MODULE 7:

Fuel Cell Bus Maintenance

College of the Desert

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XCELLSiS
The Fuel Cell Engine Company

BALLARD

FTA
Federal Transit Administration

COLLEGE OF THE DESERT
LUX ET VERITAS
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OBJECTIVES

Upon completion of this module, the technician will be able to:

- understand general maintenance procedures
- understand fuel system fueling, venting and purging procedures
- understand fuel cell engine routine service requirements
- understand the principles of the fuel cell engine service procedures
- understand the principles of the fuel system service procedures
- understand the principles of the conventional service procedures as they pertain to a fuel cell bus
- understand and interpret fuel cell engine diagnostics and fault information

7.1 General

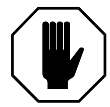
Apply the following general service instructions during maintenance. Many of the instructions are just as applicable to the maintenance of a conventional powered bus as they are to a fuel cell powered bus. These instructions are not meant to be exhaustive, or as a substitute for common sense or basic maintenance skills.

7.1.1 Warnings and Cautions

General Warnings and Cautions

- Be familiar with the safety information, hazards and emergency procedures prior to maintaining the bus.
- Always follow lockout procedures prior to servicing the bus. Lockout procedures vary, but must prevent inadvertent engine start even where various personnel are working independently.
- Be familiar with the location and operation of emergency shutdown switches. A bus normally contains two emergency shutdown switches, one mounted in the motor control center and the other at the rear of the engine compartment. These switches enable the engine to be shut down from either location, and may allow engine start from the rear of the bus.
- When elevating the bus, beware of the limitations of the blocking equipment, and always ensure that the jarring and shaking created by component removal and installation procedures do not overload the blocks, or cause the bus to become unstable.
- Always depressurize air lines prior to disconnection. Failure to do so will cause the hose end to whip uncontrollably as the air is expelled and solid particles deposited in the line to be propelled.
- Do not tamper with any control system communication signals while the bus is operating. Doing so may result in unsafe operating modes, equipment damage, or injury to personnel in or near the bus. Repair all faulty sensors or wiring before operating the bus.
- Open (disconnect) the battery knife switches prior to removing or installing electrical components.
- Understand the conditions under which the fire suppression system is active (if installed). In many buses, the fire suppression system is disabled if the batteries are discharged or if battery knife switches are open (discon-

Key Points & Notes



nected). The fire suppression system may need to be disabled during some maintenance procedures (such as during welding) to prevent false trigger.

- After torquing a bolt, add a spot of paint to the interface between the bolt head and its mating surface to indicate that torquing is complete.
- Always use a hand-held voltmeter to ensure that no voltage exists prior to servicing any electrical component.

Fuel Cell Engine Warnings and Cautions

- Always wait at least five minutes after the engine is shut down prior to servicing any fuel cell engine component in order to discharge any residual electrical charge from the fuel cell stacks and/or electrical components.
- Always ensure that stack voltmeters indicate 0 VDC prior to servicing any fuel cell engine component.
- Always use a hand-held voltmeter to ensure that a given stack is at 0 VDC prior to servicing that stack.
- Take care when handling fuel cell engine components to prevent damage.
- Some fuel cell stack components are fragile. Follow documented procedures when handling stacks to prevent damage.
- Keep foreign objects, materials, petroleum-based products, oil and grease away from the fuel cell stacks or any fuel cell engine components that pass fuel, air or coolant to or from the fuel cell stacks. Doing so may destroy the fuel cell stacks. Clean these components only as described in Section 7.1.6.
- Never introduce any leak inhibitors or other foreign substances into the water system. Doing so may destroy the fuel cell stacks.
- Replace all non-rubber gaskets once used. Replace rubber gaskets during maintenance if they have been in service for six months or if damaged.

Fuel Storage System (Rooftop) Warnings and Cautions

- Whenever possible, access rooftop components while parked indoors. If outdoors, latch the canopies open. Canopies can suddenly close when exposed to wind.
- Access rooftop components by opening one canopy and standing on the opposite (closed) canopy.

Key Points & Notes

- Where available, wear a personal safety harness and attach it to an overhead safety cable when on the bus roof.
- Never open or tighten any high-pressure fitting or component without first venting the hydrogen *and* verifying that *all* high-pressure gauges or displays indicates 10 psig or less. This ensures that the high-pressure circuit is depressurized even if one of the gauges or displays indicates an incorrect value.
- All personnel working with hydrogen storage components must have high pressure gas training or high pressure gas certification, if available.
- Close the fuel shutoff valve that supplies fuel to the engine only in case of emergency. Closing the valve during operation can damage the fuel cell stacks. Instead, turn off the engine in order to automatically close the solenoid valves associated with each hydrogen cylinder and the high-pressure manifold; this isolates all fuel within the fuel storage system.
- Take care when handling fuel storage system components to prevent damage.
- Do not walk on cylinders. Do not expose cylinders to any form of abrasion. Protect cylinders from tool impact. Do not expose cylinders to corrosive acids or bases, or add coatings.
- Do not leave tools or other items on the roof.
- Do not step on roof covers or hatches.

7.1.2 Work Procedures

- Make a sketch of component installation prior to removal and keep parts in order during disassembly to facilitate re-assembly.
- Keep parts clean, and clean them before re-assembly.
- When disconnecting unlabeled hoses or connectors, use tags to identify how they should be reconnected. After completing a repair, check wiring and hose connectors to ensure that they are properly connected and secure.
- Cover open ends of lines, hoses and fittings with caps, tape or clean plastic bags to prevent the entry of foreign objects, substances or dirt.
- To disconnect vacuum hoses, pull on the end, not the middle of the hose.

Key Points & Notes

- To uncouple electrical connectors, pull on the connector itself, not the wires.
- Replace used lock nuts. Do not substitute a regular nut for a lock nut.
- Use stainless steel hardware unless otherwise specified.
- When replacing fuses or breakers, be sure that the new fuse or breaker has the correct amperage rating.
- Understand electrical circuits prior to diagnosis and connecting the test equipment.
- Do not drop electrical components such as sensors or relays as they may become damaged. If they are dropped on a hard floor, they should be verified or replaced.
- Label replacement parts in an identical fashion to the components they replace. Install wires so that their labels are easily readable wherever possible.
- Always replace warning labels (such as for high voltage, high pressure, high temperature or hydrogen).
- When unfastening fittings, ensure that there is no pressure in the circuit before opening and open the fitting slowly so that any trapped gas can escape safely.

7.1.3 Fittings

Fuel cell engines use a variety of fittings for attaching hoses, tubes and other components. Some of the most common are described in the following sections.

7.1.3.1 Flared Tube Fittings

Flared tube fittings are commonly used on hydraulic fluid, oil, coolant and bus chassis air hoses. Each fitting consists of a tube or hose, a support sleeve and a nut that is free to turn, and a fitting body that includes male threads.

When fastening pre-swaged flared tube fittings:

1. Ensure that all parts are clean and undamaged, and that the sealing surfaces are round and smooth and free of all nicks, scratches, spiral tool marks, splits or weld beads in the seal area.
2. Align the tube flair against the nose of the fitting body. Do not apply Teflon tape or other thread compounds to the threads of fittings, sleeve or nut.
3. Tighten the nut by hand, then tighten the nut with a wrench either to the specified torque or by the specified

number of flats (as shown in Table 7-1). When using the flats method, hand tighten, mark one of the nut flats with a vertical line, and tighten. When tight, mark the body hex in line with the line on the nut.

Key Points & Notes

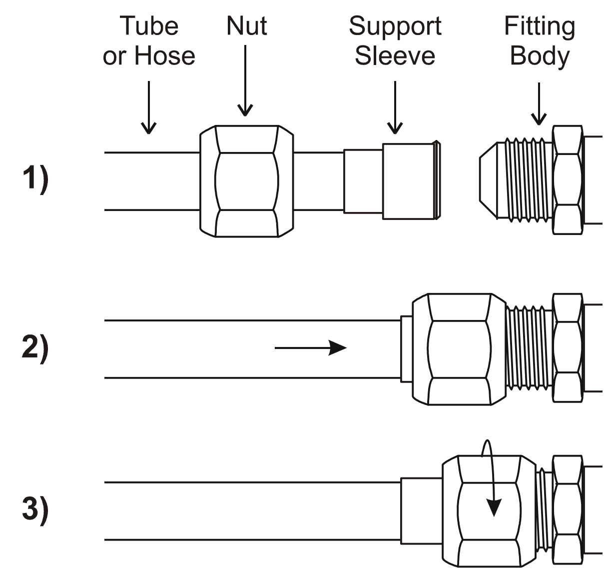


Figure 7-1 Fastening Flared Tube Fittings

Size	Thread Size	Torque (in-lb)	Torque (ft-lb)	Tube Connection (Flats)	Swivel Nut or Hose Connection (Flats)
-2	5/16-24	40 ± 5	3 ± 1	-	-
-3	3/8-24	70 ± 5	6 ± 1	-	-
-4	7/16-20	140 ± 10	12 ± 1	2	2
-5	1/2-20	180 ± 15	15 ± 1	2	2
-6	9/16-18	250 ± 15	21 ± 1	1½	1¼
-8	3/4-16	550 ± 25	45 ± 2	1½	1
-10	7/8-14	700 ± 50	60 ± 5	1½	1
-12	1 1/16-12	1000 ± 50	85 ± 5	1¼	1
-14	1 5/16-12	1250 ± 50	105 ± 5	1	1
-16	1 5/16-12	1450 ± 50	150 ± 5	1	1
-20	1 5/8-12	2000 ± 100	170 ± 10	1	1
-24	1 7/8-12	2400 ± 150	200 ± 15	1	1
-32	2 1/2-12	3200 ± 200	270 ± 20	1	1

Table 7-1 Flared Tube Fitting Torque Specifications

Key Points & Notes

Re-tighten existing flared tube fittings only. New flared tube fittings must be swaged according to manufacturer's specifications using approved equipment.

7.1.3.2 Compression Fittings

Compression fittings are commonly used on fuel lines and are rated to very high pressure. Each fitting consists of a tube, on which two ferrules are swaged and a nut is free to move, and a fitting body that includes male threads.

When fastening pre-swaged compression fittings:

1. Ensure that all parts are clean and undamaged.
2. Insert the tube with pre-swaged ferrules into fitting body until front ferrule seats. Do not apply Teflon tape or other thread compounds to the threads of fittings, ferrules or seat.
3. Tighten the nut by hand, then tighten the nut with a wrench ¼ turn beyond the original position (an increase in resistance occurs at the original position).

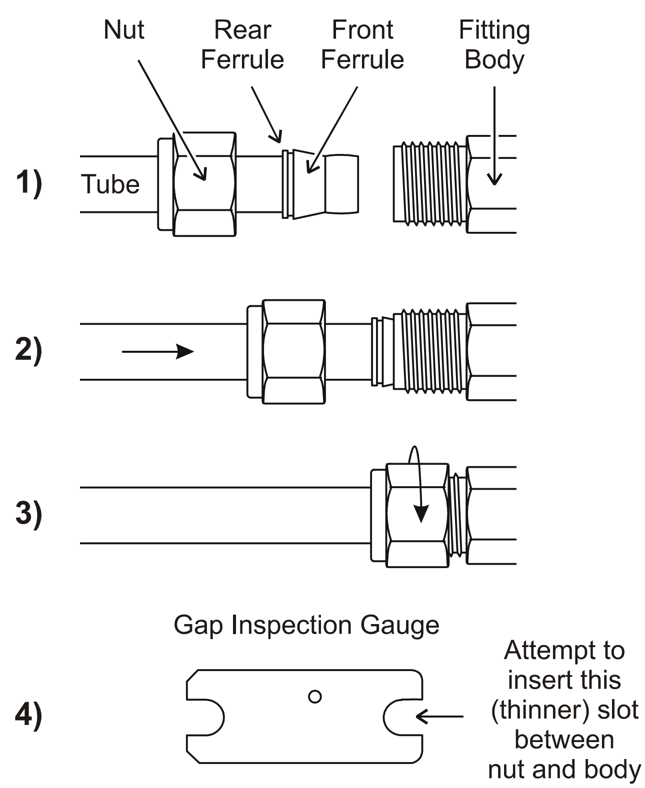


Figure 7-2 Fastening Compression Fittings

Key Points & Notes

4. Attempt to insert *the thin end* (with rounded corners) of a gap inspection gauge (for the appropriate size of tube) between the nut and fitting body: if it fits, further tighten the nut and re-test; if it does not fit, the nut is sufficiently tightened. Six different gap inspection tools are required, for 1/8", 1/4", 3/8", 1/2", 3/4" and 1" tubes.

Re-tighten existing compression fittings. New compression fittings must be swaged according to manufacturer's specifications.

7.1.3.3 Pipe Thread Fittings

Pipe thread fittings are commonly used on all manner of fluid and gas connections. Each fitting consists of a tapered thread that forms an interference fit with a mating tapped hole. Teflon tape or sealant is added to the pipe threads to aid in seal formation.

When fastening pipe thread fittings:

1. Remove any old Teflon tape or sealant from the pipe threads.
2. Apply ample new Teflon tape to the pipe threads (typically two to three turns). Ensure that the leading 1.5 threads remain clear of tape to prevent orifice blockage.
3. Screw the two components together until tight: use only wrench flats provided when applying torque (never use sleeves or enclosures). Do not exceed the following tightening torques:

   3/8" NPT: 225 in-lb (25 Nm)

   1/2" NPT: 300 in-lb (34 Nm)

   3/4" NPT: 450 in-lb (50 Nm)

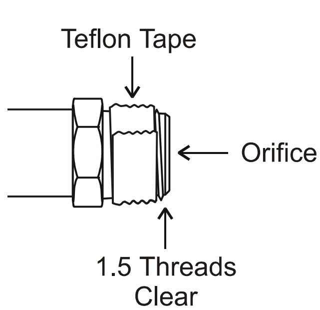


Figure 7-3 Pipe Thread Fitting

If an adequate seal cannot be achieved, replace the fitting or component as required.

Key Points & Notes

7.1.3.4 Quick-Connect Fittings

Quick-connect fittings are commonly used on fluid or gas lines that must be disconnected frequently or while under pressure. Each fitting consists of a stem and a body and the body is surrounded by a sleeve. The body, and sometimes the stem, contains a built-in check valve to minimize content spillage when disconnected.

When using quick-connect fittings:

- To couple, align stem with body and push stem into body until it clicks into place.
- To uncouple, pull body sleeve towards stem.

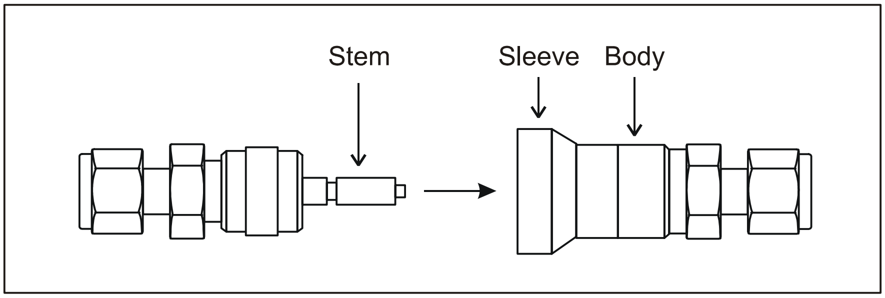


Figure 7-4 Quick-Connect Fitting

7.1.4 Valves

Fuel cell engines use a variety of valves for isolating and controlling gas and liquid flow. Some of the most common are described in the following sections.

7.1.4.1 Shutoff Valves

Shutoff valves are used on liquid and gas lines to interrupt or permit flow. Shutoff valves are also known as 2-way valves since they have two possible flow configurations: open and closed.

To use shutoff valves:

- The valve is open when the handle is parallel to the pipe on which it is mounted.
- The valve is closed when the handle is perpendicular to the pipe on which it is mounted.

Key Points & Notes

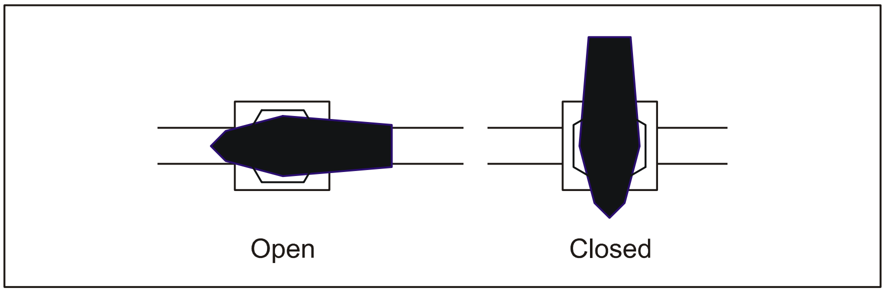


Figure 7-5 Shutoff Valve Use

7.1.4.2 Three-Way Valves

Three-way valves are used on fluid and gas lines to interrupt flow, or permit flow in either of two directions. Three-way valves therefore two flow positions and one off position.

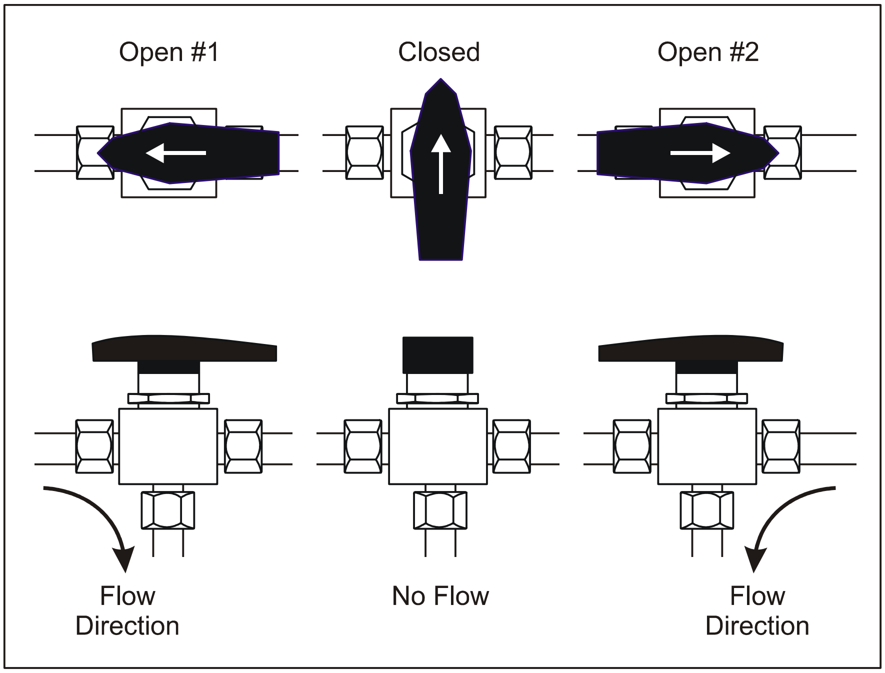


Figure 7-6 Three-Way Valve Use

To use three-way valves:

- The valve is open when the handle is parallel to the pipe on which it is mounted; the flow path passes between the direction the handle points and the outlet at the bottom of the valve
- The valve is closed when the handle is perpendicular to the pipe on which it is mounted.

Key Points & Notes

7.1.5 Materials

A fuel cell bus uses special materials to prevent contamination of the fuel cells and to provide resistance to hydrogen embrittlement. These material restrictions apply to all process lines that pass fuel, air or coolant to or from the fuel cell stacks and apply equally to the system plumbing (lines, interface fittings or connections) and component part construction.

Use only the materials specified. Failure to do so may lead to component failure or damage to the fuel cells.

Key Points & Notes

- **For any *wet* or *dry* fluid or gas components:**

  Use 316 stainless steel, Teflon, EPDM, or Viton

- **For any *dry* fluid or gas components, or *wet* components that are *not in direct contact* with process fluids that pass through the fuel cell stacks (such as the hydraulic fluid circuit):**

  Use 316 stainless steel, Teflon, EPDM, Viton, brass, copper, carbon steel, zinc, aluminum or Buna N. Stainless steel has better hydrogen embrittlement resistance than carbon steels.

- **At all times:**

  No rare earth metals, alkali metals and alkaline earth metals. These metals react with hydrogen.

  All components must be kept free of contaminants. In particular, all surfaces and components must be kept free of oils, sulfur containing pipe dope, dirt, sand, rust, metal shavings and other particulates.

7.1.6 Cleaning

A fuel cell bus requires special cleaning solutions and methods to prevent contamination of the fuel cells and to protect the hydrogen storage cylinders. Different cleaning procedures apply to each of the following four categories:

Fuel Cell Stacks And Membrane Humidifiers

Use only a dry or damp cloth when cleaning the fuel cell stack or membrane humidifier surfaces. **Never use solvents, steam, or soap or allow them to contact the components in any way. These solutions can be absorbed by the fuel cell stack or membrane humidifiers and can cause serious damage.**

Fuel Cell Engine Process Component Interior Surfaces

Use only manufacturer approved cleaning solution when cleaning the interior of any component (other than the fuel cell stacks) that passes fuel, air or coolant to or from the fuel cell stacks. **Never use soap or solvents (such as varsol, acetone, methyl-ethyl-ketone, paint thinner, lacquer thinner, gasoline, alcohol, etc.). These solutions may leave residues that could cause serious damage to the fuel cells.**

Key Points & Notes

Fuel Cell Engine Exterior Surfaces

Use standard cleaning procedures when cleaning fuel cell engine *exterior* surfaces provided that no soap or solvents contact the fuel cells or the interior of process components in any way. Use water and cleaning solution sparingly. For intensive cleaning, remove the stacks and seal manifold interfaces thoroughly to prevent contact. Do not use steam since this may penetrate electronic components or process streams.

Bus Exterior and Standard Bus Equipment (Including Hydrogen Storage Cylinders)

Use standard cleaning procedures when cleaning the exterior of the bus provided that no soap or solvents contact the fuel cells or the interior of process components in any way.

The soaps used in transit authority bus wash facilities are benign to the hydrogen storage cylinders. **Never expose the cylinders to unapproved soaps or any solvents. These solutions may corrode, weaken or seriously damage the cylinders.**

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7.1.7 Fluids

A fuel cell bus uses specific fluids within its systems. Some of these fluids are different from those used on a conventional powered bus.

Humidification Water

The humidification system uses pure de-ionized (distilled) water. Regular water is not suitable as the ions in it would cause short-circuits within the fuel cells. De-ionized water must be stored in non-metal containers to prevent ion accumulation or passed through a de-ionizing filter prior to use. Do not re-use de-ionized water.

Use only pure de-ionized (distilled) water. Do not use tap water, drinking water or any other liquid.

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Stack Coolant

The stack coolant system uses either de-ionized (distilled) water, or a custom mixture of de-ionized water with pure ethylene glycol. Regular water is not suitable as the ions in it would cause short-circuits within the fuel cells. Regular ethylene glycol is not suitable as it contains additives that can damage the fuel cell stacks. Pure propylene glycol is not suitable as it has insufficient cooling capacity. Used stack coolant may be re-used if kept clean.

Key Points & Notes

Use only de-ionized (distilled) water with or without pure ethylene glycol solution as specified by the manufacturer. **Do not use tap water, drinking water, regular ethylene glycol, propylene glycol or any other liquid. Never add leak inhibitors or other additives.**

Bus Coolant

The bus cooling system uses a standard water/ethylene glycol solution since it never comes into direct contact with the fuel cell stacks. A propylene glycol solution is not suitable as it has insufficient cooling capacity. Used bus coolant may be re-used if kept clean.

Lubrication Oil

The lubrication system uses a specified synthetic oil of specific viscosity. This oil has been specially selected for its low vapor pressure property so that oil is less likely to enter the air stream that passes through the fuel cell stacks. Used lubrication oil may be re-used if kept clean.

Use only the specified lubrication oil. Never substitute other oil brands or viscosities.

Hydraulic Fluid

The hydraulic system uses a specified hydraulic fluid, typically commercial-grade automatic transmission fluid. Used hydraulic fluid may be re-used if kept clean.

Use only the specified hydraulic fluid. Do not substitute other fluid brands or specifications without prior permission from the bus manufacturer.

Transmission Fluid

The transmission fluid circuit uses a specified, commercial-grade automatic transmission fluid. Used transmission fluid may be re-used if kept clean.

Use only the specified transmission fluid. Do not substitute other fluid brands or specifications without prior permission from the transmission manufacturer.

HVAC Compressor Oil

The HVAC compressor uses a specified, commercial-grade compressor oil. This oil has been selected for its compatibility with the type of refrigerant used. Use of other oils may lead to air conditioning equipment damage. Used compressor oil may be re-used if kept clean.

Key Points & Notes

Use only the specified HVAC compressor oil. Do not substitute other fluid brands or specifications without prior permission from the air conditioner manufacturer.

7.1.8 Hoisting and Jacking

Lift or jack a fuel cell bus using standard bus manufacturer procedures with an awareness of the following special considerations:

- A fuel cell bus typically weighs approximately 5000 lb (2300 kg) more than a diesel bus, and about 2200 lb (1000 kg) more than a CNG bus. Ensure that hoisting and jacking equipment is capable of safely supporting this weight.
- A fuel cell bus is taller than a diesel bus, especially with a roof canopy open. Ensure that sufficient space exists when hoisting or jacking the bus.
- Avoid lifting or supporting a fuel cell bus from the rear unless absolutely necessary since this may strain the fuel cell engine and/or the support chassis. **Never lift or support the bus from the rear unless all support struts are in place. Lifting or supporting the bus without the rear support struts could cause structural damage.**

7.1.9 Towing and Pulling

Towing and pulling instructions for a fuel cell bus vary according to whether the distance is less or greater than one mile (1.6 km). As an alternative to towing, the bus may be transported on a flatbed bus trailer.

Distances Greater Than One Mile

When transporting a fuel cell bus over distances greater than one mile (such as returning the bus to the transit facility after a road breakdown), tow or pull the bus using standard bus manufacturer procedures with the following restrictions:

- Disconnect the driveshaft or remove the rear axle shafts. This prevents transmission damage since it is not actively lubricated when the engine is off. It is not sufficient to place the shift selector in neutral and flat tow the bus.
- The bus may be towed from either the front or the rear. If towed from the rear, ensure that all rear support struts are in place. Towing the bus without the rear support struts in place could cause structural damage.

Key Points & Notes

Distances Less Than One Mile

When transporting a fuel cell bus over distances less than one mile (such as moving the bus within the transit facility), flat-tow or pull the bus from either the front or the rear without disconnecting the driveshaft or removing the rear axle shaft provided that:

- the towing distance does not exceed one mile (1.6 km)
- the towing/pulling speed does not exceed 5 mph (8 km/h)
- there has been no major failure within any portion of the power train
- there has been no loss of oil or fluid from the power train
- the shift selector is in neutral mode
- the towing/pulling occurs on structural components only

Do not flat tow or pull the bus even over short distances unless all above conditions are met. Doing so may cause serious damage.

7.1.10 Welding and Heating

Special safety precautions (in addition to those prescribed in standard bus welding procedures) must be applied when welding components or circuits on a fuel cell bus, or when heating components with oxygen/acetylene or propane equipment. Different welding and heating procedures apply to non-hydrogen bus chassis components and to hydrogen components and circuits.

Welding and heating are hazardous activities in the vicinity of hydrogen. Strictly follow these safety precautions.

Non-Hydrogen Components or Circuits

When welding or heating *non-hydrogen* bus chassis components or circuits, remove the component from the bus chassis if possible. If not:

1. Vent the fuel storage system (including all hydrogen storage cylinders) to 300 psig (21 barg).
2. Close all cylinder hand valves.
3. Disable the fire suppression system, if installed. (A welding arc near a fire sensor will cause it to trigger.)

Key Points & Notes

4. Clamp the welding ground as close as possible to the weld area.
5. Protect stacks and fuel storage components from sparks and splatter.

Hydrogen Components or Circuits

When welding or heating *hydrogen* components or circuits:

1. Isolate and vent the hydrogen circuit and remove component from bus
2. Weld the component away from the bus. Clean or passivate the component as required.
3. Allow component to cool to room temperature before reinstalling.
4. Install the component into the bus.
5. Purge the hydrogen circuit if required.
6. When pressurized, leak test the circuit with special attention to all weld areas.

Never weld hydrogen components or circuits on the bus.

7.1.11 Parking and Storage

A fuel cell bus may be parked or stored at either an outdoor or indoor location provided all environmental and safety requirements are satisfied.

7.1.11.1 Parking (0–1 Month)

Parking is defined as storing the bus for any period less than one month with the intention of continued operation. Parking of the bus requires attention to hydrogen safety and to freeze protection.

Hydrogen Safety

The parking location must accommodate potential hydrogen leaks. The on-board leak detection system typically inactive unless the engine is on. If the leak sensors have been unpowered for several days, they may take up to 24 hours of operation to stabilize. The fire suppression system, if installed, may be inactive when the battery knife switches are open (disconnected).

Key Points & Notes

Indoor Parking

When parking in a *hydrogen safe* facility (with specific leak detection, ventilation or electrical shut-off provisions), the fuel cylinders may remain pressurized. When parking in a *non-hydrogen safe* facility, the bus fuel cylinders must be vented to 10 psig (0.7 barg) prior to entrance. If parking the bus for several days, open (disconnect) the battery knife switches to prevent battery discharge.

Outdoor Parking

When parking outdoors, check the parking area for sources of ignition (such as operating electrical equipment) and overhead obstructions (such as wires or overpasses). If parking the bus for several days, open (disconnect) the battery knife switches to prevent battery discharge.

Freeze Protection

The parking location must prevent the fuel cell stacks from freezing at all times. All fuel cell stacks contain water in the air and hydrogen paths that is created during the power generation reaction and as a result of humidification.

In addition, some fuel cell stacks are cooled using pure deionized water, while others are cooled using a mixture of deionized water and ethylene glycol. If any of this water freezes, it can damage or destroy the fuel cell stacks. If the fuel cell stacks freeze in the absence of water, they may be harmed but not destroyed. Ice within other parts of the fuel cell engine can damage components.

Some fuel cell buses are equipped with freeze protection equipment that circulates warm water or heats specific areas in order to prevent freezing.

When parking the bus, ensure that the ambient temperature will not drop below 41 °F (5 °C). If the temperature may drop to this temperature, the options are:

- Operate the freeze protection equipment, if installed.
- Park the bus inside a heated facility. All heating equipment must conform to facility requirements (Section 10.2).
- Leave the engine running (only viable for short-term parking).
- Remove the stacks and store within a heated facility.

Key Points & Notes

7.1.11.2 Short-Term Storage (1–4 Months)

Short-term storage is defined as storing the bus for a period between one and four months with the intention to return the bus to operation. Short-term storage of the bus requires attention to hydrogen safety, freeze protection and to fuel cell stack ion protection.

Hydrogen Safety and Freeze Protection

Hydrogen safety and freeze protection for short-term storage is the same as for parking.

Fuel Cell Stack Ion Protection

Water in both the humidification system and the stack coolant system ionizes over time and can cause short-circuits within the fuel cells stacks. To minimize ionization, drain the humidification and coolant circuits.

When returning the bus to service, the humidification water and stack coolant circuits should be flushed with de-ionized water to remove residual ions from the fuel cell stacks. The on-board de-ionizing filters may become saturated with ions and need to be replaced. The control system may not permit the engine to start if the level of ionization is excessive.

7.1.11.3 Long-Term Storage (4+ Months)

Long-term storage is defined as storing the bus for a period or more than four months with no intention to operate the bus within the foreseeable future. Long-term storage of the bus requires attention to hydrogen safety, freeze protection and to fuel cell stack ion protection.

Hydrogen Safety and Freeze Protection

Hydrogen safety and freeze protection for long-term storage is the same as for parking.

Fuel Cell Stack Ion Protection

Long-term fuel cell stack ion protection requires fuel cell stack purges in addition to the short-term provisions. The purges blow compressed air through the fuel cell stacks to blow trapped water out of all circuits. The purges do not eliminate the need for fuel cell stack freeze protection.

7.1.12 Pre-Maintenance Preparation

Perform the following in preparation for fuel cell bus maintenance:

Key Points & Notes

- Maintenance of the bus is normally done in a *hydrogen safe* facility (outfitted with hydrogen leak detection equipment and automated alarm response systems) that has been certified for full bus hydrogen pressure. To maintain the bus in a *non-hydrogen safe* indoor facility that does not have these safety provisions, vent the fuel storage system to 10 psig (0.7 barg).
- Record the fuel storage pressure.
- Apply lockout procedures.
- Wait five minutes after engine shut down before conducting any maintenance on the fuel cell engine components.
- Open (disconnect) the battery knife switches when servicing electrical components. This disconnects battery power from all circuits, and may disable the fire suppression system if installed.

