Hardware Reference Manual

7600 Series

Hall Measurement System

For Use With The Following Systems:

Model 7604 Hall Measurement System

Model 7607 Hall Measurement System

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Electromagnetic Compatibility (EMC) for the 7600 Series Hall System

Electromagnetic Compatibility (EMC) of electronic equipment is a growing concern worldwide. Emissions of and immunity to electromagnetic interference is now part of the design and manufacture of most electronics. To qualify for the CE Mark, the Hall Measurement System meets or exceeds the requirements of the European EMC Directive 89/336/EEC as a **CLASS A** product. A Class A product is allowed to radiate more RF than a Class B product and must include the following warning:

WARNING: This is a Class A product. In a domestic environment, this product may cause radio interference in which case the user may be required to take adequate measures.

The instrument was tested under normal operating conditions with sensor and interface cables attached. If the installation and operating instructions in the User's Manual are followed, there should be no degradation in EMC performance.

This instrument is not intended for use in close proximity to RF Transmitters such as two-way radios and cell phones. Exposure to RF interference greater than that found in a typical laboratory environment may disturb the sensitive measurement circuitry of the instrument.

Pay special attention to instrument cabling. Improperly installed cabling may defeat even the best EMC protection. For the best performance from any precision instrument, follow the grounding and shielding instructions in the User's Manual. In addition, the installer of the Hall Measurement System should consider the following:

- Shield measurement and computer interface cables.
- Leave no unused or unterminated cables attached to the instrument.
- Make cable runs as short and direct as possible. Higher radiated emissions is possible with long cables.
- Do not tightly bundle cables that carry different types of signals.

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CHAPTER 1
INTRODUCTION

1.0 GENERAL

The Lake Shore 7600 Series Hall Effect/Electronic Transport Measurement System is an advanced integrated hardware and software system designed to characterize and analyze the electronic transport properties of materials. Designed for easy and precise operation, the 7600 Series allows the user to control both temperature and magnetic induction (field). The standard 7600 Series measures up to 2 samples at room temperature, while a 4-sample option provides up to 4 consecutive measurements without changing the hardware configuration.

Hall effect and electronic transport measurements are invaluable in characterizing the properties of a wide variety of small band gap semiconductors and multi-layer devices, highly doped semiconductors, as well as highly conducting organic and inorganic materials with low sample resistance. Materials include GaAs, InP, InAs, Si, Ge, SiGe, HgCdTe, GaN, SiC, AlN, quantum well structures, metal oxides, and organic conductors. Transport measurements of Hall effect and magnetoresistance are ideally suited for materials research, product development, and quality control.

The Hall effect measurement software is Windows® 2000 menu driven, using a standard Windows Explorer Interface with enhanced color-graphic software for system operation, data acquisition and analysis. The Hall software is designed to control system instrumentation throughout the course of an experiment and determine sample resistance, resistivity, Hall coefficient, Hall mobility, carrier concentration, or current-voltage characteristics. Real-time feedback of processed measurement data can be displayed in graphical and tabular format. The software automatically records data on multi-sample experiments with 4-contact van der Pauw samples and 6-contact Hall bar samples and stores data to the hard drive to be used for further processing, analysis, and display.

The optional Quantitative Mobility Spectrum Analysis (QMSA) software technique analyzes variable magnetic field Hall data to resolve individual carrier mobilities and densities in multi-carrier devices. The reliability and sensitivity of the QMSA software makes it the ideal technique for routine characterization of various multi-carrier materials and high mobility heterostructure devices. QMSA also has several advantages over previous conduction analysis techniques in that QMSA is fully automated, it does not require advance sample information, and it simultaneously provides individual carrier density and mobility (not an average over all the carriers).



Figure 1-1. Typical Model 7604 Hall System

1.1 SYSTEM FEATURES

- Standard system measures up to 2 samples at room temperature, while the 4-sample option provides up to 4 consecutive measurements without changing the hardware configuration.
- Quickly make measurements with the standard Model 75011 Sample Holder Module using samples mounted on plug-in sample cards.
- Multiple measurement steps can be defined in one experiment profile allowing a single profile to measure IV curves on all contacts.
- Measure Hall voltage, resistance, magnetoresistance, and current-voltage characteristics with one system.
- Calculate resistivity, Hall coefficient, and carrier concentration and mobility.
- Measure samples with resistances ranging from 10 mΩ to 10 MΩ with less than 2% measurement uncertainty with the standard 7600 Series instrumentation.
- Software runs on Windows 2000 and is a full 32 bit implementation in Visual Basic 6.0.
- User interface for navigating setups, samples, and measurements uses standard Windows Explorer Interface.
- Sample definitions, measurement setups, and measurement results are all separated items, for greater flexibility during use at a later time.
- Reduce the amount of time spent making measurements by using the fully integrated, automated computer data collection system that makes multi-sample measurements and calculates the results.
- Display real-time feedback of processed measurement data in either graphical or tabular format as the experiment is taking place.
- Produce excellent field stability using water cooled magnet coils, feedback control, high quality sensors, and advanced electronics.
- Materials: Most compound semiconductor materials SiGe, SiC, InAs, InGaAs, InP, AlGaAs, HgCdTe, and ferrites; low resistance materials including metals, transparent oxides, dilute magnetic semiconductors, and TMR materials; and high resistance materials including semi-insulating GaAs and GaN, CdTe, and photodetectors.
- Applications: (1) Make measurements for mobility spectrum analysis to evaluate multilayer materials and resolve the individual properties of multiple carriers; (2) Verify doping effectiveness by measuring active carrier concentrations; and (3) Check base contamination levels to determine impurity levels in semiconductor growth systems such as chemical vapor deposition (CVD) and molecular beam epitaxy (MBE).



Figure 1-2. Typical Model 7607 Hall System

1.2 SYSTEM SPECIFICATIONS

System specifications for the 7600 Series Hall System are provided in Table 1-1.

Table 1-1. 7600 Series Hall System Specifications *

	Model 7604	Model 7607
Sample Geometry	4-wire van der Pauw or 6-wire Hall Bar	
Number of Contacts	4 or 6	
Shunt Resistance	$>10^{-9}$ Ω	
Resistance, van der Pauw	40 mΩ to 10 MΩ (<2% uncertainty)	
Resistance, Hall bar	10 mΩ to 10 MΩ (<2% uncertainty)	
Voltage	200 V Max.	
Current	50 pA to ±1 A with source limits: ±100 mA @ 210 V, ±1 A @ 21 V	
Hall Measurement	1×10^{23} (B/t = 1000 T/mm, 5% accuracy or better; Max Carrier Density 1×10^{20} cm^{-3})	
Output Stability (per day)	±0.05% (constant room temperature)	
Uniformity	±0.1%	
Sample Interface	Standard Model 75011 Sample Holder Module	
Sample Size	10 mm square (12 mm Max.) on a 25 × 75 mm plug-in card. 50 mm square (60 mm Max.) on a 81 × 93 mm plug-in card.	
Number of Samples	2 samples can be run simultaneously	
Temperature	Room temperature or 77 K (liquid nitrogen required for 77 K)	
Electromagnet	EM4-HVA (4-inch pole faces)	EM7-HV (3- and 6-inch pole faces)
Magnetic Field, Max. with 1 inch air gap	10.4 kG (1 T) with 4-inch pole face	20 kG (2 T) with 3-inch pole face, or 15 kG (1.5 T) with 6-inch pole face
Magnet Power Supply	Model 643	Model 648
Computer	Pentium with Windows 2000 and National Instruments IEEE-488 Interface (or better)	
Hall Software	Windows compatible, menu driven, enhanced color-graphic software for system operation, data acquisition, and analysis. System software includes individual virtual instrument drivers for complete front panel operation and instrumentation control. Display real-time feedback of processed measurement data in either graphical or tabular format.	
Shipping Size (also refer to site preparation in Paragraph 2.5)		
Computer and Console	158 x 78 x 76 cm (62 x 31 x 30 in.)	158 x 78 x 76 cm (62 x 31 x 30 in.)
Electromagnet	137 x 82 x 97 cm (54 x 32 x 38 in)	81 × 117 × 119 cm (32 × 46 × 47 in.)
Magnet Power Supply	NA (mounted in the console)	914 mm W × 1168 mm D × 1219 mm H (36 in × 46 in × 48 in)
Shipping Weight (also refer to site preparation in Paragraph 2.5)		
Computer and Console	110 kg (242 pounds)	35 kilograms (75 pounds)
Electromagnet	250 kilograms (550 pounds)	680 kilograms (1500 pounds)
Magnet Power Supply	NA (mounted in the console)	281 kilograms (620 pounds)

* Also refer to the following User's Manuals for individual instrument specifications: Lake Shore Model 475 Gaussmeter, Keithley Model 2400 Sourcemeter, Keithley Model 2700 Multimeter, and Keithley Model 7709 Matrix Module.

Specifications are subject to change without notice.

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CHAPTER 2

PRE-INSTALLATION

2.0 GENERAL

This chapter provides pre-installation information for the 7600 Series Hall System. Unless a model number is specified, the information in this chapter is considered to be "generic" to all systems.

2.1 SITE PLANNING

The customer is responsible for site planning. Research physical location, environment, power, ventilation, safety, and local building, electrical, and safety codes before system installation. See Figure 2-1 for physical dimensions of a suggested site. After initial screening, evaluate sites according to location, space, power, structural integrity, and availability of cooling water.

1. **Location**: Convenient for equipment and supply delivery, and handy to related work areas for efficient operation. Especially important is sufficient access for a lift to move and place an electromagnet. Place the magnet in an area free from major vibration from motors, pumps, forklifts, etc.; it may interfere with measurements. Place the magnet as far away as possible from equipment sensitive to stray DC magnetic fields.
2. **Space**: Adequate for system installation, operation, potential expansion, service, and storage of supplies. Space and layout requirements depend on the system selected. A minimum ceiling height of 2.4 meters (8 feet) is recommended.
3. **Power**: Adequate for system requirements, potential expansion, and wiring for maximum efficiency and economy of operation. Refer to Paragraph 2.2.
4. **Structural Integrity**: Level floor strong enough to support anticipated loads and free from extraneous vibrations or magnetic fields. Heavy concrete ground floors usually prove best, not only because they have the required strength, but such a floor also transmits minimal building vibration to the system. Vibrations transmitted to consoles may degrade system performance. In general, a ground floor is preferred over a higher floor. You must also consider the need for proper lifting equipment to move the magnet to the final location.
5. **Cooling Water Requirement**: Both the electromagnet and power supply require access to cooling water. Refer to Table 2-3 for electromagnet and Table 2-4 for power supply cooling requirements.

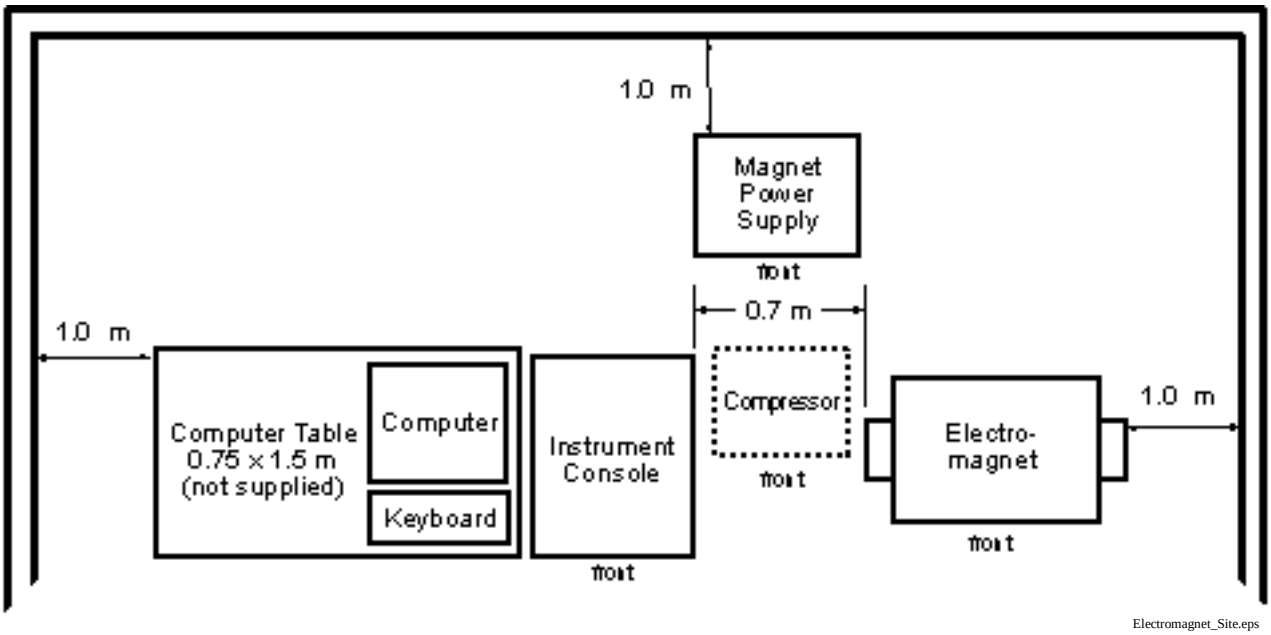


Figure 2-1. Typical 7600 Series Hall System Floor Plan

2.2 SYSTEM POWER AND GROUND REQUIREMENTS

The AC power source for the 7600 Series Hall System must be frequency and voltage regulated and isolated from sources that may generate Electromagnetic Interference (EMI). Ground Fault Interrupter (GFI) and Transient Surge Protection circuitry at the AC source are also strongly recommended. In areas where AC voltage is variable, consider a constant voltage transformer. If power outages are a problem, consider an Uninterruptible Power Supply (UPS).

CAUTION: Do not attempt to apply electrical power to the system until all instruments and power supply have been checked for proper input power settings and fuse/circuit breaker ratings.

See Table 2-1 for a list of system electrical connections. Fill in the blanks in the table for the equipment for your system, noting that not all equipment is present in all systems. Magnet power supply information is given in Section 2.5.2. The customer must provide an input power cable to the power supply. A plug is provided to mate with the socket on the back of the power supply.

The computer and flat-panel monitor can be placed on top of the instrument console. First place the instrument console top surface on top to provide more room for the keyboard and mouse. The power cords can be plugged inside the instrument console on models with spare internal outlets, or plugged into nearby wall outlets. Alternately, place the computer and monitor on an adjacent table or work surface within limits of the 3 meter (10 foot) IEEE-488 cable.

The instrument console, including the computer, monitor, and optional inkjet printer, are designed for single-phase 3-wire AC power. The Power Strip in the Instrument Console has a three-conductor power input connector which grounds equipment in the Instrument Console when plugged into a 3-wire receptacle. Do not use two-wire (without ground) AC power. If the plug does not mate with available sockets, remove the plug and attach a plug of the correct type with equal or better rating. Check with a electrician to ensure you conform to local electrical codes.

Table 2-1. Electrical Connection Requirements (Blanks cells to be filled in by the Customer)

	Power input	Power cable	Power plug
Magnet power supply		Customer provided	
Instrument console	Set for 120, 220, 230, or 240 VAC; 1 phase; 50 or 60 Hz; 4-2 A; 480 W maximum	3.8 m (12.5 ft.), rated to 15 A	Customer provided
76014 CCR compressor (optional)	Set for 208-230, 60 Hz, or 220, 230, 240 VAC, 50 Hz; 1 phase; 15-12.5 A; 3 kW	3.8 m (12.5 ft.), rated to 30 A	NEMA L6-30P (2-pole, 3 wire, 30 A, 250 VAC) male plug
Recirculating chiller (optional)			
Vacuum pump (optional)			

System Power And Ground Requirements (Continued)

Ground instrument panels and cabinets. The safety ground provides a true ground path for electrical circuitry and, in the event of internal electrical faults such as shorts, carries the entire fault current to ground to protect users from electrical shock. The Power Strip in the Instrument Console has a three-conductor power input connector which grounds equipment in the Instrument Console when plugged into a 3-wire receptacle.

When the earth ground connection is likely impaired, render the Hall System inoperative and secure it against any unintended operation until qualified service personnel verifies its safety. The connection is likely impaired if:

1. Shows visible damage.
2. Fails to perform the intended measurement.
3. Has been subjected to prolonged storage under unfavorable conditions.
4. Has been subjected to severe transport stresses.

Do not use such apparatus until qualified service personnel verifies its safety.

Electromagnetic interference (EMI) is both a natural and man-made phenomena which may degrade electronic system performance. Natural EMI includes thunderstorms, solar disturbances, cosmic rays, etc. Man-made EMI includes fixed and mobile transmitters, high voltage power lines, power tools, fluorescent lights, and other equipment containing motors, heaters, etc. Protect the AC source from EMI. Consider transient surge protectors for lightning protection.

2.3 ENVIRONMENTAL REQUIREMENTS

To meet and maintain specifications, operate the system at an ambient temperature range of 18 – 28 °C (64 – 82 °F). Operate it within the range of 15 – 35 °C (59 – 95 °F) with less accuracy. The system is intended for laboratory use. Although no specific humidity or altitude specifications exist, relative humidity of 20% to 80% (no condensation) and altitudes from sea level to 2.4 km (8,000 feet) are generally acceptable.

Adequately ventilate the work area to prevent build up of potentially life-threatening concentrations of nitrogen gas (refer to Appendix F). Oxygen content monitor/alarms should be installed near the work site to warn against low oxygen levels if liquid cryogens are used. The air-conditioning system should filter dust and other particulates to reasonable levels. Consult an air-conditioning expert about special filtering if salt air, corrosive gases, or other air pollutants exist.

2.4 COOLING WATER REQUIREMENTS

The electromagnet and magnet power supply requires cooling water. Water supply and return lines must be supplied by the customer. The electromagnet is provided with a flow switch that will prohibit operation of the power supply if the water flow rate falls below 1 gpm. A flow meter, not provided, is also useful.

Cooling water must meet flow and pressure requirements as indicated in Tables 2-3 and 2-4. Cooling water having a pH value of 6.0 to 8.0 and a calcium-carbonate concentration of <75 ppm (the quality of typical municipal drinking water) is acceptable. If the cooling water has a pH value <6.0 or a calcium-carbonate concentration >75 ppm, water conditioning may be required. Cooling with deionized water is not recommended as it can cause erosion of the copper windings. A recirculating system should be used in the following cases:

1. The tap water is not of sufficient purity,
2. The loss of cooling water down the drain is too expensive, or
3. Control of the electromagnet temperature is important.

Control of the coolant temperature can be important if the tap water is cold enough to cause water condensation on the surface of the electromagnet poles which are made of expensive and easily corroded soft iron. Condensation can also cause damage to the internal workings of the magnet power supply. Recirculating chillers are available from Lake Shore or other sources.

