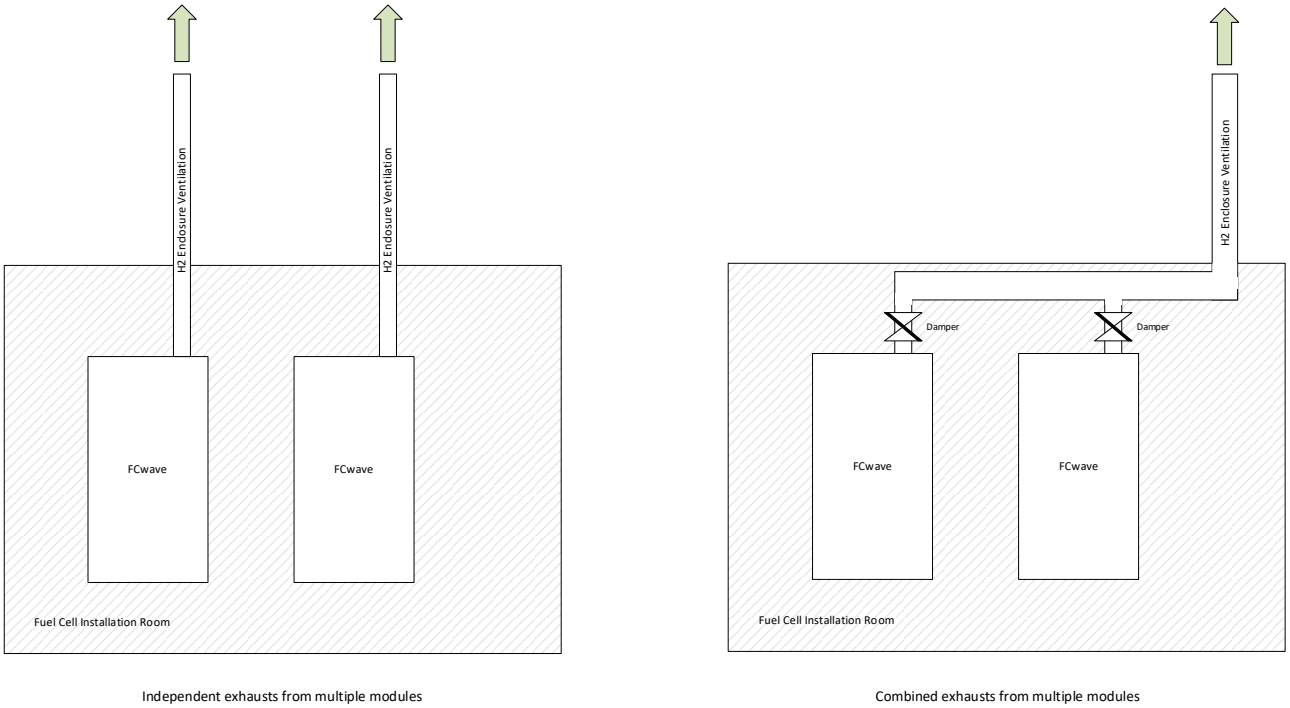


Figure 40 – Options for ventilation exhaust of multiple FCwave™ modules.

41.5. Installation Room ventilation

The air handling system in the fuel cell installation room must be sufficient to supply the FCwave™ process air. Addition ventilation of the fuel cell installation room to be determined by Classification Society or Vessel Integrator.

Ballard recommends performing a calculation according to IEC 60079-10 to establish the required ventilation rate for the fuel cell installation room. In normal operation, all probable leakage scenarios internal to the FCwave™ are managed inside the module.

41.6. Drain connections

The process water drain connection from multiple modules may be combined. It is required that integrator implements backflow prevention from module to module or from external source to module(s). The maximum allowed pressure is 25mbar.

41.7. Coolant connections

The coolant circuits from multiple modules may be combined. The integrator should consider the following:

- Each module must be provided sufficient coolant during operation.
- If individual models are in different states of operation (running / not-running), consider shutting off the cooling flow to the not-running modules.

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41.8. Safety system

The vessel control and safety system must include visual and audible signaling to crew in appropriate locations.

Recommendation is to clearly indicate which FC module is in operation inside the fuel cell room.

The FCwave™ does not provide an emergency stop button. It is the responsibility of the integrator to install adequate and accessible safety stop buttons or similar, as well as ensure the integration of FCwave™ in the emergency stop circuit.

41.9. Fuel Cell Installation Room Access

Access to the fuel cell installation room during operation shall be limited to trained service technicians and crew that have received Ballard fuel cell training

Unrestricted access to the fuel cell installation room can be permitted by the vessel authorities when all fuel cell modules are powered off and otherwise deemed permissible.

42. Maintenance

The fuel cell module requires periodic maintenance for safe operation throughout the service lifetime of the module. Contact Ballard Customer Care for training.