7.1.13 Post-Maintenance Checks

Perform the following power-off, power-on and engine-start checks after fuel cell bus maintenance:

Power-Off Checks

- Perform a leak-down test after any maintenance to the fuel delivery circuit or the fuel cell stacks.
- Perform a leak test and ground integrity on any hydrogen components or circuits that have been serviced.
- Ensure that the power cables are securely fastened to each stack and the inverter assembly.
- Ensure all electrical control cables have been connected.
- Ensure that all emergency shutdown switches are off.
- Ensure that all circuit breakers are closed.
- Ensure that the humidification, stack coolant, bus coolant, lubrication, hydraulic and transmission circuits have been filled and all vents are closed.
- Ensure that the bus chassis air system is pressurized to greater than 100 psig (7 barg).
- Ensure that all isolation valves are open on all circuits, including the cylinder shutoff valves.
- Ensure that the post-maintenance fuel storage pressure is not less than the pre-maintenance reading. If the current reading is lower, perform leak tests.

Key Points & Notes

- Ensure that the amount of fuel pressure is adequate to start the bus (absolute minimum of 100 psig; 7 barg).
- Ensure that your lockout is removed.
- Check that there are no dangers around or under the bus.

Power-On Checks

Close (connect) the battery knife switches:

- Check that all hydrogen leak indicators are powered.
- Check that all fire sensors are powered, if installed.
- Check that no alarms are active.
- Turn off the dump chopper pre-heat switch, if so equipped. When off, fuel cell power is not fed into the coolant by way of the dump chopper heater coils. This causes the fuel cell engine to warm more slowly which is advantageous in the event of a problem during startup. This switch is normally left on during normal operation.

Engine-Start Checks

Start the engine:

- If the engine fails to start, turn on the dump chopper pre-heat switch for two minutes to bleed residual voltage from the fuel cell stacks, if so equipped. Turn the switch off prior to the next start attempt.
- Have an assistant observe the rear of the bus and be prepared to shut off the engine if necessary.
- Check that the instrument panel, the message display centre, and other information systems are active and show no warnings, alarms or errors (other than a low fuel indication).

After two minutes of trouble-free operation:

- Check the humidification, stack coolant, bus coolant, lubrication, hydraulic and transmission fluid levels.

After five minutes of trouble-free operation:

- Turn on the dump chopper pre-heat switch, if so equipped.

7.2 Fuel System Operations

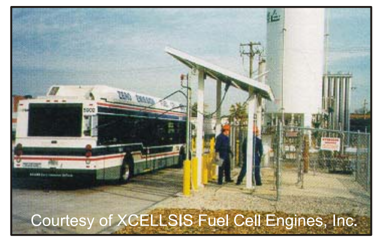
Key Points & Notes

7.2.1 Fueling

A fuel cell bus requires fueling when the hydrogen pressure in the cylinders drops to 500 psig (35 barg). At this fuel pressure, the bus provides a low fuel indication by way of dashboard lights, a message display centre or other means.

- At 500 psig (35 barg), there is fuel for about 25 miles (40 km)
- At 300 psig (21 barg), there is fuel for about 12 miles (20 km)
- At 100 psig (7 barg), fuel is absolutely essential
- At 50 psig (3.5 barg), the bus is unable to move

Fueling at BC Transit



Fueling at Chicago Transit

Fuel cell buses are fueled by way of a fueling receptacle, and are grounded during fueling by way of a grounding receptacle. These are typically located together at the rear of the bus within a special compartment. With some designs, the fueling compartment cannot be opened until the ground connection is made.

7.2.1.1 Fuel Specification

Hydrogen stored in high-pressure cylinders for fuel cell use must be very pure. In general, the fuel composition must be greater than 99.9% hydrogen, with no carbon monoxide or sulfides. Carbon monoxide and sulfide impurities can contaminate the catalyst within the fuel cells. Other impurities, although benign to the fuel cells, accumulate in the recirculating fuel delivery circuit and must be purged periodically, resulting in some hydrogen wastage.

7.2.1.2 Fueling Procedures

Hydrogen powered buses are normally fueled at a hydrogen fueling facility. When access to a fueling facility is not possible, a hydrogen tube trailer may bring fuel to the bus.

Fueling Facility Fueling Procedure

Perform pre-fueling checks. Verify that:

- the ambient temperature is above 40 °F (5 °C). If below this temperature, the fuel cell stacks must be protected from freezing. If the engine is warm and the fueling time is short, this is unlikely to be an issue. If the engine is not warm or the fueling time is long, external heat must

Key Points & Notes

be provided in a manner that is compliant with fueling facility requirements.

Figure 7-7 Hydrogen Fueling Station at SunLine Transit Agency

- all emergency fire equipment is in place
- no open flames, electric heat, sparks or smoking exist near the fueling site
- sufficient supply fuel pressure exists to fuel the bus
- the fueling supply hose is undamaged
- the fueling nozzle and internal O-ring (on hose) are clean and undamaged
- the fueling receptacle (on bus) is clean and undamaged

If any problems are found during the pre-fueling checks, do not continue with fueling.

Prepare the bus:

1. Turn the bus off, apply the parking brake, and chock the wheels.

2. Open (disconnect) the battery knife switches.

3. Record the fuel pressure.

Ground the bus:

4. Ground the bus to the fueling facility using the provided ground cable and receptacle. This is imperative to prevent static charge buildup.

Warning: Failure to provide an adequate ground may result in hydrogen auto-ignition during fueling.

Key Points & Notes

Key Points & Notes

Make fueling connections:

5. Remove the bus fueling receptacle cap. If it does not loosen by hand, a fault may have occurred and the receptacle may be pressurized; if this occurs, do not continue fueling.

6. Couple the fueling facility supply hose nozzle to the bus fueling receptacle. Turn the nozzle lever to the locked position. The nozzle and receptacle are designed to prevent air ingress into the supply hose and the bus.

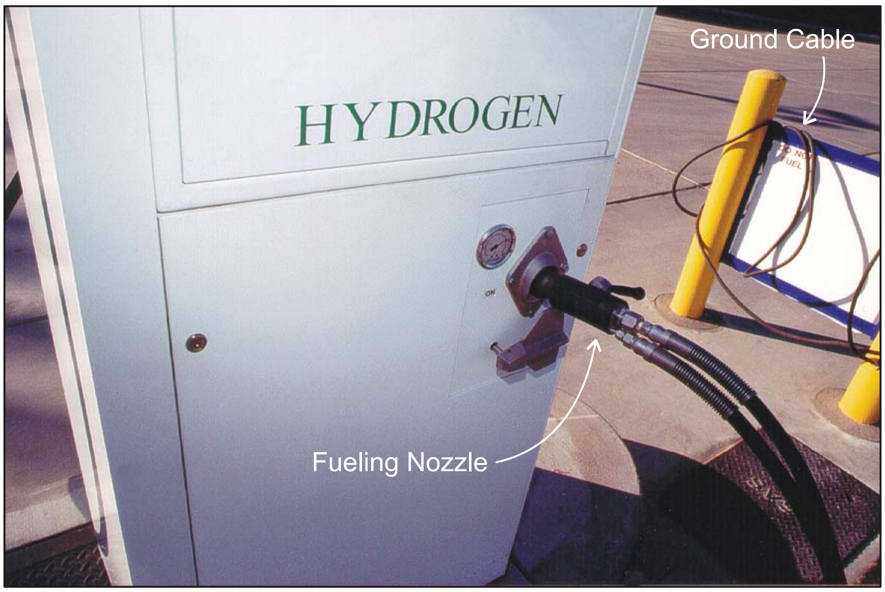


Figure 7-8 Hydrogen Fueling Equipment at SunLine Transit Agency

Fuel the bus:

7. Operate the fueling facility according to established procedures. The fueling station must never exceed the rated fueling pressure or temperature of the cylinders.

   The fueling pressure of a cylinder is higher than the normal service pressure since the heat of compression raises the temperature of the fuel as it enters the cylinders. As the cylinders cool to ambient conditions, the pressure then drops accordingly. This pressure drop can be as much as several hundred psi and does not indicate a leak. Regardless of this pressure drop, cylinder manufacturers specify the maximum allowable pressure at any temperature. For example, a cylinder with a 3600 psig (250 barg) service pressure may never exceed 4040 psig (280 barg).

   The maximum allowable cylinder temperature is a combination of the ambient temperature and the temperature

Automotive Fueling

rise during fueling. The temperature rise during fueling is governed by the fueling rate. The fueling station must therefore be calibrated to prevent cylinder overtemperature, or it must operate with reference to a temperature transducer located inside one of the bus fuel cylinders. A typical composite cylinder has a maximum allowable service temperature of 185 °F (85 °C) at any pressure.

Never exceed the cylinders' rated filling pressure or service temperature.

Figure 7-9 Fueling the XCELLSiS Phase 4 Bus at SunLine Transit Agency

After fueling:

8. Uncouple the fueling facility supply nozzle and re-cap the fueling receptacle.

9. Remove the fueling facility ground connection from the bus.

10. Record the fuel pressure and complete a fueling log.

11. Close (connect) the battery knife switches and remove the wheel chocks.

Tube Trailer Fueling Procedure

A tube trailer may be used to fuel the bus when away from the fueling facility. Tube trailers are normally supplied at a maximum pressure of 2600 psig (180 barg) and are therefore not able to fully fuel the bus to the 3600 psig (250 barg) level. Typically, five tubes are required to fuel a bus to

Key Points & Notes

Key Points & Notes

2600 psig (180 barg). Tube trailer fueling must occur outdoors.

A typical tube trailer is illustrated in Figure 7-10 and must include the following fueling equipment:

- A ground cable with a or suitable grounding clamp that can be attached to earth
- A ground cable capable of mating with the bus ground receptacle
- A fuel supply hose capable of mating with the bus fueling receptacle. The fuel supply hose must be constructed of synthetic material, stainless steel braid, and pressure tested to 1.5 times the rated pressure.
- A 3-way manual tube trailer bleed valve vented to atmosphere (to purge the supply hose)

Note: Different tube trailers may have different means of purging the supply hose.

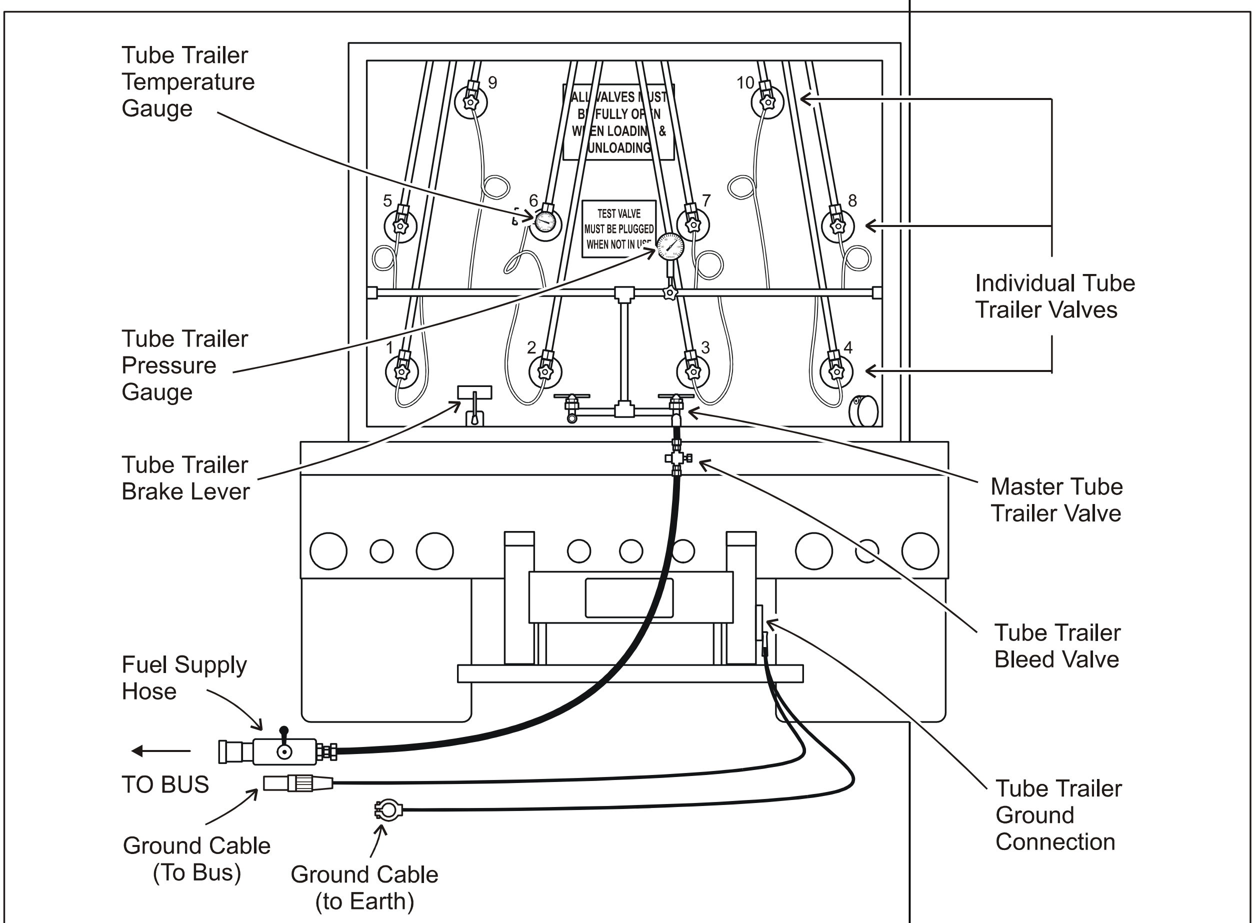
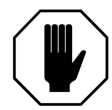


Figure 7-10 Typical Hydrogen Tube Trailer

Perform pre-fueling checks and prepare the bus as during facility fueling. Verify that:

- ambient conditions are suitable
- no ignitions sources exist all emergency equipment is in place
- the fueling supply hose, nozzle and receptacle are undamaged
- the engine is off, the parking brake is on, and the wheels are chocked
- the battery knife switches are open
- the fuel pressure has been recorded



Warning: If any problems are found during the pre-fueling checks, do not continue with fueling.

Check the tube trailer pressure:

1. Ensure that the tube trailer's pressure gauge indicates at least 500 psi (35 bar) more than the bus fuel pressure.

Make ground connections:

2. Connect the tube trailer ground cable connector to earth.
3. Connect the bus ground cable to the bus grounding receptacle.

Purge the supply hose of air:

4. Open the master tube trailer valve.
5. Ensure that the fueling receptacle is not attached to the bus.
6. Set the tube trailer bleed valve so that the gas flows into the supply hose.
7. Open any individual tube trailer valve; this pressurizes the fuel supply hose.
8. Close the individual tube trailer tank valve.
9. Set the tube trailer bleed valve so that the gas vents to atmosphere.
10. Set the tube trailer bleed valve so that the gas flows into the supply hose.
11. Repeat for a total of three times.

Make fueling connections:

12. Remove the bus fueling receptacle cap. If it does not loosen by hand, a fault may have occurred and the receptacle may be pressurized; if this occurs, do not continue fueling.

13. Couple the fueling facility supply hose nozzle to the bus fueling receptacle. Turn the nozzle lever to the locked position. The nozzle and receptacle are designed to prevent air ingress into the supply hose and the bus.

Fuel the bus using only one tube trailer tank at a time:

14. Open any individual tube trailer valve so that gas flows into the bus. Fuel the bus using only one tube trailer tank at a time.

15. Continue to fuel the bus until the sound of rushing gas stops. The bus fuel pressure should be within 200 psi (14 bar) of the supply pressure as indicated on the tube trailer pressure gauge.

16. Close the individual tube trailer valve and open another tank's valve.

17. Repeat until the bus fuel pressure matches that in any of the individual tube trailer tubes, or the tube trailer is depleted.

18. Close the master tube trailer valve, and ensure that all other individual tube trailer valves are closed.

    Never exceed the cylinders' rated filling pressure or service temperature.

Perform post-fueling activities as during facility fueling. Verify that:

- the fueling facility supply nozzle has been disconnected and the fuel receptacle cap has been installed
- the facility ground connector has been removed
- the fuel pressure has been recorded
- the knife switches are open

After completion:

19. Set the tube trailer bleed valve so that the gas trapped in the supply tube vents to atmosphere.

Key Points & Notes

7.2.2 Venting

Key Points & Notes

Hydrogen resides under three different pressures within a fuel cell powered bus: high, motive and low. The high and motive-pressures are contained within the fuel storage system, and the low-pressure is contained within the fuel delivery circuit.

High-pressure hydrogen at up to the storage capacity of hydrogen cylinders resides in the cylinders and high-pressure circuit as far as the motive pressure regulator. This cylinder pressure reduces as hydrogen is consumed by the engine. The cylinders and high-pressure circuit are pressurized at all times, and can be vented manually through the vent valve.

Motive-pressure hydrogen at an intermediate pressure (typically 178 psig; 12 barg) exists during engine run between the motive pressure regulator and the pressure regulator of the fuel delivery circuit.

Low-pressure hydrogen at nominally 20 to 30 psig (1.4 to 2 barg) exists during engine run downstream of the pressure regulator and includes all components that circulate the hydrogen through the fuel cell stacks. The actual pressure is set to match the instantaneous air pressure entering the fuel cell stacks.

The motive and low-pressure circuits automatically vent upon bus shutdown, and remain open to atmosphere whenever the engine is off.

The terms depressurizing, venting and de-fueling all mean the release of gas from a vessel. The term *venting* is used here to mean the discharge of hydrogen from the fuel storage system. The term *de-fueling* is used to mean the capture of released hydrogen for future use; the reverse of fueling. Whenever venting is required, de-fueling is a superior option where facilities exist as it conserves hydrogen. Specific de-fueling procedures are determined by the de-fueling facility.

Venting of the fuel storage system (cylinders and high-pressure circuit) is not required when the bus is going into a *hydrogen safe* facility (with specific leak detection, ventilation or electrical shutoff provisions).

Venting of the fuel storage system to 10 psig (0.7 barg) is required when the bus is going into a *non-hydrogen safe* facility or prior to some maintenance procedures.

Venting to atmospheric pressure (0 psig/barg) is required prior to maintenance access of cylinders or high-pressure circuit components. Venting of cylinders must be accompanied by nitrogen and hydrogen purges before returning to service.

Venting cylinders to 0 psig (0 barg) will potentially allow oxygen to enter the fuel cylinders!

7.2.2.1 Fuel Venting Equipment

Fuel cell buses include a roof-mounted vent valve to facilitate venting. In order to vent the fuel storage system, its high-pressure circuit and/or one or all of its cylinders, a facility venting tower or a portable venting tube must be connected to the vent valve. Typical venting equipment is shown in Figure 7-11. Direct opening of the vent valve is unacceptable since the hydrogen would be discharged in an undirected manner, thereby increasing potential damage to surrounding components and exposing personnel to an asphyxiation hazard.

Facility Venting Tower

A facility venting tower is the preferred device for venting hydrogen from the high-pressure circuit or cylinders. The facility venting tower connects to the vent valve (by way of a tube) and directs the hydrogen to a remote location where it is released into the atmosphere. A facility ground connection connects to the bus and prevents static charge buildup.

Portable Venting Tube

A portable venting tube is designed for venting or purging the high-pressure circuit and cylinders whenever a facility venting tower cannot be used. The portable venting tube connects to the vent valve and releases hydrogen above the level of the canopies. The tube and vent valve are both metal, so the portable venting tube is grounded to the high-pressure circuit once attached. It may not always be possible to attach the bus to a ground reference point when venting in the field. For this reason it is always preferable to vent at a facility with a proper ground connection.

Key Points & Notes

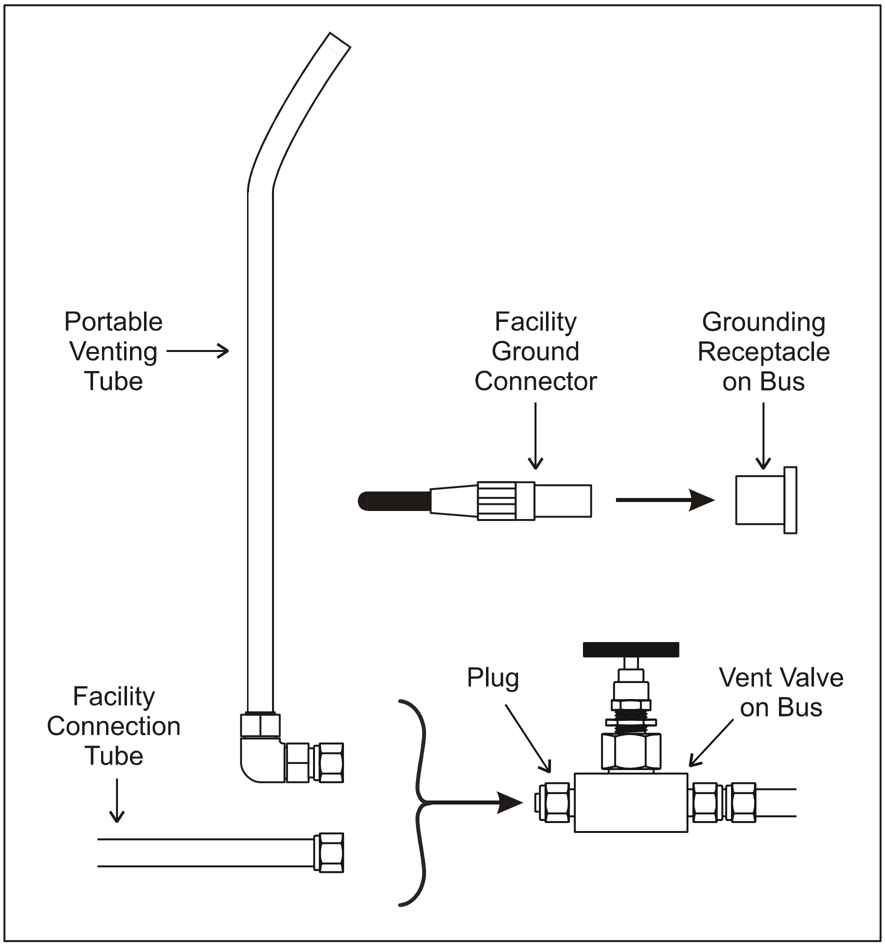


Figure 7-11 Typical Venting Equipment

7.2.2.2 Facility Venting

Venting usually occurs at a designated facility, often in conjunction with the bus fueling equipment.

When venting, heed the following warnings:

- Heed all rooftop warnings and cautions (Section 7.1.1).
- Wear eye and hearing protection at all times when venting. Gas venting can be very noisy.
- Keep all sources of ignition away. Do not smoke.
- Do not vent during an electrical storm.
- Each cylinder has an internal excess flow valve that closes if venting with an excessive flow rate. This can give the false impression that the cylinder has depressurized whereas it remains at a potentially high pressure. Accessing a cylinder in this condition is extremely dangerous; furthermore, the valve may re-open after several minutes expelling the remaining cylinder contents.

To ensure complete venting, never open the vent valve more than one turn. After venting, close the vent valve, wait five minutes, and re-check the high-pressure gauge before accessing any high-pressure component. This waiting period permits any closed excess flow valves to reset.

Prepare to vent:

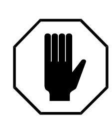
1. Park the bus in the designated venting area only and turn off the engine. Apply the parking brake and chock the wheels.
2. Insert the facility ground connector into the bus grounding receptacle.
3. Open and latch the canopy.
4. Ensure that vent valve is closed.
5. Slowly unfasten the plug from the vent valve.
6. Fasten the facility venting tower connection tube or the venting tube to the vent valve.
7. Ensure that the cylinder hand valves are *open* on any cylinder that needs to be vented. *Close* the cylinder valves on any cylinder that should *not* be vented. When venting the fuel storage system, hydrogen flows from the high-pressure circuit and from any cylinders with open hand valves.
8. Open the cylinder solenoid valves. These valves are normally open during operation and closed whenever the engine is off. Consequently, the solenoid valves must be opened using some specific sequence of switches on the side console and/or engine compartment that has been programmed into the control system. Listen for the clicking sound of the cylinder solenoid valves opening. Since the solenoid valves must remain open throughout venting, the battery knife switches must remain closed (connected).

Vent fuel:

9. Slowly open the vent valve *one turn*. If using the portable venting tube, a loud hissing sound indicates that gas is venting.

   An excessive venting flow rate causes the cylinders' internal excess flow valve to close.

Key Points & Notes



10. Have an assistant monitor the fuel pressure and allow the system to vent to the specified pressure. If a cylinder's internal excess flow valve closes, close the vent valve, wait five minutes, and slowly re-open the vent valve. When closed, the excess flow valve permits a small amount gas to escape from the cylinder to equalize the pressure.

11. Once venting is complete, close the vent valve.

12. Wait five minutes and re-read the fuel pressure. If the pressure has increased, re-open the vent valve to resume venting. If the pressure remains the same, proceed as below.

Complete:

13. Close the cylinder solenoid valves using a specific sequence of switches defined by the bus manufacturer.

14. Unfasten the facility venting tower connection tube or the venting tube from the vent valve.

15. Re-fasten the cap on the vent valve.

16. Unlatch and close the canopy.

17. Remove the facility ground connector from the grounding receptacle.

7.2.2.3 Emergency Venting

Venting normally occurs at the facility fueling station. If the fuel *must* be vented away from the fueling station, locate the bus away from sources of ignition and overhead obstructions, such as:

- open flames
- operating electrical equipment
- overhead power lines
- electrical storms
- overhead roofs, canopies or bridges

Venting with a portable venting tube is the same as for facility venting procedure except for the absence of a ground connection.

Key Points & Notes

7.2.3 Purging

Key Points & Notes

Purges flush residual gases from the fuel storage system and are used *after* cylinder maintenance, or any time the cylinder pressure has vented to atmospheric (0 psig). Purges are not required *before* servicing the cylinders or high-pressure circuit. Once vented to atmospheric pressure, the residual gas volume within the fuel storage system is too small to pose a combustible gas hazard.

A nitrogen purge eliminates air from the cylinders prior to re-exposure to hydrogen, thereby preventing the formation of a potentially combustible gas. When returning the cylinders to service, a hydrogen purge flushes out the nitrogen from the nitrogen purge, and leaves only pure hydrogen in the cylinders.

Purges are not normally performed after servicing the other high-pressure circuit components. Any residual air within the high-pressure circuit after service is automatically purged during engine operation. Purges are not required when servicing components of the motive circuit or the fuel delivery circuit. These circuits vent and are exposed to air whenever the engine is shut down, and are automatically purged during operation.

Nitrogen Purge

Nitrogen purges require a source of regulated nitrogen that is introduced through the fueling receptacle and vented through the vent valve. The vent valve must be connected to the facility venting tower connection tube or a portable venting tube.

Typical nitrogen purge equipment is illustrated in Figure 7-12 and must include:

- Multiple standard T bottles of nitrogen (99.99% minimum purity)
- To nitrogen purge one cylinder, one bottle is normally sufficient. Six bottles are required to purge eight cylinders. **Note: For convenience and speed, the bottles should be connected to a common manifold.**
- A nitrogen supply hose capable of mating with the bus fueling receptacle. The fuel supply hose must be constructed of synthetic material, stainless steel braid, and pressure tested to 1.5 times the rated pressure.

Key Points & Notes

- a venting pressure regulator (4,000-psig (275-barg) inlet; 300-psig (21-barg) outlet) with inlet and outlet pressure gauges

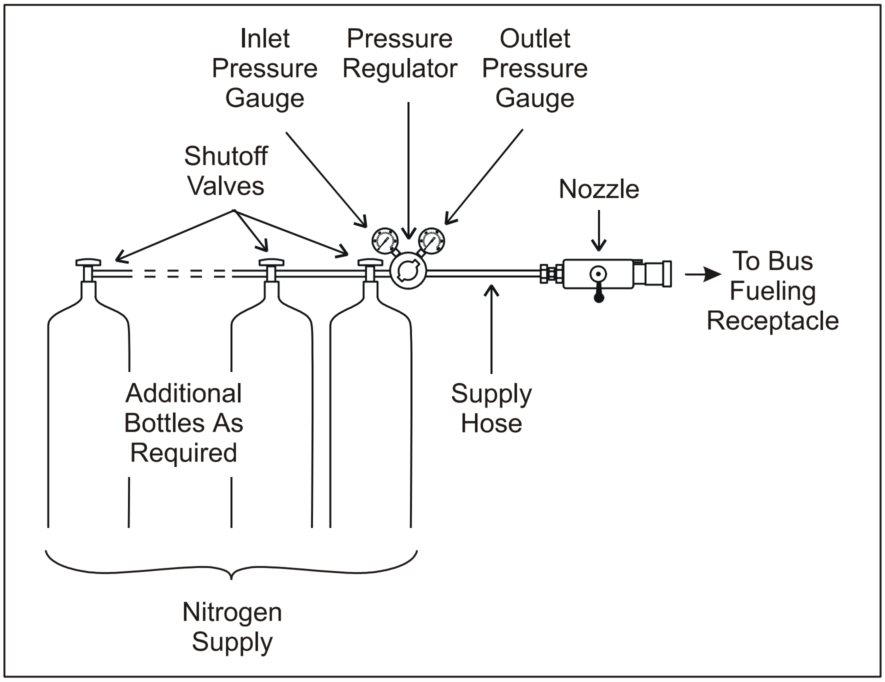


Figure 7-12 Typical Nitrogen Purge Equipment

Prepare to nitrogen purge just like during venting. Verify that:

- the engine is off, the parking brake is applied, and the wheels chocked.
- the facility ground connector is properly fitted into the bus grounding receptacle.
- the bus vent valve is attached to the facility venting tower or portable venting tube, and the valve is closed.
- the fuel storage system and associated cylinders have been vented to atmospheric pressure.
- the cylinder hand valves are open on those cylinders that need to be purged, and closed on those cylinders that can remain pressurized.
- the cylinder solenoid valves are open.

Attach supply hose:

1. Remove the cap from the bus fueling receptacle, and couple the supply hose nozzle to the bus fueling receptacle. Turn the nozzle lever to the locked position.

Key Points & Notes

Purge:

Heed all venting warnings when purging.

2. Open the shutoff valve on any of the nitrogen bottles.
3. Pressurize the fuel circuit to 100 psig (7 barg). Adjust the pressure regulator on the nitrogen supply as required.
4. Slowly open the vent valve *one turn*. If using the portable venting tube, a loud hissing sound indicates that gas is venting.

An excessive venting flow rate causes the cylinders' internal excess flow valve to close.

5. Have an assistant monitor the fuel pressure and allow the system to vent to 10 psig (0.7 barg). If a cylinder's internal excess flow valve closes, close the vent valve, wait five minutes, and slowly re-open the vent valve. When closed, the excess flow valve permits a small amount gas to escape from the cylinder to equalize the pressure.
6. Repeat purge for a total of three times, replacing nitrogen bottles as required.
7. Wait five minutes and re-read the fuel pressure. If the pressure has increased, repeat the purge procedure. If the pressure remains the same, proceed as below.
8. Proceed with a hydrogen purge if required.

Remove supply hose:

9. Uncouple the supply hose nozzle and re-cap the fueling receptacle.

Complete the nitrogen purge just like during venting. Verify that:

- the solenoid valves are closed.
- the facility venting tower connection tube or venting tube has been removed from the vent valve, and the vent valve cap has been installed.
- the facility ground connector has been removed
- the canopies are closed.

Key Points & Notes

Hydrogen Purge

Hydrogen purges require a source of regulated hydrogen that is vented through the vent valve. When purging the high-pressure circuit, plus at most a few cylinders, the hydrogen stored in the remaining cylinders may be used as a hydrogen source, provided those cylinders contain a minimum of 100 psig (7 barg) hydrogen.

If insufficient hydrogen volume exists in the remaining cylinders, a fueling facility or a tube trailer is required to provide hydrogen by way of the fueling receptacle. The vent valve must be connected to the facility venting tower connection tube or a portable venting tube.

During the hydrogen purge, it is essential to differentiate between those cylinders that *supply* the hydrogen and those that *receive* it. One supply cylinder with at least 100 psig of hydrogen is enough to purge the high-pressure circuit several times. Multiple supply cylinders with at least 100 psig of hydrogen are required to purge other cylinders.

Hydrogen purges only occur after cylinder service, and only following a nitrogen purge. With respect to this, verify that:

- the fuel storage system and associated *receiving* cylinders have been purged with nitrogen and vented to 10 psig (0.7 barg).
- the hand valves are *open* on the *receiving* cylinders (cylinders that need to be hydrogen purged) and *closed* on the *supply* cylinders (cylinders that remain pressurized with hydrogen).

In addition, prepare for the hydrogen purge just like during venting or a nitrogen purge. Verify that:

- the engine is off, the parking brake is applied, and the wheels chocked.
- the facility ground connector is properly fitted into the bus grounding receptacle.
- the bus vent valve is attached to the facility venting tower or portable venting tube, and the valve is closed.
- the cylinder hand valves are open on those cylinders that need to be purged, and closed on those cylinders that can remain pressurized.
- the cylinder solenoid valves are open.