2.5 SITE PREPARATION

The site must be prepared before your new 7600 Series Hall System arrives. The instructions in this section are generic to all Hall System installations. You will receive an order-specific site preparation sheet, you should follow those instructions. The various parts of the Hall System should be removed from their shipping pallets and moved into the designated installation area. Any special equipment required to move the Hall System should be available if necessary at the time of installation. Refer to Table 2-2.

Table 2-2. Typical Shipping Weights and Dimensions

	Model 7604 / 643 MPS / EM4	Model 7607 / 648 MPS / EM7
Instrument Console, Work Surface, and Computer	158 x 78 x 76 cm (62 x 31 x 30 in.) 110 kg (242 pounds)	158 x 78 x 76 cm (62 x 31 x 30 in.) 35 kilograms (75 pounds)
Power Supply	NA (included in console)	914 mm W × 1168 mm D × 1219 mm H (36 in × 46 in × 48 in) 281 kilograms (620 pounds)
Electromagnet	250 kg (550 pounds) 137 x 82 x 97 cm (54 x 32 x 38 in)	680 kg (1500 pounds) 81 × 117 × 119 cm (32 × 46 × 47 in.)

2.5.1 Electromagnet Site Preparation

The Hall System requires one water supply line and one return line for cooling of the electromagnet. The water connections are standard ¾-inch garden hose fittings: one female and one male. Refer to Table 2-3.

Table 2-3. Electromagnet Cooling Water Requirements and Weights

	Model 7604 / EM4	Model 7607 EM7
Cooling Water	3.8 liters per minute (1 gallon per minute) @ 45 – 75 psi * and 15 – 24 °C (59 – 75 °F)	11.4 liters per minute (3 gallons per minute) @ 45 – 75 psi * and 15 – 24 °C (59 – 75 °F)
Magnet Weight	204 kg (450 pounds)	590 kg (1300 pounds)

* Electromagnet is equipped with a flow switch that inhibits the power supply output if the water flow falls below 1 gpm.

2.5.2 Power Supply Site Preparation

The Hall System requires one water supply line and one return line for cooling of the magnet power supply. The water connections use standard ½-inch hose barb fittings. The customer must provide wiring (that follows local safety codes) to the back of the power supply. Lake Shore recommends #10 gauge four-conductor cables. Use of a customer-supplied ground fault detector (GFD) requires a 3-phase GFD. Refer to Table 2-4.

Table 2-4. Power Supply Cooling Water, Electrical Supply, and Weights

	Model 7604 / 643 MPS	Model 7607 / 648 MPS
Cooling Water	5.7 liters per minute (1.5 gallon per minute) @ 45 – 75 psi and 15 – 30 °C (59 – 86 °F)†	7.6 liters per minute (2 gallon per minute) @ 45 – 75 psi and 15 – 30 °C (59 – 86 °F)†
Supply (configured per settings provided at time of order)	3-phase with ground (4-wire). Voltages: 400 V +6% –10%, 380 V ±10%, 220 V ±10%, or 208 V ±10%, 50 to 60 Hz. Power consumption is <4.5 kVA. ‡	3-phase with ground (4-wire). Voltages: 400 V +6% –10%, 380 V ±10%, 220 V ±10%, or 208 V ±10%, 50 to 60 Hz. Power consumption is <7.6 kVA. ‡
Weight	78 kilograms (172 pounds)	225 kilograms (495 pounds)
Dimensions	483 mm W × 310 mm H × 572 mm D (19 in × 12.2 in × 22.5 in) with handles removed	559 mm W × 673 mm D × 1054 mm H (22 in × 26 in × 42 in)

† If the cooling water is too cold, it can cause condensation and severe damage to the power supply. Refer to Section 3.1.3.

‡ The customer is responsible for the power cabling between the facility power and the electrical box on the back of the power supply.

2.6 INSPECTING AND UNPACKING

Set pallets on level surface. Inspect shipping containers for external damage. Make all claims for damage (apparent or concealed) or partial loss of shipment in writing to Lake Shore within 5 days from receipt of goods. If damage or loss is apparent, notify shipping agent immediately.

Shockwatch® indicators are included to aid in judging the condition of received goods (see Figure 2-2). Please accept shipment even if the Shockwatch is red. Note it on the bill of lading and inspect for damage immediately.



Shockwatch.bmp

Figure 2-2. Shockwatch Indicator

Cut off strapping, lift off lid, and locate the packing list included with the system. Use it to check receipt of all components, cables, accessories, and manuals as the system is unpacked. Inspect for damage. Inventory all components supplied before discarding any shipping materials. **Be sure to fill out and send instrument warranty cards.**

Remove the box from the top of the Instrument Console. Use four people to lift the Instrument Console from the pallet. Do not lift the console at the top: always lift from the bottom. Note how the console was supported on the pallet for future reference. Foam blocks between the instruments support their weight during shipment; remove them, or simply leave them in place. To transport the unit, first insert the foam blocks.

If there is instrument freight damage, file claims promptly with the carrier and insurance company, and advise Lake Shore of such filings. Advise Lake Shore immediately of missing parts. Lake Shore cannot be responsible for any missing parts unless notified within 60 days of shipment. The standard Lake Shore Warranty appears on the A Page (immediately behind the title page) of this manual.

2.7 RETURN AND SHIPPING PROCEDURE

If any part of the system appears to be damaged or operate incorrectly, contact Lake Shore or a factory representative for a Returned Goods Authorization (RGA) Number. Returns may not be accepted without an RGA number. Attach a tag with the following information when returning:

1. RGA Number.
2. Model and Serial Number.
3. User's Name, Company, Address, Phone Number, and Fax Number.
4. Malfunction Symptoms.

CAUTION: If returning a power supply or electromagnet, any water left in the cooling lines may freeze during shipping and cause irreversible damage.

Pack the equipment in the original shipping crate (if possible). Fasten it upright to a pallet large enough and rated to handle the weight. Use compressed air to force water out of the cooling lines.

Affix shipping labels, **FRAGILE** warnings, **UPRIGHT** labels, and weight of the shipment on the outside of the crate. Also write the RGA number on the outside of the shipping crate and on packing slip. Use a shipping company that can handle the weight.

2.7.1 Additional Magnet Shipping Instructions

CAUTION: The magnet coils freely rest on the poles. To prevent damage, fix coils in place during shipment.

Wedge padded wood blocks or high density foam between the coils to hold them against the magnet frame. Protect the magnet by wrapping in heavy paper or plastic. Seal with plastic tape. Make a wood box large enough to cover the whole magnet without touching it and fasten it to the pallet.

2.8 SAFETY

Train personnel in proper emergency measures such as electrical power shut off, fire department notification, fire extinguishing, and personnel and records evacuation. Here is a list of suggested personnel safety considerations:

- Ground Fault Interrupter (GFI) AC circuits.
- Magnetic Field Warning Signs.
- Fire Extinguisher.
- Emergency Lighting.
- Fireproof Safe for Data, Original Software and Documentation Storage.
- Oxygen Concentration Monitor/Alarm.
- Cryogenic Safety Gloves, Apron, Goggles/Faceshield, and Apparel.

Locate in the immediate vicinity fire extinguisher(s) that extinguish all three classes of fires: A, B, and C. Class A is ordinary combustibles like wood, paper, rubber, many plastics, and other common materials that burn easily. Class B is flammable liquids like gasoline, oil, and grease. Class C is energized electrical equipment including wiring fuse boxes, circuit breakers, machinery, and appliances. Do not use chemical extinguishers even though they are less expensive and cover all classes of fires. They may damage electronic equipment. Use a Carbon Dioxide or Halon fire extinguisher.

During the planning stage, consult local experts, building authorities, and insurance underwriters on locating and installing sprinkler heads, fire and smoke sensing devices, and other fire extinguishing equipment.

Locate an oxygen concentration monitor and alarm in the system work area near the system. Locate another in the dewar storage area. LHe and LN_2 can rapidly replace the breathing atmosphere in an enclosed area with no warning. Oxygen concentration monitor and alarms are the best way to reduce this potential hazard.

Safety (Continued)

An electromagnet can generate large magnetic fields. Post signs at each entrance to the work area that state: "Warning: High Field Magnets – Fringe fields may be hazardous to pacemakers and other medical devices. Keep magnetic materials clear of area." Paint a yellow magnetic field warning line on the floor 1 meter (3 feet) from the sides of the electromagnets.

Locate a fireproof safe at or near the work site for temporary storage of data and copies of original system software and documentation. Store duplicate copies of vital data well away from the system area, also in a fireproof storage vault or safe.

Even where not required by code, install some type of automatic, battery-operated emergency lighting in case of power failure or fire.

2.8.1 Electrostatic Discharge

Electrostatic Discharge (ESD) may damage electronic parts, assemblies, and equipment. ESD is a transfer of electrostatic charge between bodies at different electrostatic potentials caused by direct contact or induced by an electrostatic field. The low-energy source that most commonly destroys Electrostatic Discharge Sensitive (ESDS) devices is the human body, which generates and retains static electricity. Simply walking across a carpet in low humidity may generate up to 35,000 volts of static electricity.

Current technology trends toward greater complexity, increased packaging density, and thinner dielectrics between active elements, which results in electronic devices with even more ESD sensitivity. Some electronic parts are more ESDS than others. ESD levels of only a few hundred volts may damage electronic components such as semiconductors, thick and thin film resistors, and piezoelectric crystals during testing, handling, repair, or assembly. Discharge voltages below 4000 volts cannot be seen, felt, or heard.

2.8.1.1 Identification of Electrostatic Discharge Sensitive Components

Below are various industry symbols used to label components as ESDS:



2.8.1.2 Handling Electrostatic Discharge Sensitive Components

Observe all precautions necessary to prevent damage to ESDS components before attempting installation. Bring the device and everything that contacts it to ground potential by providing a conductive surface and discharge paths. As a minimum, observe these precautions:

1. De-energize or disconnect all power and signal sources and loads used with unit.
2. Place unit on a grounded conductive work surface.
3. Ground technician through a conductive wrist strap (or other device) using 1 MΩ series resistor to protect operator.
4. Ground any tools, such as soldering equipment, that will contact unit. Contact with operator's hands provides a sufficient ground for tools that are otherwise electrically isolated.
5. Place ESDS devices and assemblies removed from a unit on a conductive work surface or in a conductive container. An operator inserting or removing a device or assembly from a container must maintain contact with a conductive portion of the container. Use only plastic bags approved for storage of ESD material.
6. Do not handle ESDS devices unnecessarily or remove from the packages until actually used or tested.

2.8.2 Instrument Safety

Observe the following general safety precautions during all phases of instrument operation, service, and repair. Failure to comply with these precautions or with specific warnings elsewhere in this manual violates safety standards of design, manufacture, and intended instrument use. Lake Shore assumes no liability for Customer failure to comply with these requirements.

Lake Shore instrumentation protects the operator and surrounding area from electric shock or burn, mechanical hazards, excessive temperature, and spread of fire from the instrument. Environmental conditions outside of the conditions detailed in Paragraph 2.3 may pose a hazard to the operator and surrounding area. In addition, power supply voltage fluctuations must not exceed ±10% of the nominal voltage.

Ground Instruments
To minimize shock hazard, connect instrument chassis and cabinet to an electrical ground. Most Lake Shore instruments come with a three-conductor AC power cable. Plug the power cable into an approved 3-contact electrical outlet or use a three-contact adapter with the grounding wire (green) firmly connected to an electrical ground (safety ground) at the power outlet. The power jack and mating plug of the power cable meet Underwriters Laboratories (UL) and International Electrotechnical Commission (IEC) safety standards.

Do Not Operate In An Explosive Atmosphere
Do not operate instruments in the presence of flammable gases or fumes. Operation of any electrical instrument in such an environment constitutes a definite safety hazard.

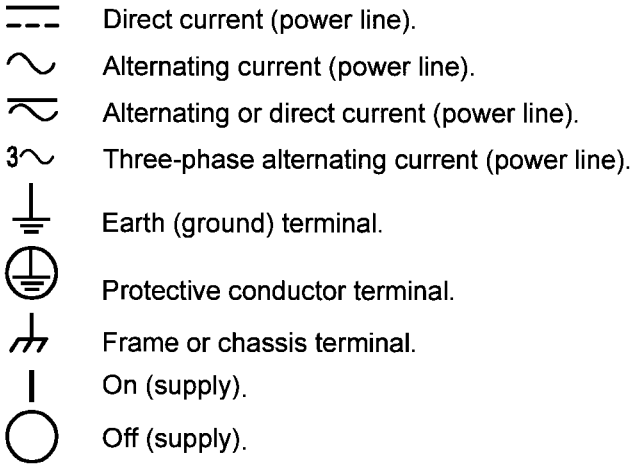
Prevent Cooling Water Condensation
Do not operate the power supply when cooling water temperature is at or lower than the dew point for local atmospheric conditions. Condensation on cooling water lines inside the power supply can cause severe damage. Refer to Paragraph 3.1.3 for additional details.

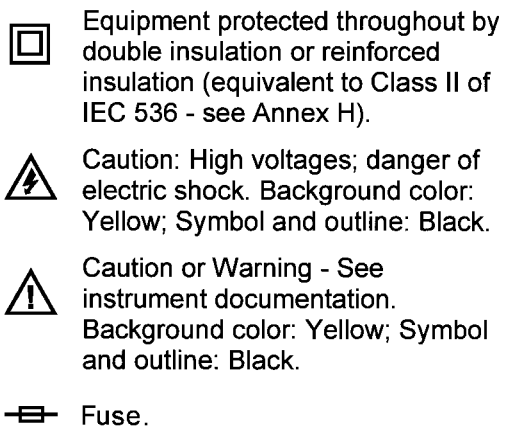
Keep Away From Live Circuits
Operating personnel must not remove instrument covers. Refer component replacement and internal adjustments to qualified maintenance personnel. Do not replace components with power cable connected. To avoid injuries, always disconnect power and discharge circuits before touching them.

Do Not Substitute Parts Or Modify Instrument
Do not install substitute parts or perform any unauthorized modification to instruments. Return the instruments to an authorized Lake Shore representative for service and repair to ensure that safety features are maintained.

Cleaning
Do not submerge any of the instruments. Clean only exterior surfaces with a damp non-abrasive cloth and mild detergent.

2.8.3 Safety Symbols





CHAPTER 3

INSTALLATION OVERVIEW

3.0 GENERAL

The 7600 Series Hall System was electrically and mechanically inspected and operationally tested prior to shipment. It should be free from mechanical damage and in good working order upon receipt. Unless a specific model number is specified, the information in this chapter is considered to be "generic" to all systems.

3.1 PLUMBING THE COOLING WATER

Provided proper flow is maintained, standard municipal water systems are generally suitable to cool the magnet and power supply. Do not use distilled water. Use a water filter, flow meter, and pressure gauges to monitor coolant water flow.

The following is a table of cooling fittings for the different size electromagnets. The customers must provide components to mate with the possible connections. If garden hose fittings are not convenient, the Customer may remove them and make alternative connections.

Magnet Size/ Flow Rate	Hose Size	Outlet/Inlet Fittings	Alternative Available Fittings/Connections
4 inch/1 gpm	½ ID × ¾ OD	Garden Hose Male	½ inch Hose Barb or Hose – Outlet
		Garden Hose Female	½ inch Hose Barb or Hose – Inlet
7 inch/3 gpm	5/8 ID × 1 OD	Garden Hose Male	5/8" hose barbs or Hose or ½ NPT (F) – out
		Garden Hose Female	5/8" hose barbs or Hose or ¾ NPT (F) – in

3.1.1 Electromagnet Cooling Water

This section provides procedures for connecting the cooling water to the EM4-HVA and the EM7-HV.

3.1.1.1 EM4-HVA Cooling Water Connections

The electromagnet is configured at Lake Shore with 10 mm (3/8 in) ID tubing and splitters to properly route the water flow through the electromagnet coils so that there is a single inlet and outlet connection to connect to the cooling water system (Figure 3-1). Also included on the outlet of the electromagnet is a water safety flow switch. The routing of water through the coils should not be altered and the flow switch should be used.

NOTE: You are responsible for providing the necessary lengths of tubing and connections to your cooling water system.

You will need to attach the water inlet and outlet hoses. See Figure 3-1 for illustrations of these connections.



Figure 3-1. Water connections for a 4 in magnet

3.1.1.2 EM7-HV Water Cooling Connections

The Model EM7-HV comes shipped with the magnet coolant hoses already attached. You will need to attach the facility water inlet and outlet hoses to the garden hose 3/4 in type connections. See Figure 3-1 for illustrations of these connections.

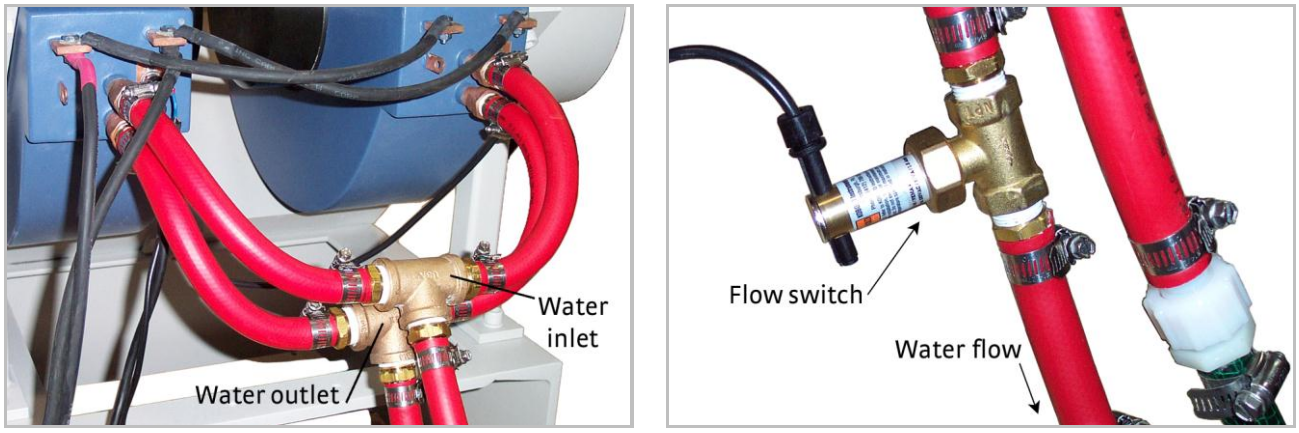


Figure 3-2. Water connections for a 7 inch magnet

3.1.2 Power Supply Cooling Water

Per the site preparation instructions (section 2.1), the user is responsible for providing the hookup from the electrical box at the back of the power supply to the electrical service.

CAUTION: Too cold a supply can cause condensation and severe damage to the power supply

3.1.2.1 Model 643 Power Supply Cooling Water Connections

Supply and return water supply lines are required to cool the magnet power supply. The water connections for the Model 643 are hose barb fittings. Hoses and clamps shown are not provided.

