50316
AUTOMATIC PRESSURE STANDARD
USER'S MANUAL

9/90
MANUAL #57-2

DH Instruments, Inc. • 1905 West Third Street • Tempe, AZ 85281 • Tel 602 / 967-1555 • Fax 602 / 968-3574

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CHAPTER 1 - INTRODUCTION

1.1 PRODUCT OVERVIEW

The DH Model 50316 Automatic Piston Gauge is an oil operated fundamental pressure standard designed for the automatic calibration of pressure gauges, transducers, and transmitters.

When equipped with various piston-cylinders, the instrument defines pressures ranging from 40 to 75 000 psi. This range may be extended in both directions using DH pressure multipliers and dividers to include pressures below atmospheric pressure, differential pressures, or high pressures to 150 000 psi.

The 50316 mechanically loads masses onto the piston assembly in response to commands output from the Piston Gauge Interface (PGI). These commands can be entered either manually on the PGI front panel or by a host computer using an IEEE 488 interface.

Once the specific masses are loaded onto the piston assembly, the piston can be floated using an outside pressure source or DH equipment such as a priming system and a servo-controlled variable volume (SCVV). When the piston is floating and at equilibrium the pressure defined by the 50316 can be stated as:

$$P = \frac{Mg}{A}$$

Where P = pressure defined by the 50316
M = mass loaded
g = gravity
A = effective area of the piston-cylinder

The 50316 comes in a standard 19" wide panel rack enclosing PGI, mass handling components and framework. To assure good environmental control and cleanliness of the metrological elements, the unit is sealed in the back with cover plates and in the front with a transparent, lockable door.

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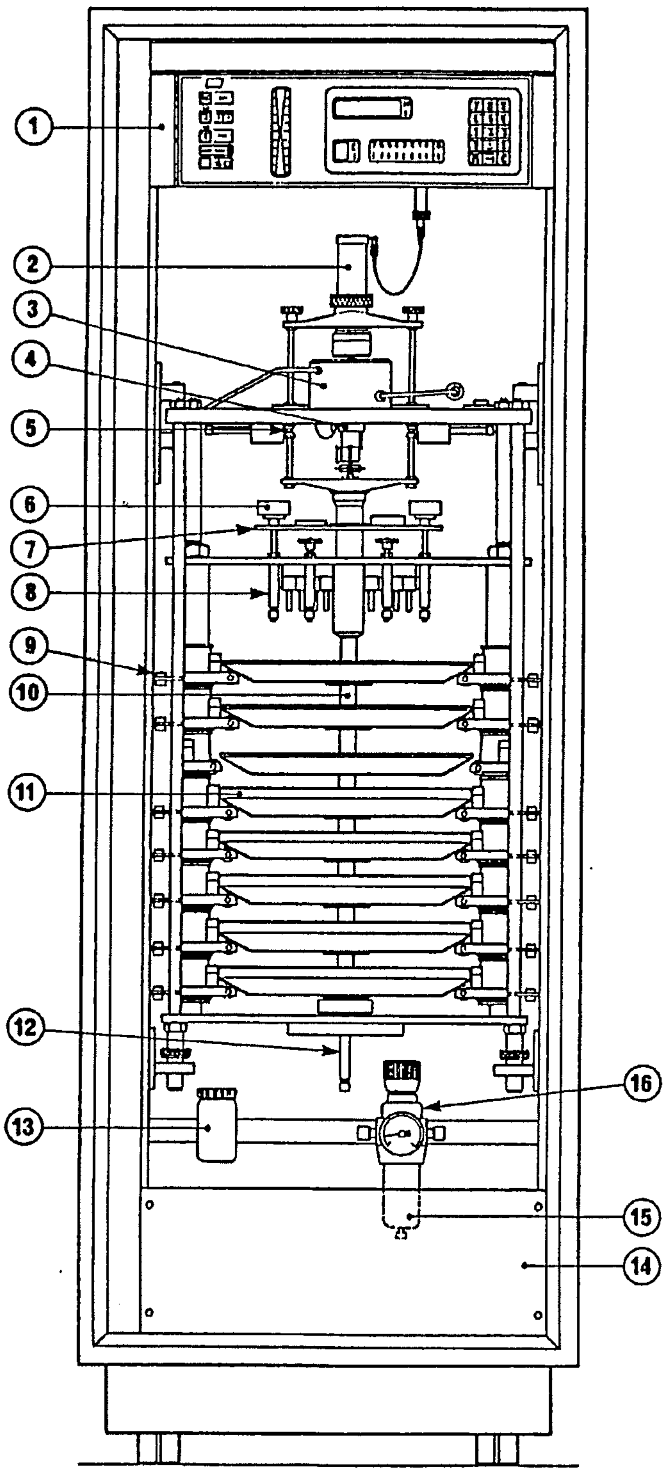
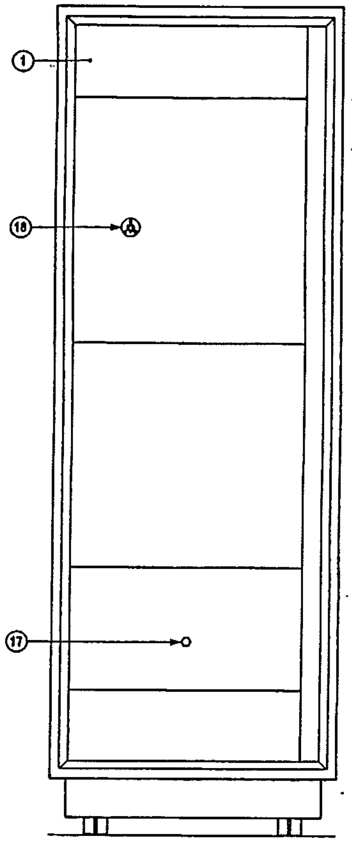
1.2 LOCATION OF THE COMPONENTS



UNIT FRONT

1) Piston Gauge Interface (PGI) module
2) Piston rotation drive motor
3) Measuring post for mounting of the piston-cylinder
4) Piston position detector
5) Vertical centering mechanism (optional)
6) Small masses, either 1 g to 1024 g or 0.1 g to 1024 in binary sequence
7) Small mass carrying plate
8) Small mass actuator
9) Large mass actuator assembly
10) Mass carrying vertebrae
11) Large mass, binary sequence
12) Mass shaft actuator
13) Oil runoff cup
14) Solenoid valve and actuator control module
15) Air line moisture trap
16) Air regulator/lubricator

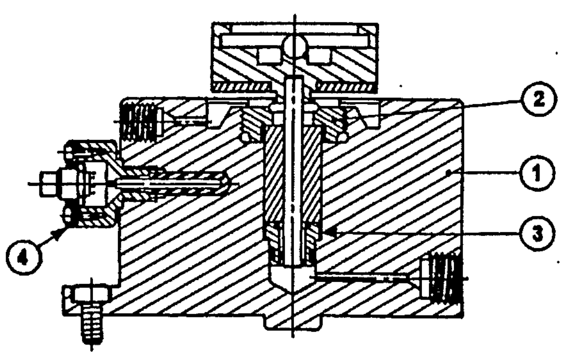


UNIT BACK

1) Piston gauge interface module
17) Compressed air supply connection
18) Pressure output connection, type DH 5000 ref.

1.3 SUBASSEMBLY DESCRIPTION

- **Piston-Cylinder Mounting Block** - A stainless steel housing which contains the piston-cylinder. A cylinder retaining nut (2) is used to hold the cylinder onto a seal assembly (3), allowing the mounting system to be a free deformation type.



A platinum resistance thermometer (4) is screwed into the thermal mass of the block to measure the piston-cylinder temperature while pressure measurements are being taken. The PRT has a four-wire type resistance output that can be read through the PGI on the IEEE 488 bus or by a remote ohmmeter.

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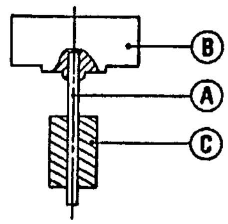
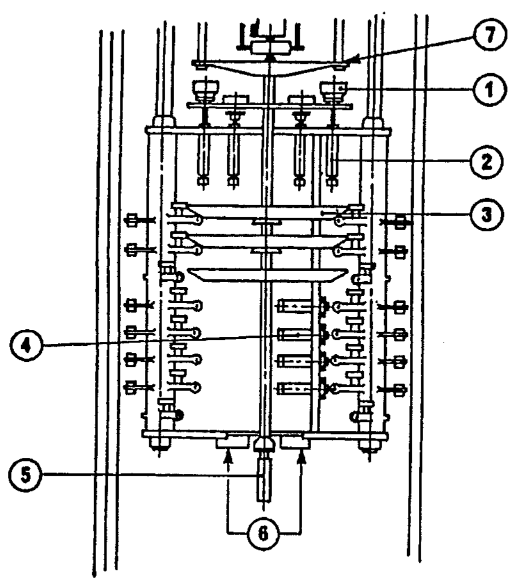
- **Piston-Cylinder** - The fundamental metrological element which transforms a pressure into a measurable force. Each piston-cylinder includes a piston (A) equipped with a plate (B) for coupling to the drive motor, and a cylinder (C).



Most DH piston-cylinders are interchangeable thanks to the fact that all pistons have the mass adjusted to 200 grams and all cylinders used in the 50316 have the same external dimensions.

The piston-cylinders are delivered in a special case with an installation tool.

- **Mass Handling System** - A stainless frame which supports the parts required for loading and unloading the masses onto the piston. The lifting system consists of a series of hinged arms moved by actuators (4) for the loading and unloading of the large masses (3) onto the mass carrying vertebrae, a series of individual small actuators (2) for the placement of the small masses (1) on the mass carrying tray, a mass shaft actuator (5) which lifts the whole mass carrying shaft to allow a lower tare mass value and therefore a lower minimum pressure, and a bridge assembly to couple the loaded masses to the piston.



The small and large masses can be loaded by hand with the two allen screws (6) removed to enable the lowest large mass to be placed.