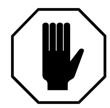
Key Points & Notes

Purge:

1. Open the hand valve on one or more of the *supply* cylinders that contain at least 100 psig (7 barg) hydrogen.

2. Have an assistant monitor the fuel pressure. Allow the circuit to pressurize to 100 psig and close all *supply* cylinder hand valves. If the pressure does not reach 100 psig, open the hand valves on additional *supply* cylinders. If all supply cylinder hand valves are open and the pressure still does not reach 100 psig, fuel the bus until the fuel pressure indicates 100 psig. Pressure greater than 100 psig is not required, but does no harm.

3. Slowly open the vent valve *one turn*. If using the portable venting tube, a loud hissing sound indicates that gas is venting.

   An excessive venting flow rate causes the cylinders' internal excess flow valve to close.

4. Have an assistant monitor the fuel pressure and allow the system to vent to 10 psig (0.7 barg). If a cylinder's internal excess flow valve closes, close the vent valve, wait five minutes, and slowly re-open the vent valve. When closed, the excess flow valve permits a small amount gas to escape from the cylinder to equalize the pressure.

5. Repeat purge for a total of three times, adding additional hydrogen as required.

6. Wait five minutes and re-read the fuel pressure. If the pressure has increased, repeat the purge procedure. If the pressure remains the same, proceed as below.

Complete the hydrogen purge just like during venting or a nitrogen purge. Verify that:

- the solenoid valves are closed.
- the facility venting tower connection tube or venting tube has been removed from the vent valve, and the vent valve cap has been installed.
- the fueling facility supply nozzle has been disconnected and the fuel receptacle cap has been installed if fuel was added externally.
- the facility ground connector has been removed.
- the canopies are closed.

7.3 Routine Maintenance

Fuel cell bus routine maintenance can be divided into the following categories:

- **Fuel cell engine procedures** that are unique to fuel cell buses
- **Fuel system procedures** that are common to those found on CNG or hydrogen powered internal combustion engine buses
- **Conventional procedures** that are typical of those normally required on any bus, although different in detail when applied to a fuel cell bus
- **Standard coach procedures** that are identical to those performed on any bus, irrespective of the type of engine

Of these four service categories, the first three are described below whereas the fourth is not as it has no bearing on fuel cell engines or hydrogen fuel systems.

The following maintenance schedules and service information is based on the Phase 3 and 4 fuel cell buses designed and built by XCELLSiS Fuel Cell Engines, Inc. This information represents the most complete description of fuel cell bus maintenance currently available, although it cannot cover all hardware configurations and variations.

Fuel cell technology is evolving rapidly, and no two current bus designs are identical. With this in mind, the maintenance information is intended to be representative of the type of service required, why it is required, and how it is done in principal, without providing hardware-specific, step-by-step instructions.

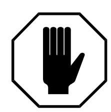
Always refer to manufacturer's instructions when servicing a fuel cell bus.

Routine maintenance is performed at Daily, Weekly, 3750 Mile (6000 km), 7500 Mile (12,000 km), 15,000 Mile (24,000 km), and 30,000 Mile (48,000 km) service intervals, or at some variation of these intervals. Representative service schedules are presented in the following tables. Procedure descriptions are presented in Sections 7.4 to 7.6.

Key Points & Notes


Courtesy of XCELLSIS Fuel Cell Engines, Inc.

Fuel Cell Buses Under Test



Daily Inspection and Service

Key Points & Notes

Fuel Cell Engine Procedures
Check ground fault monitor resistance and replace water or de-ionizing filter if required
Check stack vent fans
Inspect water traps
Inspect air system oil detector
Inspect hydrogen diffuser
Fuel System Procedures
Inspect burst disk vent cap
Conventional Procedures
Check leak indicators and sensors, and calibrate system if required
Check for fluid leaks or puddles
Check humidification water level
Check lubrication oil level
Check transmission fluid presence
Inspect air intake, air exhaust and canopies

Weekly Inspection and Service

Fuel Cell Engine Procedures
Perform leak-down test
Check cell voltage monitor
Fuel System Procedures
Perform fuel delivery circuit leak test
Conventional Procedures
Inspect fire suppression sensors
Clean stack vent fan filters
Inspect stack air inlet filters and replace if required
Inspect sintered air vents and clean as required
Inspect filter minder and replace air intake filter if indicated
Inspect lubrication oil sump magnetic plug
Drain turbocharger oil trap
Check transmission fluid level
Check hydraulic fluid level
Check stack coolant level
Check bus coolant level
Inspect hoses and tubes

3750 Mile (6000 km) Inspection and Service

Fuel Cell Engine Procedures
Perform fuel cell external and transfer leak tests
Perform glycol system integrity test
Check power cable connections
Fuel System Procedures
Perform high- and motive-pressure circuit leak test
Inspect high, motive and fuel delivery circuit components
Inspect roof vent caps
Compare fuel pressure transducer readings
Replace hydrogen particulate filter
Conventional Procedures
Inspect fire suppression hoses, nozzles and retardant tanks
Inspect belts
Inspect radiator
Inspect HVAC compressor oil
Inspect transmission

7500 Mile (12,000 km) Inspection and Service

Fuel Cell Engine Procedures
Check dump chopper resistance
Fuel System Procedures
Check the motive pressure regulator solenoid valve
Conventional Procedures
Take a lubrication oil sample
Take a transmission fluid sample
Take a hydraulic fluid sample

Key Points & Notes

15,000 Mile (24,000 km) Inspection and Service

Fuel Cell Engine Procedures
None
Fuel System Procedures
Perform cylinder installation and external inspections
Perform ground integrity tests
Conventional Procedures
Inspect and/or replace bus chassis air intake filter
Inspect and/or clean humidification water strainers
Replace lubrication system filter and oil
Replace hydraulic system filter and fluid
Replace transmission filters and fluid

30,000 Mile (48,000) Inspection and Service

Fuel Cell Engine Procedures
None
Fuel System Procedures
Perform cylinder internal inspection
Replace pressure regulator diaphragm, seal and seat replacement
Perform fire suppression system tests
Conventional Procedures
Inspect power train and stack vibration mounts

Key Points & Notes

7.4 Fuel Cell Engine Procedures

Key Points & Notes

Fuel cell engine procedures pertain to routine service that is unique to fuel cell powered buses.

7.4.1 Ground Fault Monitor Check and Conditional De-Ionizing Filter Replacement

The ground fault monitor is an integral part of the inverter. The ground fault monitor measures the approximate electrical resistance between the fuel cell stack power connections and the bus chassis. A high resistance indicates that there is little or no power leakage onto the chassis (as it should be), and a low resistance indicates that a leakage current exists. A leakage current (or "ground fault") occurs wherever a short-circuit occurs. If the resistance is too low, the ground fault monitor generates a warning or alarm.

A ground fault can occur as the result of an electrical component failure, but most occurrences result from an increase in conductivity of the humidification water or stack coolant. As the ions found in normal water conduct electricity, both these circuits use de-ionized water.

The de-ionized water ionizes over time through contact with metal. Both the humidification water and stack coolant circuits have de-ionizing filters to remove the accumulating ions, but these filters degrade with time, especially at elevated temperatures. The ground fault monitor, therefore, becomes a useful indicator of filter condition as well as guarding against dangerous short circuits.

A ground fault monitor check consists of reading the resistance as measured by the ground fault monitor. Typically, this resistance can be read directly from the bus' diagnostics interface. Ground fault readings should be taken with the bus running at the end of the service day. This ensures that all water has passed through the de-ionizing filters and as many accumulated ions have been removed as possible. Premature testing results in a low measured resistance value:

- If the resistance is >200 kΩ, no action is required
- If the resistance is <200 kΩ, assess the results:

  a) If the decrease in resistance is sudden, an electrical short may exist. Trace as required.

  b) If the decrease in resistance has been gradual (over a period of days), water ionization may be increasing.

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Replace the water sometime before the resistance drops to 120 kΩ. The resistance should increase during the subsequent engine run and remain above 200 kΩ for up to six weeks. If the water has been replaced within the last four weeks, replace the de-ionizing filters at the next convenient service interval. If the resistance drops below 40 kΩ, the filters must be replaced immediately.

De-ionizing filter media consist of a mixture of resins that take the form of small beads of plastic material. These beads are used to fill large filters directly, or are arranged into cartridges for use in small filters. Filter canisters and cartridges are designed for easy replacement; this usually involves draining all or part of the corresponding water or coolant circuit, disconnecting fittings and undoing brackets. Large canisters can be emptied and refilled with new resin.

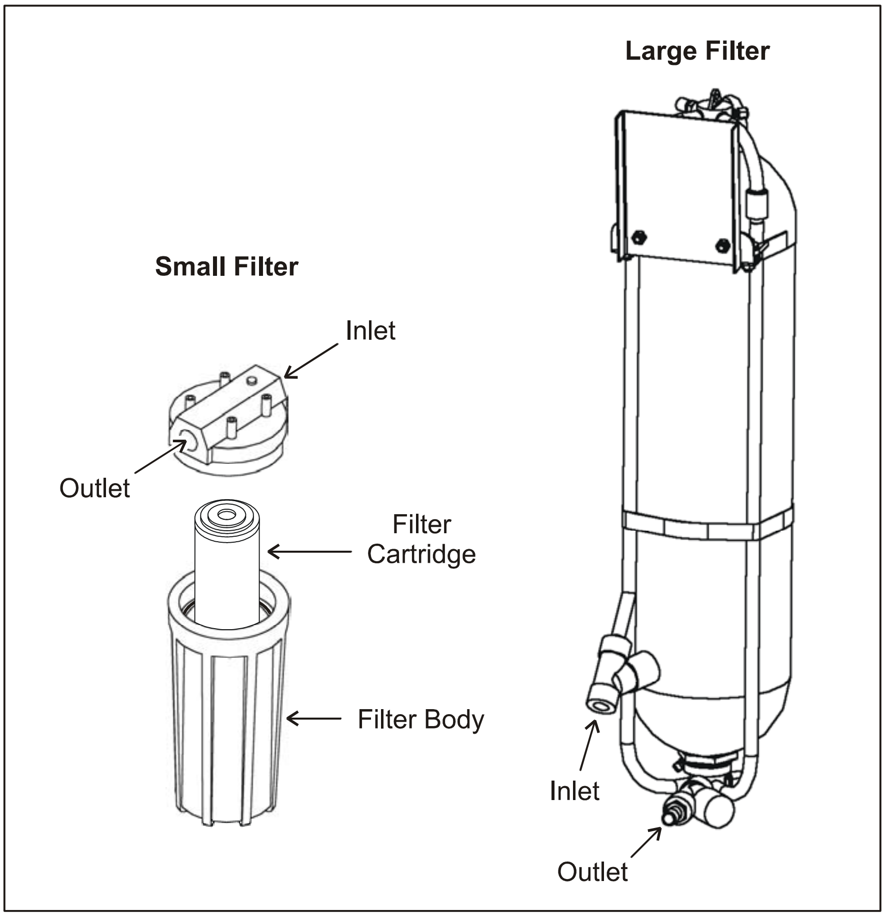

Figure 7-13 Typical De-ionizing Filters

7.4.2 Water Trap Inspections

Water traps allow the separation of liquid water from a gas stream while under pressure. In a fuel cell engine, water

Key Points & Notes

traps are used when venting a wet gas stream, or when draining a water stream with entrained gas. Typical circuits include the hydrogen purge line, the hydrogen/water separator drain or the humidifier drain.

Water traps consist of a chamber through which the water/gas mixture passes and in which the water can condense and collect. A float at the bottom of the chamber opens and closes according to water level.

Water trap inspections consist of a visual confirmation that the water traps are half-filled with water, the float is not stuck open, and the float moves freely when jostled. If the water is not present or the float is stuck open, the gas discharges through the water outlet port. In the case of a hydrogen line, this causes hydrogen discharge and a flammable gas leak hazard. If the float does not move freely, the water may not drain as required. If the float does not function properly, the water trap must be replaced.

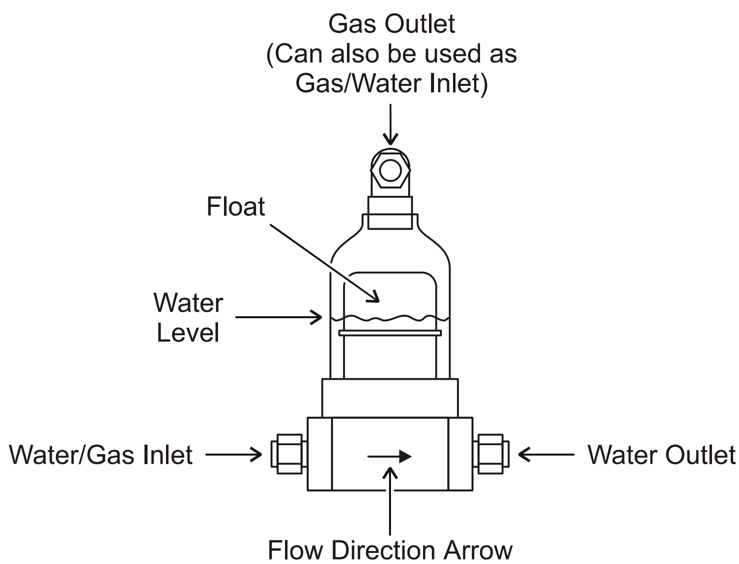

Figure 7-14 Typical Water Trap

7.4.3 Air System Oil Detector Inspection

The oil detector is installed within the air system to detect the presence of oil in the air stream. Oil presence can seriously damage the fuel cells and can potentially enter the air stream where it interacts with the air compressor or turbocharger.

The oil detector inspection is a visual check for oil presence. The oil detector contains crystals that are pale pink, but turn vibrant red when they have been exposed to oil. When

Key Points & Notes

oil exposure is indicated, inspect the air inlet filters for oil presence, and report to the bus manufacturer; do not operate the bus until repairs are completed. The oil detector must be replaced once exposed to oil.

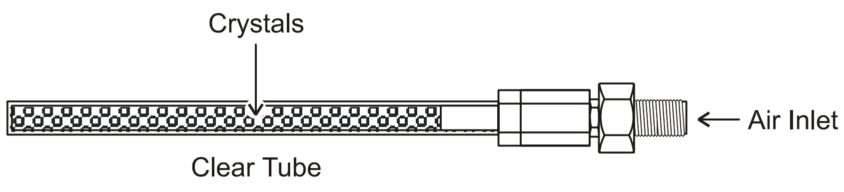

Figure 7-15 Oil Detector

7.4.4 Hydrogen Diffuser Inspection

The hydrogen diffuser disperses hydrogen purged from the fuel delivery circuit into a forced air stream. This ensures that the hydrogen concentration is lowered to well below the LFL, thereby preventing potential fire and explosions.

The hydrogen diffuser consists of a fan that passes air through a series of flow channels. An embedded tube releases hydrogen into the flow channels through a series of holes. A bus coolant tube accompanies the hydrogen tube and prevents water in the vent stream from freezing and blocking the vent holes.

The hydrogen diffuser inspection consists of a visual confirmation that the fan is operating and that the inlet and outlet are free of obstructions. The hydrogen diffuser only operates when the engine is on.

7.4.5 Stack Vent Fans Check

The stack vent fans provide positive pressure to the fuel cell stack enclosures to prevent any potential hydrogen accumulation in the event of fuel cell stack leakage.

Stack vent fan checks consist of tactile confirmation that each fan is sucking air into the corresponding fuel cell stack enclosure and an audible check for any evidence of bearing failure. Replace faulty fans. The stack vent fans only operate when the engine is on.

7.4.6 Cell Voltage Monitor Check

The cell voltage monitor measures the voltage of each fuel cell, and transmits these voltages to the control system, in addition to low-voltage warnings and alarms.

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Fuel cell stack voltages are monitored by a series of pins, each in contact with the graphite plates on either side of each individual fuel cell. These pins transmit the voltages to the cell voltage monitor, which converts the cell voltage data into digital form and generates analog warning and alarm signals. The resulting cell voltage values pass to the control system where they can be viewed directly using the bus' diagnostics interface.

A cell voltage monitor check consists of a visual assessment of all individual cell voltages for irregular high-low patterns or unusual cell voltages. These patterns are illustrated in Figure 7-16 based on the cell voltage monitor display from the XCELLSiS Phase 4 bus:

- High-low patterns are representative of one or two disconnected cell voltage monitor wires. If these are observed, note the fuel cell stack letter designator and cell number and service the cell voltage monitor the next time that stack is disassembled.
- Individual cell voltages are normally between 0.78 and 0.85 V at idle. Note any cell voltages below 0.5 V and monitor the cell daily for further degradation. A low cell voltage warning occurs at 0.4 V; alarms occur at 0.0 V and –0.2 V.
- If any cell voltage registers off-scale (above 1 V or less than –1 V without generating an alarm), note the fuel cell stack letter designator and cell number and service the cell voltage monitor the next time that stack is disassembled.

Key Points & Notes

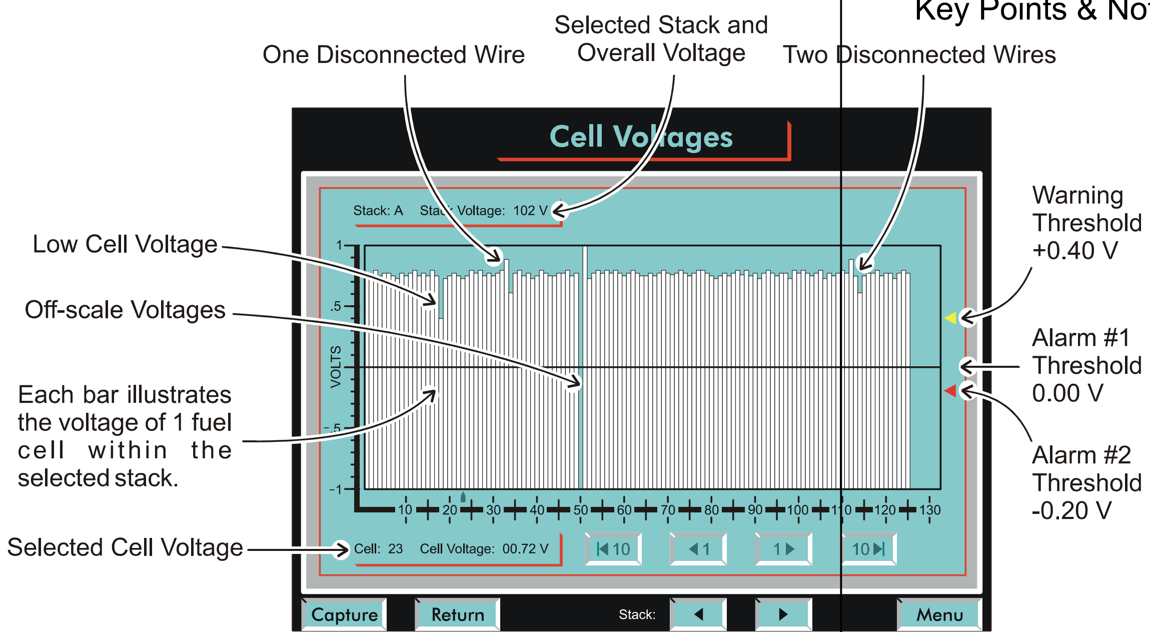


Figure 7-16 Cell Voltage Monitor Check

7.4.7 Fuel Cell Engine Leak Tests

Fuel cell stacks are designed so that the internal air, hydrogen and coolant streams never mix or leak. This is also true of membrane humidifiers, which are constructed in a similar fashion to stacks, but not of contact humidifiers (which mix the water and gas directly). In reality, some small amount of leakage always occurs. If a leak becomes excessive, replace the stack or membrane humidifier.

Leaks can be *external* (leaking to atmosphere) or *internal* (leaking from one flow path to another). External leaks result from seal malfunctions, plate cracks or other damage. Internal leaks result from membrane holes or other damage.

External and internal leaks reduce the power generating capacity of the fuel cell engine, and they permit hydrogen to mix with air, resulting in a potentially flammable mixture. The amount of mixing that can occur during an internal leak is limited by the pressure balance between the fuel and air streams; during steady state conditions, the air stream is approximately 2 psi (14 kPa) above the fuel pressure.

To combat leaks, each stack enclosure is actively ventilated and leak tests are performed routinely to quantify leakage rates. These leak tests are by far the most important set of fuel cell engine maintenance procedures and, along with the cell voltage monitor, the primary indicators of fuel cell stack

Key Points & Notes

and humidifier condition. The leak tests are important in identifying potential fire hazards, as well as maintaining the power output and efficiency of the engine.

Leak tests fall into three categories: leak-down test, external leak test and transfer leak tests.

Leak-Down Test

The leak-down test indicates the presence of leaks within any part of the fuel delivery circuit. This test uses pressure-drop principles to determine whether a leak exists in the fuel path of any of the fuel cell stacks, any of the components within the re-circulating fuel circuit (including humidifiers), or any associated plumbing.

The leak-down test measures leaks that flow both to the atmosphere and to other internal flow paths (oxidant or coolant) within the stacks. Since it operates on so many components at once, it is not good at isolating and quantifying leaks within individual stacks. However, it is quick and easy to perform and is a useful indicator of whether more detailed tests are required.

The amount of leakage flow that corresponds to a given pressure drop depends on the internal volume of all components within the test circuit. Consequently, the leak-down test thresholds cannot be stated as a general value and must be calibrated for the engine design.

External Leak Test (and Variations)

The external leak test quantifies the *total* amount of leakage from *all* flow paths (fuel, oxidant and coolant) to *atmosphere*. This test measures the leakage flow directly using an upstream mass flow meter or rotameter. Variations of this test use similar techniques to measure the leakage flow from an *individual* flow path to *atmosphere and the other internal flow paths*, or to measure the leakage flow from an *individual* flow path to *atmosphere only*.

Cumulatively, the external leak test and its variations can be applied equally to groups of stacks (typically arranged within a single enclosure or module) or individual stacks. The test thresholds must reflect the total internal volume of the test circuit. When applied to groups of stacks, external leak tests serve to indicate whether individual stack tests are required. When applied to an individual stack, the tests serve to isolate specific leaks.

Adjoining stack groups can be tested while installed on the bus, whereas individual stacks must be removed prior to

Key Points & Notes

testing. Similarly, these tests can also be applied to membrane humidifiers (in groups or individually). These leak tests do not apply to contact humidifiers, which do not require leak tests.

Transfer Leak Tests

The transfer leak tests quantify the amount of leakage from *one flow path* into *another flow path*. These leak tests measure the leakage flow directly using downstream, volumetric displacement techniques. The transfer leak tests can be applied to each combination of flow paths (fuel-to-oxidant, oxidant-to-fuel, fuel-to-coolant, etc.) but in practice are usually limited to fewer combinations.

Like the external leak test and its variations, the transfer leak test can be applied equally to groups of stacks or individual stacks using appropriate test thresholds. When applied to groups of stacks, the transfer leak tests serve to indicate whether further individual stack tests are required. When applied to an individual stack, the tests serve to isolate specific leaks. Adjoining stack groups can be tested while installed on the bus, whereas individual stacks must be removed prior to testing.

Also like the external leak test and its variations, the transfer leak tests can also be applied to membrane humidifiers, and do not apply to contact humidifiers.

Leak Test Sequence

The purpose of the stack (and humidifier) leak tests is to identify and isolate leaks so that the defective component can be replaced. When taken as a whole, the range of all possible leak test combinations is quite large and very time-consuming to conduct in their entirety.

To reduce the amount of work, specific leak tests are done in a logical sequence that successively isolate the leak while bypassing tests that are of no immediate consequence. For example, if a group of stacks fails a fuel path external test, but passes the oxidant and coolant external tests, there is no need to conduct oxidant or coolant path transfer tests. The fuel path transfer tests alone are needed to locate the leak.

The logical leak test sequence is encapsulated in a flowchart such as the one shown in Figure 7-17. Although this flowchart looks complicated, it actually simplifies the process of isolating leaks.

The leak-down test provides the initial leak assessment, and is performed at the weekly service interval. If the fuel cell engine passes this test, no further tests are required. If the fuel cell engine fails the leak-down test, a leak exists somewhere within the fuel delivery circuit. If no leaks can be found within the components of the fuel circuit or any associated plumbing (using a leak detection solution), the leak must exist within a fuel cell stack or membrane humidifier.

Fuel cell stacks are typically arranged in modules that include several stacks and associated humidifiers. These modules are tested at the 3750 mile service interval (regardless of the leak-down test results) for external leaks from all flow paths combined, and internal/external leaks from each individual flow path. If the stack module passes these four tests, no further tests are required.

If the stack module fails the external leak test from all flow paths, the leak exists within one or more individual stacks or membrane humidifiers. If the stack module fails any of the internal/external leak tests from individual flow paths, corresponding transfer tests must be performed on the entire module to isolate the leakage path. As an additional diagnostic tool, the external leakage (to atmosphere only) from the fuel path is also conducted prior to transfer tests on that circuit.

Once external and transfer tests have been completed on the overall stack module, the corresponding external and/or transfer tests are required on individual stacks or membrane humidifiers in order to isolate the faulty component.

Transfer tests that indicate leakage to or from the coolant path may originate within a stack or membrane humidifier, although leakage between gas paths can only originate within a stack due to the construction arrangement of the humidifiers. These tests necessitate the removal of the stacks and membrane humidifiers from the stack module. Individual stacks or humidifiers that fail any of these tests must be replaced.

If individual stack or membrane humidifier leak cannot be found despite leak indications at the module level, the leak exists in some portion of the manifolding that interconnects the components within the module. These leaks can be traced using leak detection solution, and repaired as required.

Key Points & Notes

Fuel cell stacks and membrane humidifiers can only be serviced by the original manufacturer. In preparation for shipping, fill humidifiers with de-ionized water, and the inlet and outlet ports on both humidifiers and stacks must be capped. Crate components securely to prevent damage during shipment. Ensure that the shipment will not be subject to freezing

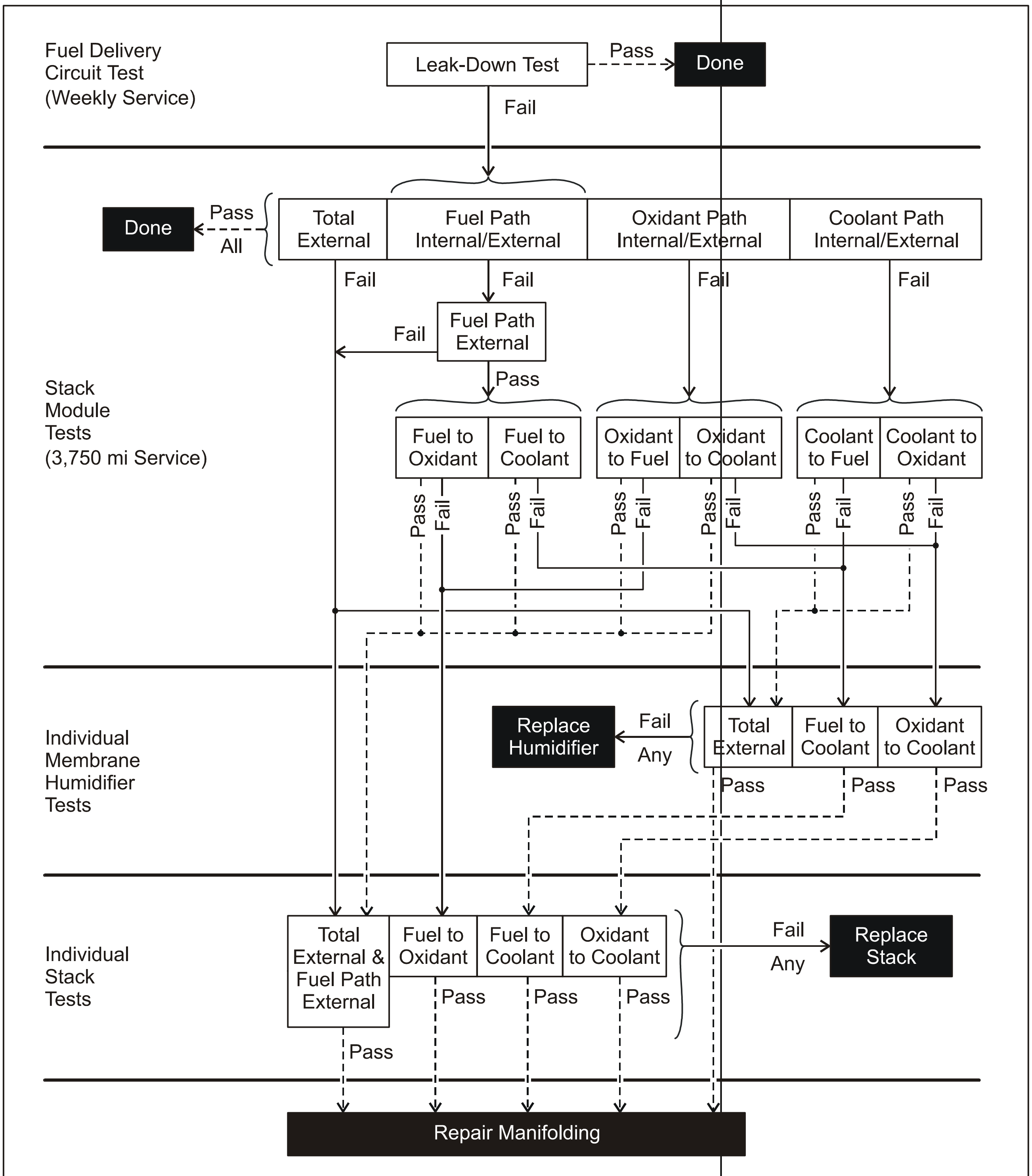


Figure 7-17 Typical Leak Test Sequence Flowchart

Key Points & Notes

Leak Test Logs

Leak test logs identify the test and summarize the resulting leak data. These records are important for assessing component behavior over time. Typical test logs are shown in Figures 7-18 and 7-19.

Bus/Module Leak Test Log

IDENTIFICATION			
Bus			
Hourmeter Reading		Technician	
Hubodometer Reading		Date	

LEAK-DOWN TEST	Test Pres. (psig)	Acceptance Threshold (psig)	Pressure After 1 Minute (psig)
External	7.0	> xxx	

STACK MODULE LEAK TESTS	Test Pres. (psig)	Acceptance Threshold (cc/min)	Module 1 (Roadside) (cc/min)	Module 2 (Curbside) (cc/min)
Total External	30.0	< xxx		
Fuel Path External	30.0	< xxx		
Fuel Path Internal/External	7.25	< xxx		
Fuel to Oxidant	7.25	< xxx		
Fuel to Coolant	7.25	< xxx		
Oxidant Path Internal/External	7.25	< xxx		
Oxidant to Fuel	7.25	< xxx		
Oxidant to Coolant	7.25	< xxx		
Coolant Path Internal/External	7.25	< xxx		
Coolant to Fuel	7.25	< xxx		
Coolant to Oxidant	7.25	< xxx		
			Disassembled: ☐ yes ☐ no	Disassembled: ☐ yes ☐ no

Figure 7-18 Typical Stack Module Leak Test Log

Key Points & Notes

Stack/Humidifier Leak Test Log

IDENTIFICATION			
Bus			
Hourmeter Reading		Technician	
Hubodometer Reading		Date	

Stack Identifier / Serial Number:						
STACK LEAK TESTS	**Test Pres. (psig)**	**Acceptance Threshold (cc/min)**	**(cc/min)**	**(cc/min)**	**(cc/min)**	**(cc/min)**
Total External	30.0	< xxx				
	7.25	< xxx				
Fuel Path External	30.0	< xxx				
Fuel to Oxidant	7.25	< xxx				
Fuel to Coolant	7.25	< xxx				
Oxidant to Coolant	7.25	< xxx				
		Replaced:	☐ yes ☐ no	☐ yes ☐ no	☐ yes ☐ no	☐ yes ☐ no

Humidifier Identifier / Serial Number:				
HUMIDIFIER LEAK TESTS	**Test Pres. (psig)**	**Acceptance Threshold (cc/min)**	**(cc/min)**	**(cc/min)**
Total External	30.0	< xxx		
Fuel to Water	7.25	< xxx		
Oxidant to Water	7.25	< xxx		
		Replaced:	☐ yes ☐ no	☐ yes ☐ no

Figure 7-19 Typical Stack/Humidifier Leak Test Log

Leak Test Box

Key Points & Notes

Leak tests require a source of regulated nitrogen to pressurize the flow paths under test. For some tests, the supply's flow rate must be measured. For other tests, measured and unmeasured nitrogen streams are required. For convenience, this flow distribution and control equipment is combined into a leak test box. A typical leak test box, linked to a nitrogen supply, is shown in Figure 7-20. The components shown have the following functions:

- The nitrogen supply consists of a standard T bottle of nitrogen with a minimum purity of 99.99%. The integral shutoff valve isolates the bottle contents.
- The nitrogen supply pressure regulator (4000-psig (275-barg) inlet; 100-120 psig (7-8 barg) outlet) with inlet and outlet pressure gauges provides first-stage regulation of the nitrogen pressure. The pressure regulator must be a *venting* type so that it can be bled to atmospheric conditions while the outlet flow path is blocked.
- The nitrogen supply tube mates with and passes nitrogen to the leak test box.
- The stack pressure regulator and gauge on the leak test box set the test pressure. An electronic pressure display could be used instead of the pressure gauge.
- The rotameter valve on the leak test box engages or bypasses the rotameters, depending on its position.
- The rotameter selection valves on the leak test box engage or disengage individual rotameters, depending on their positions.
- The rotameters on the leak test box each has a different flow range and measure the nitrogen flow. An electronic mass flow meter could be used instead of the rotameters.
- The metered supply tube mates with and passes the nitrogen from the rotameter flow path to the equipment under test.
- The unmetered supply tube mates with and passes nitrogen directly from the outlet of the stack pressure regulator to the equipment under test.