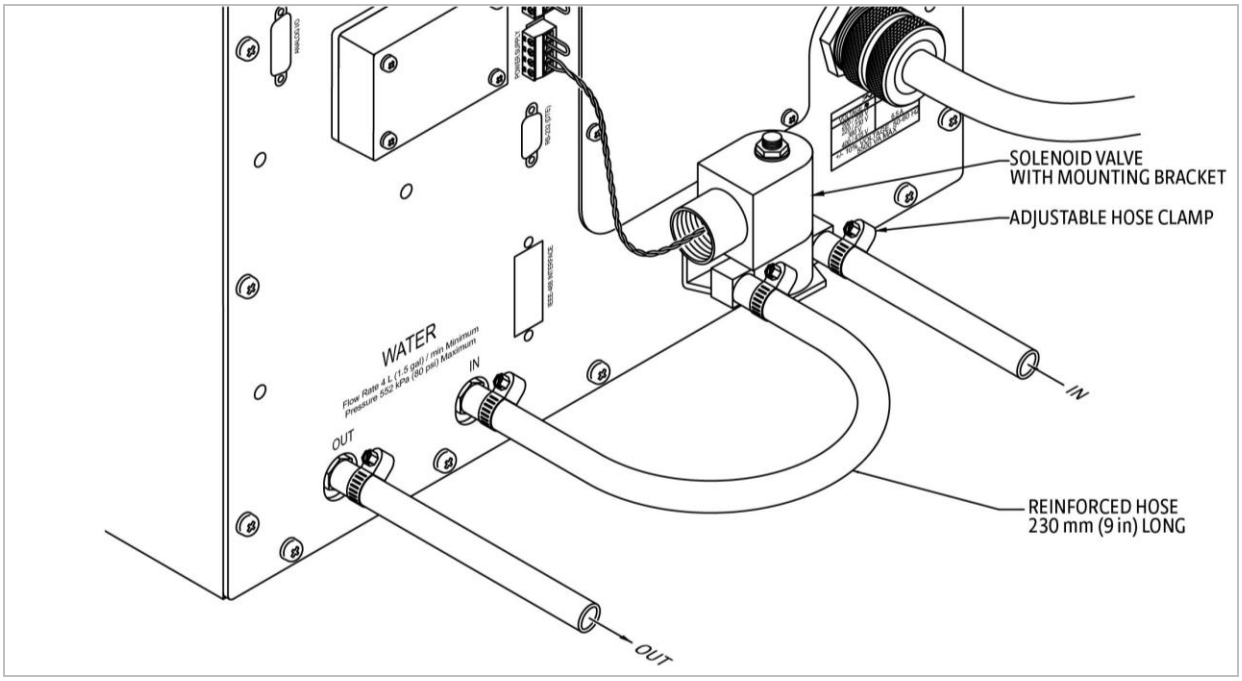


Figure 3-3. Quick Disconnects on Model 643 Power Supply

3.1.2.2 Model 648 Power Supply Cooling Water Connections

The water connections for the Model 648 uses two 12.7 mm (0.5 in) I.D. fiberglass reinforced hoses and two 20 mm (25/32 in) adjustable hose clamps . Hoses and clamps shown are not provided.

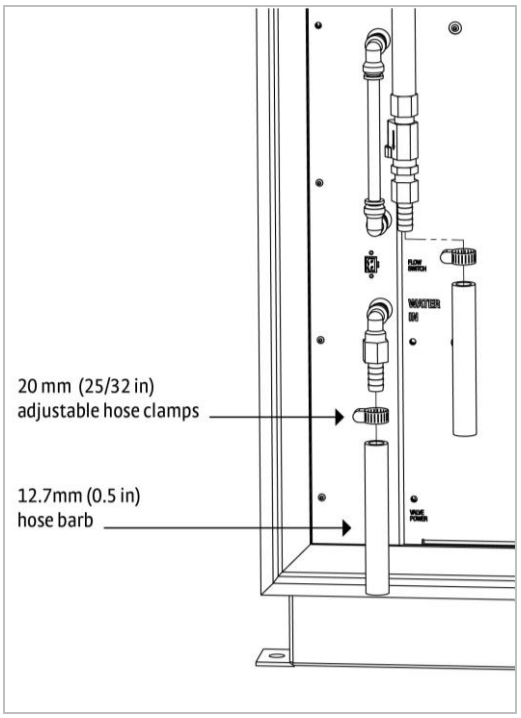


Figure 3-4. Hose Barb Fittings on Model 648 Power Supply

3.1.3 Avoiding Cooling Water Condensation

If the temperature of the cooling water is too cool relative to the air temperature and humidity, condensation can occur. Condensation inside the power supply can cause severe damage. To avoid condensation, the power supply operator must remain cognizant of the ambient air temperature, cooling water temperature, and the relative humidity. Lake Shore defines the limits of these conditions as follows: ambient temperature = 18 – 28 °C (64 – 82 °F), cooling water temperature = 15 – 24 °C (59 – 75 °F), and humidity = 20 – 80% (non-condensing). Knowing the actual state of these conditions, the operator can calculate the dew point, or temperature at which condensation will occur. Tables 3-1 and 3-2 are included to aid in dew point calculation.

NOTE: Newer power supplies are equipped with a moisture sensor. This sensor will trigger an External Fault that will inhibit the output of the power supply. This fault can also be triggered by the absence of cooling water flow.

Table 3-1. Dew Point Calculation Table (In Degrees Celsius)

	% Relative Humidity																		
°C	*100*	*95*	*90*	*85*	*80*	*75*	*70*	*65*	*60*	*55*	*50*	*45*	*40*	*35*	*30*	*25*	*20*	*15*	*10*
32	32	31	31	29	28	27	26	24	23	22	20	18	17	15	12	9	6	2	0
29	29	28	27	27	26	24	23	22	21	19	18	16	14	12	10	7	3	0	–
27	27	26	25	24	23	22	21	19	18	17	15	13	12	10	7	4	2	0	–
24	24	23	22	21	20	19	18	17	16	14	13	11	9	7	5	2	0	–	–
21	21	20	19	18	17	16	15	14	13	12	10	8	7	4	3	0	–	–	–
18	18	17	17	16	15	14	13	12	10	9	7	6	4	2	0	–	–	–	–
16	16	14	14	13	12	11	10	9	7	6	5	3	2	0	–	–	–	–	–

Table 3-2. Dew Point Calculation Table (In Degrees Fahrenheit)

	% Relative Humidity																		
°F	*100*	*95*	*90*	*85*	*80*	*75*	*70*	*65*	*60*	*55*	*50*	*45*	*40*	*35*	*30*	*25*	*20*	*15*	*10*
90	90	88	87	85	83	81	79	76	74	71	68	65	52	59	54	49	43	36	32
85	85	83	81	80	78	76	74	72	69	67	64	61	58	54	50	45	38	32	–
80	80	78	77	75	73	71	69	67	65	62	59	56	53	50	45	40	35	32	–
75	75	73	72	70	68	66	64	62	60	58	55	52	49	45	41	36	32	–	–
70	70	68	67	65	63	61	59	57	55	53	50	47	44	40	37	32	–	–	–
65	65	63	62	60	59	57	55	53	50	48	45	42	40	36	32	–	–	–	–
60	60	58	57	55	53	52	50	48	45	43	41	38	35	32	–	–	–	–	–

Example: Determine the actual air temperature and relative humidity. Find the closest air temperature in the left-hand column and the closest relative humidity across the top. If the air temperature is 24 °C (75 °F) and the relative humidity is 35%, the intersection of the two shows a dew point of 7 °C (45 °F). Therefore, for the given conditions, the cooling water must remain above 7 °C (45 °F) to prevent condensation.

3.2 HOOKING UP CABLES

There are three major parts to the 7600 Series Hall System: Instrument Console/Computer, Electromagnet/Gaussmeter Probe, and Magnet Power Supply.

3.2.1 Instrument Console/Computer

The Instrument Console contains three instruments: Models 475, 2400, and 2700, as detailed in the following paragraphs. A power distribution strip is included inside the cabinet. The computer and monitor reside on top of the console. See the foldout Figure 3-23 for a summary of system wiring.

3.2.1.1 Lake Shore Model 475 Gaussmeter

The rear panel connections of the Model 475 Gaussmeter is defined as shown in Figure 3-5 and detailed in the numbered list. Proper instrument settings are established automatically via the Hall Software Configuration Utility.

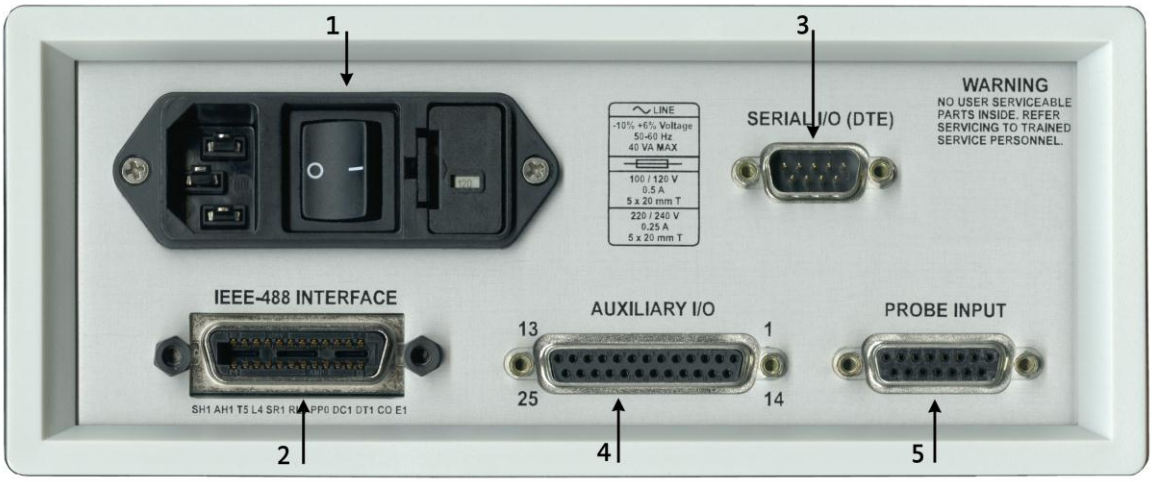


Figure 3-5. Model 475 Gaussmeter Rear Panel

1. **Line input assembly:** The AC power line cord from the power strip is connected to this location. This is also the location of the fuse drawer.
2. **IEEE-488 Interface:** This is the connection point for the IEEE-488 cable from the computer. A second cable is installed on top that runs to the Model 2400 IEEE connector.
3. **Serial I/O:** For use with RS-232C serial computer interface.
4. **Auxiliary I/O:** Provides access to the analog outputs, hardware triggers, and relays.

CAUTION: Power off the Model 475 before attaching or unattaching the probe connector. Damage may occur if connecting or disconnecting with power on.

5. **Probe Input:** Connects to the gaussmeter probe mounted on the probe holder assembly (Paragraph 3.2.3) at the rear of the electromagnet.

3.2.1.2 Keithley Model 2400 Sourcemeter

The rear panel connections of the Model 2400 Sourcemeter is defined as follows. See Figure 3-6. Proper instrument settings are established automatically via the Hall Software Configuration Utility.

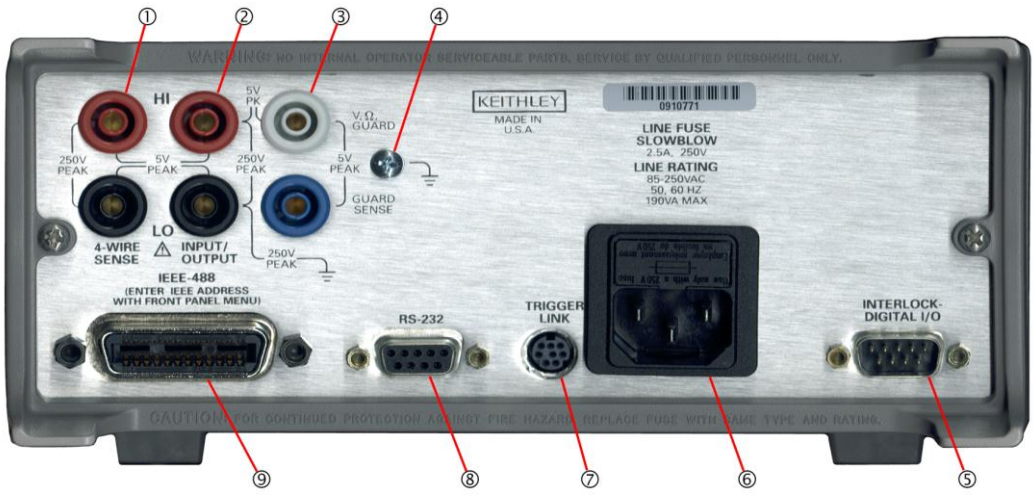
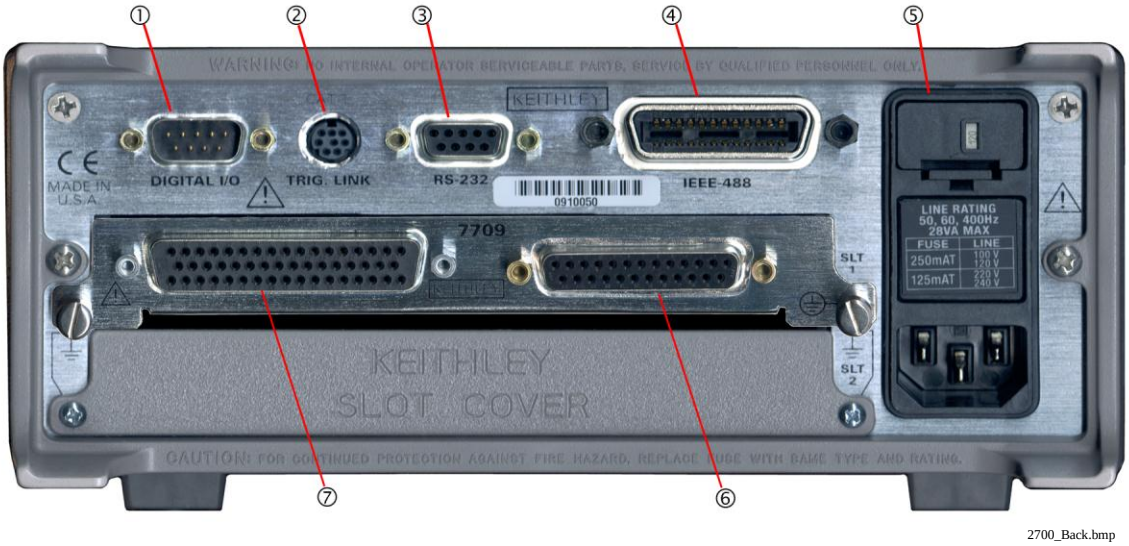


Figure 3-6. Model 2400 Sourcemeter Rear Panel

1. **4-Wire Sense:** Not used.
2. **Input/Output:** Dual bananas are installed here from the 50 pin connector on the Model 7709 Matrix Module (that is installed inside the Model 2700 Multimeter). A single wire jumper from the LO banana is connected to the ground screw.
3. Guard: Not used.
4. Earth (Chassis) Ground Screw: Attaches a single wire from the Input/Output LO banana.
5. **Interlock-Digital I/O:** Connector for digital output lines, interlock, and component handler signals. A shorting plug is installed on this connector.
6. Power Input: The AC power line cord from the power strip is connected to this location. This is also the location of the fuse drawer.
7. **Trigger Link:** Not used.
8. **RS-232:** Not used.
9. **IEEE-488:** This is the connection point for the IEEE-488 cable from the Model 475. A second cable is installed on top that runs to the Model 2700 IEEE connector.

3.2.1.3 Keithley Model 2700 Multimeter

The rear panel connections of the Model 2700 Multimeter is defined as follows. See Figure 3-7. Proper instrument settings are established automatically via the Hall Software Configuration Utility. In addition to the rear panel connectors shown below, the two Input banana plugs on the front panel are also used. See Figure 3-23.



2700_Back.bmp

Figure 3-7. Model 2700 Multimeter Rear Panel

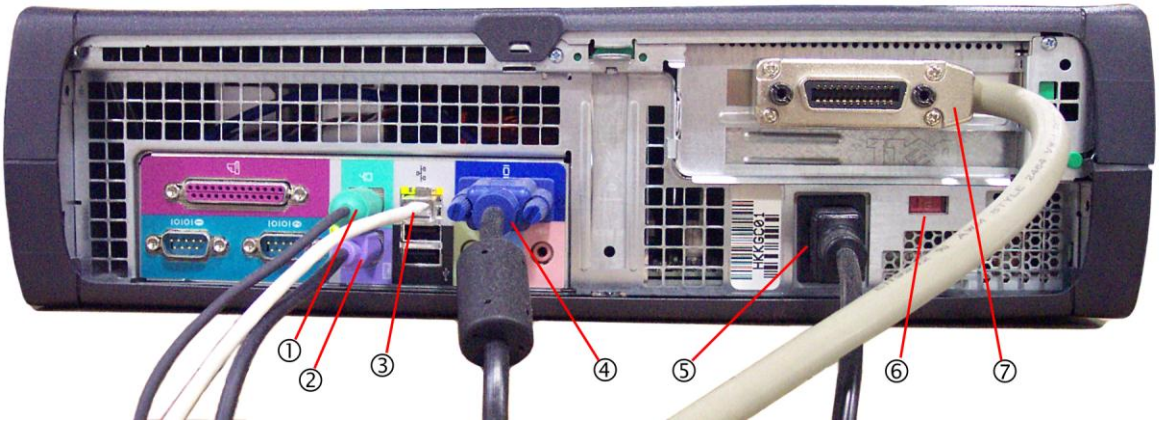
1. **Digital I/O:** Not used.
2. **Trigger Link:** Not used.
3. **RS-232:** Not used.
4. **IEEE-488:** This is the connection point for the IEEE-488 cable from the Model 2400. On a standard system, this is the end of the "daisy chain." If additional optional instruments are added, another IEEE-488 cable will be installed on top of this connector and the cable run to the added instrument.
5. Power Input: The AC power line cord from the power strip is connected to this location. This is also the location of the fuse drawer.
6. **25-pin Connector:** This connector is part of the Model 7709 Matrix Module installed in the rear of the Model 2700 Multimeter. The cable from this connector runs to the Primary connector on the Hall Sample Module.
7. **50-pin Connector:** This connector is part of the Model 7709 Matrix Module installed in the rear of the Model 2700 Multimeter. One part of the cable from this connector runs to Input banana plugs on the front panel while the second part of the cable runs to Input/Output banana plugs on the rear of the Model 2400 Sourcemeter.

3.2.1.4 Computer Connections

The computer connections are defined as follows. See Figure 3-8. The monitor (not shown) also requires input and power connections.

CAUTION: Do not install any third-party software on this computer. Installing other software may cause conflicts with the operation of the 7600 Series Hall System and can have unintended consequences. Lake Shore assumes no responsibility for damage to the system as the result of unauthorized software installation.