- **Actuator and Solenoid Valve Module** - Contains the solenoid valves and pneumatic valves which control the individual mass actuators. Each pneumatic actuator channel is controlled by a solenoid powered selectively to load various mass sequences.

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- **Piston Gauge Interface (PGI)** - Directs the operations of a type 50000 automatic pressure standard in response to commands entered either manually on the front panel or received by a computer via an IEEE-488 bus interface. The PGI controls several different functions such as:

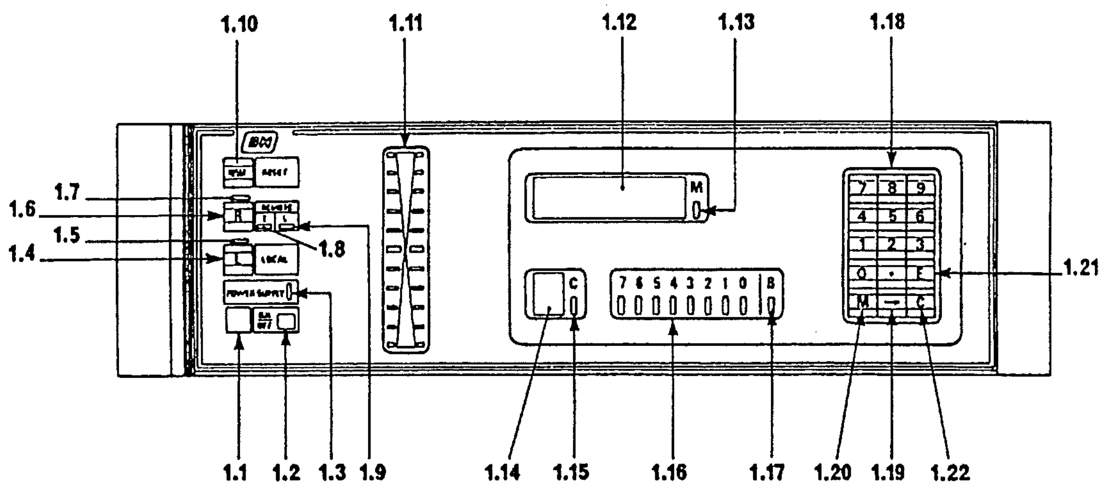
  - Loading or unloading of individual masses on the piston to achieve the total mass load required by controlling the corresponding solenoid valves.

  - The detection of piston position and the proportional display and voltage output of the position.

  - Measuring of the resistance of the platinum resistance thermometer used to monitor the temperature of the piston-cylinder so that the effective area can be compensated thermally. This resistance can also be read by a multimeter via the IEEE bus.

  - Measuring of the resistance of a reference resistor located in the PGI to enable correction of the multimeter readings for the various effects in the measuring circuit.

  - Operation of other solenoid valves than those used in the mass loading described above. These valves can be used for optional functions such as vertical centering of the piston in its stroke or for control of other functions external to the instrument like system priming and hydraulic control of other components.



Front Face

1.1) Main power pushbutton
1.2) Power indicator
1.3) Power supply voltage indicator
1.4) Local (front panel control) mode selector
1.5) Local mode indicator
1.6) Remote (computer control) mode selector
1.7) Remote mode indicator
1.8) IEEE-488 bus talk mode indicator
1.9) IEEE-488 listen mode indicator
1.10) Reset switch
1.11) Piston position indicator
1.12) Mass value display in kilograms
1.13) Mass loading mode indicator
1.14) Card number display
1.15) Card selection mode indicator
1.16) Individual bit displays of the selected card
1.17) Bit function indicator
1.18) Manual data entry keyboard

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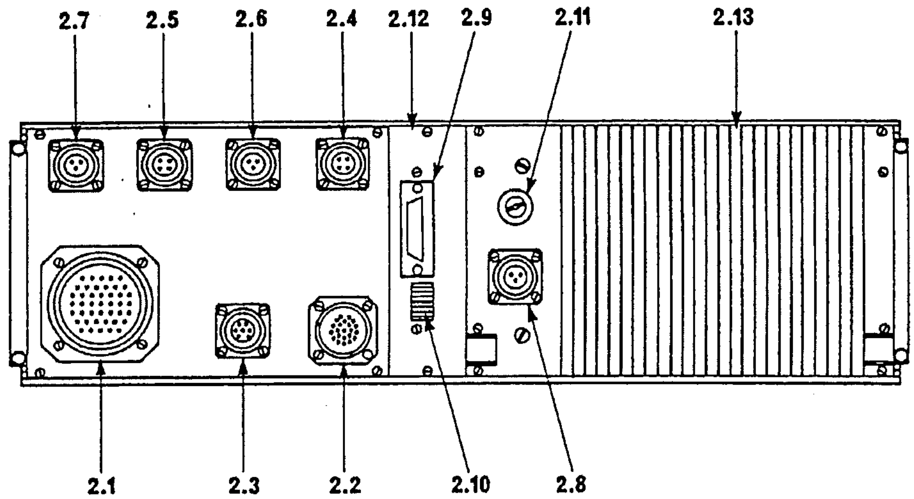

Rear Panel

Connectors for functions internal to the standard

2.1) Output to the solenoid valves, ref EF 443 AP
2.3) Piston position detector input, ref EF 17 P
2.4) Platinum resistance thermometer input, ref EM 17 P
2.6) Power to piston drive motor, ref EF 13 U
2.8) AC power to the PGI, ref EM 13 U

Connectors for functions external to the standard

2.2) Output of the relay card of the PGI (optional), ref EM 222 P
2.5) PRT output to a multimeter, used with the extra 4 connector cable supplied, ref EF 14 V
2.7) Output of the ±10 V piston position signal, ref EM 14 V
2.9) IEEE-488 bus

Miscellaneous

2.10) IEEE-488 address selection DIP switch
2.11) Fuse, 2 A slo-blow
2.12) IEEE interface module
2.13) Power supply module

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1.4 SPECIFICATIONS

Accuracy:
- N and N' Class: 0.03% of reading
- S Class: ± 0.01% of reading
- S2 Class: ± 0.005% of reading
- S' Class: ± 0.02% of reading

Pressure Range:
- 30 psi to 72,500 psi (0.2 MPa to 500 MPa)

Repeatability:
- 1/10 of stated accuracy

Mass Increments:
- Minimum mass: 2 kg
- Maximum mass: 102.303 kg
- Minimum increment: 1 gram (0.1 gram and 1 kg optional)
- Number of increments: 100,303 (1,003,045 and 98 optional)

Power Consumption:
- 250 VA

Fuse:
- 2 A slo-blow

Dimensions:
- 24"(610 mm)W x 24"(610 mm)D x 70"(1778 mm)H

Weight: 450 lbs.

Drive air:
- 75 psi, 0.2 SCFM to 120 psi

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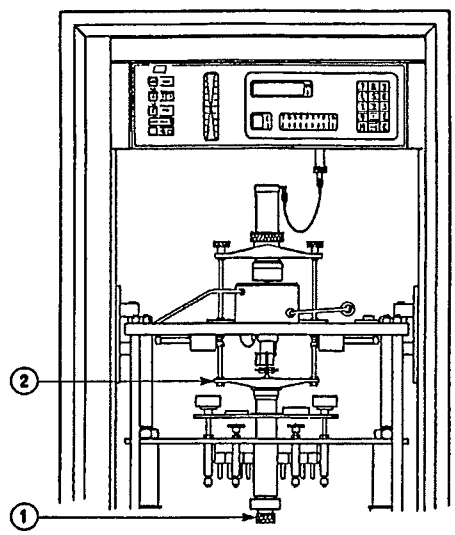
CHAPTER 2 - INSTALLATION

2.1 UNPACKING AND INSPECTION

The 50316 is delivered in a padded, six-piece crate. Once the crate is disassembled, the standard may be carefully removed and stood onto its wheels. CAUTION: Be careful when standing the unit, as the bottom of the rack will slide when the wheels contact the floor. Use some method to prevent this sliding until all four wheels are in contact with the ground. The following precautions have been taken to protect the unit during transportation:

- The piston-cylinder, masses, and mass carrying vertebrae have been removed and placed in their special boxes.
- A red locking collar (1) has been screwed into the mass carrying assembly to lock it into place.
- The actuator air supply regulator is set to 0 psi.
- The rack leveling feet are screwed fully in so that the unit may be moved on its wheels.
- A solid stainless steel plug is in place in the cylinder cavity of the mounting post.



A standard set of accessories is included with each standard as described below:

- User's manual
- Calibration Certificate and Technical Data
- O-ring mounting key ref. 40957
- O-ring assembly ref. 41096
- Liter of Hydraulic Fluid
- Quick connector, air ref. 48192
- Wrench, 10 x 12 mm
- Wrench, 13 x 17 mm
- Wrench, 16 x 18 mm
- Wrench, 18 x 19 mm
- Wrench, 19 x 24 mm
- Wrench, Allen, 4 mm
- Wrench, Allen, 6 mm
- Wrench, Socket, 8 mm
- Air hose
- Spare fuses
- PRT cable
- Power cable
- Gland, DH 5000 ref.
- Plug, DH 5000 ref.

2.2 SITE REQUIREMENTS

The 50316 can be installed in any location where the floor is relatively flat. Areas of high ambient vibration should be avoided. A source of clean, dry shop air must be available as well as either 110 or 220 VAC, depending on the standard purchased.

The standard can be moved to the required location by rolling it on its wheels. Some caution is required to be sure that the rack is pushed at a vertical point lower than the center of gravity to avoid toppling, or two people should be used to apply equal support for both sides of the unit.