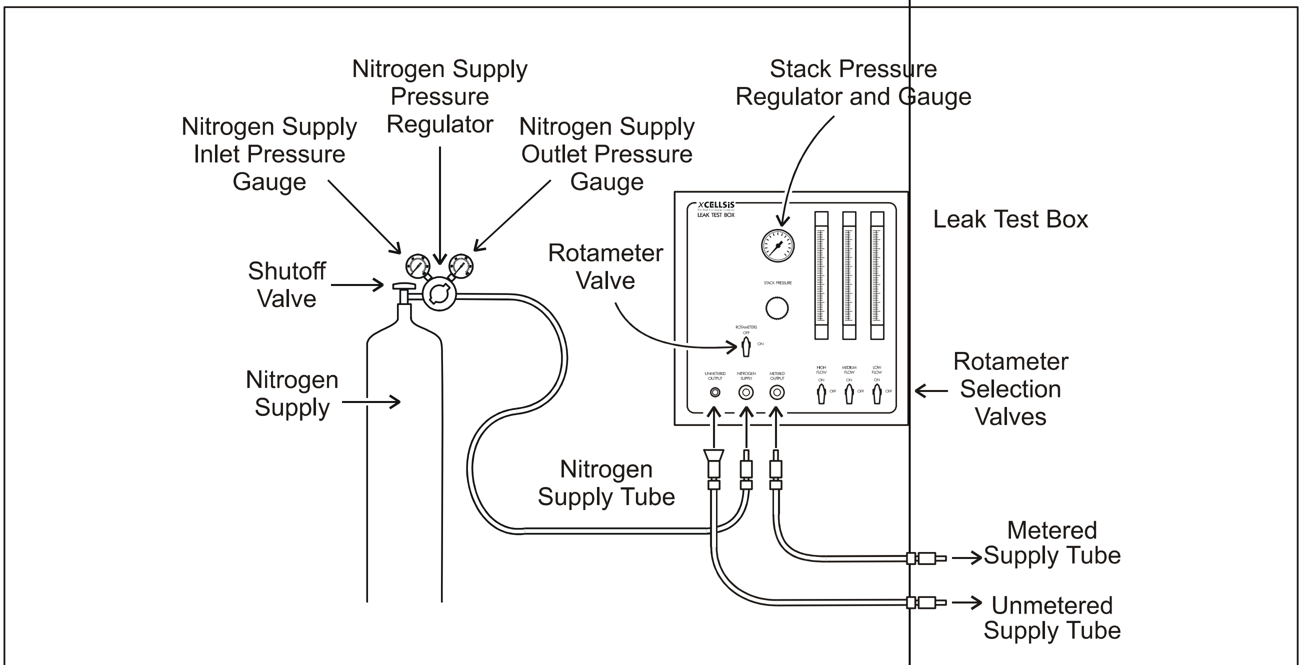


Figure 7-20 Typical Leak Test Box

Downstream of the metered and unmetered supply tubes, other special equipment is needed depending on the specific test. That equipment is described in the following sections.

When the leak test box uses rotameters instead of an electronic mass flow meter to measure the nitrogen flow, calibration curves are required to convert the rotameters readings to flow units of cc/min. These curves are derived through experiment using standard calibration procedures. Published calibration curves are valid only for the specific rotameter, pressure and gas composition indicated. A sample calibration curve is shown in Figure 7-21. When referring to a calibration curve:

- Locate the rotameter reading on the vertical axis of the graph.
- Draw a line horizontally from the rotameter reading until it intersects the calibration curve for the given test pressure.
- Draw a line vertically downwards from the intersection to the horizontal axis of the graph.
- Read the flow rate in cc/min off the horizontal axis.

Rotameters and mass flow meters must be calibrated regularly to maintain test accuracy.

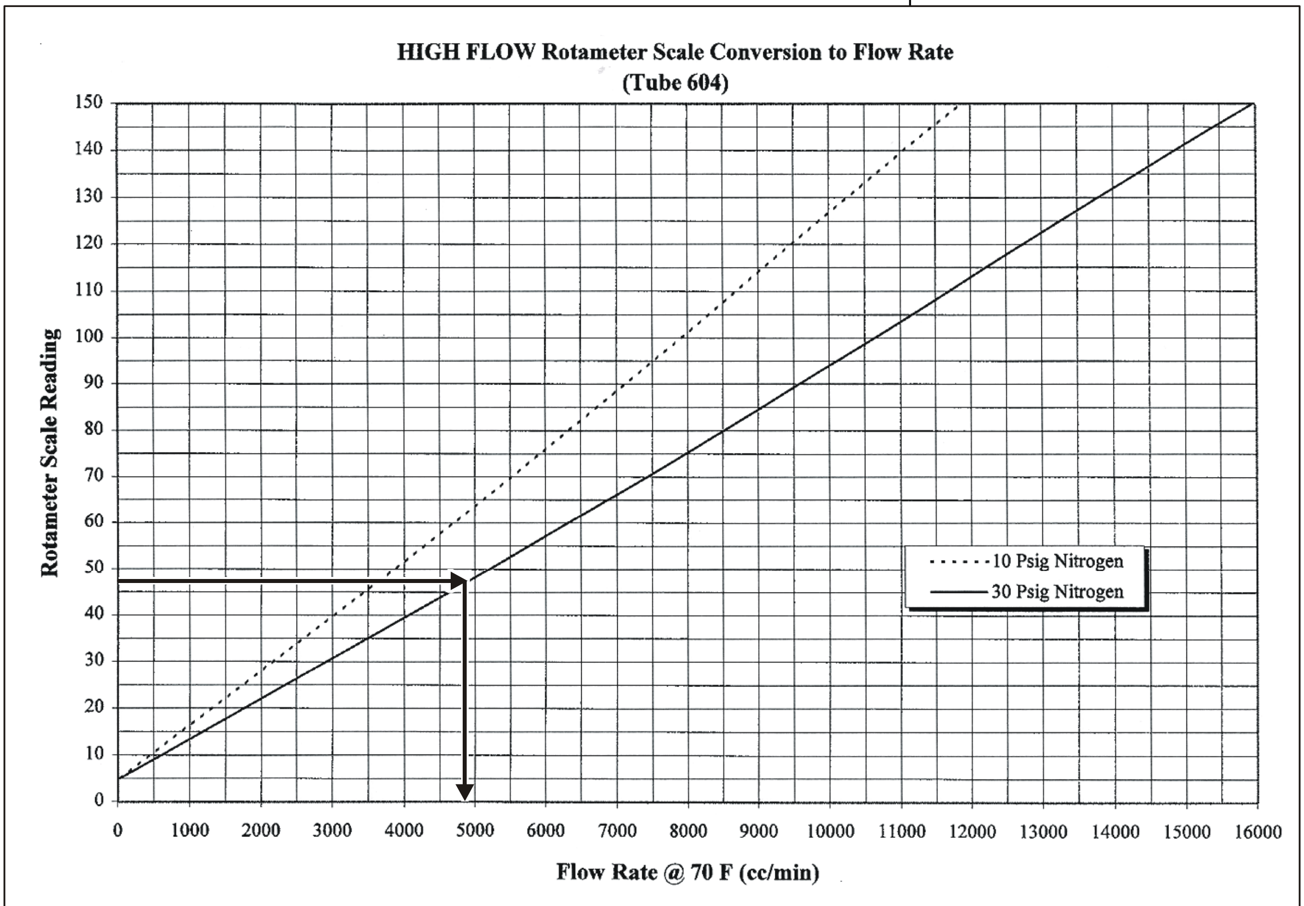


Figure 7-21 Typical Rotameter Calibration Curve

7.4.7.1 Leak-Down Test

The leak-down test indicates the presence of leaks within any part of the fuel delivery circuit by pressurizing the circuit and measuring the pressure drop over time.

The fuel delivery circuit is normally vented to atmosphere by way of the purge line whenever the engine is off. In order to pressurize this circuit, isolate it by closing the purge valve. You can then apply pressure through a pressurization port incorporated into the circuit.

Typical leak-down test equipment is illustrated in Figure 7-22 and must include the following:

- a nitrogen supply, leak test box, and metered supply tube as described above
- an extension tube with digital manometer
- two stack module blanking plates
- a stopwatch

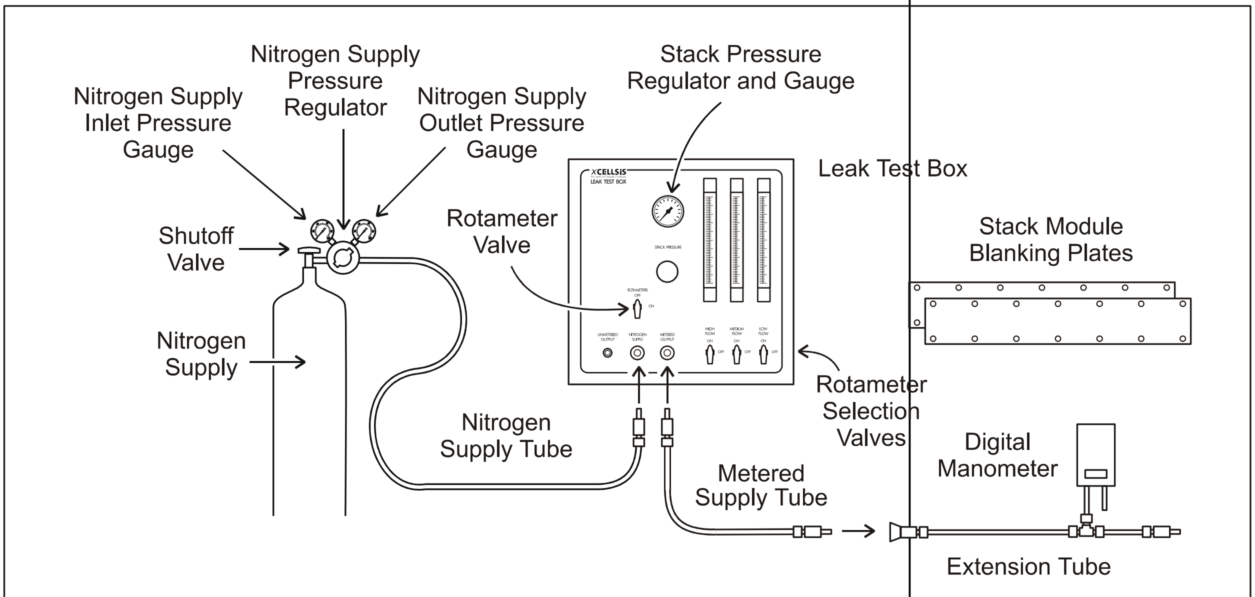


Figure 7-22 Typical Leak-Down Test Equipment

Prepare to test:

1. Ensure the fuel cell engine is warm and off. If the engine is not warm, misleading results may occur since some sealing surfaces may not have fully sealed.
2. Remove the cap from the bus' pressurization port and connect the test equipment as illustrated in Figure 7-23.

Prepare the test equipment:

3. Set the rotameter selection valves off and the rotameter valve on; this stops all flow from the metered supply tube.
4. Open the nitrogen supply shutoff valve and adjust the nitrogen supply and stack pressure regulators until the stack pressure gauge indicates 7.0 psig (0.5 barg).

Pressurize the circuit:

5. Close the bus purge solenoid valve. This valve is normally open whenever the engine is off. Consequently, the valve must be closed using some specific sequence of switches on the side console and/or engine compartment that has been programmed into the control system. Listen for the clicking sound of the solenoid valve closing.

Key Points & Notes

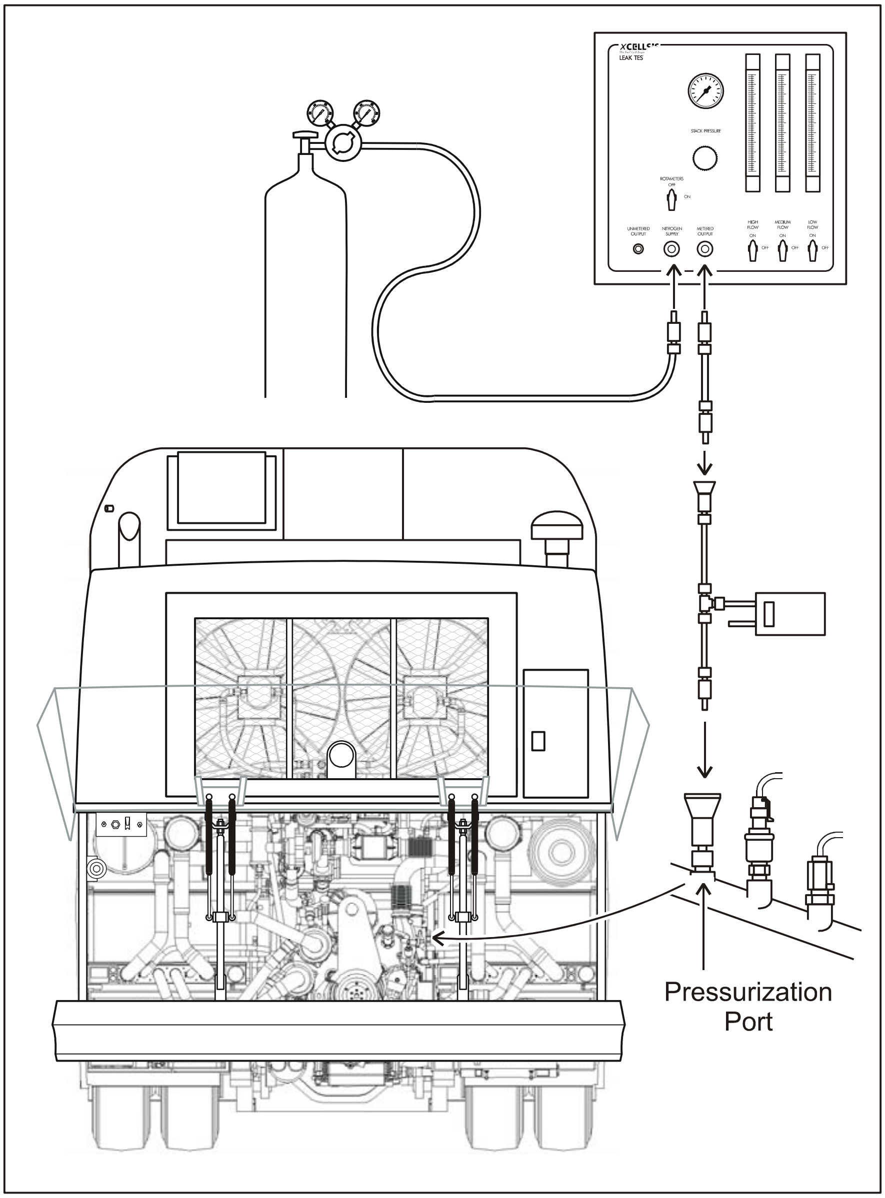


Figure 7-23 Leak-Down Test

6. Pressurize the fuel circuit by turning the rotameter valve off. This allows nitrogen to flow into the fuel delivery circuit.

7. Use a leak detection solution to confirm that no leaks exist on the leak test equipment.

8. Adjust the stack pressure regulator as required until the digital manometer indicates *7.0 psig (0.5 barg)*.

This pressure acts on one internal flow path only and causes a differential pressure across the fuel cell stack membranes. **Never exceed the test pressure. Excessive pressure may cause fuel cell stack damage.**

Key Points & Notes

9. Turn the rotameter valve on and re-read the digital manometer accurately.

Assess the results:

10. Allow one minute to pass and re-read the manometer. Record the results on the leak test log:

    a) If the pressure remains higher than the amount indicated on the test log, no further action is required.

    b) If the pressure drops to less than the amount indicated on the test log, there is an excessive leak or leaks in the fuel delivery circuit, plumbing, or the stack modules. To eliminate any leaks within the fuel delivery circuit:

        - Depressurize the test equipment, drain the stack modules, disconnect the stack module connections, and attach a blanking plate to both sides of the exposed connections. This isolates the fuel delivery circuit from the stack modules.
        - Repeat the leak test and apply a leak detection agent on every fitting and component within the fuel delivery circuit. Use a hand-held leak detector to probe the hydrogen diffuser: leaked hydrogen within the hydrogen diffuser indicates that the purge solenoid valve is leaking. Tighten any leaking fittings and/or replace leaking components and repeat the test as required until all leaks are eliminated.
        - Remove the blanking plates, re-attach the stack modules, and repeat the test.

11. Refer to the leak test sequence flowchart for additional actions.

If no further tests are required:

12. Depressurize the test equipment and close the nitrogen supply shutoff valve.

13. Open the purge solenoid valve using the specific sequence of switches defined by the bus manufacturer.

14. Disassemble the test equipment.

7.4.7.2 External Leak Test (and Variations)

Key Points & Notes

The *external leak test* quantifies the *total* amount of leakage from *all* flow paths (fuel, oxidant and coolant) to *atmosphere*. Variations of this test include the *individual internal/external leak test*, which measures the leakage flow from an *individual* flow path to *atmosphere and the other internal flow paths*, and the *individual external leak test* which measures the leakage flow from an *individual* flow path to *atmosphere only*. These tests can be applied to stack modules, individual stacks, or individual membrane humidifiers.

In each test, pressurized nitrogen is supplied to one or more terminated flow paths and the amount of nitrogen flow is measured directly. Since the flow paths are terminated, all nitrogen flow is the direct result of leakage. These tests are *upstream* tests, since the leakage is measured in terms of the dry nitrogen flowing through the leak test box upstream of the equipment under test.

Typical external leak test equipment is illustrated in Figure 7-24 and must include the following:

- a nitrogen supply, leak test box, and metered and un-metered supply tubes as described above
- two stack module leak test adapters (with non-venting quick-connection fittings)
- six stack/humidifier leak test adapters (with non-venting quick-connection fittings)
- four open (venting) stems (for quick-connection fittings)
- two linkage tubes (to mate with quick-connection fittings)
- two discharge tubes with 2-way valve (to mate with quick-connection fittings)

Key Points & Notes

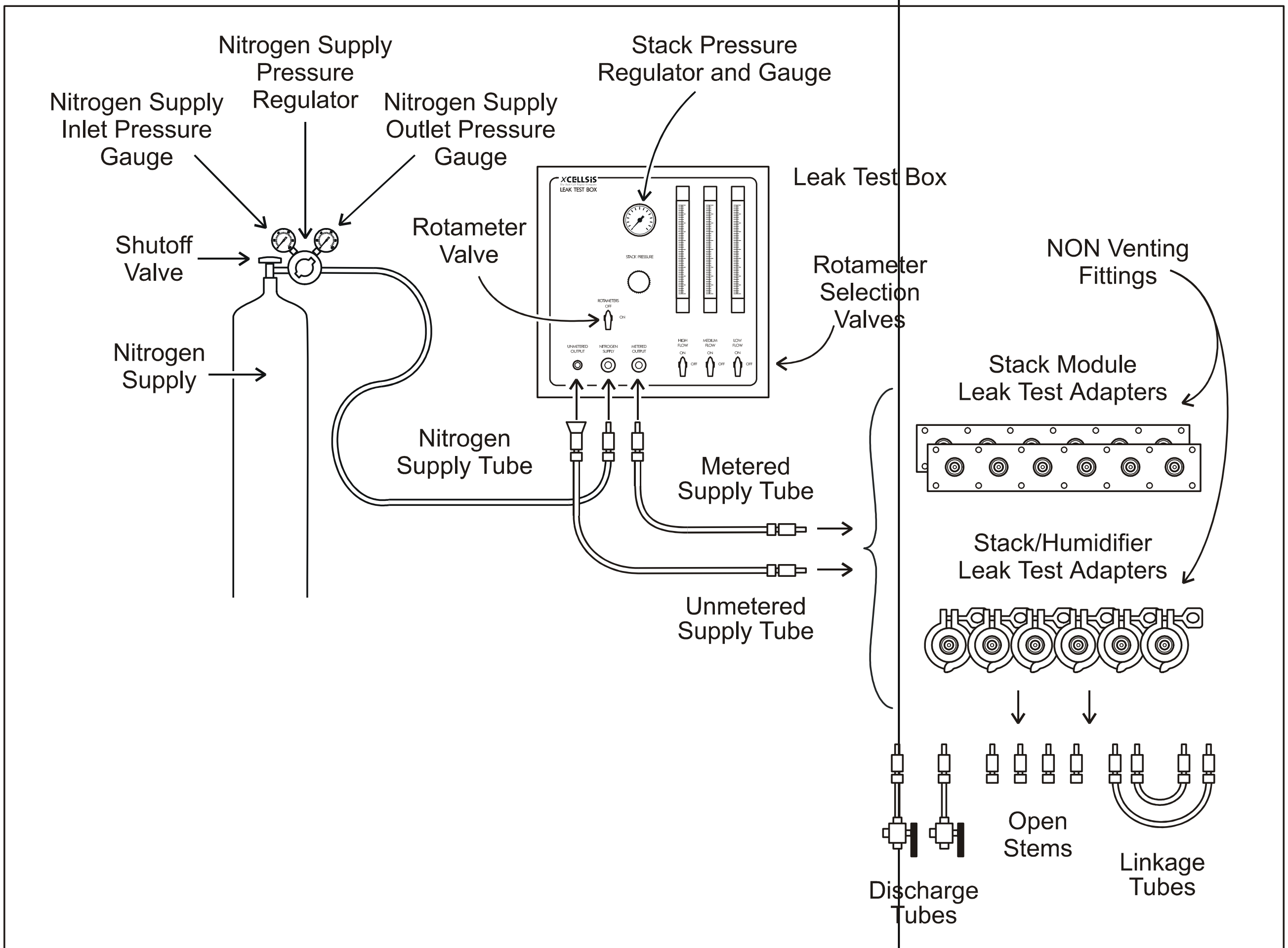


Figure 7-24 Typical External Leak Test Equipment

Total External Leak Test

In the total external leak test, all flow paths are linked together, terminated and pressurized. Since all internal circuits are pressurized together, all leakage flow must pass into the atmosphere.

Prepare to test:

1. Ensure the fuel cell engine is off.
2. When performing stack module tests, drain the modules, disconnect the module connections, and attach the stack module leak test adapter. When performing stack or humidifier tests, remove the component and attach the stack/humidifier leak test adapters.
3. Connect the test equipment as illustrated in Figure 7-25.

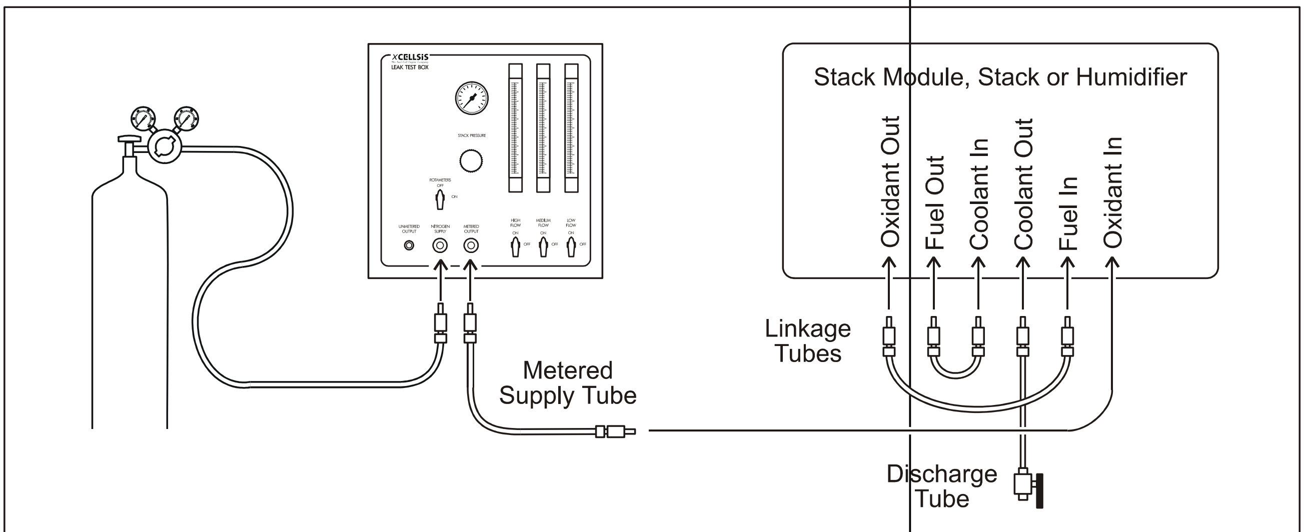


Figure 7-25 Typical Individual Internal/External Leak Test Equipment

Prepare the test equipment:

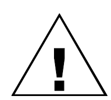
4. Set the rotameter selection valves off and the rotameter valve on; this stops all flow from the metered supply tube.

5. Open the nitrogen supply shutoff valve and adjust the nitrogen supply and stack pressure regulators until the stack pressure gauge indicates *30.0 psig (2.07 barg)*. As this pressure acts on all internal flow paths, a differential pressure across the internal membranes cannot develop.

Pressurize the circuit:

6. Turn the high flow rotameter selection valve on. This allows nitrogen to flow into the equipment under test. Allow the flow paths to pressurize until the flow indicated on the rotameter stabilizes.

7. Use a leak detection solution to confirm that no leaks exist on the leak test equipment. **Do not allow leak detection solution to contact the fuel cells or humidifier plates.**



8. Read the flow rate indicated on the rotameter: if the flow rate is too small to read accurately on the rotameter, use the rotameter selection valves to select the medium flow or low flow rotameters as required.

Complete:

9. Turn all three rotameter selection valves off.

10. Slowly open the 2-way valve on the discharge tube to depressurize the equipment under test.

Assess:

11. Convert the rotameter flow readings to units of cc/min using the published rotameter calibration curves. Record the results on the leak test log:
    a) If the flow rate is less than the amount indicated on the test log, no further action is required.
    b) If the flow rate is greater than the amount indicated on the test log, there is an excessive leak within the component under tested.
12. Refer to the leak test sequence flowchart for additional actions.

If no further tests are required:

13. Depressurize the test equipment and close the nitrogen supply shutoff valve.
14. Disassemble the test equipment.

Individual Internal/External Leak Test

In the individual internal/external leak test, one flow path (fuel, oxidant or coolant) is terminated and pressurized. Leakage gas can therefore pass from the pressurized circuit into one of the other flow paths or to the atmosphere.

This test is performed in an identical manner to the external leak with the following differences:

- Connect the test equipment as in Figure 7-26. The figure illustrates the test setup for the fuel path; if testing a different flow path the setup is similar: plumb the metered supply tube to the flow path outlet and the discharge tube to the flow path inlet. Add open stems to all other ports.
- Pressurize the flow path to *7.25 psig (0.5 barg)*, not 30.0 psig (2.07 barg).

This pressure acts on one internal flow path only and causes a differential pressure across the fuel cell stack membranes. **Never exceed the test pressure. Excessive pressure may cause fuel cell stack damage.**

Key Points & Notes

Units of "ml" and "cc" are equivalent.

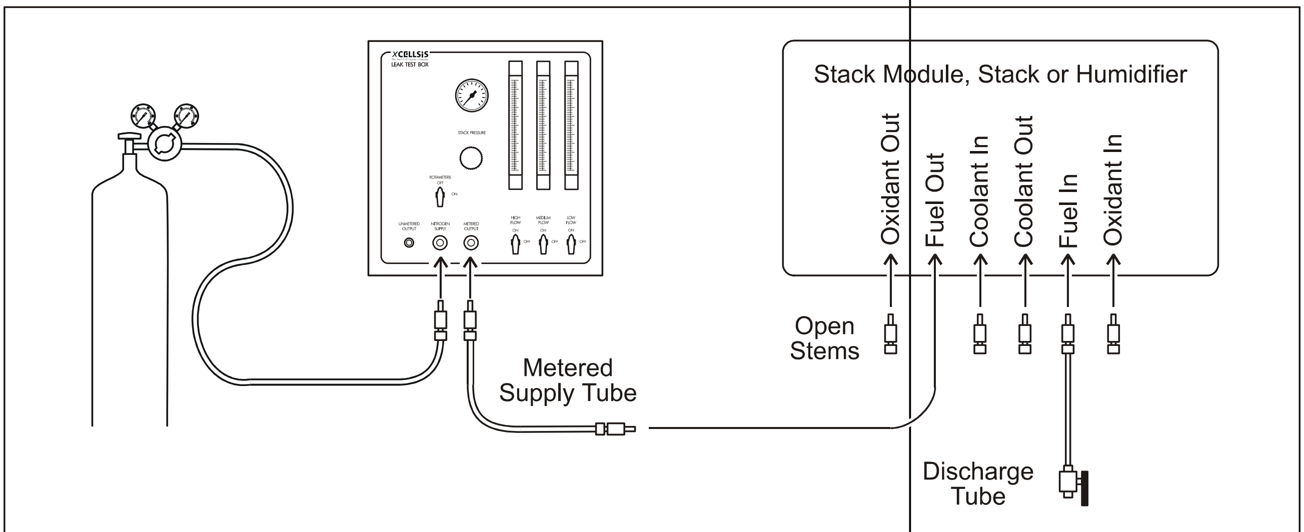


Figure 7-26 Fuel Internal/External Leak Test

Individual External Leak Test

In the individual external leak test, one flow path (fuel, oxidant or coolant) is terminated and pressurized while the other two flow paths are linked together, terminated and pressurized using a separate, unmetered gas stream. Leakage gas can therefore pass from the pressurized circuit only to the atmosphere since no differential pressure exists between the tested and untested flow paths.

This test is performed in an identical manner to the external leak with the following differences:

- Connect the test equipment as in Figure 7-27. The figure illustrates the test setup for the fuel path; if testing a different flow path the setup is similar: plumb the metered supply tube to the flow path outlet and the discharge tube to the flow path inlet. Plumb the unmetered supply tube to the outlet of either of the other two flow paths, link the two flow paths using a linkage tube, and terminate the remaining port with a discharge tube.
- Pressurize the flow path to *30.0 psig (2.07 barg)*, not 7.25 psig (0.5 barg). Since this pressure acts on all internal flow paths, a differential pressure across the internal membranes cannot develop.
- When venting, open both discharge valves in tandem to avoid a differential pressure within the equipment under test.

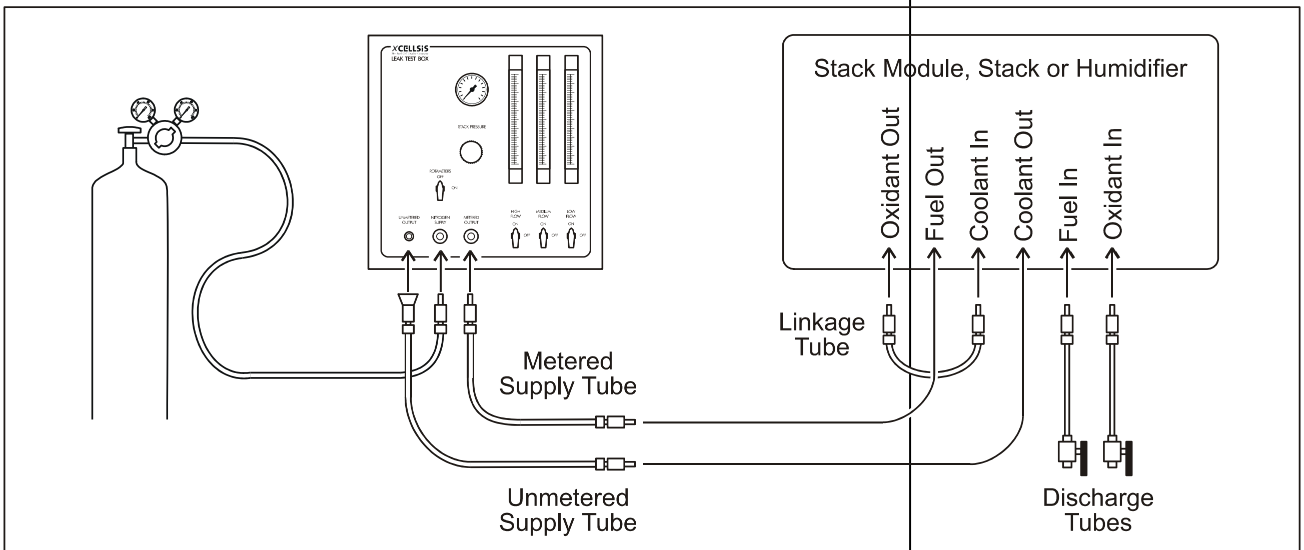


Figure 7-27 Fuel External Leak Test

7.4.7.3 Transfer Leak Tests

The transfer leak tests quantify the amount of leakage from *one flow path* (fuel, oxidant or coolant) into *another flow path.* These tests can be applied to stack modules, individual stacks, or individual membrane humidifiers. Six possible transfer leak test combinations exist:

- Fuel to oxidant
- Fuel to coolant
- Oxidant to fuel
- Oxidant to coolant
- Coolant to fuel
- Coolant to oxidant

At first glance, transfer tests that comprise complementary pairs (fuel to oxidant and oxidant to fuel) should produce the same results and therefore seem redundant. Although this is usually true, the process of pressurizing one path as opposed to the other can sometimes affect the internal seals in different ways, leading to different results. For this reason both tests are often performed.