NOTE: Because of the volatility of the computer market, the computer shown here is a typical representative. Your actual computer may vary in form, but the functions will remain.



Computer_Rear.bmp

Figure 3-8. Computer Rear Panel

1. **Mouse:** This connector goes to the computer mouse.
2. **Keyboard:** This connector goes to the computer keyboard.
3. **Ethernet:** This is the Ethernet connector for your network.

NOTE: While an Ethernet connection is provided with the computer, Lake Shore assumes no responsibility for making the computer communicate with your network.

4. **Monitor:** This connector goes to the computer monitor.
5. **Power:** This power cord runs inside the Instrument Console and plugs into the Distribution Strip. (Also run the monitor power connector to this same Distribution Strip.)
6. **Voltage Selection Switch:** If your computer includes this switch, make sure it matches your local power requirements.

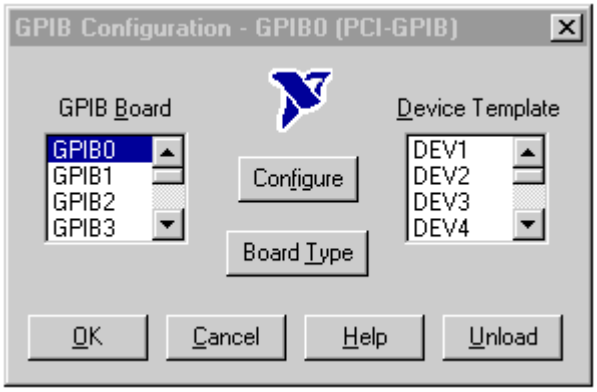


7. **IEEE-488 Interface:** This IEEE-488 connector provides the link between the computer and the instruments in the Console. The cable runs from the computer to the first instrument inside the console. Other instruments are "daisy-chained" from there.

3.2.1.5 IEEE-488 Interface Address Settings

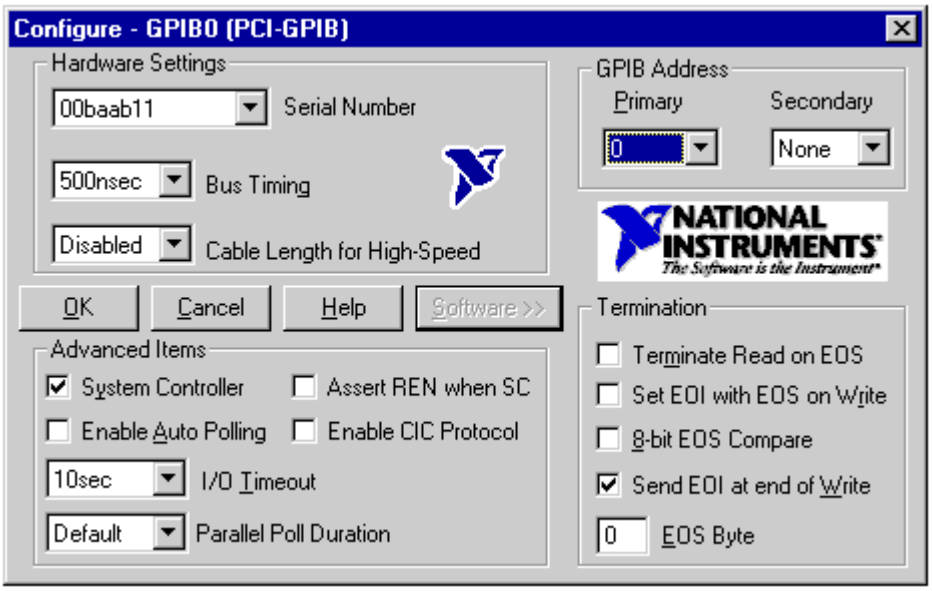
Use the following procedure to set or verify the IEEE-488 addresses for the 7600 Series Hall System.

1. Computer.
   a. Select Start/Settings/Control Panels and double-click the **GPIB** icon.
   b. On the GPIB Configuration screen, select the **Configure** button.



GPIB_2.bmp

   c. On the Configure – GPIB0 screen, ensure the GPIB Address is set as shown below: Primary = 0, Secondary = None.



GPIB_3.bmp

   d. Also on the Configure – GPIB0 screen, ensure that the "Terminate Read on EOS" box is unchecked and that all the other settings are as shown above. If you made any changes, select the OK button. If you were just verifying settings, select the Cancel button.

IEEE-488 Address Settings (Continued)

2. Lake Shore Model 475 Gaussmeter.
   a. Press the **Interface** key.
   b. Press the **Enter** key to skip Baud Rate screen.
   c. The IEEE address is displayed. Press the ▲ or ▼ key to select a setting of 8.
   d. Press the **Enter** key to save the new address.
   e. The terminators screen is displayed. Press the ▲ or ▼ key to select Cr Lf. Press the **Enter** key.

3. Keithley Model 2400 Sourcemeter.
   a. Press the **Menu** key.
   b. Press the ◄ or ► keys to select Communication, then GPIB.
   c. Press the ◄ or ► keys to select the instrument address of 24.

4. Keithley Model 2700 Multimeter.
   a. Press the **SHIFT** key and then the **GPIB** key. The GPIB ON or GPIB OFF message is displayed.
   b. If the GPIB is already ON, press ENTER and proceed to step c. Otherwise, press the ► key to place the cursor on OFF, press the ▲ or ▼ key to display the ON state, and then press ENTER.
   c. To retain the presently displayed address (ADDR) value, press ENTER. Otherwise, press the ► key to place the cursor on the address value, use the ◄, ►, ▲, or ▼ keys to display the address of 15, then press ENTER.

3.2.2 Magnet/Hall Sample Module

This section details electrical connections from the electromagnet and sample module. Magnets are wired to match the output of the power supply. In general, the magnet is wired to a nominal resistance of 0.5 ohm. However, the magnets and power supplies physically look different. The water connections should already be made (Paragraph 3.1.1).

NOTE: It is important to get the polarity of the magnet and power supply correct. Incorrect polarity will yield the wrong sign for carriers as measured by the Hall Measurement System. Correct wiring is provided in the following paragraphs and correct gaussmeter probe orientation is provided in Paragraph 3.2.3.

3.2.2.1 4-Inch Electromagnet Connections

The EM4-HVA magnet current leads are connected in series. The 4-inch magnet wiring connections are shown in Figure 3-9.

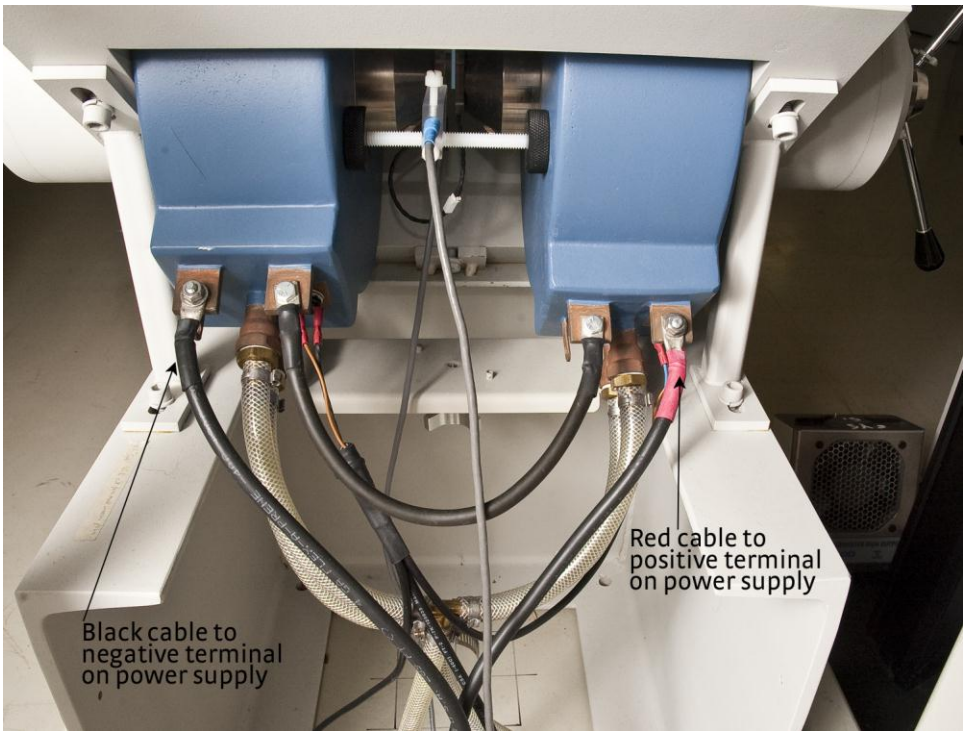


Figure 3-9. Typical 4-inch Magnet Wiring Connections

3.2.2.2 7 Inch Electromagnet Connections

See Figure 3-10 for illustrations of the electrical connections.

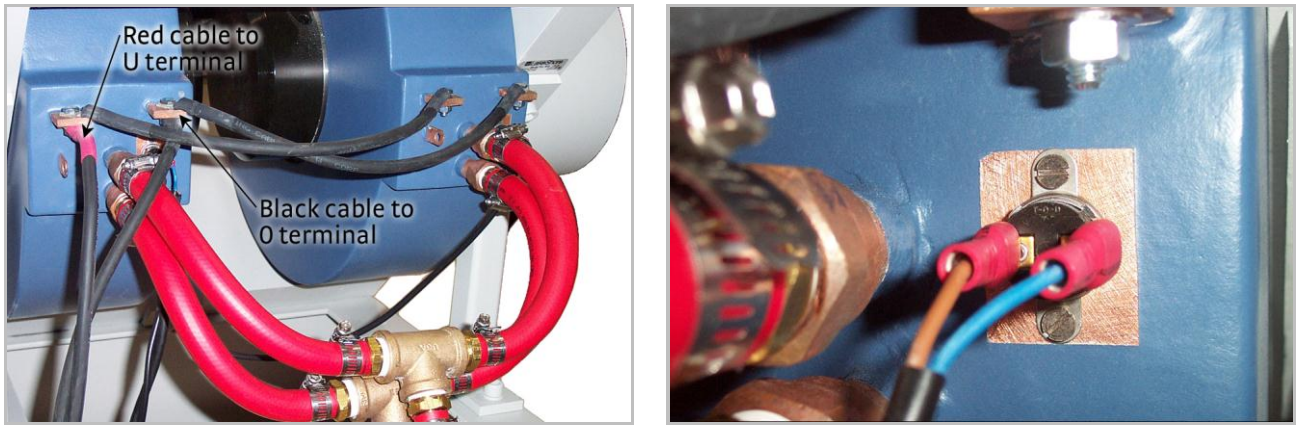


Figure 3-10. Left: Typical 7 in magnet wiring connections; Right: Typical 7 in magnet thermal switch connections

3.2.2.3 Hall Sample Module Mounting

Once the electromagnet is setup, it is time to mount the Hall Sample Module to the frame. See Figure 3-11.

1. Orient the sample module so the clamping knob is facing forward.
2. Pull the index plunger T-lock and let the assembly rotate and lock into the 45° position.

NOTE: The index plunger allows the assembly to lock into one of three positions: vertical, 45°, and horizontal. The T-lock can also be pulled out and rotated 90°, locking the handle in the "out" position, which allows the assembly to swing freely.

3. Place the sample module assembly so the two holes in the base plate aligns with two corresponding holes on the frame.
4. Install and tighten the two ¼–20×½" socket-head cap screws.
5. The clamping knob controls the height of the sample enclosure. When fully descended, a tongue attached to the tube fits snugly into a slot in the axle. This "alignment key" ensures repeatable sample alignment.

NOTE: Be sure to clamp carefully to avoid damaging the rod.

6. Use the two rotation friction screws on either side of the pillow blocks control the "tightness" of the axle rotation. The sample module should not rotate under its own weight, but also should not be difficult to rotate. Tighten the screws to increase or loosen to decrease rotational friction.

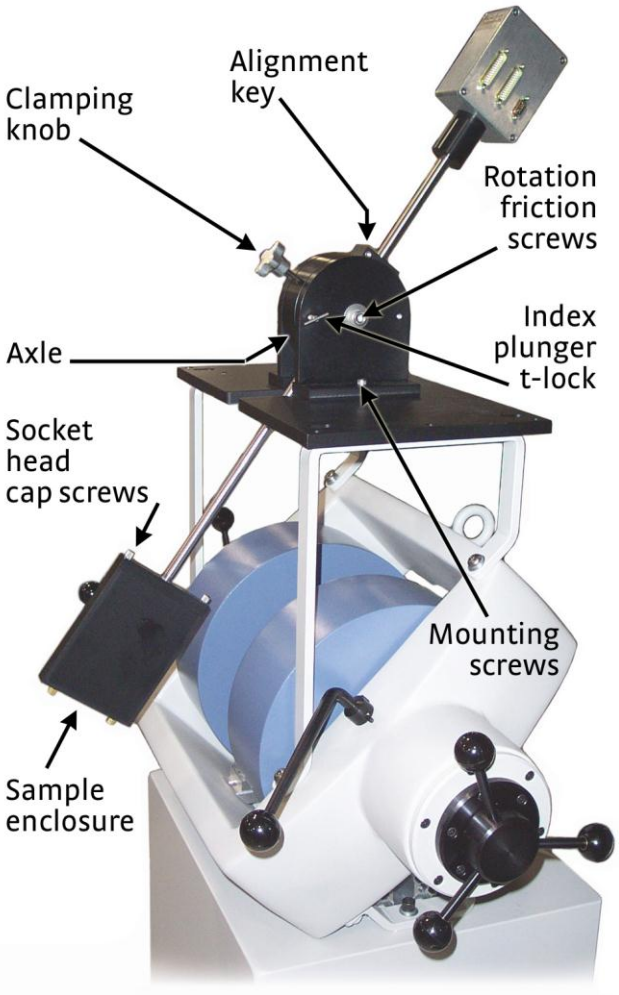


Figure 3-11. Typical Hall Sample Module Mounting

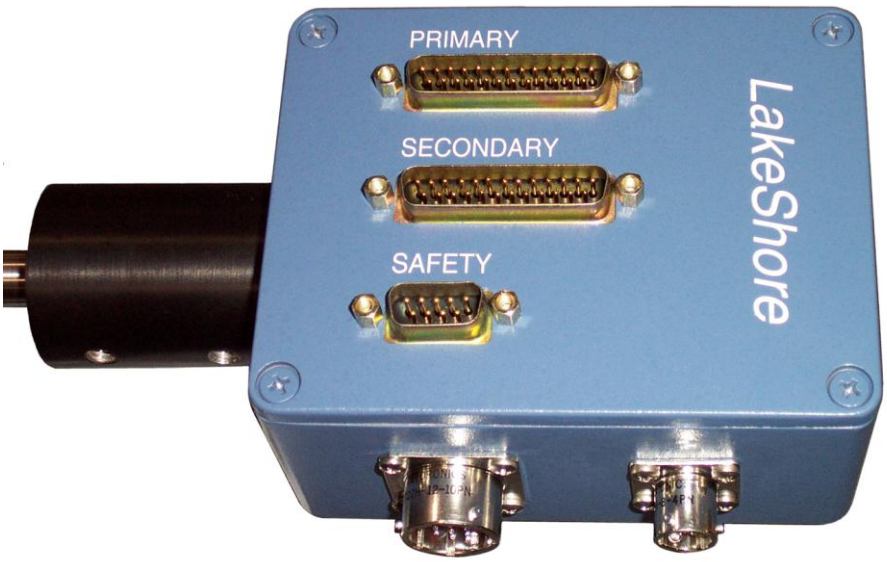
7. The sample enclosure is attached to the header block by two socket head cap screws. Since many semiconductors are light sensitive, Hall effect measurements are normally performed with the sample in the dark. There is a layer of felt between the header block and the sample enclosure to aid in keeping the interior dark. Refer to Paragraph 3.5 for instruction on changing sample cards.

CAUTION: Using the procedure detailed in Paragraph 3.4, ensure there is sufficient space between the pole caps for the sample enclosure and gaussmeter probe. In general, the smaller the gap between the poles, the higher the achievable magnetic flux density and the better the uniformity. Smaller pole faces increase the magnetic flux density, but decrease the uniformity.

8. Pull the index plunger T-lock and let the assembly rotate to into measurement position. The plunger will fall into a hole when the assembly reaches vertical.

3.2.2.4 Hall Sample Module Connections

The top of the Hall sample module provides connection points to the two sample card mounting connectors at the bottom of the module. See Figure 3-12. Refer to Paragraph 3.5 for further details on sample mounting.



Stick_Head.bmp

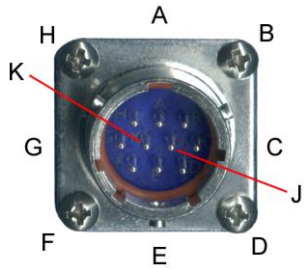
Figure 3-12. Typical Sample Module Connections

1. **Primary:** In the standard 2-sample Hall system, the Primary 25-pin D-style connector provides electrical connection to the front (A) side of the 2 sample card connectors at the bottom of the sample module. The cable from Primary runs to the 25-pin connector on the Model 7709 Matrix Module installed in the Model 2700 Multimeter (top slot).
2. **Secondary:** Not used in the standard 2-sample Hall System. When equipped with the 7600-4 option, the Secondary 25-pin connector provides electrical connection to the rear (B) side of the 2 sample card connectors at the bottom of the sample module. The cable from Secondary runs to the 25-pin connector on the second Model 7709 Matrix Module installed in the Model 2700 Multimeter (bottom slot).
3. **Safety:** This 9-pin D-style connector is not used.
4. **4-Pin Connector:** While not used for standard Hall measurements, the 4-pin connector provides user access to outboard unnumbered solder pads on the B side of both small sample cards.



4-pin Connector Pin	Sample Card Solder Pad
A	Connector 1, B side, contact finger closest to notch
B	Connector 1, B side, contact finger furthest from notch
C	Connector 2, B side, contact finger closest to notch
D	Connector 2, B side, contact finger furthest from notch

5. **10-Pin Connector:** While not used for standard Hall measurements, the 10-pin connector provides user access to extra solder pads 7 thru 10 on the small or large sample card in position 1 only.



10-pin Connector Pin	Sample Card Solder Pad
K	7
F	8
H	9
G	10

3.2.3 Gaussmeter Probe Holder Installation

Use the following procedure to mount the gaussmeter probe holder. It is best to loosely install the assembly first without a probe in the holder, then once the assembly is "close" to a usable position, place a probe in the holder and make the final adjustments.

1. Place the gaussmeter probe holder assembly at the end of the extruded frame located between the magnet coils. Use the 5/32 inch hex wrench to mount the holder to the extrusion. See Figure 3-13. This screw also provides side to side adjustment of the holder assembly.
2. Use the 3/16 inch hex wrench to adjust the height and rotation of the post.
3. Use the 3/16 inch hex wrench to adjust the clear plastic probe holder attached to the post. This screw provides up and down adjustment of the probe holder.