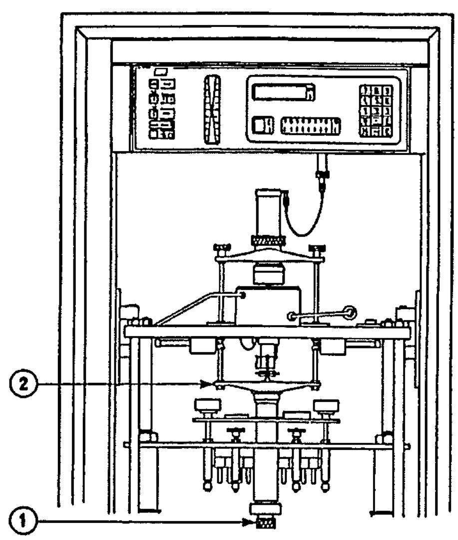
2.3 INITIAL SETUP

- **Leveling The Standard**

  Level the standard with the four leveling pads under the rack using the 19 mm wrench. Refer to the bubble level on the top plate of the mass handling system for level indication. Do not worry at this time about a precise level since the process should be repeated once the masses have all been loaded.

- **Removing The Locking Collar**

  Unscrew and remove the red locking collar (1) shown in the figure below. The mass carrying bridge (2) is now free to move.



- **Connecting The Standard To An Air Supply**

  Connect the supplied flexible air hose to an appropriate connector using a hose clamp and then to a shop air supply circuit. Push the quick connector on the other end of the hose onto the mating fitting on the back of the rack. Pressurize the pneumatic line and check for leaks. Adjust the air regulator located inside the rack, beneath the mass handling assembly, to 80 psi (0.55 MPa).

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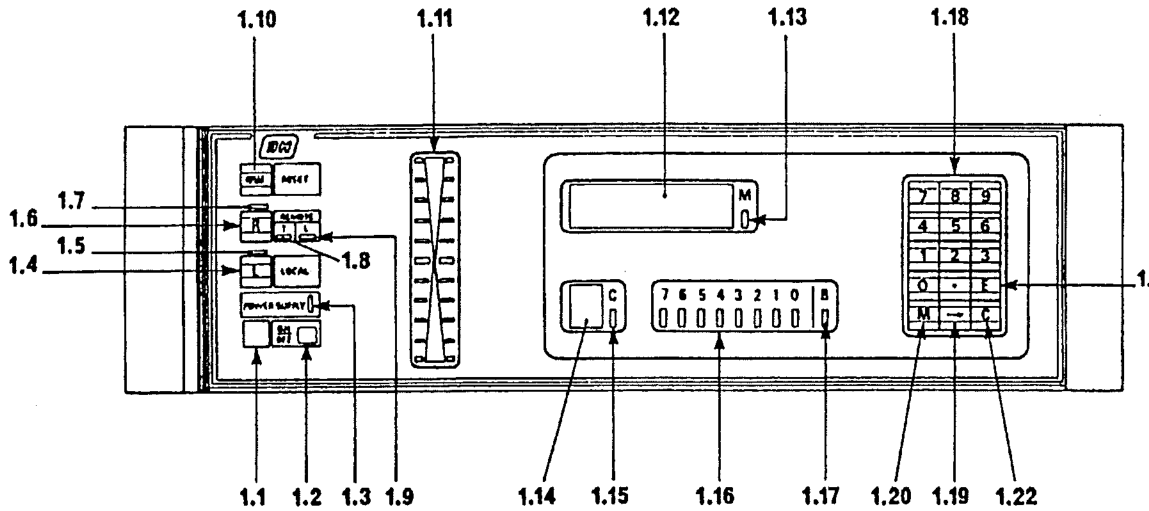
- **Installing The Large Masses**

1) Remove the mass shaft actuator (12 in the overall system drawing) from the mass handling assembly bottom plate by unscrewing the two socket head screws.



2) Turn on the PGI. Actuate the 2048 gram mass loader by pressing "C" (1.22) then "1" on the keyboard to select card 1. Press "E" (1.21) to select the enter mode and then "3" on the keyboard to select bit 3. The top set of lifters will spread allowing insertion of the 2048 gram mass. Hold the mass in place and press "3" again. The arms will close on the beveled edge of the mass, supporting it. Keep hands in the center of the mass to avoid contact with the closing lifter arms.

3) Slip vertebra #1 of the mass carrying shaft through the central hole of the mass and hand tighten into the mass carriage above. If a problem occurs when inserting the vertebra into the carriage, check to see that the retention ball of the vertebra is fully in. If not, rotate the top of the vertebra counter-clockwise until it is.

4) Using two 18 mm wrenches, hold the mass carriage at the flats on the shaft and tighten the vertebra moderately. Place a 4 mm allen wrench into the socket head lock screw in vertebra bottom and tighten.

5) Install the rest of the large masses and vertebrae following steps 2 through 4. The corresponding PGI bit assignments are below:

Mass (grams)	Card	Bit
4096	1	4
8192	1	5
16384	1	6
32768 (16384, #1 and #2)	1	7
32768 (16384, #3 and #4)	2	0

6) Install the lower element into vertebra #8. Lightly tighten the element while holding the preceding vertebra with an 18 mm wrench. Place a 4 mm allen wrench into the socket head lock screw in the bottom of the lower element and tighten.

7) Reinstall the mass shaft actuator to the bottom of the lower plate of the mass handling assembly.

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- **Installing The Small Masses**

With the 50316 connected to the compressed air supply, the ends of the small mass actuators will protrude through the holes in the small mass carrying tray. When the corresponding mass solenoid is activated, the appropriate actuators are retracted and the masses may be placed in the tray.

NOTE: For mass values of 1 to 8 g, only one actuator is used. For those masses above 8 g, two separate masses whose sum is equal to the required mass value are installed.

The bit assignments used for the various small masses for both the 1 gram and the 0.1 gram options are described in Chapter 5 - Interfacing.

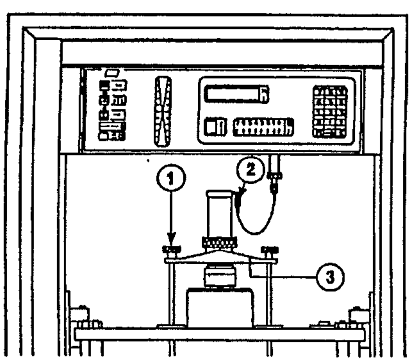
- **Cleaning The Piston-Cylinder**

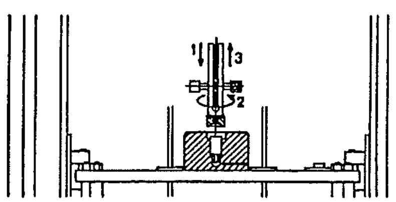
Before installing, the piston-cylinder should be cleaned with some type of nonresidual type solvent such as Freon or chlorothene using the following procedure:

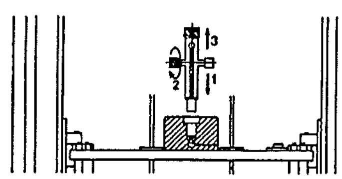
- Immerse the cylinder in the solvent and wipe both the inside and the outside with a lint free cloth.
- Immerse the shaft portion of the piston in the solvent and wipe thoroughly with a lint free cloth. Do not immerse the top plate portion of the piston as fluid can be trapped in the grooves or mass cavity and cause a mass error. Wipe the top plate with a cloth only.
- Slide the piston into the cylinder with the numbered end of the cylinder facing the piston top plate. If the piston and cylinder are clean, they will move freely. If not, reclean both.
- Once the piston-cylinder is clean, dip the piston shaft into some of the lubrication fluid and put the piston back into the cylinder to lubricate both parts. Make sure that no lubrication fluid contaminates the piston top plate. Do not invert the piston when the shaft is coated with oil.

- **Removing The Cylinder Plug From The Standard**

Unscrew the motor power supply cord (2). Unscrew the two knurled knobs (1) and lift the bridge (3) and motor assembly off of the tie rods.







Using the end of the special cylinder tool with the raised tabs, unscrew the notched cylinder retaining ring in the mounting post. A spring-loaded ball will keep the nut on the tool. Turn the tool over and slip the open end of the tool over the cylinder plug and tighten the tool screw. Pull out the plug.

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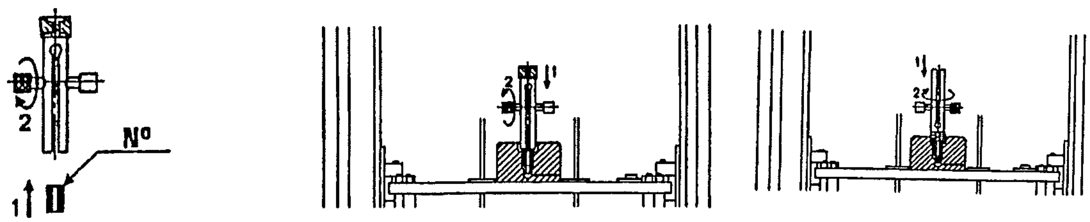
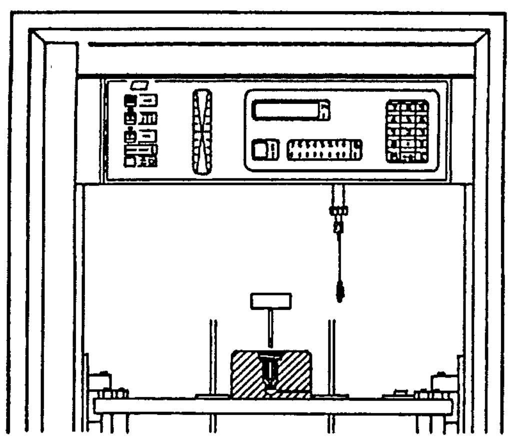
- **Installing The Cylinder**

Remove the cylinder plug from the tool and insert the cylinder into the tool with the numbered end in the tool. Slide the cylinder into the mounting post. Invert the tool and reinstall the cylinder retaining nut. Hand tighten until the nut seats snugly against the cylinder. Do Not force.



- **Installing The Piston**

Bring oil to the top of the cylinder using an external pressure generation source. Keep the oil flowing through the cylinder until no air bubbles are noted in the fluid. If the 50316 is part of a larger automated system such as a DH Model 50300 with automatic priming, refer to that section in the system manual.