In each transfer test, pressurized nitrogen is supplied to a single terminated flow path and is allowed to leak to another flow path and the ambient environment. The specific leakage coming out of the other flow path is then measured using volumetric displacement techniques. The remaining flow

Key Points & Notes

path plays no part in the test and is vented to atmosphere so that pressure cannot build up within it.

Transfer tests are *downstream* tests, since the leakage is measured in terms of the nitrogen flowing out of a flow path, downstream of the equipment under test. The nitrogen flow measurement equipment on the leak test box is not used.

Downstream test measurements are complicated by the fact that stacks and humidifiers are fundamentally wet so that some water always passes out of a flow path in conjunction with the leakage gas. The resulting wet gas stream cannot be measured using rotameters or electronic mass flow meters and the water content must be excluded from the leakage calculation.

For this reason, leakage measurements are made using a water-filled graduated cylinder assembly. This assembly consists of a pair of nested, graduated cylinders, with the inner cylinder inverted. At the start of the test, both cylinders are completely full of water. As the wet gas is introduced into the inner cylinder, the water combines with the water already there, and the gas accumulates at the top of the cylinder, causing it to rise. The leakage gas can therefore be obtained directly by measuring the quantity of gas that accumulates within the inner cylinder over a period of time.

Typical transfer leak test equipment is illustrated in Figure 7-28 and must include the following:

- a nitrogen supply, leak test box, and metered supply tubes as described above
- two stack module leak test adapters (with non-venting quick-connection fittings)
- six stack/humidifier leak test adapters (with non-venting quick-connection fittings)
- two open (venting) stems (for quick-connection fittings)
- one discharge tube with 2-way valve (to mate with quick-connection fittings)
- one vent tube with 3-way vent valve (to mate with quick-connection fittings)
- graduated cylinder assembly (water-filled)
- stopwatch

Key Points & Notes

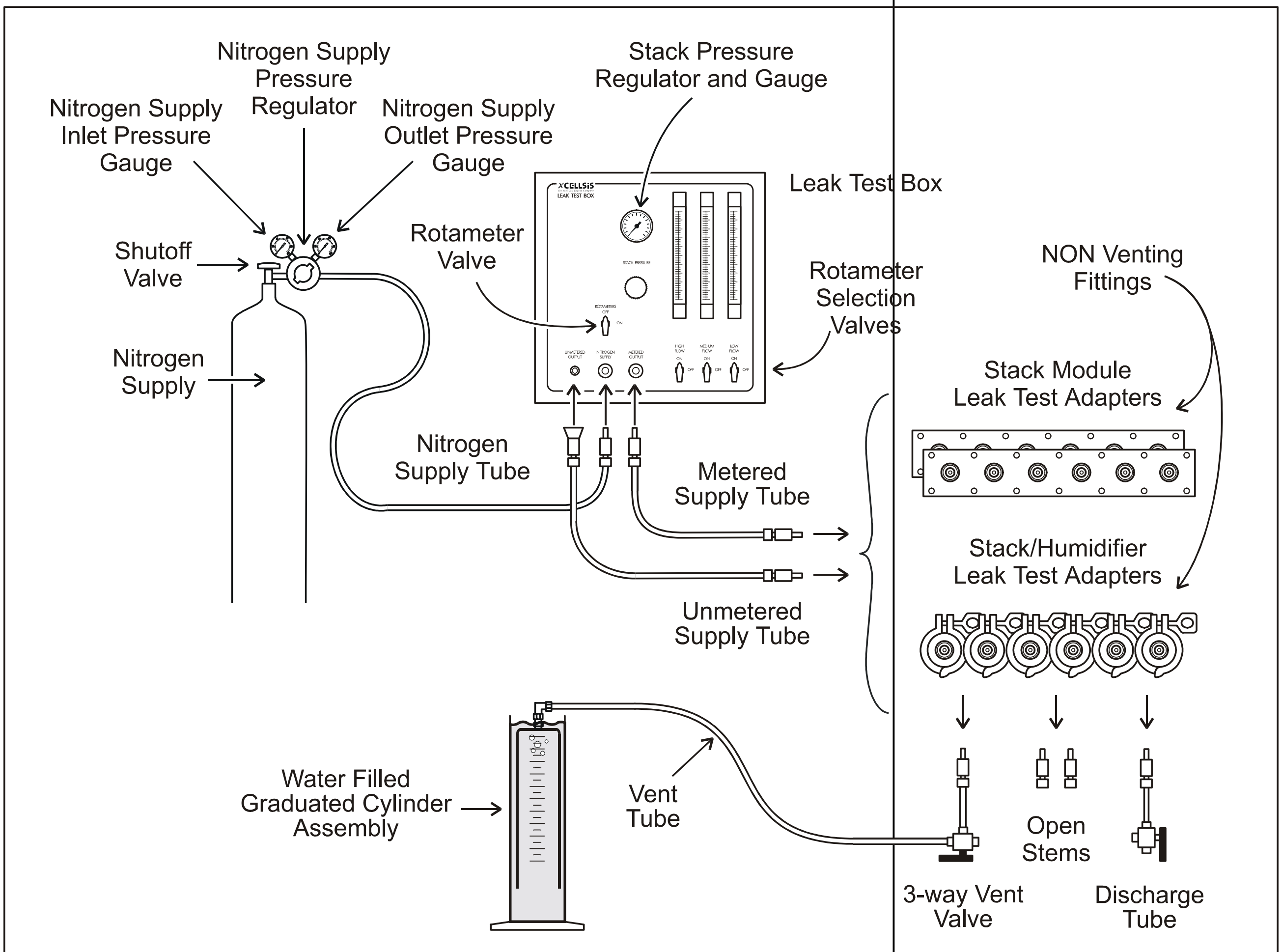


Figure 7-28 Typical Transfer Leak Test Equipment

Prepare to test:

1. Ensure the fuel cell engine is off.
2. When performing stack module tests, drain the modules, disconnect the module connections, and attach the stack module leak test adapter. When performing stack or humidifier tests, remove the component and attach the stack/humidifier leak test adapters.
3. Connect the test equipment as in Figure 7-29. The figure illustrates the test setup for the fuel to oxidant test; if testing a different combination of flow paths the setup is similar: plumb the metered supply tube to the source flow path outlet and the discharge tube to the source flow path inlet. Attach the vent tube and water-filled graduated cylinder assembly to the measured flow path inlet and leave the outlet closed (by virtue of the non-venting

Key Points & Notes

quick-connection fitting). Add open stems to the remaining two ports.

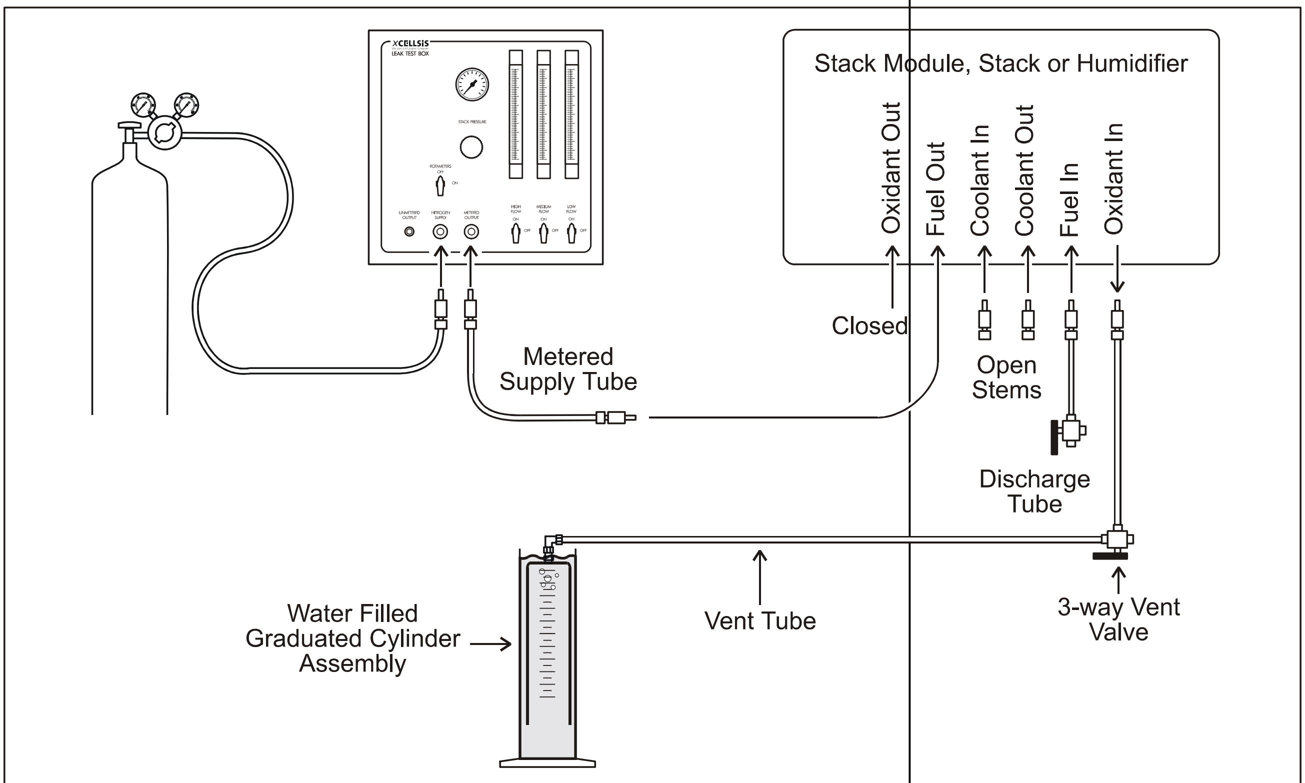


Figure 7-29 Fuel to Oxidant Transfer Leak Test

Prepare the test equipment:

4. Detach the vent tube from the leak test adapter and turn the vent valve so that any air trapped in the inner graduated cylinder expels to atmosphere. Re-attach the vent tube.

5. Set the rotameter selection valves off and the rotameter valve on; this stops all flow from the metered supply tube.

6. Open the nitrogen supply shutoff valve and adjust the nitrogen supply and stack pressure regulators until the stack pressure gauge indicates *7.25 psig (0.5 barg).*

This pressure acts on one internal flow path only and causes a differential pressure across the fuel cell stack membranes. **Never exceed the test pressure. Excessive pressure may cause fuel cell stack damage.**

Pressurize the circuit:

7. Turn the rotameter valve off. This allows nitrogen to flow into the equipment under test.

Key Points & Notes

Key Points & Notes

8. Use a leak detection solution to confirm that no leaks exist on the leak test equipment. **Never allow leak detection solution to contact the fuel cells or humidifier plates.**

9. Set the vent valve position so that any leakage gas expels to atmosphere.

10. Once a steady state stream of gas is established, simultaneously turn the vent valve so that the leakage gas passes into the graduated cylinder assembly and begin timing.

11. Continue collecting gas until two minutes has passed, then simultaneously turn the vent valve so that the leakage gas expels to the atmosphere and stop timing.

12. Read the displaced volume in the *inner* graduated cylinder and calculate the flow rate as follows:

$$\text{Flow rate [cc / min]} = \left(\frac{\text{Volume [ml]}}{\text{Time [min]}} \right)$$

Complete:

13. Turn the rotameter valve on. This interrupts the nitrogen flow.

14. Slowly open the 2-way valve on the discharge tube to depressurize the equipment under test.

Assess:

15. Record the results on the leak test log:

    a) If the flow rate is less than the amount indicated on the test log, no further action is required.

    b) If the flow rate is greater than the amount indicated on the test log, there is an excessive leak within the flow path tested.

16. Refer to the leak test sequence flowchart for additional actions.

If no further tests are required:

17. Depressurize the test equipment and close the nitrogen supply shutoff valve.

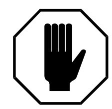
18. Disassemble the test equipment.

7.4.8 Power Cable Connection Checks

Key Points & Notes

Power cables link the fuel cell stacks to the inverter, and the inverter to the drive motor and dump choppers. If any of these power cables are not attached during operation of the fuel cell stacks, a very large charge can result with no discharge path presenting a serious shock hazard.

The power cable connection checks consist of checking by hand that each of the power cable connections are tightly connected. Some connectors have a molded arrow on their ends that indicate the location of its locking pin. All cables tighten clockwise.



When tightening cables, ensure that they do not spring back to their original position. Take care to avoid inadvertently loosening connections in this way.

7.4.9 Glycol System Integrity Test

The glycol system integrity test ensures that no leakage exists between the air and coolant circuits. The air and stack coolant streams come into close contact within the humidifiers and the stacks. The air and bus coolant streams come into close contact within the intercooler, aftercooler, and condenser. Any glycol leak into the air stream could cause serious fuel cell damage as glycol can poison the fuel cell catalyst.

The glycol system integrity test is similar to a conventional radiator leakage test and consists of pressurizing each coolant path in turn and measuring any pressure drop over time. Test equipment typically consists of a standard radiator system pressure tester, an external digital manometer, and a stopwatch. The digital manometer is more accurate than the pressure gauge that normally accompanies the pressure tester.

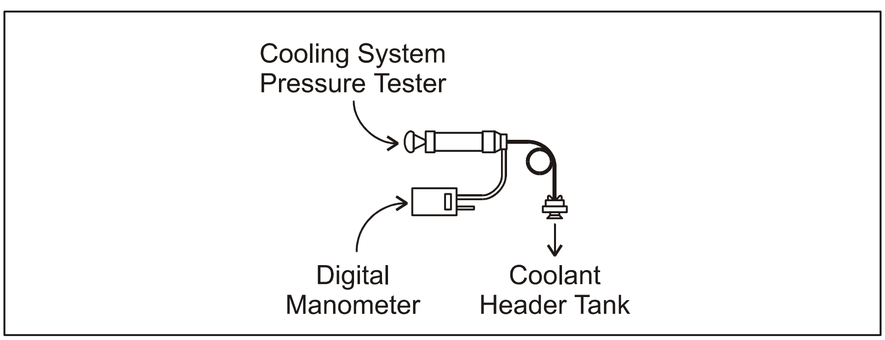


Figure 7-30 Typical Glycol Integrity Test Equipment

Key Points & Notes

To perform the glycol system integrity test, the stack and bus coolant circuits must be fully charged and the engine must be off. The system pressure tester is applied, in turn, to the stack and bus coolant header tank fill ports. Ensure that the tester makes a fully sealed connection with the fill port. Each circuit is pressurized using the tester pump until the manometer indicates 16 psig (1.1 barg). After 20 minutes, the manometer pressure must be re-assessed:

- If the pressure remains greater than 15.5 psig (1.07 barg), no action is required.
- If the pressure drops to less than 15.5 psig (1.07 barg), inspect all fittings and components associated with that coolant circuit (including the pressure tester connection) for leaks: Tighten any leaking fittings and repeat the test. If no leak can be found but the pressure loss persists, contact the bus manufacturer. Do not operate the bus until authorized to do so by the bus manufacturer.

Test results are normally recorded on a test log that indicates the date, the hourmeter and odometer readings and the measured pressure drop.

7.4.10 Dump Chopper Resistance Check

A dump chopper is essentially a resistor in contact with a coolant stream. This resistor converts electrical power into heat either during startup (to hasten warmup) or during situations where excess power must be “dumped”. The dump chopper is typically installed in the stack coolant circuit, but some buses include a second dump chopper in the bus or HVAC coolant circuits.

The dump chopper resistor is part of an assembly that may contain other fluid flow control equipment. The resistor itself consists of a series of individual resistive elements that are wired together in parallel. Each element has the same resistance so that the power absorption is shared equally. If an element burns out (becomes an open circuit), the net parallel resistance of the remaining elements increases.

The dump chopper resistance check uses an ohmmeter to confirm that the overall resistance is within specifications. The resistance is measured directly across the entire resistor by removing the power cables from each dump chopper assembly with the engine off. Moisture within the electrical portion of the dump chopper can affect resistance values slightly.

Key Points & Notes

Resistance specifications are unique to each bus design. The low end of the acceptable resistance range represents the expected value if all elements are functional; lower resistances indicate that the resistor is completely short-circuited. The high end of the acceptable resistance range represents the expected value if at most two elements have burned out; higher resistance indicate that an unacceptable number of elements are no longer functional. If measurements are within the specified range, no further action is required. If the measurements are outside the specified range, individual resistor elements must be replaced as required.

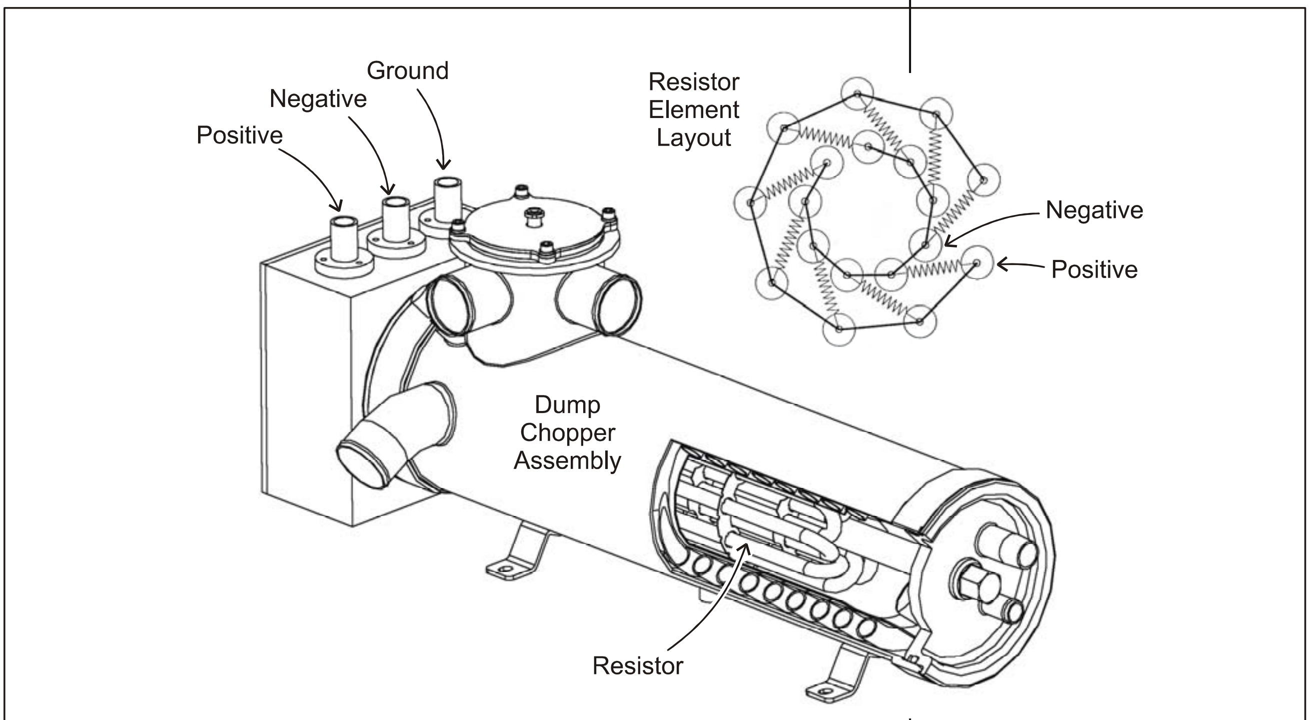


Figure 7-31 Dump Chopper

7.5 Fuel System Procedures

Key Points & Notes

Fuel system procedures pertain to routine service that is common to that found on CNG or hydrogen powered internal combustion engine buses.

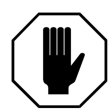
7.5.1 Fuel Circuit Leak Tests

Fuel circuit leak tests ensure that fuel is not leaking from any part of the system. These tests augment the use of the on-board leak detection system to mitigate potential fire hazards.

Hydrogen is present in three circuits of different pressures:

- high-pressure circuit at high pressure up to 3600 psig (250 barg)
- motive-pressure circuit at intermediate pressure of 178 psig (12 barg)
- fuel delivery circuit at the low-pressure of up to 30 psig (2 barg)

Leak tests are conducted using a hand-held leak detector and leak detection solution as described in Section 6.1.1.



Never tighten any fitting while it is under pressure; doing so could cause the fitting to shatter with serious personal injury. Never loosen a fitting while under pressure; doing so may cause the fitting or component to be propelled with extreme force.

High-Pressure Circuit Leak Test

The high-pressure circuit is always pressurized so that it can be tested for leaks while the engine is off. However, to obtain meaningful results, the leak test must be performed when the circuit contains at least half of its service pressure i.e. 1800 psig (125 barg). Inspect fittings and components for damage when performing the leak test.

To test for leaks, apply a leak detection solution to every fitting, connection and component, including:

- semi-spherical ends of cylinders, including end bosses
- pressure relief devices and valves
- shutoff, vent and other hand valves
- solenoid, check and excess flow valves
- hydrogen particulate filter
- fueling receptacle

- pressure and temperature transducers, switches and gauges

If a leak is detected, vent the high-pressure circuit to 10 psig (0.7 barg) (and cylinder, if applicable), tighten leaking fittings, and repeat the test. **Do not *tighten* any fitting while it is under pressure. Doing so could cause the fitting to shatter with serious potential injury.**

Replace any component or fitting that continues to leak despite tightening. **Do not *loosen* any fitting on the high-pressure circuit or any cylinder without first venting the high-pressure circuit to atmospheric pressure. Vent individual cylinders prior to loosening any fitting or component associated with that cylinder. Do not loosen or adjust cylinder solenoid valves in any way.**

Cylinders that have been vented to atmospheric pressure and exposed to air require nitrogen and hydrogen purges before fueling.

After repairing a leak, pressurize the component and repeat the leak test.

Motive-pressure Circuit Leak Test

The motive-pressure circuit is only pressurized during engine operation, so the engine must be on to test for leaks. Inspect fittings and components for damage when performing the leak test.

To test for leaks, apply a leak detection solution to every fitting, connection and component, including:

- motive pressure regulators or regulator assemblies
- fuel shutoff and other hand valves
- solenoid valves
- pressure transducers, switches and gauges

If a leak is detected, shut down the engine to vent the motive-pressure circuit, tighten the leaking fittings, and repeat the test. **Do not *tighten* any fitting while it is under pressure. Doing so could cause the fitting to shatter with serious potential injury.**

Replace any components or fittings that continue to leak despite tightening. **Do not *loosen* any fittings on the motive-pressure circuit without first shutting down the engine to vent the fuel.**

Key Points & Notes

The motive-pressure circuit is connected to the high-pressure circuit at the motive pressure regulator. Therefore, the regulator (or its assembly) is always exposed to high-pressure fuel. **Do not service the motive pressure regulator without first venting the high-pressure circuit.**

Fuel Delivery Circuit Leak Test

The fuel delivery circuit is only pressurized during engine operation so the engine must be on to test for leaks. Inspect fittings and components for damage when performing the leak test.

To test for leaks, use a hand-held leak detector to probe every fitting, connection and component, including:

- pressure regulator
- ejector
- contact humidifiers
- hydrogen/water separator
- filters
- water traps
- burst disk
- solenoid valves
- check valves
- stack module interface hoses
- pressure, temperature and level transducers, switches and gauges

If a leak is evident using the hand-held leak detector, apply a leak detection solution to localize it.

If a leak is detected, shut down the engine to vent the fuel delivery circuit, tighten the leaking fittings, and repeat the test. Do not *tighten* any fitting while it is under pressure. Doing so could cause the fitting to shatter with serious potential injury.

Replace any components or fittings that continue to leak despite tightening. Do not *loosen* any fittings on the fuel delivery circuit without first shutting down the engine to vent the fuel.

If a leak appears to originate within the fuel cell stacks, perform the fuel cell engine leak tests (Section 7.4.7).

7.5.2 Fuel System Inspections

Key Points & Notes

Fuel system inspections ensure the overall integrity and safety of the fuel system. Specific checks include vent cap inspections, component inspections, and fuel pressure transducer comparisons.

7.5.2.1 Vent Cap Inspections

Vent caps seal the end of gas pressure relief lines to prevent debris and water from getting in and clogging the line. Besides clogging the line, water can expand through freezing and damage the line or components.

Vent lines serve all three fuel circuits. The vent lines are linked to:

- each cylinder pressure relief device (two per cylinder)
- the motive-pressure circuit pressure relief valve
- the fuel delivery circuit burst disk

All hydrogen vents are at roof level. During a hydrogen release, the vent pressure is sufficient to blow the cap off the vent line.

The vent cap inspections consist of a visual confirmation that each vent cap is firmly installed, undamaged and unobstructed.

The vent caps associated with the pressure relief devices (PRD) and the motive-pressure relief valve should be completely sealed with silicone.

The burst disk vent cap should be screwed into place: do not attach the burst disk vent cap with silicone. A seal of silicone would result in pressure buildup within the line, and the consequent false trigger of the nearby pressure switch, resulting in alarm shutdown.

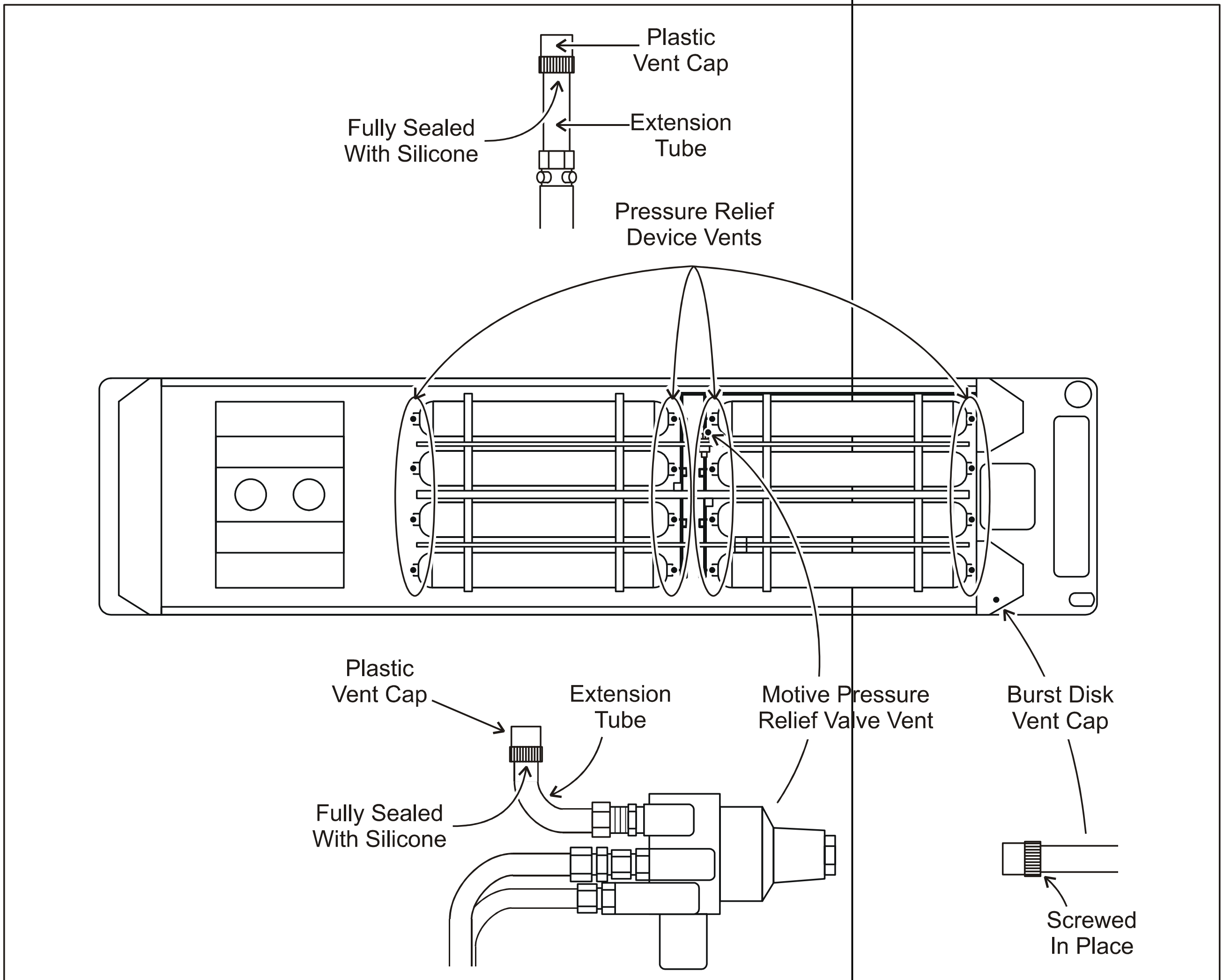
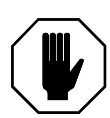


Figure 7-32 Typical Vent Cap Locations

Some vent caps include an extension tube to align the discharge point with holes in the canopy or to otherwise prevent obstruction. Alter these extension tubes if required to maintain alignment. For vent lines that protrude through holes in the canopy, confirm that each cap is located within the canopy hole, that it is protected by the hole, and that it does not stick out beyond the canopy surface.

If a vent cap is damaged or missing, check for water or dirt in the vent line and clean as required. Replace the cap as soon as possible. **Damaged, missing or incorrectly sealed vent caps can lead to pressure relief component failure.**



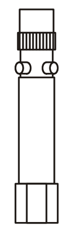
Key Points & Notes

7.5.2.2 Component Inspections

Component inspections apply to all components in the high-pressure, motive-pressure and fuel delivery circuits. Refer to Section 7.5.2 for a component inspection list.

Component inspections consist of a visual confirmation that no component shows signs of deformities or other damage. Check that all electrical connections to solenoid valves, transducers and pressure switches are tight and uncorroded. Wherever possible, check the security of electrical connections by hand.

Check specifically that pressure relief devices are not exuding their eutectic compound. To check, run your finger over each of the two protrusions; they should be flat or slightly concave. If not, the eutectic compound is starting to protrude and the PRD must be replaced. Confirm that all hand valve handles are tight.



Fuel cylinder inspections form a special class of component inspections and are described in detail in Section 7.5.6.

7.5.2.3 Fuel Pressure Indicator Readings Comparison

The fuel pressure within the cylinders and high-pressure circuit is normally measured using multiple pressure transducers or gauges. The pressure value is normally displayed at various locations on the bus, such as on a message display center, through the diagnostics interface, within the fueling box, or by other means. If any one of these indicators is faulty, you may get the false impression that the high-pressure circuit is depressurized (thereby permitting access) while it is not.

The fuel pressure indicator readings comparison consists of a visual confirmation that all indicators display approximately the same pressure, typically within 250 psi (17 bar). If the values do not coincide, the faulty indicator must be traced and replaced.

7.5.3 Hydrogen Particulate Filter Replacement

The hydrogen particulate filter collects any debris that may enter the high-pressure circuit during fueling. This filter impedes hydrogen flow as it clogs and therefore must be replaced periodically.

As with all high-pressure circuit maintenance, the circuit must be vented to atmospheric pressure prior to access although it is not necessary to vent any of the cylinders. To disassemble, unscrew the filter enclosure from the filter

Key Points & Notes

base. Inspect the retaining spring for damage and replace as required. Replace the filter element and ensure that it is oriented correctly prior to installation. Check the filter for leaks once the circuit is pressurized.

The used filter element and any accumulated material may provide useful diagnostic information when troubleshooting fuel storage system problems. Return this material to the bus manufacturer on their request.