CAUTION: Exercise care when handling the gaussmeter probe; its tip is very fragile. Stressing the probe tip may alter its calibration. Any excess force can easily break the sensor. Broken sensors are not reparable.

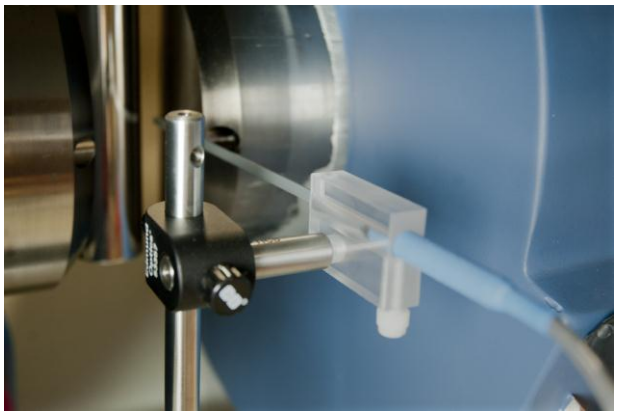


Figure 3-13. Gaussmeter Probe Holder Installation

4. Carefully place the gaussmeter probe into the holder. Turn top screw to hold it in position. Do not over tighten. Always secure the gaussmeter probe by the body; securing the tip can cause irreparable damage.
5. Do any final adjustments to the probe holder assembly to ensure the probe is in the proper position between the Hall Sample Module and the magnet pole pieces. Rotate the probe so the flat side is parallel with the pole faces and secure it.

NOTE: To make room for the gaussmeter probe, the gap to the right of the sample enclosure (when viewed from the front of the electromagnet), needs to be about 3 – 4 mm (about 1/8 inch) larger than the gap to the left.

3.2.3.1 Gaussmeter Probe Orientation

The orientation of the gaussmeter probe is critical to field control. If you are unsure of correct orientation, use the following procedure.

1. With the magnet power supply OFF and local regulation set to zero, place the gaussmeter probe in the electromagnet noting the orientation of the Lake Shore Snowflake symbol.
2. Turn the power supply ON in Internal Programming mode. Manually set a positive current of a few amps corresponding to approximately 500 Oe.
3. Read the gaussmeter display in the Hall software to ensure the field reading is positive. If the field reading is negative, reverse the orientation of the probe.
4. When done, reduce current to zero and turn OFF power supply.

3.2.3.2 Changing Probes

An Electrically Erasable Programmable Read Only Memory (EEPROM) is included in each probe. The EEPROM stores specific information that the gaussmeter requires for operation. The information includes serial number, probe sensitivity, and field compensation data.

CAUTION: The probe must be connected to the rear of the gaussmeter before applying power. Probe memory may be erased if connected with power on.

When the instrument is powered up, the probe memory is downloaded to the gaussmeter. This is how the built-in gaussmeter knows which ranges are available and which error correction to apply. To change probes, first turn power off, remove the existing probe, and then plug in the new probe. When power is restored, the characteristics of the new probe are downloaded to memory. Normal operation may continue after the new probe offset is nulled using the Zero Probe operation. If the instrument is powered up with no probe attached, the Hall software will report an error message.

3.2.3.3 Probe Handling

Although every attempt has been made to make the probes as sturdy as possible, the probes are still fragile. This is especially true for the exposed sensor tip of some transverse probes. Care should be taken during measurements that no pressure is placed on the tip of the probe. The probe should only be held in place by securing at the handle. The probe stem should never have force applied. Any strain on the sensor may alter the probe calibration, and excessive force may destroy the Hall generator.

CAUTION: Care must be exercised when handling the probe. The tip of the probe is very fragile. Stressing the Hall sensor can alter its calibration. Any excess force can easily break the sensor. Broken sensors are not repairable.

When the probe is not in use, the protective tubes provided should be placed over the probe handle and stem in order to protect the tip. When not in use, the probe should be stored separately in some type of rigid container. The cardboard and foam container that Lake Shore probes are shipped in may be retained for probe storage.

3.2.3.4 Probe Operation

In the DC mode of operation, the orientation of the probe affects the polarity reading. On a transverse probe, the Lake Shore name printed on the handle indicates the side for positive (+) flux entry. On an axial probe, positive (+) flux entry is always from the front of the probe. See Figure 3-14.

NOTE: For best results, the instrument and probe should warm up for at least 5 minutes before zeroing the probe, and at least 30 minutes for rated accuracy. The probe and the zero gauss chamber should be at the same temperature.

If the exact direction of the magnetic field is unknown, the proper magnitude is determined by turning on **Max Hold** and slowly adjusting the probe. As the probe turns and the measured field rises and falls, its maximum value is held on the display. Make note of the probe orientation at the maximum reading to identify the field orientation.

3.2.3.5 Probe Accuracy Considerations

NOTE: Probe readings are dependent upon the angle of the sensor in relation to the magnetic field. The farther from 90° the angle between the probe and the field, the greater the percentage of error. For example, a 5° deviation causes a 0.4% error, a 10° deviation causes a 1.5% error, etc.

NOTE: For best results, the instrument and probe should warm up for at least 5 minutes before zeroing the probe, and at least 30 minutes for rated accuracy. The probe and the zero gauss chamber should be at the same temperature.

The user must consider all the possible contributors to the accuracy of the reading. Both the probe and instrument have accuracy specifications that may impact the actual reading. The probe should be zeroed before making critical measurements. The zero probe function is used to null (cancel) out the zero offset of the probe or small magnetic fields. It is normally used in conjunction with the zero gauss chamber, but may also be used with an open probe (registering the local earth magnetic field).

NOTE: Use care to ensure the zero gauss chamber does not become magnetized. Using a magnetized chamber to zero a probe can lead to erroneous field readings. It is a good practice to periodically degauss the chamber. If no professional degausser is available, a bulk tape degausser (Verity VS250, Data Devices PF211, or equivalent) may be used.

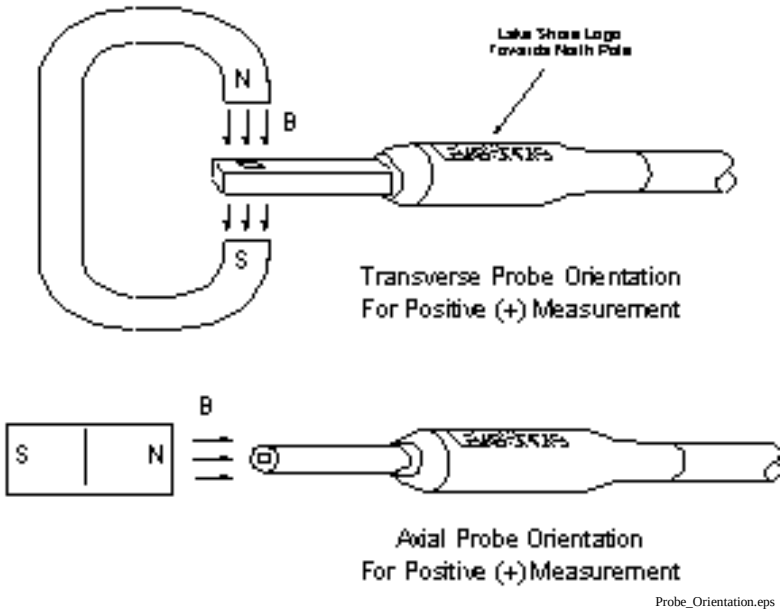


Figure 3-14. Probe Orientation For Positive Measurement

NOTE: The Model 475 Gaussmeter does not read the temperature compensation table stored in the gaussmeter probe.

Probe readings are dependent on the angle of the sensor (Hall sensor) in relation to the magnetic field. Maximum output occurs when the flux vector is perpendicular to the plane of the sensor. This is the condition that exists during factory calibration. The greater the deviation from orthogonality (from right angles in either of three axes), the larger the error of the reading. For example, a 5° variance on any one axis causes a 0.4% error, a 10° misalignment induces a 1.5% error, etc. See Figure 3-15.

Tolerance of instrument, probe, and magnet must be considered for making critical measurements. The accuracy of the gaussmeter reading is better than ±0.20% of reading and ±0.05% of range. Absolute accuracy readings for the gaussmeter and probe is a difficult specification to give, because all the variables of the measurement are difficult to reproduce. For example, a 1° error in alignment to the magnetic field causes a 0.015% reading error. Finally, the best probes have an accuracy of ±0.15%. This implies that the absolute accuracy measurement of a magnetic field is not going to reliably be better than ±0.15% under the best of circumstances, and more likely to be 0.20% to 0.25%.

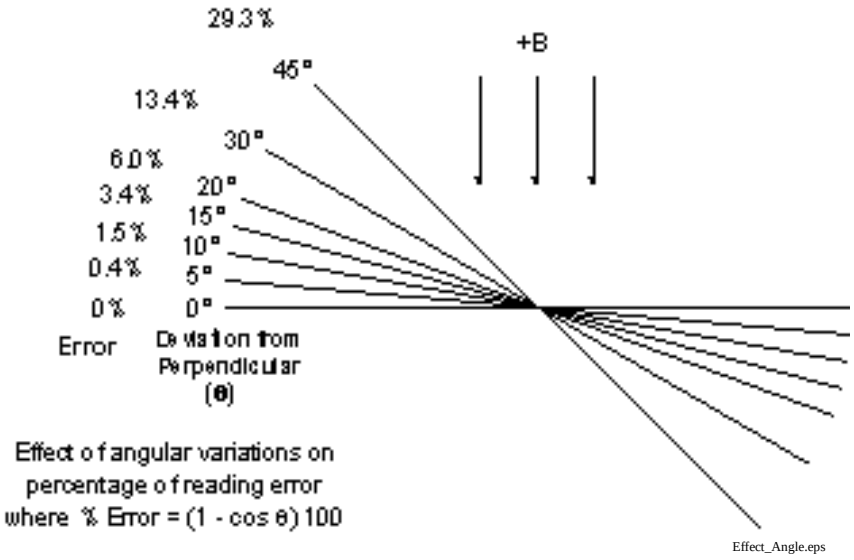


Figure 3-15. Effect Of Angle On Measurements

3.2.4 Power Supply

Although two different models of power supply are used, they have similar wiring connections. Per the site preparation instructions (Paragraph 2.2), the Customer is responsible for providing the hookup from the electrical box at back of the power supply to the electrical service.

3.2.4.1 Model 643 Magnet Power Supply Wiring

Follow this procedure to make the Model 643 electrical connections.

1. Locate the electromagnet current leads on the electromagnet. Uncoil the leads and using the bolts and nuts located on the Model 643 output lugs, connect the positive (red) lead to the positive output and the negative (black) lead to the negative output (Figure 3-9). A safety cover is provided to be installed over the power supply output lugs if desired; refer to the Model 643 manual for additional information.

NOTE: The positive and negative power supply output terminals connected to the magnet current leads must be wired properly to maintain the correct magnet field direction

2. Locate the fault indicator cable connected to the flow and thermal switches on the electromagnet coils. Connect the green terminal block to the top flow switch location on the Model 643 rear panel (Figure 3-16).

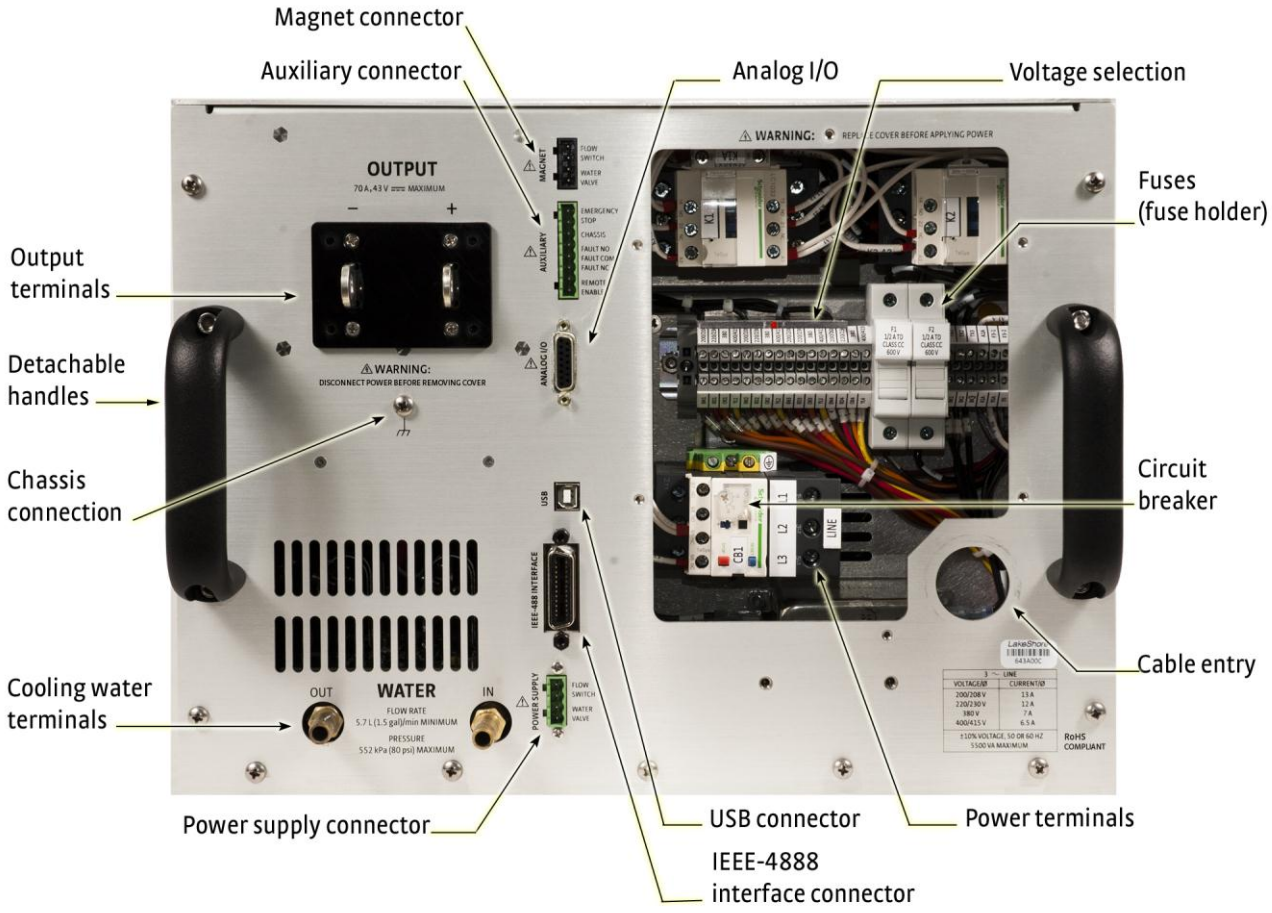


Figure 3-16. Model 643 Rear Panel Connections

3.2.4.2 Model 648 Magnet Power Supply Wiring

Model 648 wiring is shown in Figure 3-17 and Figure 3-18 and described in the following bulleted list.

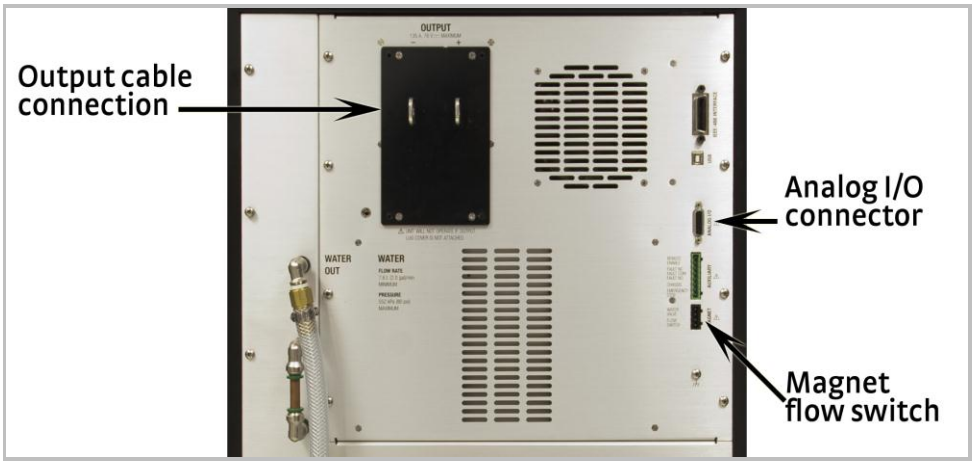


Figure 3-17. Model 648 Front and Rear Panel Connections

- **Analog I/O connector** —connects to the analog output 25 pin D-sub socket on the rear panel of the Model 475 gaussmeter.

NOTE: The positive and negative power supply output terminals connected to the magnet current leads must be wired properly to maintain the correct magnet field direction.

- **Power supply output; positive (+)** — the wire marked in red goes to the positive terminal of the electromagnet.
- **Power supply output; common (–)** —the wire marked in black goes to the negative terminal of the electromagnet.
- **Magnet flow switch —**this is the power supply inhibit connector. It is connected to a single water flow and two thermal cutoff switches in series, any of which can inhibit the output of the power supply. The first two pins on this connector are shorted out. A fault can also be caused by detection of internal condensation.



Figure 3-18. Model 648 Magnet Flow Switch

3.3 MANAGING THE COOLING WATER FOR BOTH THE ELECTROMAGNET AND THE POWER SUPPLY

The Model 7604 HMS can be connected to the cooling water in series and the Model 7607 HMS needs to be connected to the cooling water in parallel. Follow the procedures in sections 3.3.1 and 3.3.2 to prepare the cooling water appropriately.

3.3.1 Connecting the Cooling Water in Series with the 4 Inch Magnet

The Model 7600 HMS can be connected to the cooling water in series, with the electromagnet and power supply sharing a single inlet and outlet flow path from the cooling water system. A block diagram of this setup is shown in Figure 3-22. The water flow path should go first to the electromagnet and then to the power supply. Additional hose couplings (not included) may be needed to complete the series flow path. The power supply water flow solenoid is not used in series configuration.

1. Locate the 10 mm (3/8 in) inlet tubing on the electromagnet and connect it to the supply of your facility's water system (Figure 3-19).
2. Locate the 10 mm (3/8 in) outlet tubing on the electromagnet and connect it to the inlet to the Model 643 power supply. The water flow solenoid is connected at the factory; remove the connection from the solenoid to the power supply inlet.
3. Locate the 10 mm (3/8 in) outlet tubing of the power supply and connect it to the return of your facility's water system.

CAUTION: The cooling water temperature must be above the dew point (the temperature at which condensation will occur) to avoid damage to the Model 643 power supply. Refer to the Model 643 user's manual for additional information.