Slide the piston into the cylinder. If necessary, lower the oil level in the mounting post using the hydraulic exhaust valve. Keep the piston top plate slightly above the measuring post to prevent displaced oil from contacting the bottom of the plate.

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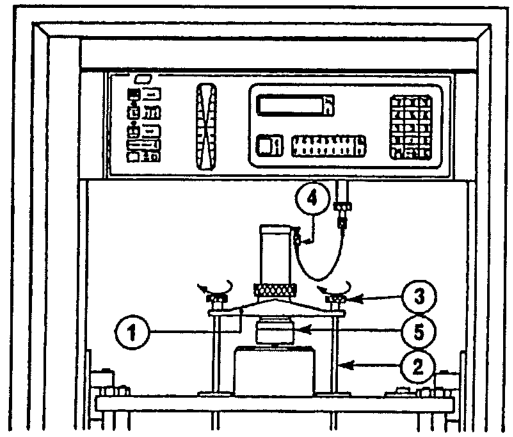
- **Installing The Bridge And Connecting The Motor To The Piston**

Lower the bridge (1) and motor assembly onto the tie rods (2) of the mass carrying assembly. Reinstall and hand tighten the two knurled nuts (3). Push down the piston lock-out (5) while pulling lightly on the lock-out retainer pins and turn 1/6 of a revolution until the system snaps into place. The pins should now be visible in the piston plate holes.



Reconnect the motor power supply cable (4).

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CHAPTER 3 - OPERATION

3.1 PRELIMINARY STEPS

Be sure that all the initial setup procedures listed in Chapter 2 have been done. In addition, using the steps described in the following checklist will assure good metrological integrity of the measurements taken:

- Clean the piston-cylinder before installing
- Make sure the cylinder is mounted with the numbered end up
- Be sure that the two knurled nuts on the mass carrying tie rods are tight
- Check the motor to drive connection for proper alignment
- Purge all air from the hydraulic circuit
- Check that the piston is rotating
- Always put the piston at the bottom of the stroke before large reductions of pressure
- Calibrate the instrument under test in an orientation as close to its normal operating mode as possible
- Frequently recheck that the standard is level

Whenever the piston or the piston and cylinder are removed and reinstalled, the hydraulic circuit is broken, or a hydraulic leak is suspected, the following quick procedure should be used to seat all components and check for system leaks:

1) With the standard on and the piston rotating, load the 8192 g mass.
2) Increase system pressure until the piston is at the upper stroke limit.
3) Leave the standard under pressure for a few minutes to assure that all the components of the measuring post are properly aligned and no system leaks are present.
4) Slowly reduce the system pressure until the piston reaches the lower end of the stroke and vent all pressure.

3.2 TAKING PRESSURE MEASUREMENTS

Once all the setup and preliminary steps are done, the standard may now be used to define pressure. The steps necessary to define this pressure are: 1) Load the required mass for the desired pressure. 2) Float the piston. 3) Maintain the piston within an acceptable displacement range from the exact center of its stroke (piston in equilibrium).

Many different hardware configurations are possible for controlling the 50316, but they can be generally listed by three levels:

1) Manual control - The mass required is calculated and loaded by the user. The PRT output is monitored by an ohmmeter and used for the calculation. This control mode requires some method of increasing system pressure and floating the piston besides the Pressure Generation Bench normally supplied by DH.

2) DH 50300 System automatic control - Consists of the 50316 and a DH Pressure Generation Bench which contains a Servo-controlled Variable Volume (SCVV), a priming system (either option 01 or option 02), a Pressure Control Interface (PCI), and an optional IEEE-488 interfaceable multimeter. The priming system is controlled by extra bits on the solenoid cards of the PGI

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of the 50316 and the SCVV is controlled by the PCI. All components communicate via an IEEE-488 interface bus.

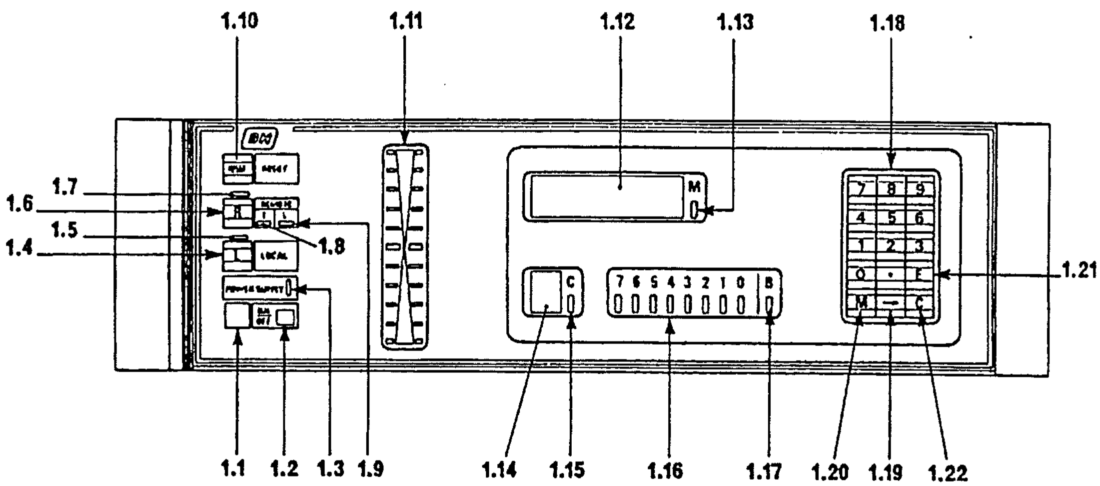
3) Computer control - This mode of control uses a host computer, supplied by DH or the user, in addition to all the hardware listed is #2 above. The computer controls mass loading and system priming with the PGI, and floats the piston and maintains piston equilibrium with the PCI via commands sent on the IEEE-444 bus.

All of these levels can be done with commands by the user from the front panels of the components or a host computer; or, for a true turn-key system, DH Instruments can provide COMPASS 50000 pressure control and calibration software.

3.3 MASS LOADING

To load a mass or combination of masses onto the piston, corresponding bits of the solenoid cards of the PGI must be set (state of 1). The PGI must be in Local mode ((1.4 illuminated). This condition is true on initial power-up of the PGI or may be selected under computer control. As described in Chapter 2, the procedure for selecting the mass to be loaded is:

1) Using the keypad on the PGI front face, press "C" (1.22) to select the card mode of entry.
2) Press the number of the desired card to be selected on the keypad.
3) Press "E" to enter the bit selection mode.
4) Press the number of the desired bit to be set on the keypad.



The card and bit assignments for the masses are:

MASS (g)	CARD	BIT
1 through 128	0	0 through 7
256 through 32768	1	0 through 7
32768	2	0

Pressing the pushbuttons corresponding to these masses will cause the mass to toggle between the load or unload state depending on its previous state. For example, if the bit was previously set (mass loaded), depressing the pushbutton will cause the mass to unload. The correspondingly numbered bit on display (1.16) will indicate the state of the bit.

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It is also possible to load and unload masses temporarily by using the pushbuttons in a momentary switching manner. In this case, the mass change will only last as long as the pushbutton is depressed. This is accomplished, after the card mode has been selected, by pressing the right arrow key (1.19) to select the momentary mode which will cause all bits on the display (1.16) to go off. Then press the key numbered with the bit to be operated. As long as this key is depressed, the mass selected will be loaded and the corresponding bit indicator will be lit.

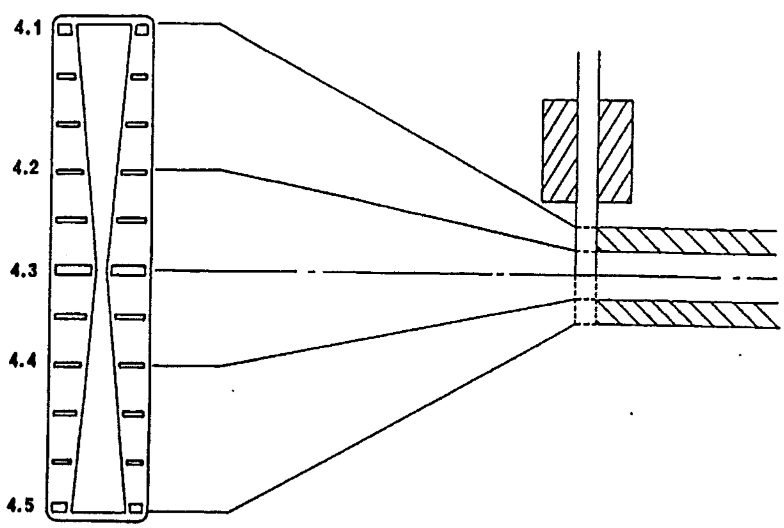
In either the normal or the temporary loading mode the total mass loaded in kilograms will be indicated on the display (1.12).

If the masses are to be loaded under computer control, see Chapter 5 - Interfacing. A complete description of all the mass loading cards, bits, and pinouts is included in this chapter.

3.4 FLOATING THE PISTON

Once the correct mass value has been calculated and loaded, system pressure needs to be increased until the piston is floating between the upper and lower limits of its stroke. This can be done using a DH Pressure Generation Bench (with or without a host computer), or some other pressure generation system available to the user. The DH bench is covered under an additional manual which, combined with this manual, comprises the complete instructions for a DH 50300 pressure standard.

However the pressure is increased or decreased to the 50316, once the piston begins to move, its position in the stroke can be monitored in two ways. First, the PGI front panel will show the piston position on the digital bar display (1.11) with the stroke limits and midfloat position (referenced to the label on the front of the measuring post) indicated by thicker markings on the scale.