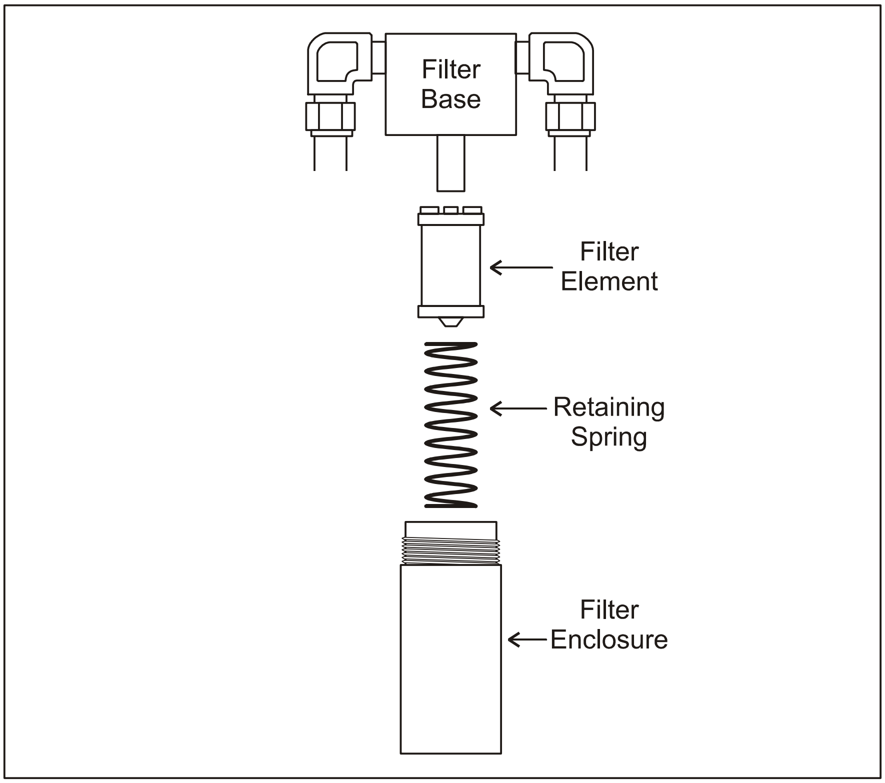


Figure 7-33 Typical Hydrogen Filter

7.5.4 Motive Pressure Regulator Solenoid Valve Check

The motive pressure regulator reduces the high pressure of the cylinders to an intermediate pressure during operation. This regulator is outfitted with a solenoid valve that isolates the fuel cell engine from the fuel storage system whenever the engine is off.

Upstream of the solenoid valve, pressure is retained when the engine is off. Downstream, pressure is vented when the engine is off. If the solenoid valve leaked while the engine is off, hydrogen would continue to vent through the inactive hydrogen diffuser, resulting in a potentially flammable mixture.

Key Points & Notes

The motive pressure solenoid valve check is a confirmation that all operating and non-operating pressures are correct. Incorrect values indicate solenoid valve leakage.

View the high and motive pressures while the engine is on:

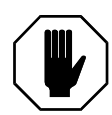
- The motive-pressure display should indicate 170 – 186 psig (11.5 – 12.5 barg).
- The high-pressure display should indicate the current fuel pressure within the hydrogen cylinders (varies between 300 psig (21 barg) when effectively empty, up to 3600 psig (250 barg) when fully fueled.)

Shutdown the engine and view the high and motive pressures:

- If the motive pressure drops to 0 psig/barg and the high pressure remains stable at the fuel pressure, the solenoid valve is not leaking and no further action is required.
- If the motive pressure does not drop to 0 psig or the high pressure is less than the fuel pressure (or is dropping), the solenoid is leaking and the pressure regulation assembly needs to be replaced. Confirm the leak using a portable hydrogen leak detector directed at the hydrogen diffuser.

7.5.5 Ground Integrity Check

The flow of hydrogen can result in static electricity buildup. This static can generate sparks and provide ignition to a flammable gas mixture. To eliminate this potential hazard, all *metal* hydrogen-containing equipment on the bus is thoroughly grounded.



Ground integrity is essential to hydrogen safety.

The ground integrity check consists of verifying by ohmmeter that all portions of the high-pressure, motive-pressure and fuel delivery circuits are grounded. Refer to Section 7.5.1 for a component list. This check proceeds by touching the first probe of the ohmmeter to a known ground point (such as the fueling grounding receptacle), and touching the second probe to the metal body of every component and length of tubing within the immediate vicinity. The meter should show continuity for each item.

Any reading other than continuity indicates a lack of grounding integrity. Once the ground integrity of a given component has been established, it can act as the new ground reference: in this way, the entire fuel system can inspected, incrementally moving farther away from the original ground reference at each step.

Concurrent with the continuity measurements, visually inspect all components and ground connections for corrosion, and check each ground connection by hand for tightness. Repair ground connections as required.

7.5.6 Fuel Cylinder Inspections

The fuel cylinders hold the majority of all the hydrogen on the bus, and are subject to the highest fuel pressures. To assure the safety of the cylinders, inspections of their installation and their external and internal surfaces are required.

7.5.6.1 Fuel Cylinder Installation Inspections

Fuel cylinder installation inspections consist of a visual confirmation that each cylinder is affixed to the bus roof in an appropriate manner. A typical fuel cylinder installation is shown in Figure 7-34.

To inspect the cylinder installation, check that:

- the surface of the installed cylinder is clear of all objects by at least $^3/_4$" (20 mm)
- the lines to the cylinder show no evidence of damage due to bus flexure or cylinder expansion
- water and other fluids can drain freely from the cylinder's position
- the label is clearly visible

To inspect the cylinder mounting bracket installation, check that:

- the cylinder mounting system allows the cylinder to expand and contract as the internal pressure fluctuates without causing the cylinder to be abraded
- the interface between the cylinder and the bracket is lined with a rubber pad to allow limited movement of the cylinder
- the rubbers pads are in place and in good condition
- the cylinder is firmly restrained
- the cylinder and brackets are firmly attached to the bus and do not permit rocking or other looseness
- the bolts that secure the brackets to the bus are present and tight

Key Points & Notes

Refer to the scope at the start of this manual for other courses offered by the College of the Desert pertating to high-pressure gas training and cylinder safety and certification training.

Key Points & Notes

- where brackets are bolted to sheet metal panels, washers with minimum 3" (76 mm) outside diameter are used
- the brackets are in good condition
- a $^{1}/_{2}$" SAE washer is used in conjunction with bracket bolts
- the clamp-down bolts that secure the cylinder to the mounting bracket are properly torqued to manufacturer's specifications.
- the metal straps do not touch the cylinder at any point
- the hardware, bolt and bus attachments do not exhibit severe corrosion or cracking

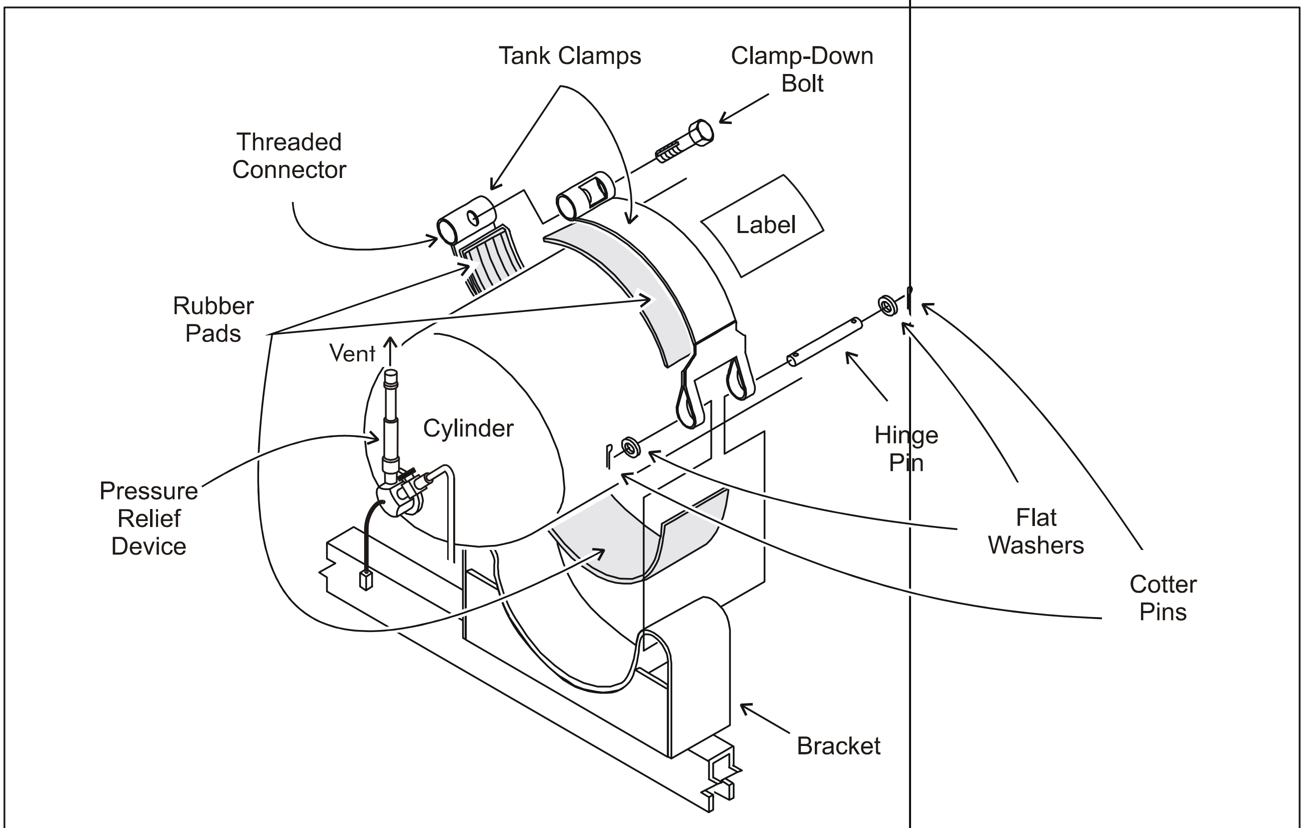


Figure 7-34 Typical Cylinder Installation

To inspect the cylinder pressure relief device installation, check that:

- all pressure relief devices are installed and are of a type approved by the bus manufacturer
- the pressure relief device vents pass without obstruction through holes in the roof canopies so as to vent external to the bus, are free of debris, and are capped (see Section 7.5.2.1)

Key Points & Notes

7.5.6.2 Fuel Cylinder External Inspections

Fuel cylinder external inspections consist of an assessment of any external damage on *all* cylinders.

Inspection Documentation

Cylinder external inspection records provide a permanent chronicle of cylinder history. Inspection results are normally recorded on a test log that indicates the date, the hourmeter and odometer readings, cylinder serial numbers, and observed damage levels for all components in each inspection category. Damage descriptions, repairs and other relevant comments must also be added to the inspection documentation.

Tools

Assemble the following tools in preparation for the external cylinder inspections:

- mirrors to provide visual access to obscured portions of the cylinders
- depth gauge to measure cut depth
- caliper or ruler to measure cut length

Preparation

In preparation for the external cylinder inspections:

1. Check the cylinder's inspection and service record, and/or speak to the bus drivers and maintenance personnel for information on known conditions or incidents that may have caused damaged to the cylinder. Incidents that may lead to the cylinder being condemned include but are not limited to:
    - dropping or impacts of the cylinder
    - exposure of cylinder to excessive heat, fire or harsh chemicals
    - accidents
2. Open canopies or remove shields to access all cylinder surfaces.
3. Clean the outside surface of the cylinders using clean water or water mixed with a mild soap solution consistent with bus exterior cleaning procedures. Do not remove or add coatings of any type. Contact the cylinder manufacturer if surface re-finishing is required.

Key Points & Notes

4. Ensure cylinders are well illuminated for damage observations.

Never expose hydrogen storage cylinders to unapproved soaps or solvents (such as varsol, acetone, methyl-ethyl-ketone, paint thinner, lacquer thinner, gasoline, alcohol, ammonia, etc.). These solutions may corrode, weaken or seriously damage the cylinders. Contact the manufacturer if in doubt.

Damage Observations

Cylinder damage is categorized as either level 0, 1, 2, or 3 depending on severity. Refer to the Table 7-2 and Figure 7-35 when performing the external cylinder inspection.

Composite cylinders do not dent like all-metal cylinders. **Impacts may cause more severe damage within the wall of the cylinder than at the surface, as the surface tends to return to its original shape after impact.**

Damage Level	Observations and Limiting Parameters
Cut, Scratch, Abrasion and Scuff Damage	
Level 1	Shallow cuts, scratches, abrasions or scuffs are noticeable in the laminate. The depth and length of these defects are too small to be measured. A very limited amount of carbon fibre or epoxy has been worn away.
Level 2	Definite cuts, scratches, abrasions or scuffs are noticeable in the laminate: Defects over 1" (25 mm) long are **less** than 0.06" (1.5 mm) deep Defects under 1" (25 mm) long are **less** than 0.08" (2 mm) deep
Level 3	Definite cuts, scratches, abrasions or scuffs are noticeable in the laminate: Defects over 1" (25 mm) long are **more** than 0.06" (1.5 mm) deep Defects under 1" (25 mm) long are **more** than 0.08" (2 mm) deep

	Observations and Limiting Parameters
Impact Damage	
Level 1	Highly localized imprinting as caused by impact of a small stone. Damage is limited in both length and depth. Small random hairline cracks in the resin surface parallel to the reinforcing fibers, but **not** localized in one area of the cylinder. These cracks are common on glossy laminate surfaces and are **not** a sign of impact damage.
Level 2	Light impact damage indicated by scuffs, surface discoloration, concentration of micro-cracks and/or a **few** broken fibers. A coin tap test does **not** indicate damage.
Level 3	Heavy impact damage indicated by **obvious** scuffs, surface discoloration, concentration of micro-cracks and/or **numerous** broken fibers. A coin tap test indicates damage. Obvious damage to cylinder ports; the end boss or valve is skewed and/or leaking.
Chemical Surface Damage	
Level 1	Minor discoloration and/or etching of the cylinder surface caused by a mild non-corrosive contaminant. The contaminant is easily removed by cleaning.
Level 2	The cylinder surface has been exposed to a corrosive chemical. Discoloration is not easily removed by cleaning, but there are no soft spots, blistering, swelling, etching, unraveling of fibers, or removal of resin.
Level 3	Heavy chemical attack has occurred. The cylinder surface shows any of the following: • soft spots • blistering • swelling • etching • unravelling of fibers • resin removal
Fire and Excessive Heat Damage	
Level 3	The cylinder has been exposed to excessive heat or fire. The cylinder surface shows any of the following: • darkening • charring • bubbling of epoxy
Weather Damage	
Level 1	Discoloration or chalking of the epoxy on the cylinder surface external after prolonged exposure to sunlight, but no evidence of loose fibers.
Gas Leaks	
Level 3	Cylinder does **not** hold gas at full pressure when outlets are definitely undamaged and properly sealed as verified by applying a leak detection solution.

Table 7-2 Cylinder Damage Levels

Key Points & Notes

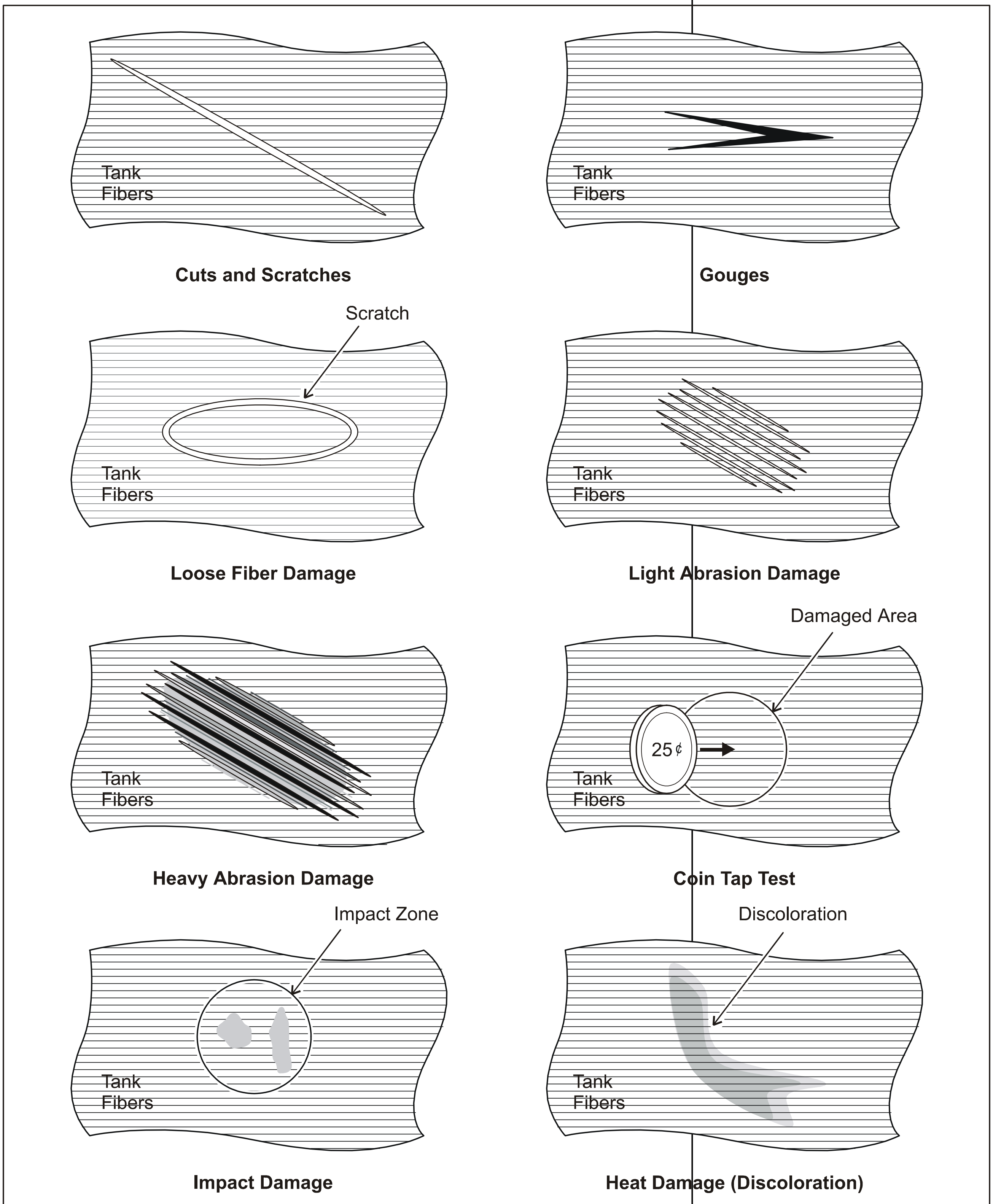


Figure 7-35 Composite Cylinder Damage

Procedure

Key Points & Notes

For each cylinder, check and inspect the following:

1. Check cylinder data:
   - Check that the cylinder's pressure rating is equal to the pressure it is being used for
   - Check the cylinder service life: cylinders that have reached their service life must be replaced.
   - Check that the cylinder serial number is clearly legible on the cylinder label. If the serial number is not legible, contact the manufacturer for a replacement label. Record each serial number.
2. Inspect exterior surface of cylinder laminate for cuts, loose fibers, abrasion, wear or dents and assess cylinder damage level according to Table 7-2 and Figure 7-35. Pay particular attention to cylinder areas in contact with the cylinder clamps.
3. Inspect the exposed aluminum end boss (at both ends of the cylinder):
   - Check for signs of corrosion and assess damage level according to Table 7-2 and Figure 7-35.
   - Using a leak detection solution, check the O-ring seal between the end boss and the cylinder shell for leakage.
4. Inspect the mounting bracket (at both ends of the cylinder):
   - Confirm that the rubber extrudes beyond the top and bottom metal portions of the clamp and is well seated. Use a mirror as required to inspect the bottom clamp.
   - Remove top clamp of the mounting bracket and inspect cylinder laminate for wear, and assess cylinder damage level according to Table 7-2 and Figure 7-35.
   - With top clamp of the mounting bracket removed, inspect the rubber pad for deterioration.
5. Perform a coin tap test:
   - Grasp a quarter between your fingers, tap on the cylinder surface, and listen to the sound it makes.
   - Compare zones of potential damage to undamaged areas. Cylinder and dome areas have naturally different sounds.

- If differences in sound are evident within like areas, the cylinder is damaged (Level 2) and must be repaired by the manufacturer. If uncertain, contact the manufacturer.

6. Inspect the pressure relief devices (at both ends of the cylinder):

   - Using a leak detection agent, inspect pressure relief devices for leaks.
   - Check that the pressure relief devices are not exuding their eutectic compound: run your finger over each of the two protrusions; they should be flat or slightly concave. If not, the eutectic compound is starting to protrude and the pressure relief device must be replaced.

Key Points & Notes

Disposition

Assess cylinder damage with reference to Table 7-3.

Damage Level	Description	Action
External Cylinder Damage Levels		
Level 0	Cylinder is not damaged	No action is required. The cylinder may return to service.
Level 1	Cylinder is slightly damaged	Leave the cylinder in service, but isolate the source of damage to prevent further damage. Contact the manufacturer for repair procedures and use approval.
Level 2	Cylinder is damaged, but can be repaired	Remove cylinder from service and contact the manufacturer for inspection/repair.
Level 3	Cylinder is damaged and cannot be repaired	Remove the cylinder for service, condemn and return to the manufacturer for recycling.

Table 7-3 Cylinder Disposition

7.5.6.3 Fuel Cylinder Internal Inspection

Fuel cylinder internal inspections consist of an assessment of any internal damage on *one* cylinder.

Tools

A boroscope is required for internal cylinder inspections.

Procedure

Key Points & Notes

For *one* cylinder:

1. Vent the cylinder to atmospheric conditions and close its shutoff valve.

2. Confirm that the cylinder has vented by measuring the resistance of the cylinder solenoid valve coil and comparing it to manufacturer's specifications. A short circuit (0 Ω) indicates that the solenoid valve has failed and that high-pressure gas may be trapped within the cylinder despite venting or other procedures.

   An increase in resistance indicates that some form of corrosion or material buildup has occurred within the coil or connecting wires. If the resistance increase is sufficient, the solenoid may not draw enough current to actuate the valve and high-pressure gas may be trapped within the cylinder despite venting or other procedures.

   Report any resistance variations to the bus manufacturer. If you are in any way uncertain that the cylinder has fully depressurized, open the manual lockdown assembly on the cylinder end boss according to manufacturer's instructions.

Do not access the cylinder unless you are positive it has fully vented.

3. Remove the end boss (with pressure relief device attached) and O-ring from the *non*-solenoid valve end of the cylinder.

4. Using the boroscope, inspect interior surface of the cylinder liner for corrosion pitting, moisture or damage. Record the cylinder tag identifier, serial number and observation results.

Key Points & Notes

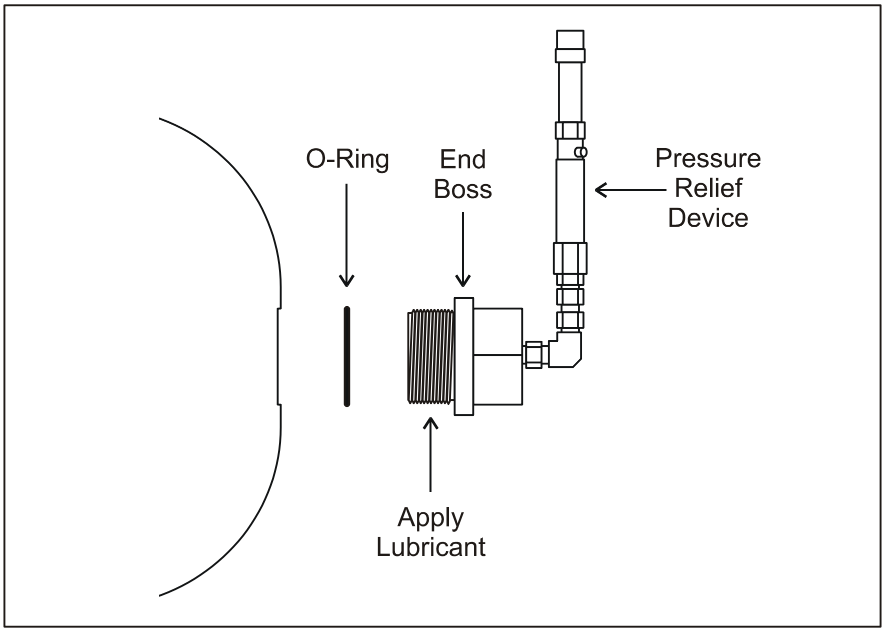


Figure 7-36 Cylinder Internal Inspection

Report any damage to the manufacturer before proceeding.

5. Replace the O-ring, apply the manufacturer approved thread lubricant to the end boss threads, and torque the end boss into the cylinder according to manufacturer's specifications. Ensure that at least seven threads have engaged. Confirm that the pressure relief device points straight up, and adjust as required.

6. Open the shutoff valve, nitrogen purge, and hydrogen purge the cylinder. Once pressurized, perform a leak test in the vicinity of cylinder end boss.

7.5.7 Pressure Regulator Diaphragm, Seal and Seat Replacement

The pressure regulator reduces the hydrogen gas pressure for use in the fuel cell engine. The regulator diaphragm, seals and seats must be replaced periodically as a preventative measure to prevent leaks that could otherwise occur due to hydrogen embrittlement.

The pressure regulator service uses a manufacturer supplied kit and instructions. Perform a leak check and a ground integrity check on the regulator after installation.

7.6 Conventional Procedures

Key Points & Notes

Conventional procedures pertain to routine service that is typical of any bus, although different in detail on a fuel cell bus.

7.6.1 General Inspections

General inspections provide a quick check for obvious bus damage or failures.

7.6.1.1 Air Intake and Exhaust Inspection

The air intake draws process air from the ambient environment. The air exhaust discharges depleted air back to the environment. Both the intake and exhaust are at roof level.

The air intake and exhaust inspection consists of a visual confirmation that neither component is obstructed or damaged. Clear or replace as required.

7.6.1.2 Canopy Inspections

The canopies cover and protect the fuel cylinders and other roof components.

The canopy inspection consists of a visual confirmation that no canopy displays obvious damage. If canopy damage exists, check for cylinder and cylinder installation damage; repair as required.

7.6.1.3 Fluid Leak Checks

The bus uses a variety of fluids in the coolant, lubrication, hydraulic, transmission and HVAC circuits.

The fluid leak checks consist of a visual confirmation that no fluid leaks or puddles are evident. Check for leaks and puddles:

- beneath the bus
- in the engine compartment
- in the cooling compartment
- in the radiator compartment
- on or around the power train
- in the holding tank area

As the fuel cell engine produces water, some water naturally accumulates beneath the holding tank drain valves as well as under water trap drain ports. This water can be ignored, unless substantial enough to indicate leaking components.

Identify the type of fluid by its color and viscosity, and assess the severity of any leak. Repair as required.

7.6.2 Leak Detection System Checks and Conditional Calibration

The leak detection system guards against hydrogen leaks and must be checked for functionality and calibrated for accuracy. If any part of the system is not functioning or is uncalibrated, the system may fail to detect gas leaks, resulting in a potential fire hazard. The bus may not be operated without a fully functional leak detection system.

Key components of the leak detection system include leak indicators (or some other form of system controller) and leak sensors.

7.6.2.1 Leak Indicator Checks

Some leak detection systems include leak indicators that display gas concentration, alarm or fault information associated with each leak sensor. Typically, the leak detection system indicators are only active when the engine is on.

The leak indicator checks consist of a visual confirmation that each indicator is powered, does not display any error codes, and indicates no hydrogen presence. Specific messages and error codes depend on the leak detection system manufacturer, but in general the codes differentiate between warning or alarm triggers (at 5, 15 and 25% LFL) and different types of faults. All faults or errors must be remedied according to manufacturer's instructions.

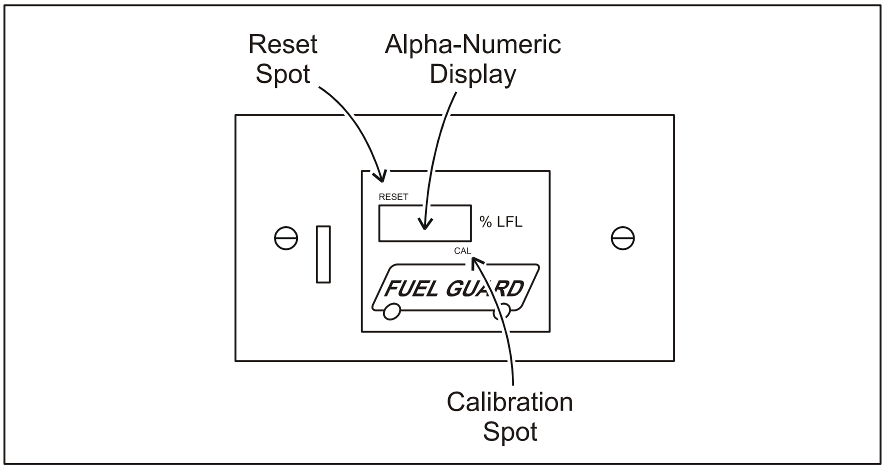


Figure 7-37 Typical Leak Indicator

Key Points & Notes

Key Points & Notes

During normal operation, the indicators display the hydrogen concentration value in %LFL at the corresponding sensor location. Leak sensors tend to drift over time and as a result the leak indicators may display a hydrogen concentration where none exists. However, all leak indications must be taken seriously and be either confirmed or disproved using a hand-held leak detector in the vicinity of the sensor. All legitimate leaks must be traced and repaired. False readings below 4% LFL may be ignored. If a false reading above 4% LFL occurs, calibrate the system (Section 7.5.5.3).

7.6.2.2 Sensor Inspections

The leak sensors detect hydrogen presence and are located at key locations throughout the bus. These sensors must be undamaged for the leak detection system to operate properly. Typically, the leak sensors are only active when the engine is on.

Each leak sensor consists of the sensor base, a sintered flame arrestor, a foam splash guard, vibration isolators and an electrical connector. The sensor base contains the sensor electronics into which gas passes through the sintered flame arrestor. The foam splash guard prevents water and dirt from plugging the flame arrestor. The vibration isolators reduce shocks to the sensor. The electrical connector passes power and signals to and from the sensor.

The sensor inspections consist of a visual confirmation that no sensor components are missing, and that all components are undamaged and free of cracks, distortion, dirt or obstruction. Replace components as required. The splash guard may be cleaned with soapy water if not excessively dirty. If replacing the splash guard, trim the new unit as required using the shape of the original splash guard as a guide.

Replace the sensor if the flame arrestor is impeded in any way. **Do not attempt to clean the sensor with steam, solvents or other cleaning solutions.**

Key Points & Notes

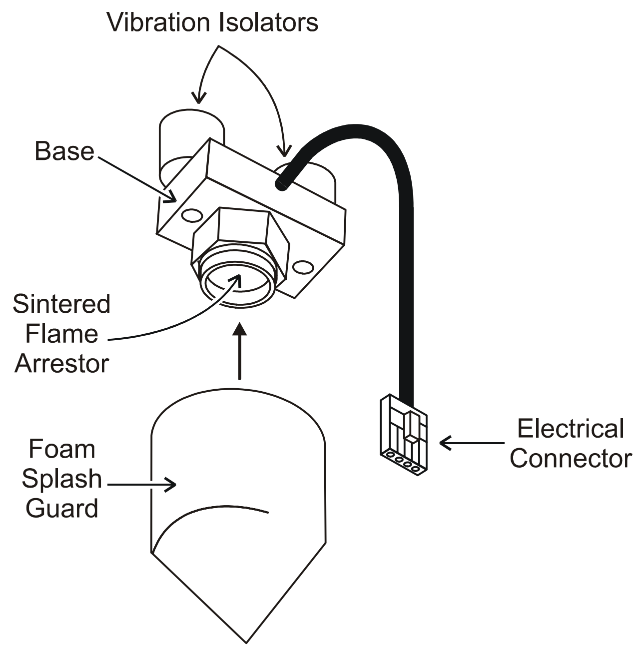


Figure 7-38 Typical Leak Sensor

7.6.2.3 System Calibration

The leak detection system must be calibrated periodically to correct for sensor drift and aging. On systems that include leak indicator displays, the system is commonly calibrated whenever any indicator displays greater than >4% LFL with no gas present.

System calibration consists of exposing each sensor to laboratory gases with 0 and 50% LFL hydrogen and programming the leak detection system controller at each of the two concentrations. In effect, these two reference gas concentrations establish the "zero" point (system offset) and the "span" (system scaling factor) for the interpretive algorithms. After calibration, the leak detection system interprets detected gas concentrations relative to these two calibration reference points.