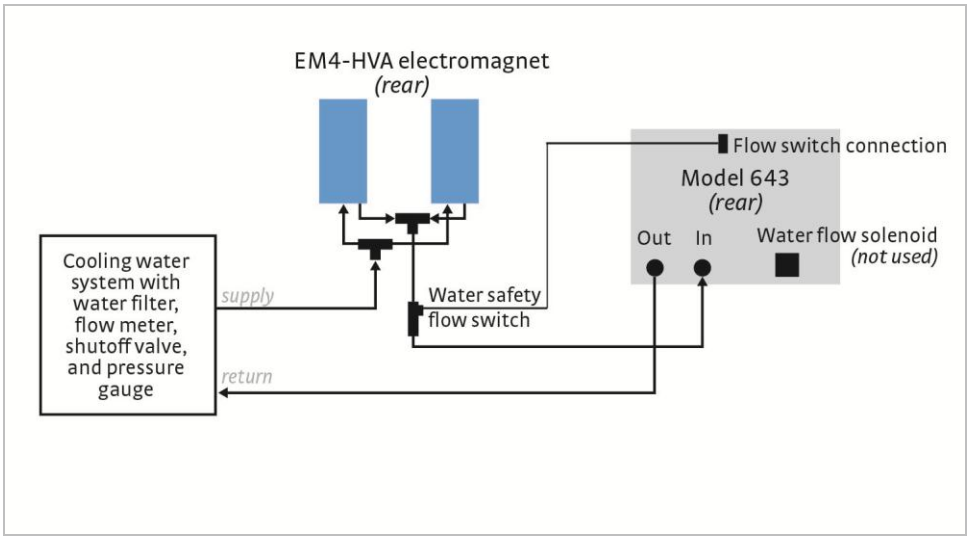


Figure 3-19 Electromagnet and power supply series cooling water configuration

3.3.2 Connecting the Cooling Water in Parallel with the 7 Inch Magnet

The Model 7607 HMS needs to be connected to the cooling water in parallel, with the electromagnet and power supply each getting independent inlet and outlet cooling lines. A block diagram of this setup is shown in Figure 3-20. Two connections are required from the cooling water system; the required splitters are not included.

1. Locate the 10 mm (3/8 in) inlet and outlet barb connections on the electromagnet and connect them to your facility's water supply.
2. Locate the 10 mm (3/8 in) inlet and outlet barb connections on the rear panel of the power supply and connect them to your facility's water supply.

3. ***Optional:*** if the electromagnet water pressure drop is too great to allow flow to the magnet, install a flow proportioning valve in the magnet power supply branch as shown in to balance the two flow paths.

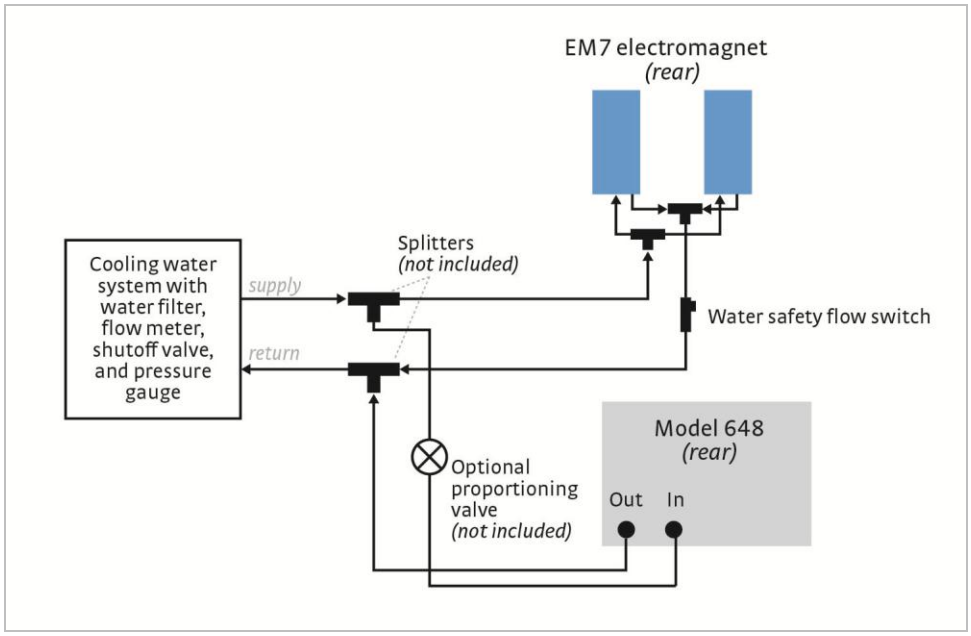


Figure 3-20 Electromagnet and power supply parallel cooling water configuration

3.4 CHANGING THE MAGNET GAP

While changing the magnet gap is an easy procedure, there are a sufficient number of cautions that must be observed to warrant a separate section. The controls shown in Figure 3-21 are typical for all magnets.

CAUTION: Before changing the magnet gap, remove the Gaussmeter probe from the holder. This will prevent any stress from being place on the probe if narrowing the gap.

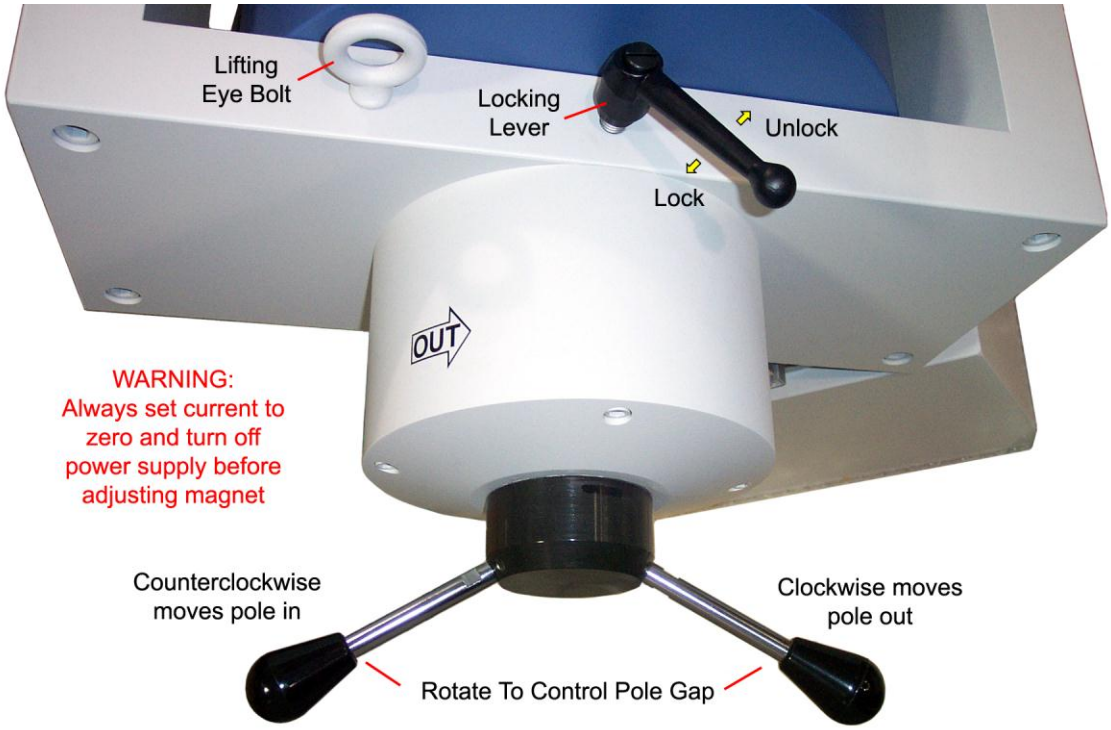
1. Remove the gaussmeter probe. Place the probe in a safe place where it will not be stressed or crushed.

WARNING: Always set the current to zero and turn off the power supply before attempting to adjust the magnet gap.

2. After setting current to zero and turning off the power supply, use the locking levers to unlock the poles.

NOTE: The locking levers for the 4-inch magnet include both left- and right-handed threads, and therefore will operate oppositely to lock and unlock the poles.

3. Rotate the handles clockwise to move the poles out, or counterclockwise to move the poles in.
4. Move the locking levers to the locked position.
5. Reposition the Gaussmeter probe.
5. Turn on the power supply and run the magnet through one complete loop (maximum positive and negative fields). This will "set" the poles into a stable position.



Magnet_Gap.bmp

Figure 3-21. Setting the Magnet Gap

3.5 CHANGING SAMPLE CARDS

The lower part of the Hall Sample Module contains two connectors mounted to the underside of the header block. As shown in Figure 3-22, the connectors are labeled "1" and "2", and the sides of the sample cards are labeled "A" and "B". The "A" side of the sample card is marked with a circle, while the "B" side is marked with an "X".

Overall wiring from the Hall Sample Module is shown in Figure 3-23 – Hall System Wiring. Specific sample card to connector wiring is detailed in Figure 3-24 – Hall System Switching Matrix.

Two types of small sample cards are available: dual and single. The dual sample card (P/N 671-209) is designed specifically for use with the 7600 Series Hall System. Standard Hall Systems can measure two 1 × 1 cm samples simultaneously, mounted on the "A" side of two sample cards. The optional 7600-4 Hall System can measure four samples, with the samples mounted on both the "A" and "B" sides of the two sample cards. The single-sample cards (P/N 671-201) from the Lake Shore 75/77/95/9700 Series Hall Measurement Systems can also be used. Refer to Paragraph 4.6 for further details on the small sample cards.

Two other sample cards are available: large and prober. Both the large (P/N 671-202) and prober (P/N 671-205) cards can accommodate 5 × 5 cm samples, with the large card having solder pads and the prober card having four tungsten needle probes for contact with the sample. Refer to Paragraph 4.7 for further details on the large sample cards.

Contact size and metallurgy can have a significant impact on measurement accuracy. Sample preparation and contacting is the user's responsibility. Refer to Appendix A – Hall Effect Measurements, for general Hall effect measurement theory and a discussion of Hall sample geometries. Also refer to Appendix B – Electrical Contacts To Semiconductors, for references to literature on contact formation.

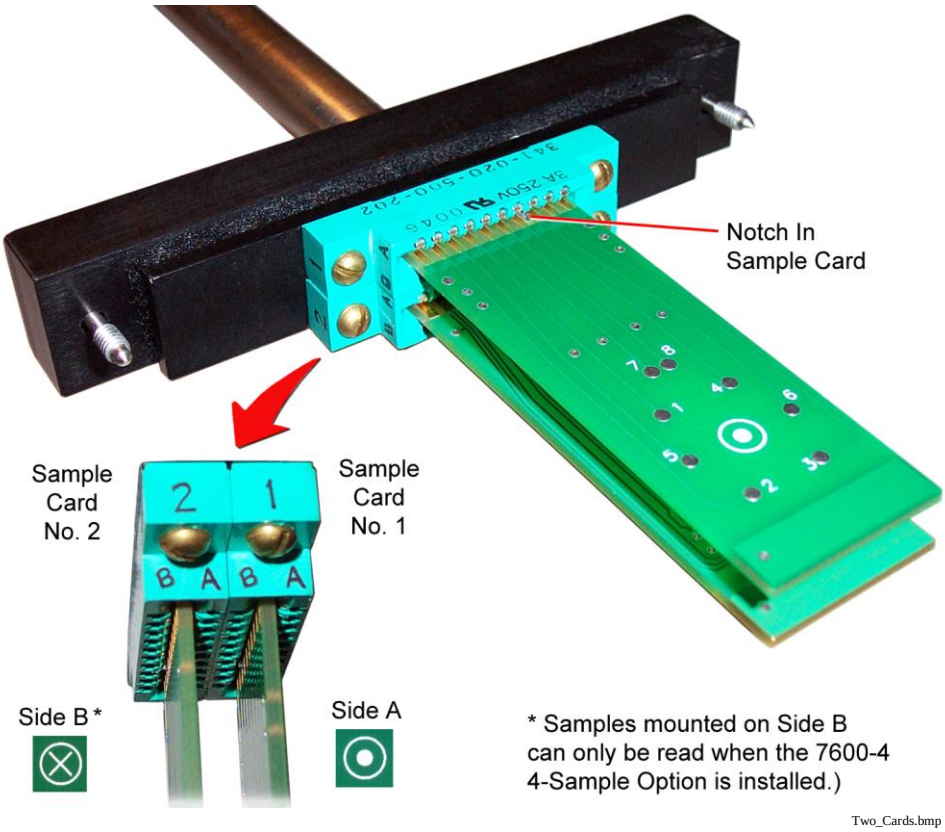
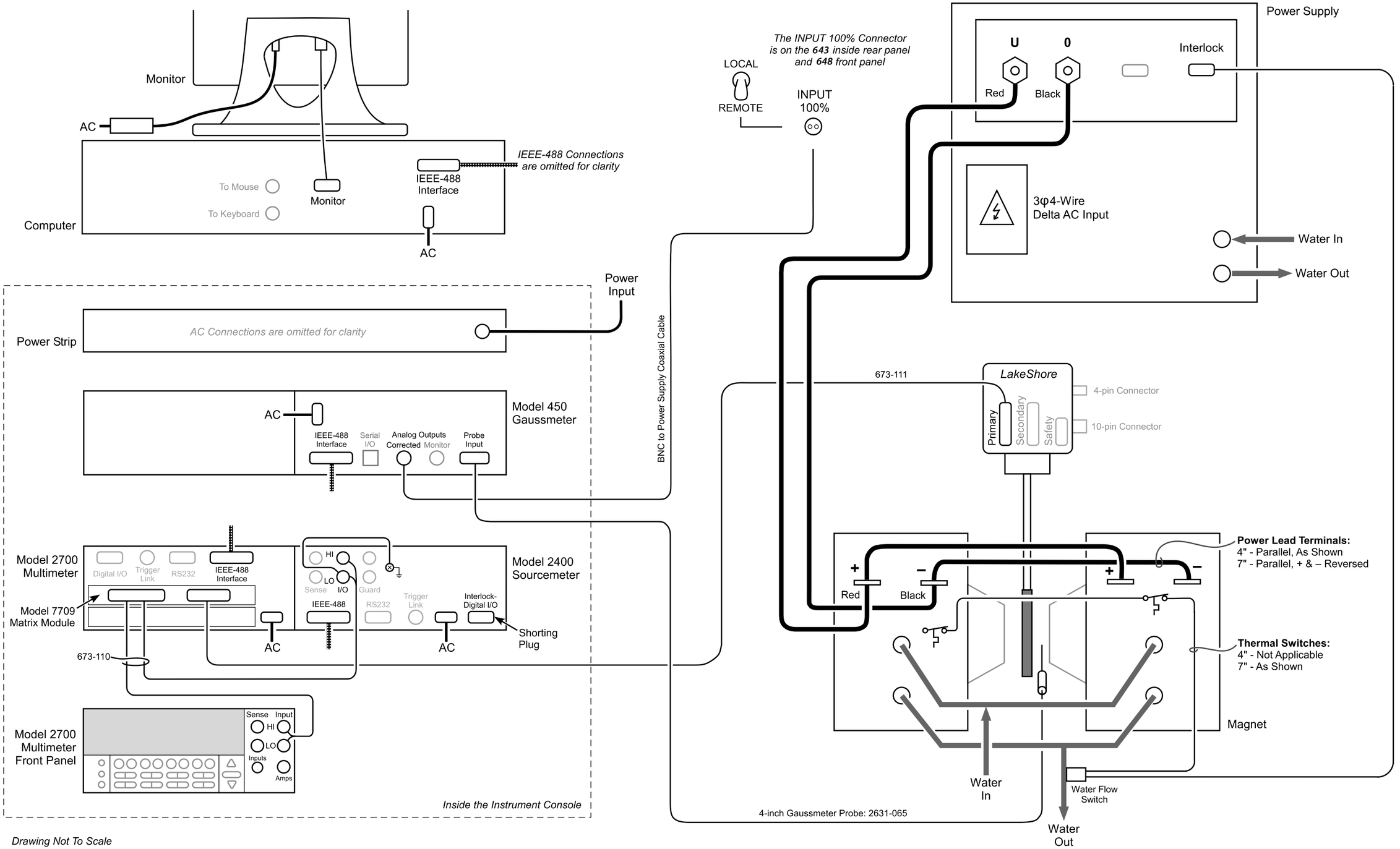


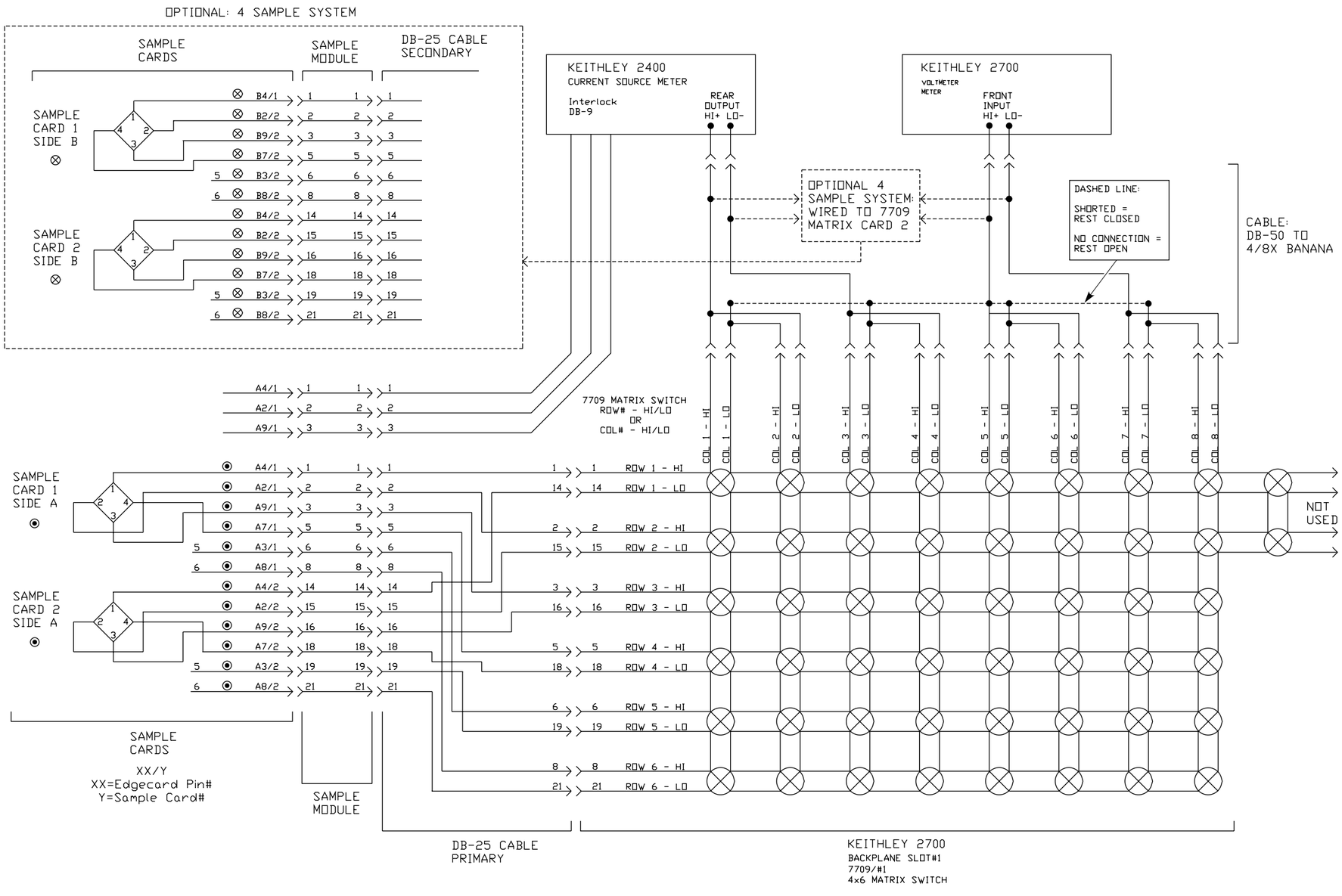
Figure 3-22. Sample Card Mounting Details