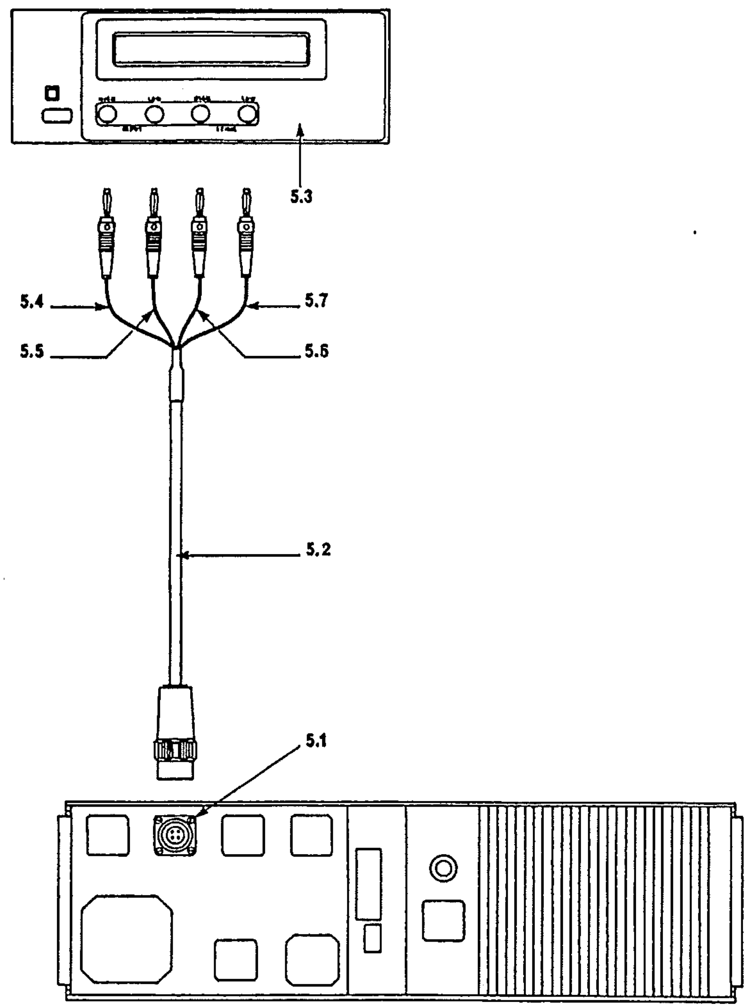
4.1 - Upper stroke limit
4.2 - Top of measuring zone
4.3 - Reference height (midstroke)
4.4 - Bottom of measuring zone
4.5 - Lower stroke limit

Second, the PGI has an output voltage available, proportional to the piston position, which can be read both on the IEEE-488 bus (see Chapter 5) and as an analog signal on connector 2.7 on the rear panel of the PGI. In both cases, the signal is +10 V to - 10 V with 0 V indicating the midfloat position. The resolution is 100 mV.

3.5 READING THE PLATINUM RESISTANCE THERMOMETER

A platinum resistance thermometer is mounted in the rear of the mounting post. This is used to monitor the piston-cylinder temperature so that the effective area can be corrected for thermal effects.

An ohmmeter or multimeter with computer interface and four-wire resistance measurement capability is required for the measurement. This device can be provided by DH Instruments if requested.



The reading of the PRT is accomplished by connecting the provided four-wire cable to the connector (5.1) on the rear panel of the PGI, connecting the four plugs to the readout device, and closing the PRT relays using the "S" command as described in the chapter on interfacing.

The hookup to the meter is as follows:

- Yellow wire (5.4) - Input high
- Green wire (5.5) - Input low
- Brown wire (5.6) - Sense high
- White wire (5.7) - Sense low

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CHAPTER 4 - CALCULATIONS

4.1 FUNDAMENTAL THEORY

The general pressure formula can be used to give the pressure at the reference level of a standard according to:

$$P = Mg\frac{\left(1-\frac{\rho_a}{\rho_m}\right)}{A_{(\theta,P)}}$$

Where:

P	=	Nominal pressure required
M	=	Total mass loaded on the piston
g	=	Acceleration due to gravity
ρ_a	=	Air density
ρ_m	=	Mass density
$A_{(\theta,P)}$	=	Effective area of the piston-cylinder at temperature 0 and pressure P

The parenthetical expression containing the air and mass densities is the correction due to the effect of air buoyancy on the masses. Under standard gravity and air density conditions, pressure is defined as:

$$P = Mg_n\frac{\left(1-\frac{\rho_a}{\rho_n}\right)}{A_{(\theta,P)}}$$

Where: $g_n = 9.80665 \text{ m/s}^2$

Using the expression: $$Kn_{(\theta,P)} = g_n\frac{\left(1-\frac{\rho_a}{\rho_m}\right)}{A_{(\theta,P)}}$$

And using substitution yields: $$P = Kn_{(\theta,P)}M \qquad (2)$$

The effective areas of DHI piston-cylinders are controlled so that Kn is a whole number when θ = 20°C and P = zero. The term Kn is called the normal conversion coefficient and represents the pressure created under standard conditions when a mass load of 1 kg, placed onto the piston-cylinder is put into equilibrium.

Many different piston-cylinders, which can be used with the specific models purchased, allow combinations to be tailored to specific applications. Kn's with pressure units per kg in both psi and MPa are available. A complete list can be found in the DH Type 50000 Automated Piston Gauge brochure.

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4.2 GRAVITY CORRECTIONS

The Kn given in the piston-cylinder calibration certificates is referenced to the standard gravity value of 9.80665 m/s^2. Since the acceleration due to gravity, gl, at the location where the standard is used is usually different from this number, a means of adjusting the defined pressure to the new gravity is required. This correction can be derived as below.

Since:

$$P = Mgl \frac{\left(1-\frac{\rho_a}{\rho_m}\right)}{A_{(\theta,P)}}$$

By setting:

$$Kl_{(\theta,P)} = gl \frac{\left(1-\frac{\rho_a}{\rho_m}\right)}{A_{(\theta,P)}} \qquad (3)$$

One obtains:

$$Kl_{(20,0)} = gl \frac{\left(1-\frac{\rho_a}{\rho_m}\right)}{A_{(20,0)}} \qquad (3')$$

$$Kl_{(20,0)} = gn \frac{\left(1-\frac{\rho_a}{\rho_m}\right)}{A_{(20,0)}} x \frac{gl}{gn}$$

$$Kl_{(20,0)} = Kn_{(20,0)}\, x \frac{gl}{gn}$$

$Kl_{(20,0)}$ is the local pressure to mass conversion, which is defined by the piston-cylinder used and the location where it is used.

4.3 TEMPERATURE AND PRESSURE DISTORTION CORRECTIONS

When the piston-cylinder temperature is other than 20°C and the gauge pressure is other than zero, the change in effective area is defined by:

$$A_{(\theta,P)} = A_{(20,0)}\,[1+(\alpha_c+\alpha_p)(\theta-20)]\,(1+\lambda P) \qquad (4)$$

Where:

$A_{(\theta,P)}$ = effective area at temperature θ and pressure P

$A_{(20,0)}$ = effective area at 20°C and pressure of zero

α_c = thermal coefficient of expansion of the cylinder

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α_p	=	thermal coefficient of expansion of the piston
θ	=	temperature of the piston-cylinder
λ	=	pressure distortion coefficient of the effective area
P	=	pressure

4.4 TEMPERATURE CALCULATIONS

Most DH pressure standards come with platinum resistance thermometers mounted in the measuring blocks which contain the piston-cylinders. The output of these PRT's are used to calculate the temperature, θ, of the piston-cylinder so that the effective area value can be compensated. This correction is valid over the range of 0 - 40°C. The temperature is proportional to the resistance according to the following formula:

$$\theta = \frac{(R\theta - R0)}{0.389}$$

Where:

θ	= temperature in degrees C
$R\theta$	= resistance of the platinum RTD at temperature θ
$R0$	= resistance of the platinum RTD at 0°C
0.389	= conversion for ohms to degrees C according to DIN norm 43760

To eliminate the effect of the measurement wiring on the resistance of the PRT, a four-wire measurement system is used. Two of the wires are used to provide a constant 5 mA maximum power to the RTD and two are used for the measurement.

4.5 GENERAL FORMULA

By combining and substitution of the previous equations, a general equation can be derived in which the specific operating parameters at the test point can be entered to find pressure:

$$Kl_{(\theta,P)} = Kl_{(20,0)}\ x\ [1-(\alpha_c+\alpha_p)(\theta-20)]\ (1-\lambda P)$$

If we let:

$$C_\theta = [1-(\alpha_c+\alpha_p)(\theta-20)$$

and:

$$C_g = \frac{gl}{gn}$$

Then:

$$Kl_{(\theta,P)} = Kl_{(20,0)}\ x\ C_\theta\ x\ (1-\lambda P)$$

And since:

$$Kl_{(20,0)} = Kn_{(20,0)}\ x\ C_g$$

We get for pressure:

$$P = Kn_{(20,0)}\ x\ C_g\ x\ C_\theta\ x\ (1-\lambda P)\ x\ M$$

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4.6 FLUID HEAD CORRECTIONS

The calculations in the previous sections are used to define the pressure at the reference level of the piston, in most cases the bottom of the piston. This position is identified on the standard, when the piston is at the midfloat position, by a label marked "reference level" on the standard.