Typical leak detection system test equipment is illustrated in Figure 7-39 and must include the following:

- "Zero Air" (pure air) calibration gas
- "Span Gas" (2% hydrogen (50% LFL)) calibration gas
- Calibration gas regulator and sensor connector assembly
- System specific programming tool. Some systems use a magnetic calibrator for this purpose; the calibrator has "zero" and "span" ends that are placed near appropriate

Key Points & Notes

spots on the corresponding leak indicator during calibration.

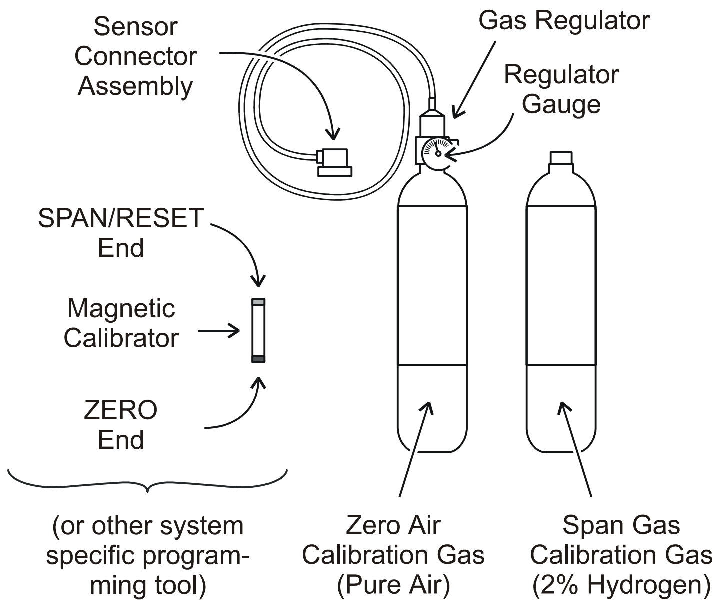


Figure 7-39 Typical Leak Detection System Calibration Equipment

Leak detection system calibration usually requires two people. One person applies the calibration gases to the sensors while the other person programs the system. Test results are normally recorded on a calibration record that indicates the date, the hourmeter and odometer readings, and sensor serial numbers.

Specific calibration (and particularly programming) procedures depend on the leak detection system manufacturer but generally involves the following steps. Systems usually display calibration related messages, fault or error codes by way of the leak indicators or other means.

Prepare to calibrate:

1. Ensure that the leak detection system is powered and is free of faults or errors. All errors must be cleared before calibration can proceed.

2. Ensure that no combustible gas is present.

Apply Zero Air:

3. Assemble the zero air test equipment, and open the regulator valve for a couple of seconds so that the sensor connector assembly is flushed out with the test gas.

Key Points & Notes

4. For each leak sensor:

   a) Remove the foam splash guard, and inspect the sensor and ensure that the sintered flame arrestor is intact, undamaged and clean.

   b) Place the end of the sensor connector assembly onto the flame arrestor, and open the regulator valve to apply Zero Air to the sensor.

   c) Program the leak detection system using the system specific programming tool. If applicable, view the leak indicator codes to confirm that the calibration was successful.

   d) Close the regulator valve and remove the sensor connector assembly from the sensor.

Apply Span Gas:

5. Repeat steps 3 and 4 using the span gas test equipment.

Complete:

6. Wait while system stores the new calibration values into memory.

7. Confirm that each sensor now indicates 0% LFL. Repeat calibration as required; if a sensor cannot be successfully calibrated, it must be replaced.

8. Disassemble test equipment.

7.6.3 Fluid Level Checks, Samples and Assessments

The fuel cell bus uses the following fluids:

- humidification water
- stack coolant
- bus coolant
- lubrication oil
- hydraulic fluid
- transmission fluid
- HVAC compressor oil

These fluids must be present in adequate quantities and be free of contamination for proper engine operation. Like a conventional powered bus, fluid levels may be reduced through leakage or lost during maintenance procedures, and contaminants may be introduced from external or internal

Key Points & Notes

sources. Unlike a conventional powered bus, the fuel cell bus produces water, does not burn oil, and does not generate combustion related contaminants.

Standard fluid procedures include level checks, sample collections, and condition assessments as described in the following sections.

7.6.3.1 Humidification Water

Level Check

The humidification water level check is normally done with reference to a header tank sightglass. The engine may be on or off and the water may be hot or cold for the level check. Water for the humidification circuit is drawn from the product water stream produced by the fuel cells; thus, any water shortfall indicates that the bus is not recovering sufficient water from the air exhaust stream.

Humidification water may be added directly through a fill port. Use only clean de-ionized (distilled) water. Record the amount of water added.

The humidification water circuit is pressurized during operation but depressurizes upon engine shutdown. **Always turn off the engine before opening the fill port.**

7.6.3.2 Stack Coolant

Level Check

The stack coolant level check is normally done with reference to a header tank sightglass. The engine may be on or off and the coolant may be hot or cold for the level check.

Stack coolant may be added directly through a fill port. Use only clean de-ionized water with or without pure ethylene glycol as specified by the manufacturer. Record the amount of coolant added.

The stack coolant circuit is pressurized during operation and remains pressurized for some period of time after engine shutdown. **Always turn off the engine and relieve the circuit pressure before opening the fill port.**

7.6.3.3 Bus Coolant

Level Check

The bus coolant level check is normally done with reference to a header tank sightglass. The engine may be on or off and the coolant may be hot or cold for the level check.

Key Points & Notes

Bus coolant may be added directly through a fill port. Use a standard water/ethylene glycol mixture. Record the amount of coolant added.

The bus coolant circuit is pressurized during operation and remains pressurized for some period of time after engine shutdown. **Always turn off the engine and relieve the circuit pressure before opening the fill port.**

7.6.3.4 Lubrication Oil

Level Check

The bus lubrication oil level check is normally done with reference to a dipstick. The engine must be off for an accurate level indication, but the oil must be hot or cold. Do not allow any dirt or foreign matter to enter the oil while removing or re-inserting the dipstick. If it is necessary to lay the dipstick down, ensure that it lies on a clean surface.

Lubrication oil may be added directly through a fill port. Use the specified lubrication oil only. Record the amount of oil added.

The lubrication oil circuit is pressurized during operation but depressurizes on engine shutdown. **Do not open the fill port while the engine is on.**

Inspection

The bus lubrication oil sump is fitted with a magnetic drain plug in order to collect metal filings or debris. Material accumulation of this sort indicates component wear or damage, and provides useful diagnostic information when troubleshooting or anticipating power train problems.

The magnetic drain plug has a two-part nut, such that you can remove the inner nut without draining the oil, or remove both to drain the oil.

All collected materials should be retained for future analysis and be labeled with the bus identification, date, odometer and hourmeter readings. Alert the bus manufacturer immediately if significant material has collected and return the debris on their request. The plug must be clean before re-insertion.

Sample

Bus lubrication oil samples can provide useful diagnostic information when troubleshooting or anticipating power train problems. Oil samples can be drawn directly from the

Key Points & Notes

oil sump drain plug. Samples should be collected in sealable containers of approximately $^1/_2$ cup (120 mL) volume and be labeled with the bus identification, date, odometer and hourmeter readings. Alert the bus manufacturer immediately upon evidence of discoloration, contamination, foreign materials or other fluids; return the sample on their request.

7.6.3.5 Hydraulic Fluid

Level Check

The bus hydraulic fluid level check is normally done with reference to a header tank sightglass. The engine must be off for an accurate level indication, but the fluid may be hot or cold.

Hydraulic fluid may be added directly through a fill port. Use the specified hydraulic fluid only. Record the amount of fluid added.

The hydraulic fluid circuit is pressurized during operation but depressurizes on engine shutdown. **Do not open the fill port while the engine is on.**

Sample

Bus hydraulic fluid samples can provide useful diagnostic information when troubleshooting or anticipating power train problems. Fluid samples can be drawn directly from the hydraulic circuit drain plug. Samples should be collected in sealable containers of approximately $^1/_2$ cup (120 mL) volume and be labeled with the bus identification, date, odometer and hourmeter readings. Alert the bus manufacturer immediately upon evidence of discoloration, contamination, foreign materials or other fluids; return the sample on their request.

7.6.3.6 Transmission Fluid

Presence Check

The transmission fluid presence check is normally done with reference to a dipstick. The engine must be off, but the fluid may be hot or cold.

The transmission fluid presence check does not give accurate level information when performed cold, but it provides a quick indication of massive fluid loss prior to starting the engine.

Key Points & Notes

Level Check

The bus transmission fluid level check is normally done with reference to a dipstick, or using an electronic method specific to the transmission manufacturer. Where an electronic method is available, it is preferable to the manual method since it is more reliable and provides more information. The engine must be off for an accurate level indication, but the fluid must be at its normal operating temperature.

Transmission fluid may be added directly through a fill port. Use the specified automatic transmission fluid only. Record the amount of fluid added.

The transmission fluid circuit is pressurized during operation but depressurizes on engine shutdown. **Do not open the fill port while the engine is on.**

Sample and Inspection

Bus transmission fluid samples can provide useful diagnostic information when troubleshooting or anticipating transmission problems. Fluid samples can be drawn directly from the transmission drain plug. Samples should be collected in sealable containers of approximately $^{1}/_{2}$ cup (120 mL) volume and be labeled with the bus identification, date, odometer and hourmeter readings.

Check the fluid for the following:

- **Dirt**: Investigate source of dirt and eliminate.
- **Water**: Some condensation appears in the transmission fluid during operation. For obvious water contamination, inspect and pressure test the transmission cooler. Replace leaking coolers.
- **Glycol**: Glycol in the transmission hydraulic system requires immediate action to prevent malfunction and serious damage. Completely disassemble, inspect and clean the transmission. Remove all traces of glycol and varnish deposits resulting from glycol contamination. Replace friction clutch plates contaminated with glycol.
- **Metal Particles**: Metal particles in the transmission fluid indicates internal transmission damage. If metal particles are found in the sump, the transmission must be disassembled and closely inspected for the source of the metal. Clean all internal and external hydraulic circuits, cooler, and all other areas where the metal particles could lodge.

Key Points & Notes

Alert the bus manufacturer immediately upon evidence of discoloration, contamination, foreign materials or other fluids; return the sample on their request.

7.6.3.7 HVAC Compressor Oil

Inspection

The HVAC compressor oil inspection can provide useful diagnostic information when troubleshooting or anticipating compressor or refrigerant circuit problems. The oil is self-contained within the compressor and can be viewed through a sightglass. Check the oil for the following:

- **Colorless or Light Yellow Oil**: Good.
- **Brown Oil**: Indicates copper plating caused by moisture in the system or acidic oil. Return the compressor to the manufacturer for oil replacement.
- **Black Oil**: Indicates carbonization caused by air in the system or the presence of wear particles that contain iron. Return the compressor to the manufacturer for oil and filter replacement.
- **Green Oil**: Indicates water in the system, and that copper plating may have occurred. Return the compressor to the manufacturer for inspection of shaft seals, bearings, gears and rotors, and oil and filter replacement.
- **Gray or Silver (Metallic) Particles**: Indicates the presence of wear particles that contain aluminum. This is usually caused by bearing wear or piston scoring. Return the compressor to the manufacturer for inspection of worn or damaged components, and oil and filter replacement.

Alert the bus manufacturer immediately upon evidence of discoloration, contamination, foreign materials or other fluids.

7.6.4 Turbocharger Oil Trap Drain

Lubrication oil becomes infused with air as it interacts with the turbocharger. This air must be removed to prevent the oil from turning into a froth. This is accomplished using a separator vessel on the oil return line, which directs the air stream to an oil trap. This air stream carries a small amount of oil with it that collects in the oil trap while the air escapes through an air vent.

Key Points & Notes

The turbocharger oil trap drain consists of opening a drain port on the bottom of the oil trap and removing any accumulated oil.

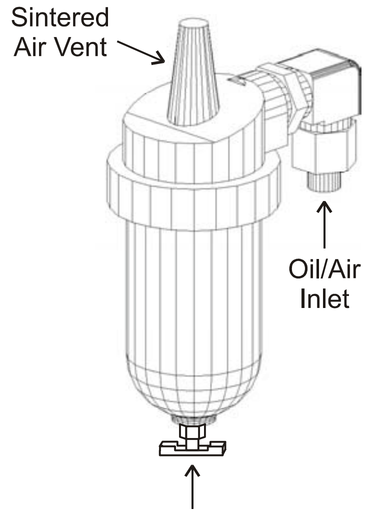


Figure 7-40 Typical Oil Trap

7.6.5 Fire Suppression System Inspections and Tests

The fire suppression system must be inspected for damage and tested for functionality. If any part of the system is damaged or not functioning, the system may fail to detect or suppress fires. The bus may not be operated without a fully functional fire suppression system.

Key components of the fire suppression system include a system controller, fire sensors, nozzles and hoses, and retardant tanks.

7.5.5.1 Sensor Inspections

The fire sensors detect fire presence and are located at key locations throughout the bus. These sensors must be undamaged for the fire suppression system to operate properly. Typically, the fire sensors are only active when the bus battery knife switches are closed (connected).

Each fire sensor includes two windows, an LED, and a pair of electrical connectors. The windows pass infrared energy into the sensor electronics. The LED provides a power and fault indication. The electrical connectors pass power and signals to and from each sensor. The sensors of a given zone are arranged in a serial fashion so that the output of one sensor is the input of the next. The output connector associ-

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ated with the terminating sensor of each zone contains an "end-of-line" resistor.

The sensor inspections consist of a visual confirmation that all sensors are powered (LED on), operating without fault indication (LED not flashing), and free of damage, cracks, distortion, dirt or obstruction. Clean the sensor windows using water and non-abrasive towels or rags as required.

Do not attempt to clean the sensor with steam, solvents or other cleaning solutions.

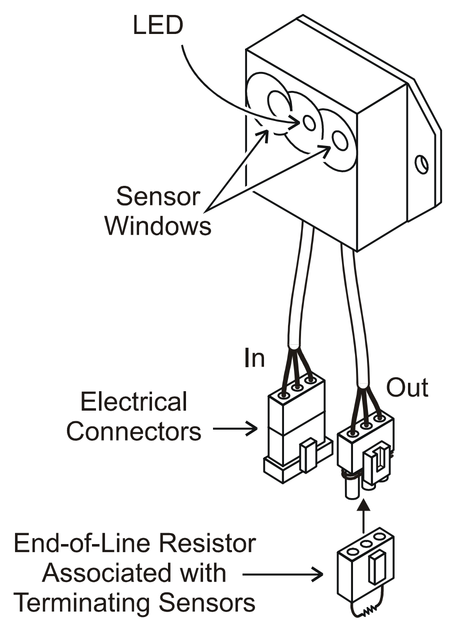

Figure 7-41 Typical Fire Sensor

7.5.5.2 Hose, Nozzle and Retardant Tank Inspections

The hoses and nozzles distribute and discharge the contents of the fire retardant tanks in the event of a fire.

Hose inspections consist of a visual confirmation that all accessible distribution hoses are free of cuts, tears, abrasion, cracks or damage. Remove sources of abrasion.

Nozzle inspections consist of a visual confirmation that all nozzles are functional, undamaged and unobstructed. Nozzles are of two styles, depending on their mounting location. For nozzles with a hinged cap, ensure that the hinged nozzle cap is normally closed but opens easily. For nozzles with a blow-off cap, ensure that the cap is seated on the end of the nozzle.

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Retardant tank inspections consist of a visual confirmation that all tanks are undamaged and at the correct charge pressure. A tank is fully charged if its valve pressure gauge pointer is within the green arc at room temperature. (If the tank is cold, allow it to warm up to room temperature). If the pointer is outside the green arc, replace the retardant tank and have it charged or serviced.

Replace damaged components as required.

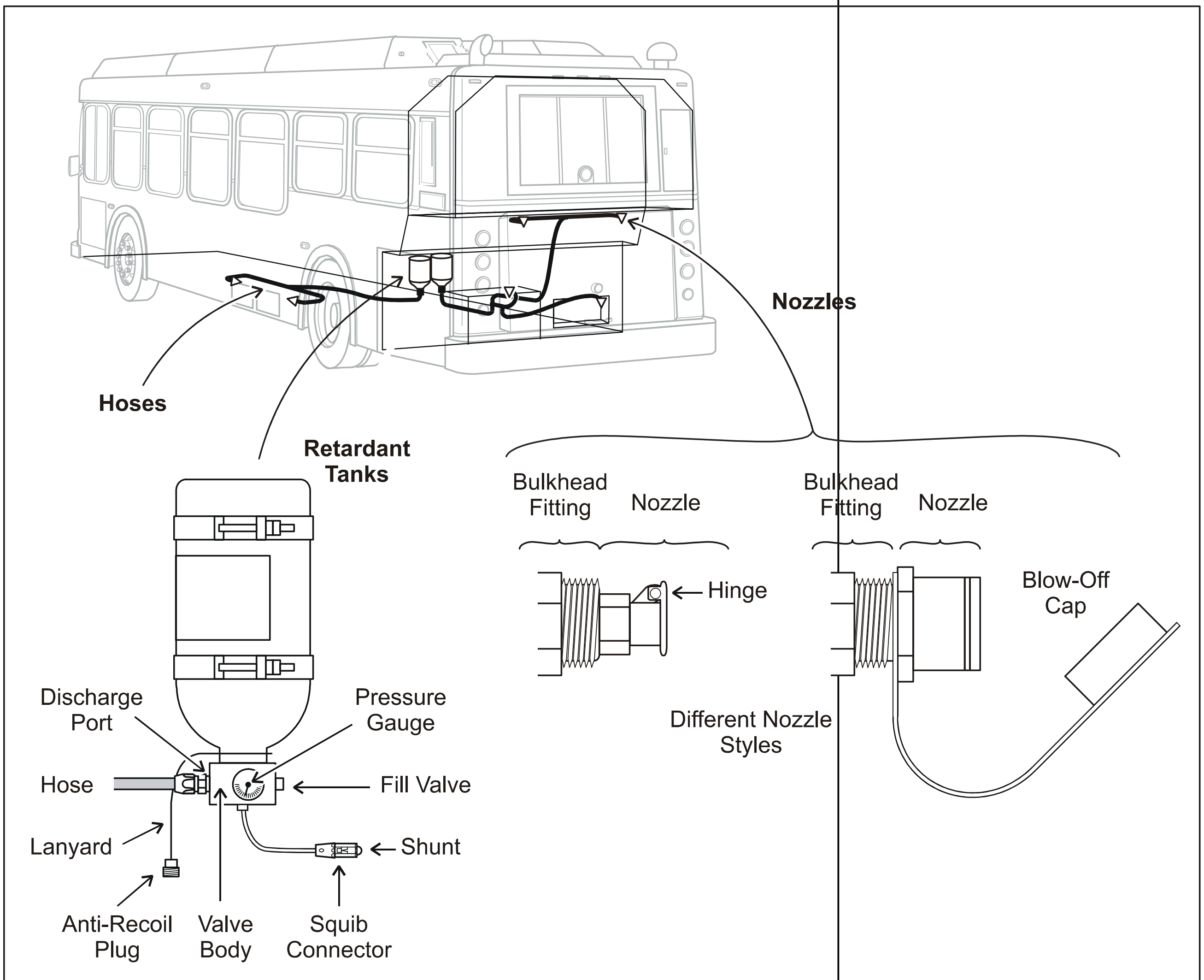

Figure 7-42 Typical Fire Retardant Distribution Equipment

7.5.5.3 System Tests

The fire suppression system must be tested periodically for functionality.

System tests consist of disconnecting each fire retardant tank and substituting an electronic device that indicates

Key Points & Notes

whether the tank *would have* discharged under the test conditions. Different test conditions are simulated using a second electronic device in contact with each fire sensor. The simulated test conditions comprise:

- False Alarm Immunity Test (all sensors)
- Fire Response Test (all sensors)
- Engine Shutdown Test (1 sensor only)
- Fault Test (all zones)

Typical fire suppression system test equipment is illustrated in Figure 7-43 and must include the following:

- one source simulator
- one extinguisher valve simulators per fire retardant tank

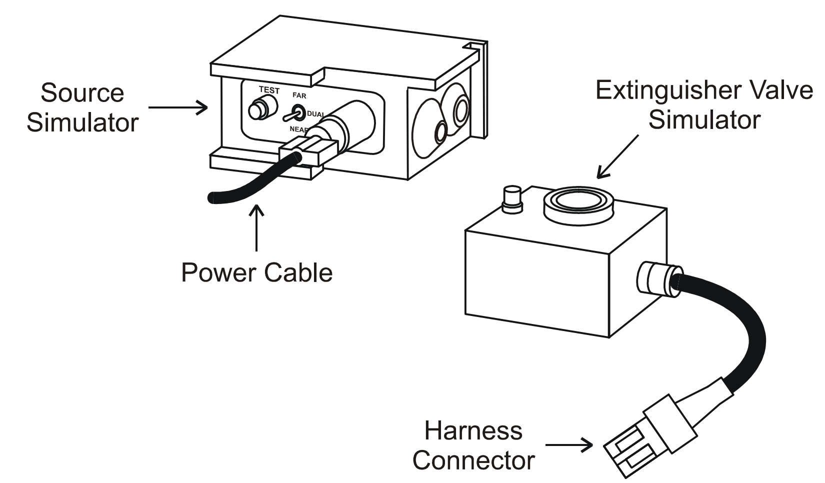

Figure 7-43 Typical Fire Suppression System Test Equipment

Fire suppression system tests usually require two people. One person operates the source simulator while the other person monitors the extinguisher valve simulators. Test results are normally recorded on a test record that indicates the date, the hourmeter and odometer readings, and a pass or fail indication for each test.

Specific test procedures depend on the fire suppression system manufacturer but generally involves the following steps.

Preparation

Prepare to test:

1. Disconnect the squib connector from the electrical wiring harness at the tank valve of each tank. **Failure to dis-**

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connect all fire retardant tanks will result in retardant discharge during testing.

2. Connect a valve simulator to the harness disconnected from each fire retardant tank as shown in Figure 7-44.
3. Connect the source simulator power cable to the bus batteries.
4. Ensure the bus control system is active.
5. Ensure that the fire suppression system is powered and operating without fault indication.

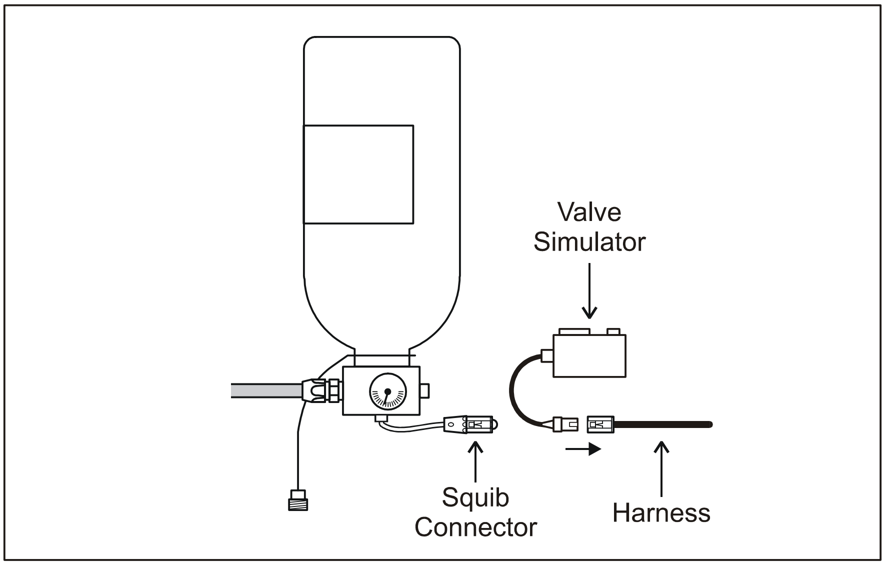

Figure 7-44 Extinguisher Valve Simulator in Use

False Alarm Immunity Test (Bus Off)

For *each* fire sensor:

1. Ensure the bus engine is off.
2. Align the source simulator with the fire sensor face as shown in Figure 7-45.

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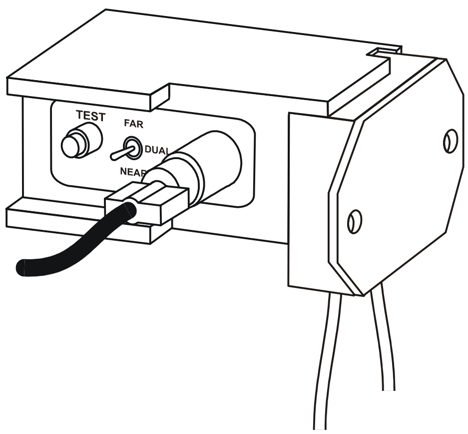

Figure 7-45 Source Simulator in Use

3. Set the source simulator to its *near* false alarm test mode and operate. Confirm that the bus control system *does not* register a fire alarm and the valve simulator associated with the current zone *does not* trip.

4. Repeat step 3 with the source simulator set to its *far* false alarm test mode.

If a sensor false triggers, reset the fire suppression system controller and repeat the test. If the fault persists, replace the sensor.

Fire Response Test (Bus Off)

For *each* fire sensor:

1. Ensure the bus engine is off.

2. Align the source simulator with the fire sensor face as shown in Figure 7-45.

3. Set the source simulator to its fire test mode and operate. Confirm that the bus control system *does* register a fire alarm and the valve simulator associated with the current zone *does* trip after a period of time (as defined by the bus manufacturer).

4. Reset the fire suppression system controller.

If a sensor does not trigger, clean the sensor windows, check alignment with source simulator, and repeat the test. If the fault persists, replace the sensor.

Engine Shutdown Test (Bus On)

For *one* fire sensor:

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1. Start the bus.
2. Align the source simulator with the fire sensor face as shown in Figure 7-45.
3. Set the source simulator to its fire test mode and operate. Confirm that the bus control system *does* register a fire alarm and that the engine *shuts down* automatically after a period of time (as defined by the bus manufacturer). Confirm that the valve simulator associated with the current zone *does* trip soon after the engine shuts down (the time period as defined by the bus manufacturer).
4. Reset the fire suppression system controller.

If the engine does not shut down, it is incorrectly connected with the fire suppression system.

Fault Test (Bus Off)

For each zone:

1. Ensure the bus engine is off.
2. Disconnect the terminating connector with the end-of-line resistor. Confirm that the bus control system registers a *system fault* but the valve simulator associated with the current zone *does not* trip.
3. Reset the fire suppression system controller.
4. Re-install the end-of-line resistor.

If the bus does not register a system fault, the bus is incorrectly connected with the fire suppression system.

Post-Test Checks

Once all tests are complete:

1. Disconnect the source simulator and valve simulators, and reconnect the fire retardant tank squib connectors.
2. Ensure that the fire suppression system is powered and operating without fault indication.

7.6.6 Mechanical Inspections

Mechanical inspections relate to the general condition of the fuel cell engine and related components. Specific checks include hose, radiator, transmission, belt and vibration mount inspections.

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7.6.6.1 Hose and Tube Inspections

Hoses transfer fluids throughout the fuel cell engine. Hoses and tubes are constructed of a variety of materials, depending on the fluid they convey. Standard materials (typical of hydraulic systems) are used to convey oil, hydraulic fluid, automatic transmission fluid, coolant and water. Teflon tubes are used to convey hydrogen, air or water. Silicone hose is used to convey hydrogen.

Hose inspections consist of a visual confirmation that all visible hoses and tubes are free of cuts, tears, abrasion or damage. Inspect all hose/tube interfaces with sections of metal tubing. If damaged, replace as required using the same hose material. Remove any sources of abrasion.

7.6.6.2 Radiator Inspection

The radiator transfers waste heat to the environment. The cooling capacity of a radiator is directly related to its surface area. Any material that clogs the radiator fins reduces the effective surface area and thereby reduces the effectiveness of the radiator.

The radiator inspection consists of a visual inspection for radiator obstructions, including dust, dirt, plant matter and bugs. Vacuum or air blow the radiator face as required. Do not use pressurized water to clean the radiator if there is any chance of the water contacting the fuel cell stacks or membrane humidifiers.

In addition, visually check the fan blades and other components for damage. Replace as required.

7.6.6.3 Transmission Inspection

The transmission is subject to standard inspections as defined by the transmission manufacturer. Typical inspections check for:

- loose mounting bolts
- fluid leaks
- damaged or loose hoses
- worn, frayed or improperly routed electrical harnesses
- worn, damaged, loose or corroded electrical connectors or motor speed pickup
- worn or out-of-phase driveline U-joints

In addition:

- Visually inspect the transmission air breather for cleanliness, damage or obstruction. The air breather cap should move freely. Remove the air breather cap and clean using soap and water or replace as required. Do not spray steam, water or cleaning solution directly at the air breather.

Key Points & Notes

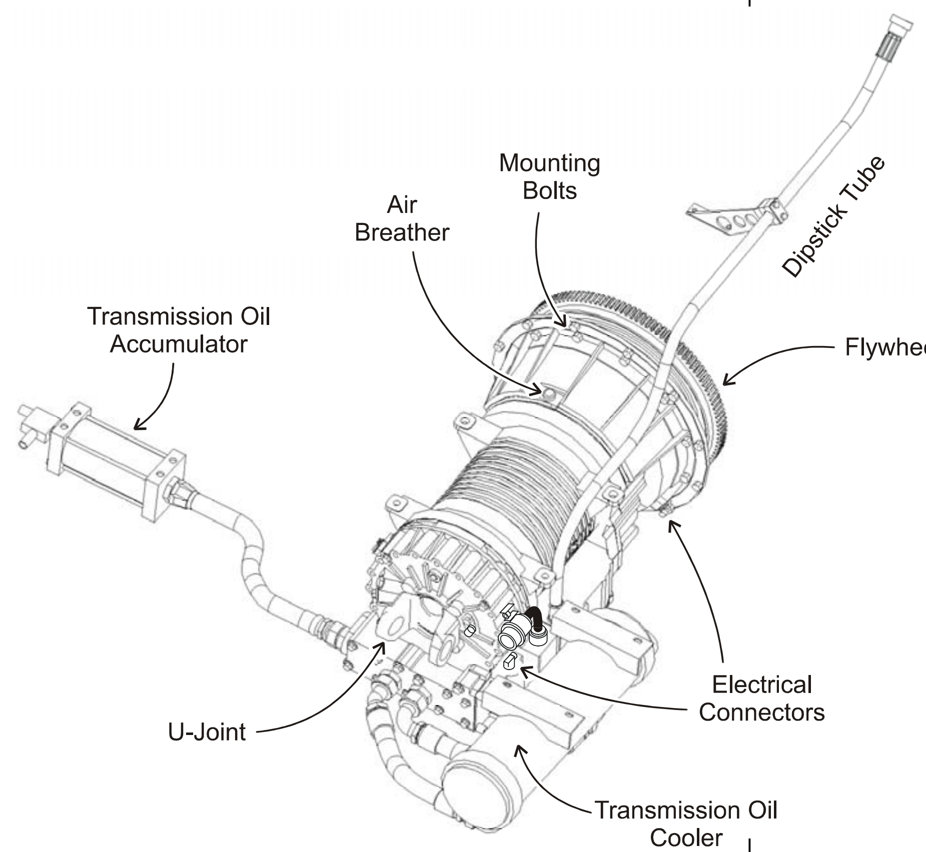

Figure 7-46 Typical Transmission Inspections

7.6.6.4 Belt Inspections

The belts transfer power to the alternator and HVAC compressor.

The belt inspections consist of a visual check for alignment, looseness, cracks, wear or damage. Replace belts or repair belt systems as required. Some belts are permanently aligned (by design) and others use special alignment jigs. Generally, belts are self-tensioned using automatic tensioner devices.

7.6.6.5 Vibration Mount Inspections

The vibration mounts minimize the transfer of vibrations from the bus chassis to the power train and stack modules.

The vibration mount inspections consist of a visual check for missing components (bolts, nuts, etc.), cracks, distortion or other damage. Replace mounts as required. Vibration mounts are designed to accept a high torque to ensure a

Key Points & Notes

solid installation. Use a torque wrench to ensure that the mounting torque of each mount meets the bus manufacturer's specification.

7.6.7 Filter Inspections and Replacement

Filters collect particulate and/or liquid debris from the circuits in which they are installed. Filters impede flow as they clog and must be cleaned or replaced periodically.

7.6.7.1 Stack Air Inlet Filter Inspection and Conditional Replacement

The stack air inlet filters are installed specifically to trap oil particles (originating from the air compressor or turbocharger lubrication circuits) before they can enter the fuel cell stacks. Oil can seriously damage or destroy fuel cells. Some bus designs use two filters (each installed on half of the air stream) while other buses use a single filter (installed on the whole air stream).

The stack air inlet filters must be inspected for oil presence, and replaced whenever oil is detected. However, oil presence is a serious situation and has greater ramifications than just replacing the filter: alert the bus manufacturer immediately and do not operate the bus until repairs are completed. At a minimum, repairs include tracing and eliminating the oil leak and thoroughly cleaning all contaminated air system components.