It is the responsibility of the customer to carry out the maintenance tasks according to the maintenance schedule. Additionally, the customer must keep maintenance records listing each task, along with dates, fuel cell module serial number, operating hours, replaced parts, and any measurement values. The records must be provided to Ballard upon request.

43. Module Shipping and Storage

The FCwave™ module is designed to be installed in a dedicated fuel cell room fulfilling the relevant fire protection and ventilation requirements as per SOLAS and Classification Society. Generally, all the electrical components are stored in a dry room. Always place the equipment indoors for safety reasons.

Minimum requirements of warehouse/dry room storage:

Temperature between -40 °C to +60 °C
0-95% relative humidity
No condensing
Corrosion-proof atmosphere
No dripping water

For sub-zero storage after integration, consult Ballard and ensure proper precautions have been taken. Refer to Table 59 for a specified and exhaustive list.

Modules operated with deionized water are required to be flushed, according to Table 59.

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CAUTION **Ensure the low temperature coolant loop (detailed in section 19) is supplied with the appropriate coolant temperature range for the intended storage temperature.**

System	Coolant	Indoor storage conditions	Need to do this preparation
HT Loop	50/50 DI water-Ethylene Glycol	-40° to 60°C	Drain and flush with 50/50 Ethylene Glycol /DI water
LT Loop	50/50 Water-Glycol	-40° to 60°C	Drain and flush with 50/50 Glycol/water

Table 59 – Module Storage Preparations.

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44. Appendix

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Internal Document

Revision Record			
Rev	**CO**	**Description**	Date
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Performed by:	CSO, DER	2024-05-03
Checked by:	KJK, OMO	2024-05-03
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Process Exhaust Hydrogen Content

Full Title: Process Exhaust Hydrogen Concentration

Abstract: The process exhaust hydrogen concentration is analyzed. The result is that in all situations the ventilation/airflow, release rate, and release type lead to a non-hazardous zone according to IEC 60079-10-1.

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1.0 Background

This document is intended to provide information on the potential hydrogen concentrations that can be present in the FCwave process exhaust and the resulting zone at the exhaust point. It is not covering the Hydrogen Enclosure Ventilation.

2.0 FCwave Operation

The FCwave is designed based on a dilution principle where air is used to dilute any hydrogen present down to a safe level. The gas present in the process exhaust is a mix of oxygen depleted air (product from the electrochemical reaction), air (from stack bypassing), and hydrogen (from purging).

The target is to dilute the hydrogen content to below 25% of LFL (1%v of H2). The safety systems in the FCwave, collectively provide assurance, that if an error occurs, safety features are in place to shut down hydrogen supply and maintain a high dilution.

2.1 Steady State Operation

During steady state operation of the FCwave the source of hydrogen is from purging. This purging happens following an internal algorithm adjusting the purge cycle based on current drawn from the fuel cell stack. At minimum load the air flow required for the electrochemical reaction is not enough to ensure high dilution. Therefore, an air bypass valve is incorporated to allow for increased air flow in these situations, resulting in high dilutions.

With this dilution principle the measured hydrogen concentration of the exhaust is as listed in Table 2-1.

Table 2-1: *Hydrogen Concentration in Exhaust*	
55 kW	<1%v H2 (dry volume)
200 kW	<1%v H2 (dry volume)
Startup	<1%v H2 (dry volume)

The ventilation/airflow, release rate, and release type lead to a non-hazardous zone according to IEC 60079-10-1[1].

During ramping the concentration is not different from steady state operation.

2.2 Startup

During startup it is ensured that air flow is initiated, and sufficient ventilation is present before any hydrogen is entering the system. This ensures that ventilation is always available, and the needed dilution is achieved.

The purge cycle in startup is adjusted to remove water and nitrogen from the anode side of the stack.

With this dilution principle the calculated hydrogen concentration of the exhaust is as listed in Table 2-1.

The ventilation/airflow, release rate, and release type lead to a non-hazardous zone according to IEC 60079-10-1.

[1] Based on IEC 60079-10-1, Table D.1, Figure F.3, and Figure F.4.

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2.3 Shutdown

During shutdown purging is stopped before air flow. Any residual hydrogen will be consumed by the electrochemical reaction. Thus, there are no sources of release and hence a non-hazardous zone.

2.4 Abnormal operation

During abnormal operation any release will be stopped immediately and there will be no persistent hydrogen present. The air flow is maintained to secure high dilution.

The ventilation/airflow, release rate, and release type lead to a non-hazardous zone according to IEC 60079-10-1.

3.0 Definitions and Acronyms

Table 3-1: Definitions and Acronyms	
LFL	Lower Flammability Level

4.0 Reference documents

Table 4-1: Reference documents	
IEC 60079-10-1	Explosive Atmospheres – Part 10-1: Classification of Areas – Explosive Gas Atmospheres
MAN002	FCwave Integration Manual

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