When it is not possible to align the reference levels of the instrument under test and the standard, a correction defined by the following formula must be made:

$$\Delta P = \rho \; x \; g \; x \; \Delta h$$

Where:

- ΔP = fluid head correction
- ρ = density of the fluid at operating pressure P
- Δh = difference in height between the reference levels of the standard and the instrument under test
- g = acceleration due to gravity

The ΔP correction is negative if the instrument under test is above the reference level of the standard or:

$$P_{\text{instrument under test}} = P_{\text{standard}} - \Delta P$$

The ΔP correction is positive if the instrument under test is below the reference level of the standard and therefore:

$$P_{\text{instrument under test}} = P_{\text{standard}} + \Delta P$$

4.7 SAMPLE CALCULATIONS

Assuming that the following parameters are given on the calibration report and technical data for the standards used:

- $A_{(20,0)}$ = measured effective area at 20°C and zero gauge pressure
- $Kn_{(20,0)}$ = pressure to mass conversion at 20°C, zero gauge pressure, and standard gravity
- α_p = thermal coefficient of expansion for the piston
- α_c = thermal coefficient of expansion for the cylinder
- λ = pressure distortion coefficient of the piston-cylinder
- $R0$ = resistance value of the PRT at 0°C

- **Adjustment Of Pressure To Mass Conversion For Gravity**

To calculate the local conversion coefficient from the one given in the calibration certificate:

$$Kl_{(20,0)} = Kn_{(20,0)} \, x \, \frac{gl}{gn}$$

- **Calculation Of Pressure At The Reference Level Of The Standard**

Once the local conversion has been determined, it can be compensated for the temperature and pressure distortion effects. This value used with the total mass loaded on the piston is used to calculate the pressure defined.

$$Kl_{(\theta,P)} = Kl_{(20,0)} \, x \, C_\theta \, x \, (1-\lambda P)$$

With:

$$\theta = \frac{(R\theta - R0)}{0.389}$$

Then:

$$P = Kl_{(\theta,P)} \, x \, M$$

Alternatively, if the corrections for temperature and pressure effects are not required for the accuracy of the calibration, $Kl_{(20,0)}$ may be substituted.

- **Calculation Of The Correction Due To Pressure Head**

If the test and reference levels are not at the same height, then a head correction must be applied as described in Section 4.6. The ΔP term can be either negative or positive, depending on the relative reference heights of the two instruments.

- **Simplified Pressure Calculation**

For applications where the highest accuracy is not imperative, and the value of the distortion coefficient is relatively small when assessed over the full calibration range, a median conversion coefficient can be used for any pressure point. This coefficient can be arrived at by:

$$Kl_{\left(\theta,\frac{Pmax}{2}\right)} = Kl_{(20,0)} \, x \, C_\theta \, x \left(1 - \frac{\lambda P_{max}}{2}\right)$$

If this equation is used, then an additional uncertainty on pressure will need to be assigned as:

$$\pm \frac{\lambda P_{max}}{2}$$

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CHAPTER 5 - INTERFACING

5.1 OVERVIEW

All communications between the 50300 and the host computer are done via an IEEE-488 interface. Commands are available to do mass loading in several modes, operate the pressure priming system, operate the servo-controlled variable volume, and read various parameters of the piston gauge.

The format of how these commands are transmitted from the controlling computer can vary due to the large number of possible combinations of computers and IEEE interfaces on the market. Therefore, although a complete description of the commands is given in this chapter, the exact syntax for the individual application must be handled by the end user of the system.

The IEEE address for the PGI is set at the factory at 04 for the standard 50316 and 03 for the 0.1 gram option. If this address conflicts with another component in the system, the rocker switch on the rear panel of the PGI can be switched to select another address. An individual command to the 50316 should be tried to confirm the new address.

5.2 COMMAND SUMMARY

C	Enables manipulation of the individual bits of the cards controlling mass loading, priming, and other functions.
L	Places the PGI in local mode to enable manual manipulation of the functions.
M	Simultaneously loads required mass and unloads previous mass load.
M+	Loads required mass and then unloads previous mass.
M-	Unloads previous mass and then loads required mass.
S	Controls the relays connecting the platinum resistance thermometer to an external meter.
V	Places the PGI in a state which allows reading of piston position.

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5.3 COMMAND DESCRIPTION

C

PURPOSE: Enables the controller to change the individual bits of the output cards located in the PGI or the PCI of the standard. These bits control relays used for functions such as mass loading, system priming, and other parameters of the 50200 (see Appendix for a complete description of the bit assignments and card addresses for selecting the PGI).

SYNTAX: "C",W,Y,Z,V

REMARKS: W = number of the card desired. This can be 0 through 5, dependent on system configuration.

Y = sum of the values of the bits to be selected. This sum must be betweem 1 and 255.

Z = state to which all the selected bits will be changed. Zero is the default and turns all bits off. One turns all bits on.

V = Time in milliseconds from 0 to 9999 ms. This time is a restriction set on the command. The command will be carried out only for the stipulated time and then the bits will revert to their previous state. If no time is given, the command will be permanent until a different command is sent to change the same bits.

EXAMPLE: OUTPUT 704; "C",1,6,1 - Bits 1 and 2 (2^1 and 2^2) of card 1 in the PGI are turned on. This command would load the 512 and 1024 gram masses.

OUTPUT 705; "C",2,255,0,1000 - All bits on card 2 in the PCI will go to state 0 for a period of one second.

ERROR: If the "Y" variable is greater than 255, the instruction will not be executed and the 50300 will issue a service request to the computer.

L

PURPOSE: This command allows the PGI to be set into either the local mode or the remote (computer controlled) mode of operation.

SYNTAX: "L",A

REMARKS: A = 0 for remote mode operation or 1 for local (manual) control.

EXAMPLE: OUTPUT 704;"L",1 - Places the PCI in local mode. All functions of the PGI are now operable from the front panel controls.

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M

PURPOSE: Enables the simultaneous loading of the mass required for the next pressure and the unloading of mass previously loaded. This mode of mass loading is the fastest, but should only be used when a pressure overshoot is not a problem in the calibration.

SYNTAX: "M",A

REMARKS: A = total mass value to be loaded onto the piston, including the tare mass of the standard (piston and mass carriage) in kilograms. This number must be between 2 and 102.303.

EXAMPLE: OUTPUT 704; "M", 50.025 - Loads a total mass load of the tare (usually 2 kg) and an additional 48.025 kilograms.

M+

PURPOSE: Loads the desired mass load on the piston and then unloads the previous mass load. This procedure allows a positive pressure change without overshoot.

SYNTAX: "M+",A

REMARKS: A = same as in "M" command above. This mode, though, would first load the mass "A" and then unload the previous mass load afterwards. The piston will now go to the bottom of its stroke before the higher mass is loaded.

EXAMPLE: OUTPUT 704; "M+",75 - Assuming that the previous "M' command had just been used and 50.025 kg is on the piston, 75 kg would be loaded and then the masses from the 50.025 value that are not used for the new mass load are removed.

M-

PURPOSE: Unloads the previously loaded mass and then loads the required mass for the next pressure point. This mode of mass loading allows pressures lower than the previous one to be attained without overshoot.

SYNTAX: "M-",A

REMARKS: A = same as "M" command above. The piston will rise to the top limit as the mass is removed and then the new mass is added.

EXAMPLE: OUTPUT 704; "M-",53.200 - Assuming that the previous 75 kg mass is still loaded, this mass is removed and then 50.200 kg is loaded on the piston.

S

PURPOSE: Either opens or closes the relays connecting the PRT to an external IEEE interfaceable ohmmeter.

SYNTAX: "S",A

REMARKS: A = Either zero to open the relays, thus disconnecting the PRT; or one, allowing the PRT resistance to be read by the meter.

EXAMPLE: OUTPUT 704; "S",1 - Closes the relays and permits the PRT resistance to be read via a four-wire resistance measurement.

V

PURPOSE: Enables the PGI of the 50316 to transmit a voltage signal proportional to the piston position. This voltage can vary from +10 V at the top limit of the piston stroke to -10 V at the bottom. The signal is necessary to verify that the piston is in its measuring zone where it can float free of all forces except the mass load and the balancing pressure on its effective area. Outside of this measuring zone, the piston is influenced by springs which assist it in achieving equilibrium.

SYNTAX: "V"

REMARKS: This command will allow the PGI to transmit the voltage. A subsequent command must now be given to read the voltage. Although the voltage corresponding to piston position varies within the limits described above, the most significant levels are:

+10 V	Upper stroke limit of the piston
+4 V	Top limit of the measuring zone
0 V	Midstroke (reference height)
-4 V	Lower limit of the measuring zone
-10 V	Lower stroke limit of the piston

EXAMPLE: OUTPUT 704; "V"
ENTER 704; A - The voltage of the displacement transducer of the piston will now be read into the computer and stored as the variable A.

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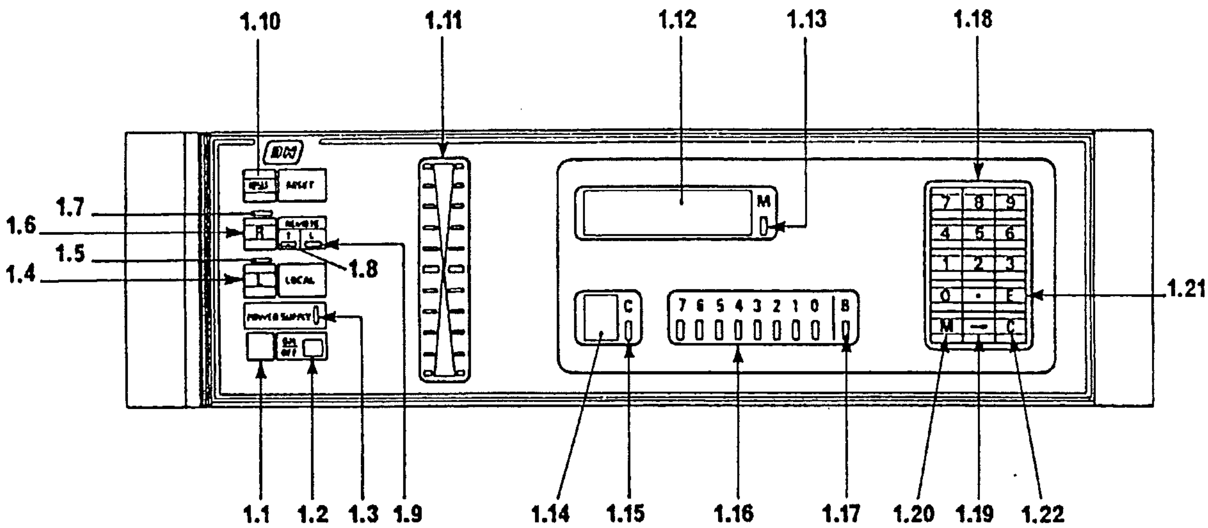
5.4 BIT LEVEL FUNCTION

The individual bits of the cards in the PGI can be controlled to perform such functions as mass loading, standard resistor and PRT reading, and piston position with the keypad on the PGI front panel. The format for all of these functions is the same. All that changes is the card selected and the bits required. The format for the elementary bit functions is:

1) Press the "C" key (1.21) to select the "card" function. The card function indicator (1.15) will light; the display (1.14) will indicate 0 for card 0.