The stack air inlet filters are of cartridge design, and are accessed by removing a cover. Cartridges can then be inspected and exchanged directly. Replacement cartridges must be installed in the correct orientation. When replacing a filter cartridge, inspect O-rings or other sealing surfaces for damage, and replace or repair as required. Clean the filter enclosure as required.

Label the used filter element with the bus identifier, filter location, date and odometer reading and return along with any accumulated material to the bus manufacturer on their request.

7.6.7.2 Stack Fan Filter Cleaning and Replacement

The stack fan filters accompany the stack vent fans that provide positive pressure to the fuel cell stack enclosures. These fans prevent any potential hydrogen accumulation in the event of fuel cell stack leakage.

The stack fan filters consist of a foam or fine mesh material that is clamped or screwed in place. This filter material can

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be removed and cleaned using soap and water, and must be replaced if damaged.

7.6.7.3 Air Intake Filter Minder Inspection and Conditional Filter Replacement

The air intake filter removes particulate debris from the process air stream inlet. This filter is usually accompanied by a standard filter minder.

The filter minder monitors the absolute gauge pressure just downstream of the air inlet filter and thereby provides a visual indication of filter condition. When the filter is clean, there is little gauge pressure. As the filter clogs, the pressure downstream of the filter decreases (drawing a vacuum) and the absolute gauge pressure indication increases accordingly.

The filter minder visual indicator is latched, to show the highest recorded differential pressure, and changes from yellow to red when the filter needs replacement. A reset button resets the indicator.

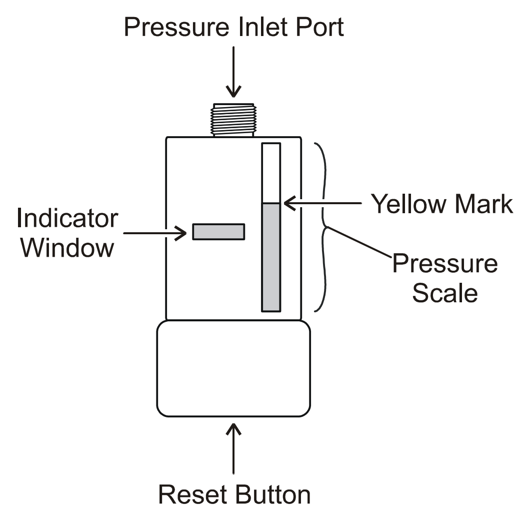

Figure 7-47 Typical Filter Minder

Inspect the filter minder pressure scale and record the pressure reading. If the indicator window is red instead of yellow, replace the filter element. The air intake filter is of cartridge design, and is typically replaced by removing a cover and exchanging the cartridge directly. The replacement cartridge must be installed in the correct orientation.

When replacing the filter cartridge, inspect O-rings or other sealing surfaces for damage, and replace or repair as required. Clean the filter enclosure as required. After filter element replacement, press the reset button on the filter minder and check that the yellow indicator mark shows 0.

Label the used filter element with the bus identifier, filter location, date and odometer reading and return along with any accumulated material to the bus manufacturer on their request.

7.6.7.4 Sintered Air Vent Inspection and Cleaning

Sintered air vents accompany various components that either vent air to atmosphere, or are vented to atmosphere at all times in order to prevent pressure buildup. Typical components with sintered air vents include the air compressor, alternator and variable vane controller. (The term "sintered" refers to a powder that has been coalesced into a solid by heating.)

Inspect all sintered air vents for cleanliness, damage or obstruction. Remove and clean using soap and water or replace as require.

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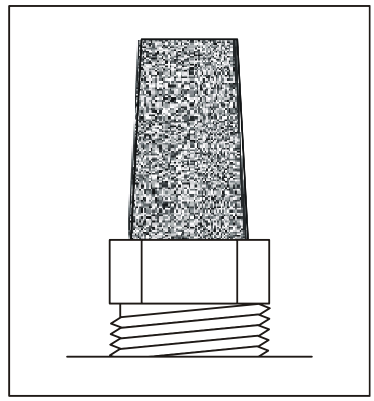

Sintered Air Vent

7.6.7.5 Bus Chassis Air Intake Filter Replacement

The bus chassis air intake filter removes particulate debris from the *bus chassis* air stream inlet.

The bus chassis air intake filter is of cartridge design, and is typically replaced by removing a cover and exchanging the cartridge directly. The replacement cartridge must be installed in the correct orientation. When replacing the filter cartridge, inspect O-rings or other sealing surfaces for damage, and replace or repair as required. Clean the filter enclosure as required.

Label the used filter element with the bus identifier, filter location, date and odometer reading and return along with any accumulated material to the bus manufacturer on their request.

7.6.7.6 Strainer Inspection and Cleaning

The water strainers remove particulate debris from the humidification water and stack coolant circuits. These strainers are installed to trap any resin beads that may escape from the de-ionizing filters that could otherwise migrate into and clog the fuel cell stacks. As a result, these strainers tend to be installed at the inlet and outlet of each bank of de-ionizing filters, and sometimes at the outlet of the water and/or stack coolant header tanks.

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Each strainer consists of an element mounted within a body. Water or coolant flows through the strainer in such a fashion that any debris collects within the element. The element can be accessed by way of a removable end cap.

Inspect each strainer with the engine off by draining the water or coolant as required (to prevent it from gushing out of the strainer while open) and removing the end cap. Check each strainer for debris, particularly de-ionizing resin beads: if present, alert the bus manufacturer immediately and do not operate the bus until repairs are completed. At a minimum, repairs include tracing and eliminating the source of debris. Retain all collected material and clean the strainer with water prior to re-installation.

Label any collected material with the bus identifier, strainer location, date and odometer reading and return to the bus manufacturer on their request.

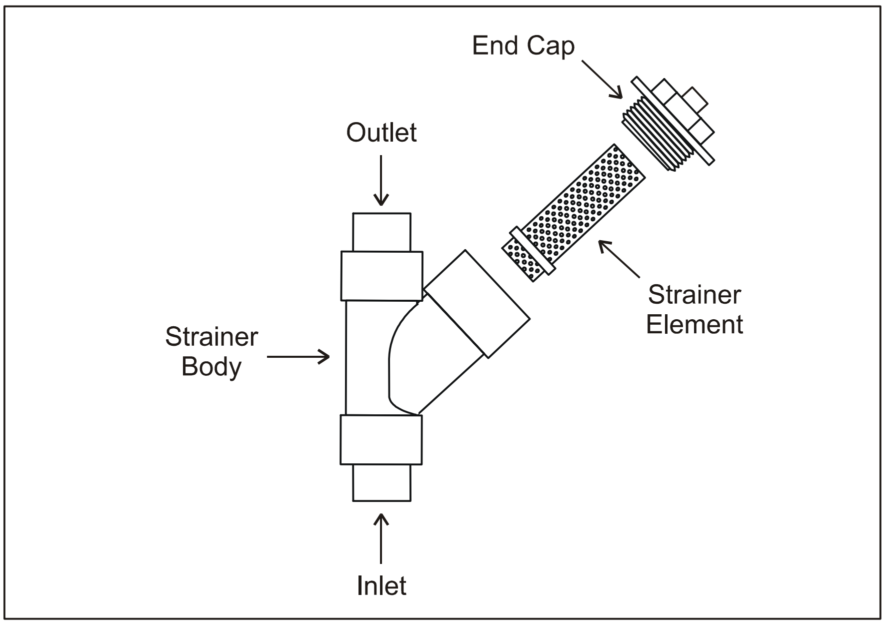

Figure 7-48 Typical Strainer

7.6.7.7 Lubrication System Filter and Oil Replacement

The lubrication system filter removes particulate debris from the lubrication circuit.

The lubrication oil is usually changed in conjunction with the filter. This is convenient since the oil must be drained prior to removing the filter in order to avoid spillage. Drain the oil by way of the oil sump drain plug; retain a sample and inspect as described in Section 7.6.3.4.

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The lubrication oil filter consists of a replaceable canister, much like a standard automotive oil filter. Unscrew the used filter, wet the sealing surfaces of the new filter with oil, and use a filter wrench to install a half-turn past hand-tight. Use only the specified replacement part. Once installed, fill the lubrication oil circuit and check the level as described in Section 7.6.3.4.

Label the used filter element with bus identifier, filter location, date and odometer reading and return with any accumulated material to the bus manufacturer at their request.

7.6.7.8 Hydraulic System Filter and Fluid Replacement

The hydraulic system filter removes particulate debris from the hydraulic circuit.

The hydraulic fluid is usually changed in conjunction with the filter. This is convenient since the fluid must be drained prior to removing the filter in order to avoid spillage. Drain the fluid by way of the circuit drain plug; retain a sample and inspect as described in Section 7.6.3.5.

The hydraulic system filter consists of a replaceable canister, much like a standard automotive oil filter. Unscrew the used filter, wet the sealing surfaces of the new filter with fluid, and use a filter wrench to install one-half turn past hand-tight. Use only the specified replacement part. Once installed, fill the hydraulic circuit and check the level as described in Section 7.6.3.5.

Label the used filter element with the bus identifier, filter location, date and odometer reading and return along with any accumulated material to the bus manufacturer on their request.

7.6.7.9 Transmission Filter and Fluid Replacement

The transmission filters remove particulate debris from the transmission fluid.

The transmission fluid is usually changed in conjunction with the filter although it may not be necessary to drain the fluid in order to change the filters (depending on the transmission). If changing the fluid, drain by way of the transmission drain plug; retain a sample and inspect as described in Section 7.6.3.6.

The transmission filters consist of replaceable elements. Exchange the elements according to the transmission manufacturer's instructions. Use only the specified replacement parts. Once installed, fill the transmission and check the level as described in Section 7.6.3.6.

Label the used filter elements with the bus identifier, filter location, date and odometer reading and return with accumulated material to the bus manufacturer on their request.

Key Points & Notes

Key Points & Notes

7.7 Diagnostics

Diagnostics pertains to methods of troubleshooting bus faults that fall outside of routine maintenance.

The following diagnostic interface information is based on the pre-production Phase 4 fuel cell bus designed and built by XCELLSiS Fuel Cell Engines, Inc., and represents the most advanced approach to fuel cell diagnostics currently available. Fuel cell technology is evolving rapidly, and no two bus designs are identical. With this in mind, the diagnostic interface information is intended to be representative of the type of equipment used, although details vary from one bus model to another.

7.7.1 Diagnostics Interface

Bus diagnostics are performed using a portable diagnostics interface that provides real-time access to transducer and control signals. The diagnostics interface:

- displays individual bus systems schematically with instantaneous analog and digital signal state indications
- displays individual fuel cell and overall stack voltages
- provides a fuel cell and stack voltage data capture utility
- indicates abnormal and near-abnormal states of analog signals
- indicates abnormal states of digital signals
- calculates important operating values instantaneously
- provides an alarm history

Concurrent with the diagnostics interface, the on-board data acquisition computer monitors and stores transducer signal values at one-second intervals whenever the bus operates. This data is stored on a memory card that may be downloaded to a host computer for later analysis.

The diagnostics interface is designed either to operate on a portable computer, or on a touch screen monitor. Portable computer screen objects are selected using a mouse. Touch screens objects are manipulated by pressing the touch-sensitive cells associated with that object.

Touch screen cells are organized in a grid pattern as shown in Figure 7-49; these cells are combined to form push buttons and other screen objects. In both portable computer and touch screen configurations, color and shape are used to distinguish between the different button functions, and

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between buttons that cause an action to occur, and those that are inactive.

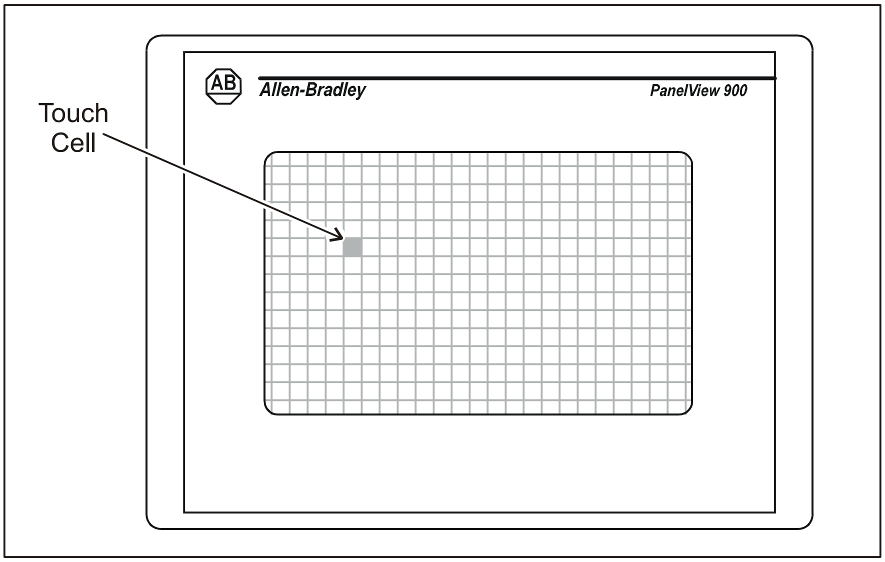

Figure 7-49 Touch Screen Active Cells

7.7.2 Diagnostic Interface Screens

The diagnostics interface is started by plugging it into the corresponding bus connector and, in the case of the portable computer version, running a program. The menu screen appears after the diagnostics interface initializes. A sample menu screen in shown in Figure 7-50.

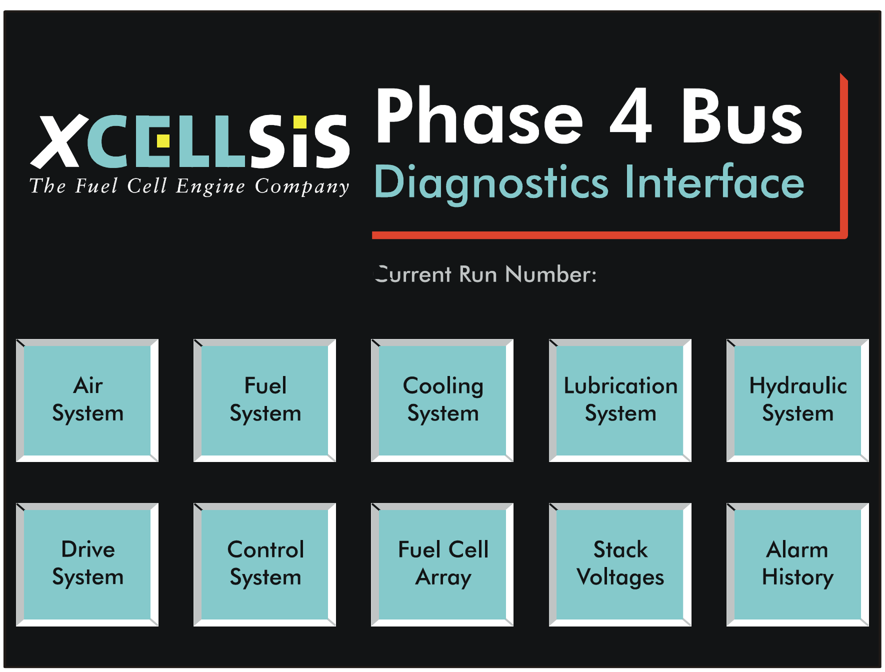

Figure 7-50 Sample Menu Screen

Key Points & Notes

The menu screen is used to select all other screens. There are fundamentally four types of screens accessible from the menu screen: schematic screens, control screens, voltage screens, and alarm history screens. A typical screen hierarchy is shown in Figure 7-51. Some screens have multiple pages.

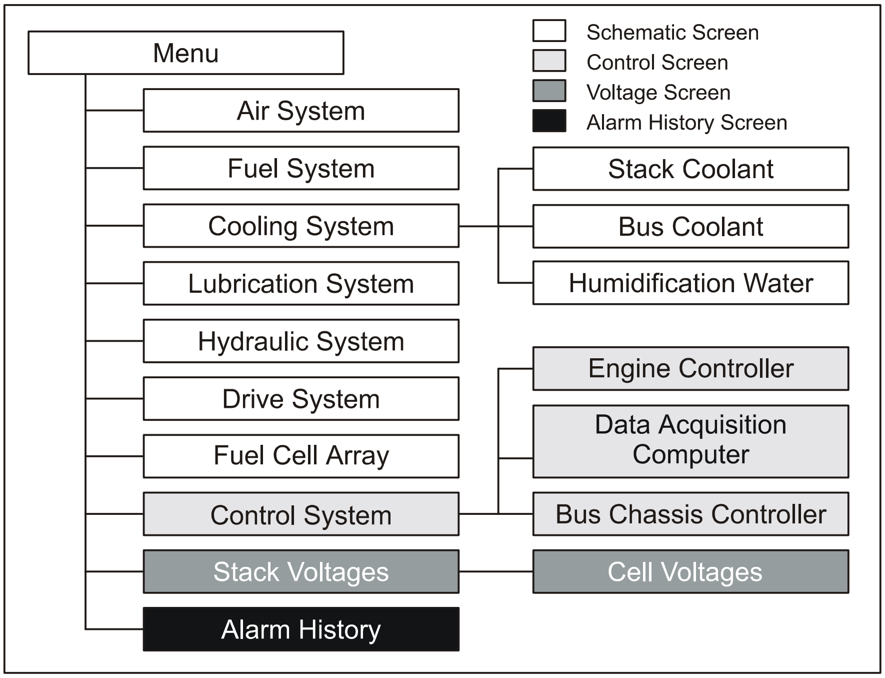

Figure 7-51 Sample Screen Hierarchy

7.7.2.1 Schematic Screens

The schematic screens present a pictorial representation of a given system. On the screen are also displayed analog values for each transducer, and state representations for each digital signal within that system.

The schematic screen uses icons or figures to represent the signal components. All signals are labeled with the tags used throughout bus documentation. When a system screen is activated, all of the icons indicate their current state, and are then updated once per second.

Signals originating with the fuel cell engine controller are tied to engine warnings and alarms. These signals have square symbols. Signals originating with the data acquisition computer are not tied to engine warnings and alarms. These signals have round symbols.

Some screens (such as this one), include other parameters, such as power and pressure readings, organized within a ta-

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ble. These data items are for display only and do not change color.

Where a numeric value appears next to an icon, the icon is for an analog signal and the value shown is the current value. Analog signals result from transducers like pressure sensors, temperature sensors, flow meters, etc. Analog signal icons have four color states used to represent *undefined* (white), *normal* (green), *warning or near-abnormal* (yellow) and *alarm or abnormal* (red) operation. Additionally, a flashing red color indicates a diagnostic system error (such as if the signal cable is unplugged).

Where a numeric value does not appear next to an icon, the icon is for a digital signal. Digital signals result from devices such as pressure switches, level switches, solenoid valves, cell voltage alarms, etc. Digital signal states are represented by icon color: green icons indicate *open*, *on*, or *normal operation* as appropriate; red, blue, purple or yellow icons indicate *closed*, *off* or *abnormal operation*, as appropriate.

As a troubleshooting aid, each schematic screen is accompanied by a table that indicates the normal operating range, warning threshold, and alarm threshold for each signal.

7.7.2.2 Control Screens

The control screens present a sequential representation of all control system inputs and outputs, upon which are displayed analog values for each transducer and state representations for each digital signal. Much of the data presented in the control screens is represented elsewhere within the schematic screens, but the control screens are organized according to the physical layout of the controller.

Key Points & Notes

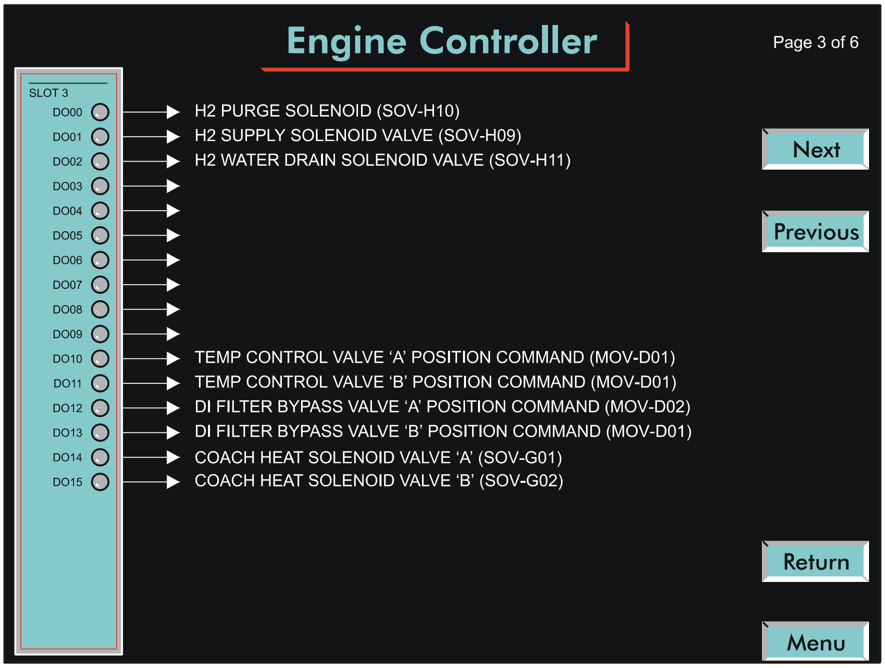

Figure 7-52 Sample Engine Controller Screen

Typically, each controller input or output card is represented on a separate control screen page. A sample engine controller screen is illustrated in Figure 7-52.

The control screen shows a list of signals with its full name and corresponding tag identifier.

Analog signals display their current value after the signal name. The values are updated once per second. The colors of the analog values do not change.

Digital signals have a light to the left of the signal name. The light illuminates green or red depending on the signal state in the same manner as within the schematic screens. If no signal is received, the light remains gray.

7.7.2.3 Voltage Screens

The voltage screens display fuel cell operating information and are divided into a stack voltages screen and a series of cell voltages screens.

Stack Voltage Screen

The stack voltages screen displays the overall voltage of each fuel cell stack. A sample stack voltages screen is illustrated in Figure 7-53.

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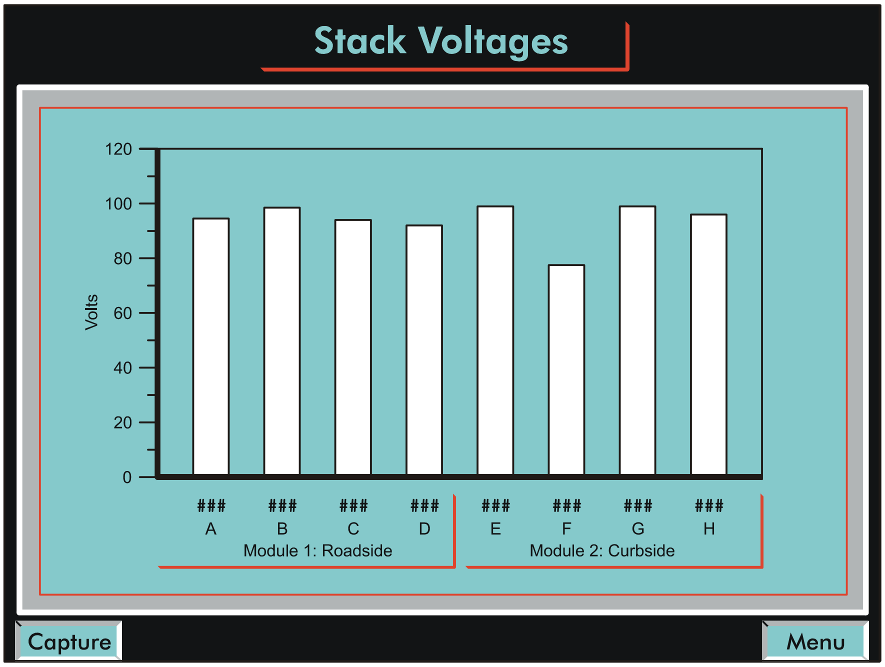

Figure 7-53 Sample Stack Voltages Screen

The stack voltages screen displays the voltage of each fuel cell stack as a bar graphs. Specific voltage levels are indicated beneath the bar for each stack. Pressing any bar displays the cell voltages screen for that stack.

The stack voltages screen includes a capture button that saves the previous 30 seconds of all fuel cell voltage data at half-second intervals when pressed. Each time the button is pressed, the data is stored to the data acquisition computer memory card using sequential file names. This data may be downloaded to a host computer for later analysis.

Cell Voltages Screens

The cell voltages screen displays individual fuel cell voltages within a given stack. A sample cell voltages screen is illustrated in Figure 7-54.

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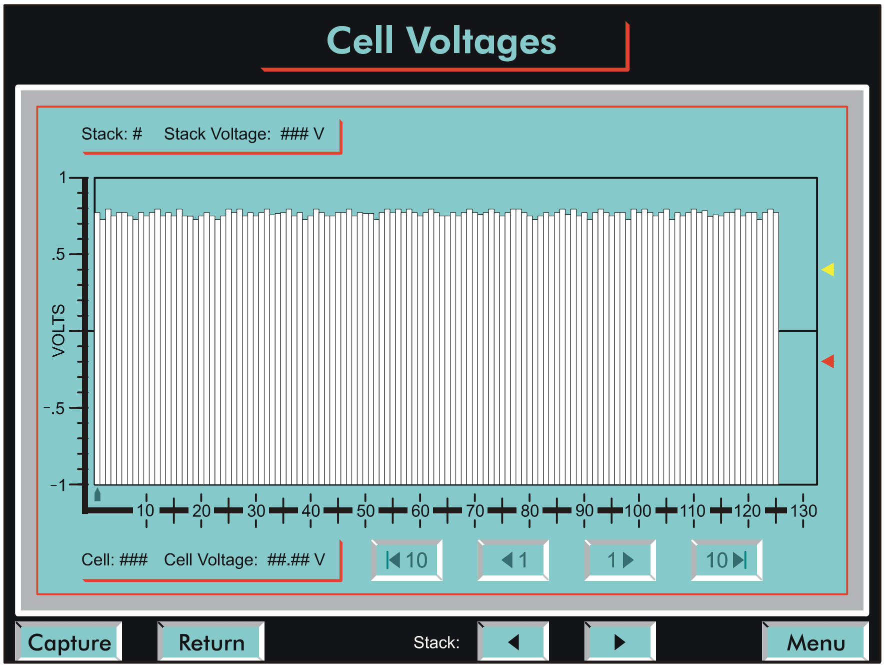

Figure 7-54 Sample Cell Voltages Screen

The cell voltages screen displays individual fuel cell voltages within a given stack as a bar graph. The stack identifier, and total stack voltage is indicated at the top left hand corner. The right and left arrow keys select other stacks.

A cursor (illustrated beneath cell 1) denotes the selected fuel cell. The selected fuel cell number and voltage is displayed at the bottom left hand corner. The 10- and 1- right and left arrow keys next to the cell voltage display change the cursor position.

The upper arrow at the right indicates the cell voltage monitor warning threshold. The lower arrow at the right indicates the cell voltage monitor alarm threshold. An intermediate cell voltage monitor alarm threshold, at 0 V, is not shown graphically.

The capture button saves cell voltage data in the same manner as the capture button on the stack voltages screen.

7.7.2.4 Alarm History Screen

The alarm history screen displays sequential warning and alarm messages. A sample alarm history screen is illustrated in Figure 7-55.

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Figure 7-55 Sample Alarm History Screen

The alarm history screen displays bus warnings and alarms in chronological order with the oldest fault displayed at the top of the list. New faults append to the bottom of the list as they are received. The cursor keys scroll through the list.

Each entry contains an `HH:MM:SS` time code (24-hour clock), the fault code, the sequential bus run number, and a `MM/DD/YY` date code. The fault list is contained on the data acquisition computer hard drive in an alarm file. Once 998 entries have been received, a new file is created.

Alarm codes cannot be logged when the data acquisition computer hard drive is removed from the bus. Once installed, fault entries are appended to the existing alarm file, or if non-existent, a new alarm file is created.

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7.8 Faults

The bus control system automatically detects unusual or unsafe operating conditions. These conditions result in fuel cell engine warnings and alarms that alert the driver by way of dashboard lights, a message display center, or other means. Cumulatively, these fault indications facilitate the process of troubleshooting engine problems.

7.8.1 Warnings

Warnings occur in response to fuel cell engine operating conditions that are outside the normal operating range but do not pose an immediate danger to passengers or risk of component damage.

When a warning occurs:

- an instrument panel light comes on
- a fault message appears on the driver's message display center (if installed), and is registered within the data acquisition computer (accessible through the diagnostics interface)
- the fuel cell engine controller automatically tries to correct the fault
- the engine does not shut down
- available power may be reduced

Warnings are not latched, and therefore clear automatically when the fault condition disappears. If the warning persists, or the fault condition worsens, an alarm may occur. If the warning does not clear, the bus should be returned to the maintenance facility for repair.

7.8.2 Alarms

Alarms occur in response to fuel cell engine operating conditions that are outside the normal operating range and may potentially pose a danger to passengers or risk of component damage. In practice, only fire and gas leak alarms indicate a potential threat to passenger safety and all other alarms conditions are designed to protect the fuel cell engine or other equipment from damage.

The bus engine must shut down in the event of an alarm. Control strategies vary as to whether the shutdown is immediate, delayed, or at the discretion of the operator. In any event, the bus should be steered to a safe location and shut down manually as soon as it is safe to do so, even if the de-

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lay associated with automatic shutdown has not fully passed.

When an alarm occurs:

- an instrument panel light comes on and a buzzer may sound
- a fault message appears on the driver's message display center (if installed), and is registered within the data acquisition computer (accessible through the diagnostics interface)
- the fuel cell engine controller automatically tries to correct the fault
- the engine either shuts down immediately or within a short period of time
- available power until shutdown may be reduced
- in the event of a fire alarm, fire retardants (if a fire suppression system is installed) discharge into the appropriate zones soon after shutdown

Alarms are latched and are reset by turning the engine off and on. The engine will not start if an alarm condition persists.

7.8.3 Fault Messages

Each warning and alarm is accompanied by a specific fault message. These fault messages are visible either through a driver's message display center, if installed, and/or the diagnostic interface (alarm history screen; Section 7.7.2.4). Fault messages are typically alphanumeric in nature and help clarify the exact nature of the fault as opposed to the generic indication that results when an instrument panel light comes on.

Supplemental fault codes may be generated by specific components, such as the inverter, transmission or leak indicators. These fault codes can be monitored and interpreted using manufacturer specific diagnostic equipment and documentation.

Multiple Faults

When an engine problem occurs, multiple warnings and alarms often result in rapid succession much like a domino effect. When a single-line driver's message display center is used, some method of prioritizing the messages is programmed into the control system. Typically:

Key Points & Notes

- alarms take precedence over warnings
- messages scroll
- messages clear once the fault condition clears
- there is a limit to the total number of messages

Fault Record

Fault messages that appear on a driver's message display center are transitory in nature, and are only visible as long as the control system is powered. In addition, the occurrence of multiple faults can obscure the initial cause of a sequence of faults. To compensate, all fault messages are stored in a permanent chronological record with the data acquisition computer. This record can be viewed on the alarm screen of the diagnostics interface, or downloaded to a host computer for later analysis.

Fault List

Fault messages are cryptic due to memory and processing requirements and may consist of only a code instead of words. The specific conditions, thresholds and controller responses associated with each fault message are cross-referenced within a fault list. The fault list may include operational messages in addition to warnings and alarms. A portion of a sample fault list is shown in Table 7-4.

An essential part of every message is the delay that occurs before the message is activated. The delay allows the controller to confirm the signal, and to let momentary conditions pass without activating the alarm. Serious faults that pose a threat to humans or equipment are given the shortest delay.

Fault conditions that do pose little or no threat to humans or equipment have longer delays. Fault conditions that are active prior to startup are given the longest delays in order for conditions to stabilize as components energize.

Key Points & Notes

Message	Fault Class	Condition
OK TO START	Message	No faults exist
OK TO DRIVE	Message	The engine has warmed up and bus is ready to drive
BUS SHUTTING OFF	Message	Voltage bleed-down is underway
STARTUP FAILED	Alarm	Startup failure
LOW FUEL PRESSURE	Warning	Low-pressure in hydrogen cylinder(s); bus is low on fuel
MODERATE GAS LEAK	Warning	Moderate hydrogen leak has been detected
SIGNIFICANT GAS LEAK	Alarm	Significant hydrogen leak has been detected
GAS SENSOR FAIL	Warning	A hydrogen sensor has failed
CHECK TRANSMISSION	Warning	A transmission fault
ALTERNATOR FAIL	Alarm	An alternator fault
FIRE ALARM	Alarm	Fire is detected
FIRE SENSOR FAIL	Warning	A fire sensor has failed
LOW OIL PRESSURE	Warning	Low oil pressure

Table 7-4 Sample Fault List (Portion)