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Figure 3-23. Typical 7600 Series Hall System Wiring

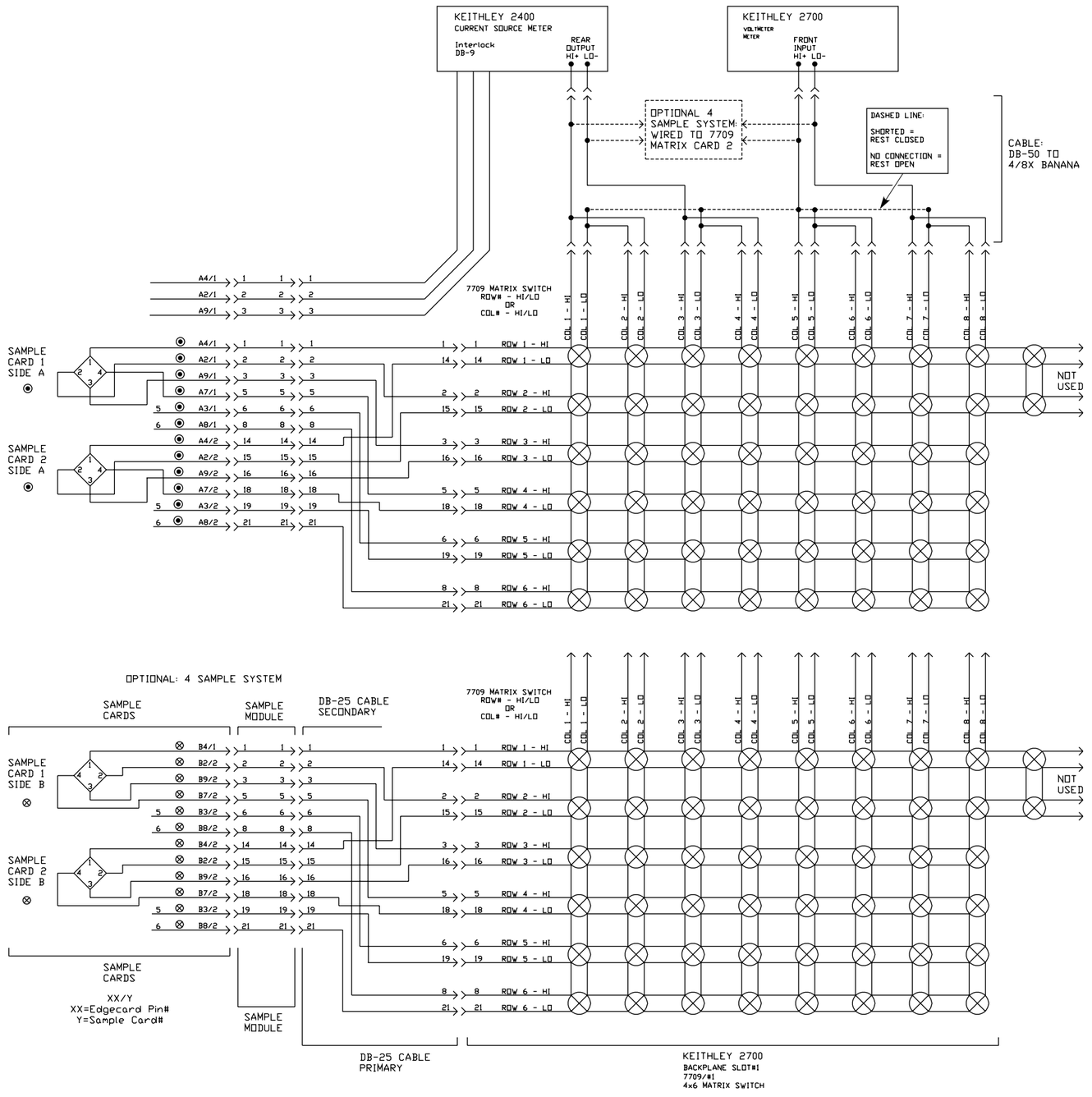
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Figure 3-24 . Typical 7600 Series Hall System Switching Matrix (Sheet 1 of 2)

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Figure 3-24. Typical 7600 Series Hall System Switching Matrix (Sheet 2 of 2)

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CHAPTER 4

OPTIONS & ACCESSORIES

4.0 GENERAL

This chapter provides details of the 7600 Series Hall System model numbers and selected options and accessories. Refer to the Lake Shore website (www.lakeshore.com) for the latest options and accessories.

4.1 MODELS

The list of 7600 Series Hall System Model Numbers is provided as follows.

Model	Description Of Models
7604	10 MΩ System with EM4 Electromagnet and 643 Magnet Power Supply (2.5 kW).
7607	10 MΩ System with EM7 Electromagnet and 648 Magnet Power Supply (9.25 kW).

Power Configurations. The instrument console and magnet power supply are configured at the factory for customer-selected power as follows:

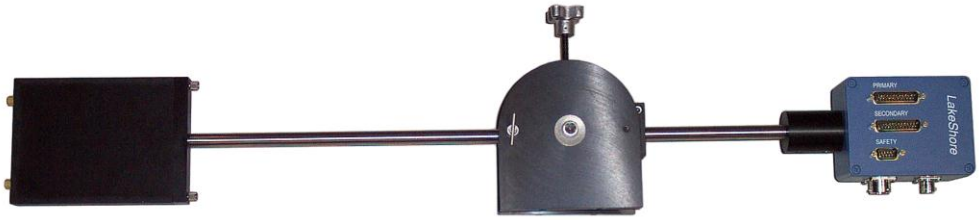
	Power Configurations
Instrument Console	Choice of 100 V, 120 V, 220 V, or 240 V, 50 or 60 Hz., single phase.
Magnet Power Supply	Choice of 200 V, 208 V, 220 V, 230 V, 380 V, 400 V, or 415 V, 50 or 60 Hz., three-phase.

4.2 OPTIONS

The list of options is provided as follows.

Model	*Description Of Option*
3464	**Dual Thermocouple Input Option Card for the Model 336 Temperature Controller.** Adds two thermocouple inputs to the Model 336. A microprocessor on the card manages the A/D and communication with the Model 336. Refer to the Lake Shore Model 336 Temperature Controller User's Manual.
750QMSA	**QMSA Software Package.** Adds the Lake Shore Quantitative Mobility Spectrum Analysis (QMSA) Software Program. QMSA provides a method for analyzing multi-conduction semiconductors with field-dependent Hall measurements. Refer to the Lake Shore QMSA Software User's Manual.
750TC	**Model 336 Temperature Controller.** The 750TC option adds a Lake Shore Model 336 Autotuning Temperature Controller to the basic system. This allows the user to measure and record the temperature of the sample holder. Further, when used in conjunction with a heater or oven, the system can control the temperature. This option is useful when dealing with temperature sensitive samples. Includes all cabling and rack mount provisions for installation into a Hall System. Refer to the Lake Shore Model 336 Temperature Controller User's Manual. • Model 336 Temperature Controller (P/N 1336) • Model 336 Connector Kit (P/N 1336) • Full Rack-Mounting Kit (P/N 117-003) • Model 336 User's Manual (P/N 119-011) • Cable, Sensor/Heater (P/N 655-451) • Cable, IEEE-488, 1 meter (P/N 029)

Options (Continued)

Model	*Description of Option*
75011	**Sample Holder Module.** Consists of one Hall Sample Holder Module in addition to the module provided with the basic system. 
7600-4	**Four Sample Option for 7600 System.** Includes additional cabling and instrumentation to enable reading of four simultaneous samples. • Model 7709 Matrix Card (P/N 671-614) • Cable, 50-Pin to Bananas (P/N 673-110) • Cable, DB25 Male to Female (P/N 673-111)
76014 *	**Closed-Cycle Refrigerator (CCR).** Provides a variable temperature environment with helium exchange gas cooled by a closed cycle refrigerator. No liquid cryogens are required. The sample probe and rotation stage are provided. The sample is surrounded by helium gas at a pressure slightly above atmospheric, so samples can be changed without breaking vacuum or warming up the cryopump. The 750TC Temperature Controller Option must be ordered separately. Pump out of the vacuum jacket to 100 Pa (0.1 torr) is required before cool down. Operation for more than one week continuously or at temperatures greater than room temperature requires a dedicated diffusion pump or turbomolecular pump. Refer to Paragraph 4.4 for details.
76016 * †	**High-Temperature Oven.** Provides an Oven Sample Module (OSM) for temperature controlled operation from just above ambient to 800 K (527 °C) with required 750TC temperature control and power booster options. Refer to Paragraph 4.5 for details.

* Requires the 750TC Option.

† Requires the 3464 Thermocouple Option Card.

4.3 ACCESSORIES

Accessories are devices that perform a secondary duty as an aid or refinement to the primary unit. Refer to the Lake Shore website for additional listing of magnetic accessories and recirculating chillers.

Model	*Description Of Accessory*
4060	**Standard Zero Gauss Chamber.** Used for field nulling the gaussmeter probe. (P/N 145) Size: 32 mm square × 60 mm deep (1.3 inches square × 2.4 inches deep). Bore: 13 mm diameter × 51 mm deep (0.5 inch diameter × 2 inches deep).
671-202	**Hall Sample Card, Small, Single Sample.** For 1×1 cm samples.
671-202	**Hall Sample Card, Large.** For 5×5 cm samples.
671-205	**Hall Sample Card, Large, with 4 Pressure Probes.** For 5×5 cm samples.
671-209	**Hall Sample Card, Small, Dual Sample.** For 1×1 cm samples.
671-211	**Spare CCR Sample Module.** Extra Model 76014 CCR sample module.
671-260	**Sample Wire.** Wire in box for making sample contacts. Silver-plated copper, 75 µm diameter.
760SC10-50	**Sample Card Case.** Contains 49 blank cards for mounting 1 × 1 cm samples (671-209) and 1 pre-mounted InAs reference sample.
IF-5	**Indium Foil Sheets (Quantity 5).** When used as a washer between temperature sensors and refrigerator cold stages, indium foil increases the thermal contact area and prevents the sensor from detaching due to vibration. It also may be used as a sealing gasket for covers, flanges, and windows in cryogenic applications. Each sheet is 50 × 50 × 0.12 mm (2 × 2 × 0.005 in.).

4.4 76014 CLOSED CYCLE REFRIGERATOR OPTION

The Model 76014 option provides a variable temperature environment with helium exchange gas cooled by a Closed Cycle Refrigerator (CCR). No liquid cryogens are required. Stable operation at a range of temperatures is made possible by balancing the cooling power provided by the CCR against two heater circuits powered by the Model 336 Temperature Controller. The sample is surrounded by helium gas at a pressure slightly above atmospheric, so samples can be changed without breaking vacuum or warming up the cryopump. The required 750TC Temperature Controller and power booster options must be ordered separately. Pump out of the vacuum jacket to 100 Pa (0.1 torr) is required before cool down. Operation for more than one week continuously or at temperatures greater than room temperature requires a dedicated diffusion pump or turbomolecular pump.

4.4.1 Specifications

- **Sample Well Temperature**: 10 to 350 K (–273 to +77 °C).
- **Sample Size**: 12 × 15 × 1 mm (W × L × T) maximum.
- **Contacts**: 6 solder posts provided; 6 additional unguarded feedthru pins available on connector.
- **Sample Structure**: Hall bar or van der Pauw.
- **Exchange Gas**: Quality may be industrial grade (99.9% minimum purity) helium gas for purging and pressurizing the sample well. Sample well filled with helium gas allows rapid sample exchange, even when cold.
- **Refrigerant**: Quality of the helium gas for the compressor and expander must be minimum 99.995% pure with a dew point less than –50 °C (–58 °F) at 2070 kPa (300 psig).
- **Cool Down Times**: to 20 K in 120 minutes for the system; to 12 K in 12 minutes for the sample tube/holder.
- **Sample Resistances** up to 1 TΩ (1×10^{12} Ω).
- 38 mm (1.5 inch) O.D. tail fits into 41 mm (1.6 inch) electromagnet gap.
- Rotation stage for precise sample alignment or study of orientation effects.
- **Cryostat**: APD Omniplex with 204SL CCR and CTI Compressor, water cooled (3 liters/minute).
- **Sample Module Weight/Dimensions**: 40 kg (88 pounds); 90 × 36 × 36 cm (36 × 14 × 14 in.).
- **Compressor Weight/Dimensions**: 90 kg (200 pounds); 51.4 × 43.2 × 50.8 cm (20.3 × 17.0 × 20.0 in.).

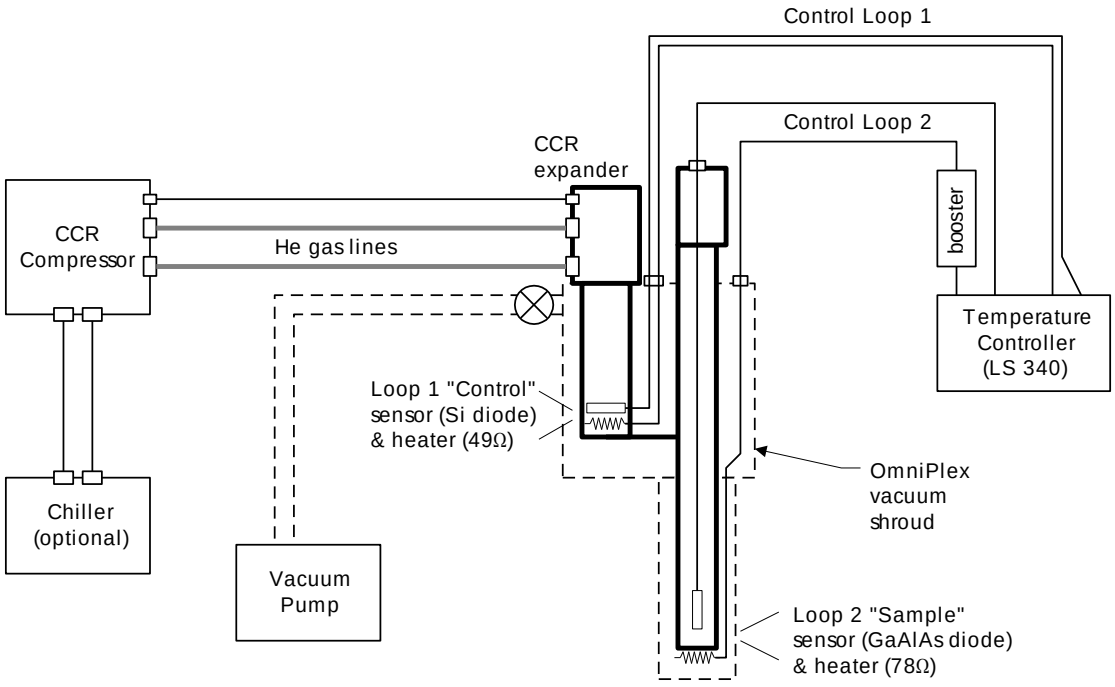


Figure 4-1. Model 76014 CCR Block Diagram
(The electromagnet and measurement systems are not shown)