2) Using the keypad numbers, enter the number of the card required. For instance, if card 2 is desired push the 2 key and the display will indicate that number. The bit status LED's (1.16) will display the state of the 8 bits of that card. An illuminated LED indicates a set bit which corresponds to closed solenoid in the control drawer.

3) To change the state of the bit, press the "E" key. The card function indicator will go off and the bit function indicator (1.17) will light.

4) Change the required bits by pressing the key with the number corresponding to the bit to be changed. Each push on the key will toggle the bit state; if the bit is set, it will be reset when the key is pressed. In the case of the mass load cards (see next section) the sum of the loaded masses which are loaded on the piston from that card will be shown on the display.

5) The bits can be momentarily toggled by pressing the arrow right key to select the momentary mode. Again, the state of the card bits will be shown. Now when the numbered key is pressed, the bit will activate only as long as the key is held.

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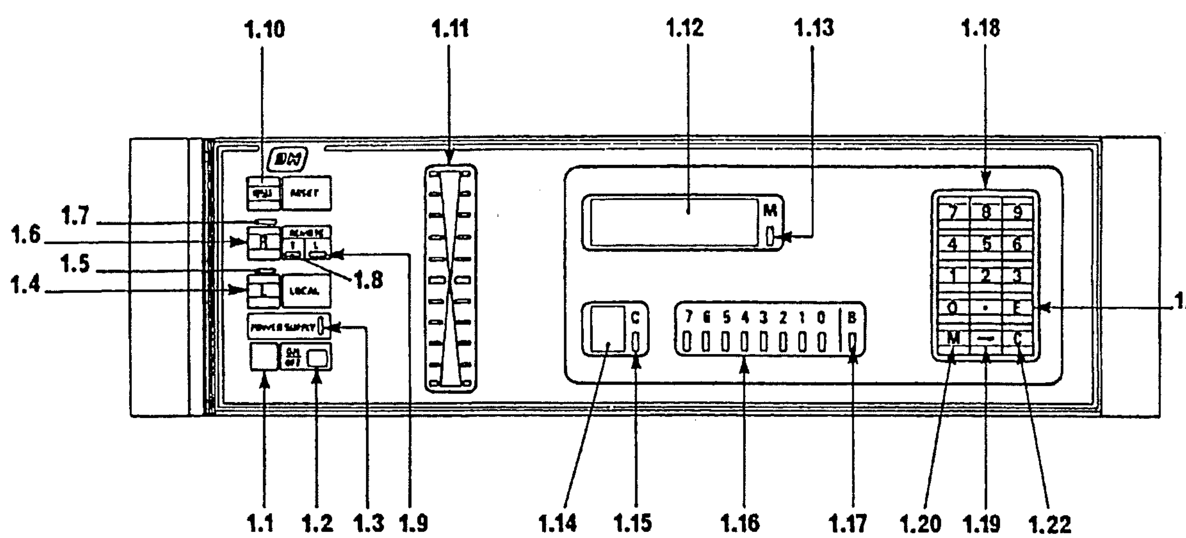
5.5 DESIGNATION OF THE PGI CARD ASSIGNMENTS

CARD POSITION

0	Control of the 1 to 128 gram individual masses.
1	Control of the 256 to 32 768 gram masses.
2	Control of the other 32 768 mass, mass carrying shaft, centering bit and type 01 priming valves.
3	Control of the individual masses for 0.1 gram resolution option and type 01 priming valves.
4	Optional card for the control of equipment external to the 50316.
5	Closes contacts for reading of the platinum resistance thermometer and reference resistor.

5.6 DESIGNATION OF THE PGI BIT ASSIGNMENTS

Each of the cards in the PGI have 8 bits numbered 0 through 7. These individual bits have specific functions and their output can be read on the rear connectors of the PGI.



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0 - Output Card in Slot 0

Function: Control of individual masses 1 g to 128 g.

Pin on Connector 443 RP (See 2.1)	Bit	Decimal Value	Function
1	0	1	1 g
2	1	2	2 g
3	2	4	4 g
4	3	8	8 g
5	4	16	16 g
6	5	32	32 g
7	6	64	64 g
8	7	128	128 g

1 - Output Card in Slot 1

Function: Control of individual masses 256 g to 32,768 g.

Pin on Connector 443 RP (See 2.1)	Bit	Decimal Value	Function
9	0	1	256 g
10	1	2	512 g
11	2	4	1024 g
12	3	8	2048 g
13	4	16	4096 g
14	5	32	8192 g
15	6	64	16384 g
16	7	128	32768 g

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2 - Output Cards In Slot 2

Function: Control of individual masses and external valves.

Pin on Connector 443 RP (See 2.1)	Bit	Decimal Value	Function
17	0	1	32768 g
18	1	2	2000 (mass carrying shaft)
19	2	4	Vertical centering
20	3	8	Open
21	4	16	Type 01 priming inlet valve
22	5	32	Type 01 priming exhaust
23	6	64	valve (restricted)
24	7	128	Type 01 priming exhaust valve
			Open

3 - Digital Output Card In Slot 3 (Optional)

Function: Control of individual solenoids or other switchable devices external to the 50212.

NOTE: Bits 4 through 7 become the 0.1, 0.2, 0.4 and 0.8 gram mass control bits if the system has the 0.1 gram option

Pin on Connector 443 RP (See 2.1)	Bit	Decimal Value	Function
25	0	1	Open
26	1	2	Open
27	2	4	Open
28	3	8	Open
29	4	16	Open
30	5	32	Open
31	6	64	Open
32	7	128	Open

NOTE: If the 0.1 gram option has been ordered, bits 0 through 2 become the priming system hydraulic inlet valve, restricted exhaust valve, and unrestricted exhaust valve respectively.

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4 - See Input/Output Card Manual or Description of the Optional Card Used.

5 - Relay Card in Slot 5

Function: Operation of relays for the platinum resistance thermometer and the reference resistor.

Bit	Decimal Value	Function
0	1	PRT Relay 0
1	2	PRT Relay 1
2	4	PRT Relay 2
3	8	PRT Relay 3
4	16	Reference Resistor Relay 4
5	32	Reference Resistor Relay 5
6	64	Reference Resistor Relay 6
7	128	Reference Resistor Relay 7

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CHAPTER 6 - MAINTENANCE AND REPAIRS

6.1 ROUTINE MAINTENANCE

During normal operation, no special maintenance should be required for the 50316 except maintaining adequate fluid levels to avoid trapped air in the hydraulic system and checking the pneumatic circuit to be sure that no water or contamination are found. A separator/filter with a clear plastic trap is provided on the regulator.

The precautions listed in the section on the preliminary setup of the 50316 should be taken and periodically rechecked. This will help assure good metrological integrity at all times.

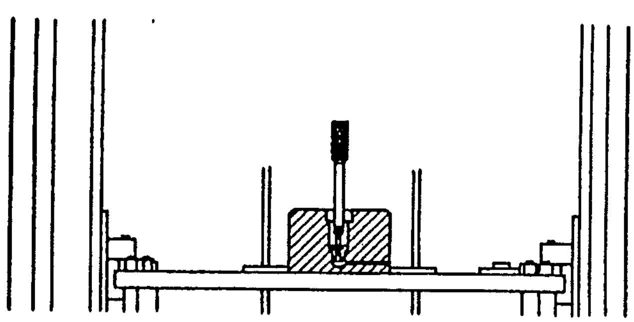
The 50316 is equipped with an oil runoff cup located at the lower rear of the rack. This cup should be checked and emptied when full. Never reuse this oil in the system.

6.2 RECALIBRATION OF THE PISTON-CYLINDER AND MASSES

Periodic recalibration of the piston-cylinder and masses assures the long term reliability and optimal metrological performance of the system. It also gives and maintains traceability to national standards. Though other organizations can perform these calibrations, it is recommended that DH Calibration Services be used in order to have data which allows the exploitation of piston-cylinder K_n factors and whole number masses. The DH calibration chain also assures long-term repeatability of the system well inside of the accuracy tolerances.

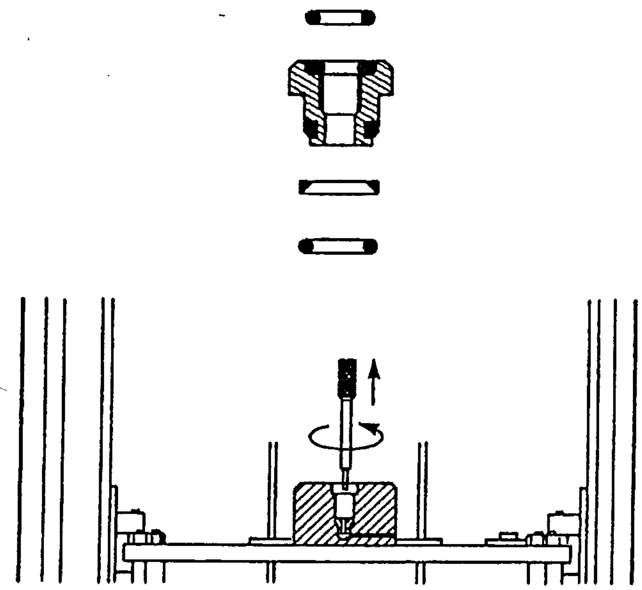
The recommended recalibration interval for the metrological elements is two recalibrations on one year cycles and then, if there is no significant change over this time period, two year intervals.

6.3 CHANGING THE O-RING ASSEMBLY



The mounting post of the 50316 is designed with a removable O-ring assembly to allow easy replacement of failed O-rings. The O-ring life is normally at least a year long, but may vary with frequent piston-cylinder changes. To replace O-rings:

Remove the piston and cylinder and screw the O-ring assembly removal tool in the assembly body. Pull upwards on the tool to extract the assembly.



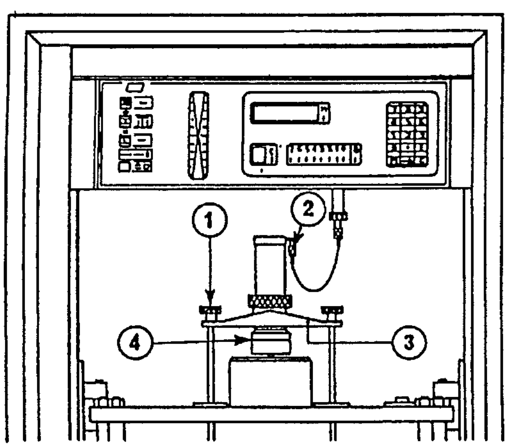
The O-rings can now be removed, inspected, and replaced if defective. The upper O-ring is an "R5" metric ring and the lower gland contains a "R6" anti-extrusion ring and O-ring as shown. The DH part number for the O-ring assembly is 41096 and the anti-extrusion ring is 36871.

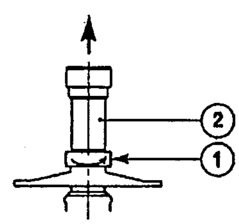
After replacing the O-rings, insert the tool into the O-ring assembly and push the assembly into the seat. Unscrew and remove the tool.

6.4 MOTOR REPLACEMENT

The motor used for rotating the piston is a replaceable unit. To remove or replace the motor, perform the following steps:

1) Unscrew the two knurled caps (1) on the mass carrying bridge and the motor power supply (2). Uncouple the bridge and piston in the reverse order as the assembly described in the preliminary setup section of this manual.





2) Remove the motor from the bridge by unscrewing the locking collar (1) and lifting off the motor.

3) Reinstall the new motor in the reverse order from steps 1 and 2. Be sure that the engagement pins on the bridge coupling are visible in the holes in the piston head. The knurled nuts holding the bridge to the mass carrying assembly should only be hand tightened.

6.5 REPLACING SOLENOID VALVES IN THE ACTUATOR CONTROL MODULE

If one of the mass actuators or other functions controlled by the PGI does not operate, the problem may be in a faulty solenoid valve. Before working on this module, bleed all pressure from the compressed air circuit.

Remove the four front panel screws from the module and slide it out of the rack. Remove the top perforated cover plate.

Since the solenoid valve consists of two subassemblies, an electrical part - the coil, and a pneumatic part - the valve, a process of elimination is required. If the valve makes no sound when activated by the PGI, then the coil should be checked first.

- **Checking the coil** - Remove the muffler or the upper pressure connection, unscrew the knurled cap which secures the coil, and lift off the coil. Place another coil from an adjacent valve onto the valve and use that coil and it associated bit command on the PGI to test the valve functioning.

  If the valve now works, the coil needs replaced. If the coil clicks, but the valve does not open, then the valve is probably defective. If everything works in this new configuration, then the electrical control circuit of the malfunctioning valve is suspect.

- **Replacing the valve** - If the coil has not already been removed, remove it now as described above. Remove the two blue tubes from the connection (see below). Unscrew the two valve mounting screws.

  Remove the valve and replace it in the reverse order of the disassembly.

- **Disconnecting the compressed air tubes from the solenoid valves** - To disconnect, pull the red O-ring on the tube fitting towards the connector body (away from the tube). Pull the blue tube from the fitting, taking care not to exert a sideways force.

  To reconnect, push the blue tube onto the fitting. An initial resistance will be noted, then this will release and a second resistance will be felt when the tube actually seats. Pull the red O-ring towards the tube to complete the connection.

6.6 FUSE REPLACEMENT

The power supply module of the PGI has a main 1A fuse located on the rear panel and six internal fuses to protect various parts of the electronic system of the 50316. Once the power supply module is removed from the PGI the fuses can be identified as below and reeplaced if blown. All fuses are of the slow-blow type.

(3.1) - Piston drive motor - 0.125A

(3.2) - 19V Solenoid power supply - 3.15A

(3.3) - 5V Power supply - 3.15A

(3.4) - On/off LED - 0.050A

(3.5) - +15v Power supply - 0.125A

(3.6) - -15V Power supply - 0.125A

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CHAPTER 7 - TROUBLESHOOTING

SYMPTOM	POSSIBLE CAUSE	SOLUTION
• Poor piston stability	• Dirty piston-cylinder • Insufficient lubricating fluid	• Clean piston-cylinder • Refill reservoir
• Piston does not rotate	• Bad motor power cable • Blown fuse • Burned out motor • Piston drive disengaged	• Check cable • Replace fuse • Replace motor • Reconnect drive
• Aberrant measurements	• Trapped air in the pressure system • Incorrect mass load	• Bleed pressure circuit • Check solenoid valve operation
• Improper mass loading operation	• Inadequate air pressure	• Check air supply

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APPENDICES

- Values of the Correction Factor C_g
- Temperature Correction
- Temperature Correction
- Pressure Conversion Factors
- DH 400 High Pressure Flexible Tubes
- Sebacate Data
- Krytox Material Data Sheet

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VALUES OF THE CORRECTION FACTOR C_g AS A FUNCTION OF LOCAL GRAVITY

$$C_g = \frac{g_L}{g_M}$$

g_L : local gravity

g_M : standard gravity = 9.80665 m/s^2

g_L (m/s^2)	C_g
9.7800	0.99728
05	33
9.7810	0.99738
15	44
9.7820	0.99749
25	54
9.7830	0.99759
35	64
9.7840	0.99769
45	74
9.7850	0.99779
55	84
9.7860	0.99789
65	95
9.7870	0.99800
75	05
9.7880	0.99810
85	15
9.7890	0.99820
95	25
9.7900	0.99830
05	35
9.7910	0.99840
15	46
9.7920	0.99851
25	56

g_L (m/s^2)	C_g
9.7930	0.99861
35	66
9.7940	0.99871
45	76
9.7950	0.99881
55	86
9.7960	0.99891
65	96
9.7970	0.99902
75	07
9.7980	0.99912
85	17
9.7990	0.99922
95	27
9.8000	0.99932
05	37
9.8010	0.99942
15	47
9.8020	0.99953
25	58
9.8030	0.99963
35	68
9.8040	0.99973
45	78
9.8050	0.99983
55	88

g_L (m/s^2)	C_g
9.8060	0.99993
9.80665	1.00000
9.8070	1.00004
75	09
9.8080	1.00014
85	19
9.8090	1.00024
95	29
9.8100	1.00034
05	39
9.8110	1.00044
15	49
9.8120	1.00055
25	60
9.8130	1.00065
35	70
9.8140	1.00075
45	70
9.8150	1.00085
55	90
9.8160	1.00095
65	100
9.8170	1.00106
75	11
9.8180	1.00116
85	21

g_L (m/s^2)	C_g
9.8190	1.00126
95	31
9.8200	1.00136
05	41
9.8210	1.00146
15	51
9.8220	1.00157
25	62
9.8230	1.00167
35	72
9.8240	1.00177
45	82
9.8250	1.00187
55	92
9.8260	1.00197
65	202
9.8270	1.00208
75	13
9.8280	1.00218
85	23
9.8290	1.00228
95	33
9.8300	1.00238
05	43
9.8310	1.00248
15	53

TEMPERATURE CORRECTION

Piston And Cylinder In Tungsten Carbide

$value \text{ of } C_\theta = 1 - (\alpha_P + \alpha_C)(\theta - 20) \qquad \alpha_P + \alpha_C = 9x10^{-6}{}^\circ C^{-1}$

(°C)	C_θ
5	1.00014
6	1.00013
7	1.00012
8	1.00011
9	1.00010
10	1.00009
11	1.00008
12	1.00007
13	1.00006
14	1.00005
15	1.00004
16	1.00004
17	1.00003
18	1.00002
19	1.00001

(°C)	C_θ
20	1.00000
21	0.99999
22	0.99998
23	0.99997
24	0.99996
25	0.99996
26	0.99995
27	0.99994
28	0.99993
29	0.99992
30	0.99991
31	0.99990
32	0.99989
33	0.99988
34	0.99987

(°C)	C_θ
35	0.99986
36	0.99986
37	0.99985
38	0.99984
39	0.99983
40	0.99982
41	0.99981
42	0.99980
43	0.99979
44	0.99978
45	0.99978
46	0.99977
47	0.99976
48	0.99975
49	0.99974

TEMPERATURE CORRECTION

Piston In Steel And Cylinder In Tungsten Carbide

$$C_\theta = 1 - (\alpha_P + \alpha_C)(\theta - 20)$$

α_P : Thermal expansivity of steel = 1.05×10^{-5} [°C^{-1}]
α_C : Thermal expansivity of tungsten carbide = 4.50×10^{-6} [°C^{-1}]
θ : Temperature of the piston cylinder [°C]

(°C)	C_θ
5	1.00023
6	1.00021
7	1.00020
8	1.00018
9	1.00017
10	1.00015
11	1.00014
12	1.00012
13	1.00011
14	1.00009
15	1.00008
16	1.00006
17	1.00005
18	1.00003
19	1.00002

(°C)	C_θ
20	1.00000
21	0.99999
22	0.99997
23	0.99996
24	0.99994
25	0.99993
26	0.99991
27	0.99990
28	0.99988
29	0.99987
30	0.99985
31	0.99984
32	0.99982
33	0.99981
34	0.99979

(°C)	C_θ
35	0.99978
36	0.99976
37	0.99975
38	0.99973
39	0.99972
40	0.99970
41	0.99969
42	0.99967
43	0.99966
44	0.99964
45	0.99963
46	0.99961
47	0.99960
48	0.99958
49	0.99957