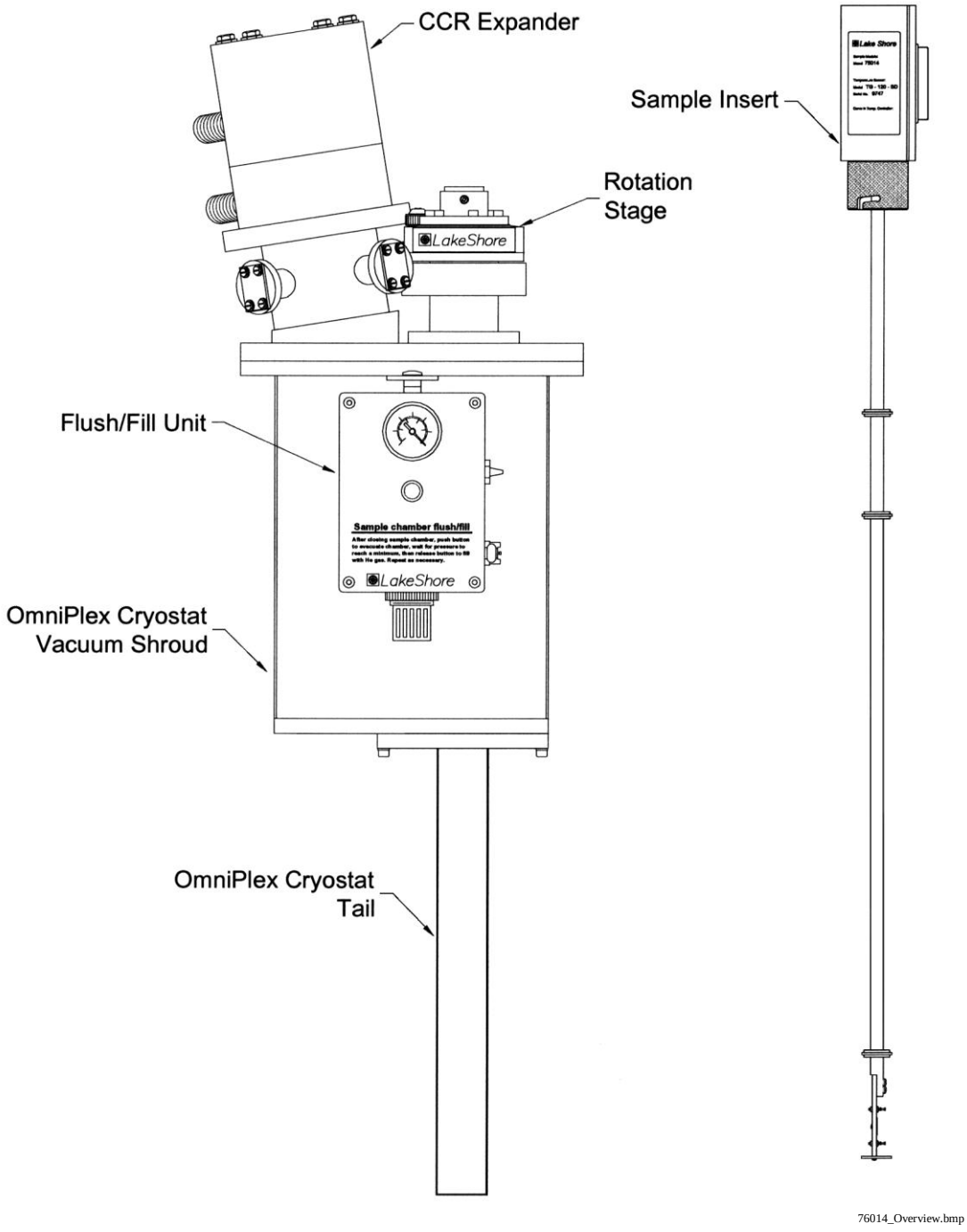


Figure 4-2. Model 76014 CCR Assembly Overview.
View from front of electromagnet

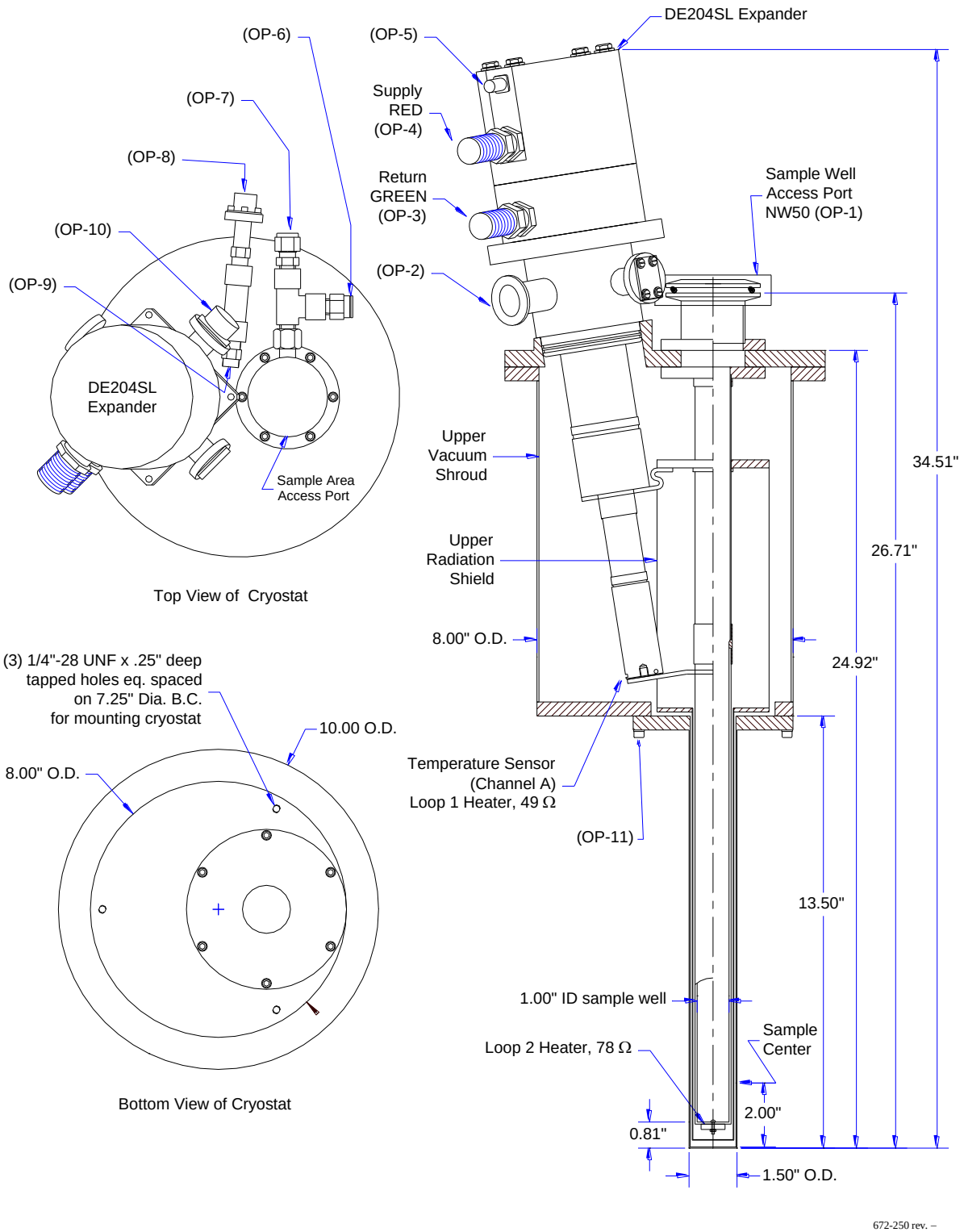


Figure 4-3. OmniPlex Cryostat for the Model 76014 CCR.
View from front of electromagnet. Newer units have the expander rotated 90 degrees from the orientation shown, so the connection ports face towards the rear.

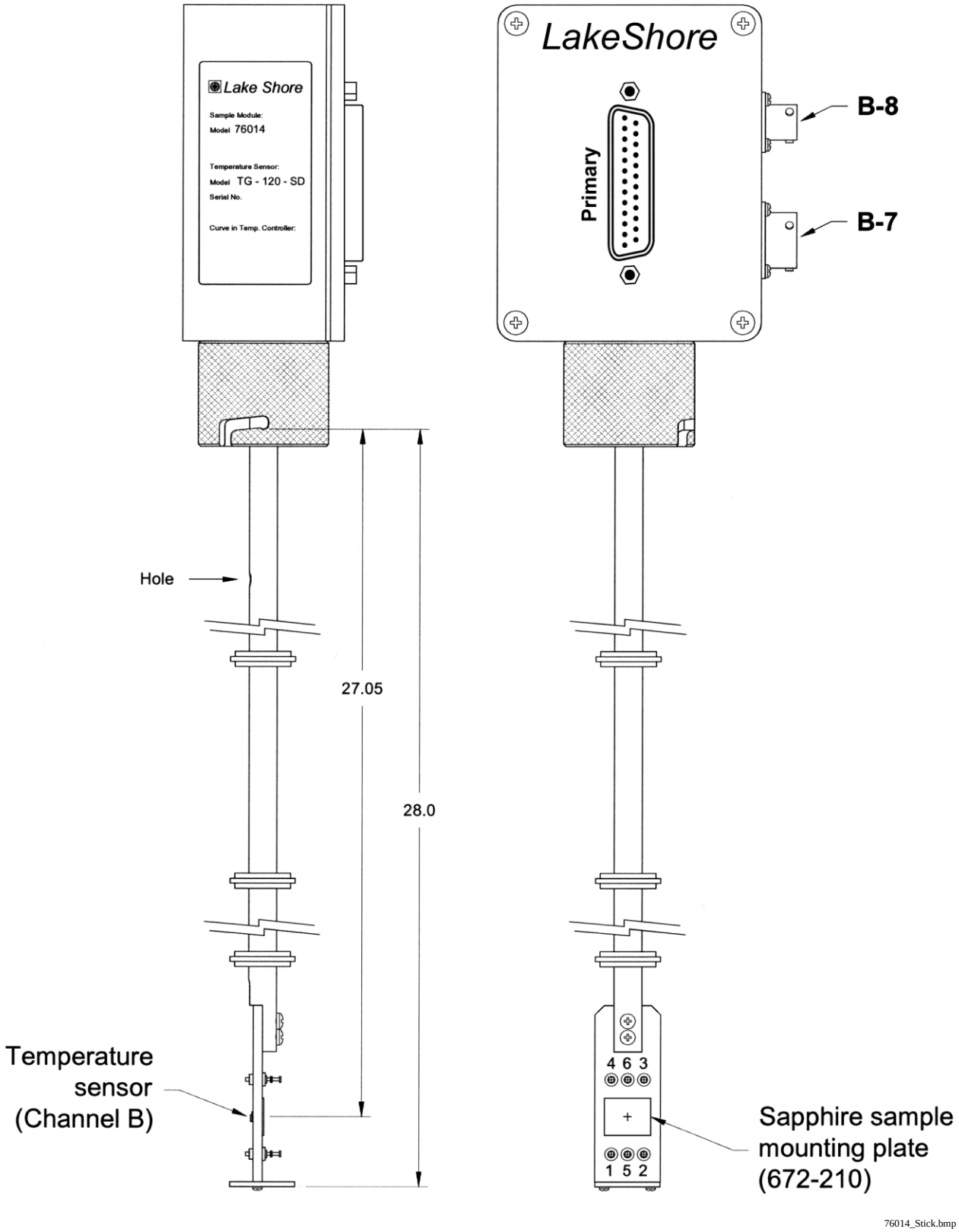


Figure 4-4. Model 76014 CCR Sample Insert

Table 4-1. OmniPlex Cryostat Connection Point and Interface Designations.
The locations of the connections listed below are shown in Figure 4-3.

	OmniPlex Cryostat
OP-1	Sample well access port, NW-50 flange, 25.4 mm (1.0 inch) clear bore
OP-2	Vacuum shroud pumpout port, NW-25 flange
OP-3	Return helium gas connection to compressor (GREEN)
OP-4	Supply helium gas connection from compressor (RED)
OP-5	Expander power, 4-pin circular connector, from compressor (BLUE)
OP-6	Sample well relief valve, 7 kPa to 14 kPa (1 psig to 2 psig) cracking pressure
OP-7	Sample well exchange gas inlet, Swagelok for 6.35 mm (1/4 inch) OD tube
OP-8	Loop 2 heater (78 Ω), 2-pin circular connector (RED)
OP-9	Vacuum shroud relief valve, 7 kPa to 14 kPa (1 psig to 2 psig) cracking pressure
OP-10	Loop 1 temperature sensor and heater (49 Ω), 10-pin circular connector (RED), see Table 4-3
OP-11	Tail vacuum shroud

Table 4-2. Sample Connection Wiring for the 76014 Sample Insert.
The wire resistance is measured from the connector on the junction box to the sample contact post.

Connector	*Pin*	*Use*	*Wire R*
B-1 Primary	**1**	Sample connection # 1	35 Ω
	2	Sample connection # 2	
	3	Sample connection # 3	
	5	Sample connection # 4	
	6	Sample connection # 5, I+ for Hall bars	
	8	Sample connection # 6, I– for Hall bars	
B-7	**A**	Sample card pad 10; "Sensor" temperature sensor (Channel **B**), V–	8 Ω
	B	Sample card pad 9; "Sensor" temperature sensor (Channel **B**), V+	
	C	Sample card pad 8; "Sensor" temperature sensor (Channel **B**), I–	
	J	Sample card pad 7; "Sensor" temperature sensor (Channel **B**), I+	
	D-K	unused	—
B-8	—	unused	—

Table 4-3. Wiring of OmniPlex Loop 1 Cable (# 263941B11)
Connects OmniPlex cryostat 10-pin connector for Loop 1 heater and temperature sensor (OP-10) to the Model 336.

Connection	*Pin*	*Use*	*Connection*	*Pin*
OP-10	**A**	I+ Temperature sensor excitation current (Channel **A**)	(**G-16**) on Model 336	**5**
	B	V+ Temperature sensor output voltage (Channel **A**)		**4**
	C	V– Temperature sensor output voltage (Channel **A**)		**2**
	D	I– Temperature sensor excitation current (Channel **A**)		**1**
	E	I+ Heater (Loop 1), 49 Ω	(**G-5**) on Model 336	**Hi**
	F	I– Heater (Loop 1)	(**G-6**) on Model 336	**Lo**
	G-K	unused		

4.4.2 Site Preparation

The customer is responsible for site preparations preceding installation of the Model 76014 Closed Cycle Refrigerator. The following is a summary of the preparations which must be completed *before* the arrival of the Lake Shore Engineer.

1. The Model 76014 Closed Cycle Refrigerator is shipped in two crates. One crate contains the compressor and hoses while the second crate contains the sample module and expander.
2. The refrigerator and compressor should be uncrated and inspected for damage *upon arrival*. The customer should examine the enclosed copy of the packing list in order to check the order for completeness.
3. The refrigerator requires a gas cylinder and regulator capable of delivering clean, dry helium gas (standard grade) at controlled pressure of 600 – 800 kPa (85 – 115 psig) above atmosphere.
4. Vacuum pump to evacuate the sample module to a pressure of 100 Pa (0.1 torr) or lower. Intermittent operation is possible. See full discussion in section 4.2. Vacuum hose 3 m (10 ft.) long is provided with KF-25 fittings (KF-16 on older units).
5. The compressor requires a 208 VAC, single phase, 15 A power connection (total power = 3 kVA). It also requires cooling water at a flow rate of 2.6 liter/min (0.7 gal/min). The compressor uses 3/8 inch Swagelock fittings for its water connections.

The sample modules available with 7600 Series Hall systems may have additional requirements not provided with the measurement system. Check to make sure these are available when the system arrives.

The Model 76014 CCR requires additional cooling water for the compressor. Check appropriate manuals to verify water requirements in Table 4-4 and follow any plumbing instructions. The plastic tubing is provided with Swagelok® fittings for connection to the compressor. Any fittings required on the inlet or outlet ends must be provided by the customer.

Table 4-4. Compressor Cooling Water Requirements for Model 76014 CCR Option

	Compressor for 76014 CCR Sample Module
Room ambient temperature	10 – 38 °C (50 – 100 °F).
Water inlet temperature	4 – 27 °C (40 – 80 °F)
Water outlet temperature, max.	41 °C (105 °F)
Water inlet pressure	240 – 700 kPa (35 – 100 psig)
Water flow, min.	2.7 liters/min (0.7 gpm)
Pressure drop at minimum flow	85 kPa (12 psi)
Water supply connections	Plastic tubing (3/8 inch O.D. × 40 foot long) provided, Swagelok fittings
Water chiller cooling capacity	3.3 kW (11,000 BTU/hr)

4.4.3 Setup Procedures

Setup must be performed in the following cases:

1. Initial setup following shipping or long term storage.
2. Quick setup following sample module exchange in the electromagnet.

The 76014 CCR can be removed from an electromagnet and stored on a stand without detaching many of the connections, so Case 2 is simpler and often does not require all the steps in the initial setup. Table 4-5 lists the steps required for setup. The table gives an overview and also can be used as a checklist.

Table 4-5. Model 76014 CCR Setup Steps

Reference refers to the relevant section in this manual. An asterisk (*) indicates the procedure is not always required.

Initial	Quick		Description	Reference
1	–	4.4.3.1	OmniPlex Unpacking and Assembly	4.4.3.1
2	**1**	4.4.3.2	OmniPlex Installation in the Electromagnet	4.4.3.2
3	**2**	4.4.3.3	Sample Well Helium Purge Gas Connection	4.4.3.3
4	–	4.4.3.4	Compressor Set Up and Initial Test	4.4.3.4
5	**3**	4.4.3.5	Gaussmeter Probe Installation and Orientation	4.4.3.5
6	**4**		Check OmniPlex connections	Table 4-3
7	**5***	4.4.3.6	Rotation Stage Alignment	4.4.3.6
8	**6***	4.4.3.7	Temperature Controller Setup	4.4.3.7

4.4.3.1 OmniPlex Unpacking and Assembly

1. Verify that the site chosen for the electromagnet and associated hardware is adequate for a Model 76014 CCR:
   • Ceiling clearance of at least 2 m (6.5 ft.) above the floor for sample holder insertion or removal.
   • Locate compressor close enough to the electromagnet for the 3 m (10 ft.) helium gas hoses to reach.
   • The cryostat is heavy; move it with great care. The tail can be damaged by bumping into other objects, especially the magnet pole pieces.
   • Construct a stand to hold the cryostat when not mounted on the magnet. The stand must be sturdy and not tip over or allow the tail of the cryostat to bump against anything. Locate the stand where helium gas line removal is not necessary when moving the cryostat between the magnet and the stand.
2. Locate OmniPlex manual. The manual consists of the following sections (actual order in binder may vary):
   • General: General for Laboratory Systems.
   • OmniPlex Top Loading Exchange Gas Cryostat.
   • Compressor (shipped with compressor): CTI Model ARS-8200 Water-Cooled Helium Compressor.
   • Expanders, Models DE-202 and DE-204.
   • Helium Gas Lines.
3. Unpack OmniPlex sample module. It ships in a long cardboard box. Do not lift by the plastic shipping tail. The OmniPlex is top heavy (expander end) and can be difficult for one person to lift. Set OmniPlex on a solid, clean table with the expander lying down against the table surface. Save packaging in case future shipping is required.
4. Remove shipping tail. Remove the (6) #10-24 × 5/8" SHC screws holding the tail to the vacuum shroud. Save screws for Tail Vacuum Shroud installation. Carefully pull shipping tail off of sample well tail. The shipping tail should have foam wraps inside. Slip them over the sample well tail with a screwing motion. Save the white PVC shipping tail with the packing materials in the shipping box.
5. Install Tail Radiation Shield. (**NOTE:** The Tail Radiation Shield is sometimes shipped already installed.) Locate and unpack the tail radiation shield and screws. Carefully slide the Tail Radiation Shield over the Sample Well Tail. Carefully peel back any tape ends to allow the radiation shield flange to seal flush. Rotate the Tail Radiation Shield to match the tape marks so it is in the same orientation as the last time it was assembled. Use a 7/64" hex wrench to install the (6) #6-32 × 3/8" SHC screws. Reattach the tape to hold the superinsulation to the Tail Radiation Shield.

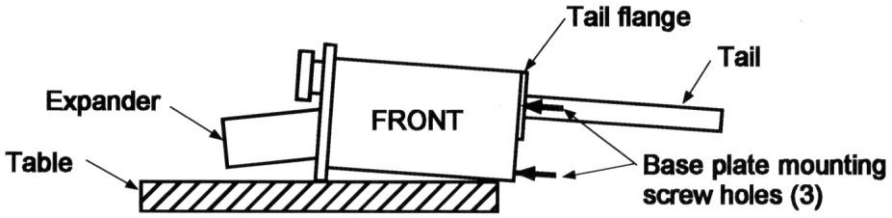


Figure 4-5. OmniPlex Orientation for Base Plate Installation

6. Install Tail Vacuum Shroud. Locate and unpack the tail vacuum shroud and its O-ring. Clean and install the O-ring in the groove of the Tail Vacuum Shroud. Carefully slide the Tail Vacuum Shroud over the Tail Radiation Shield. Rotate to align so the part number sticker is at the outer diameter of the vacuum shroud and the screw holes are aligned. Use a 5/32" hex wrench to install the (6) #10-24 × 5/8" SHC screws.
7. Install the base plate. Hang tail end of OmniPlex vacuum shroud just over edge of table (Figure 4-5). Orient base plate according to the appropriate instructions below.
   • EM4 base plate only (672-136): The smoothest surface should be oriented towards the base of the OmniPlex (will face up when OmniPlex is mounted on the EM4 magnet stand). The tail goes through the hole in the base plate. Align the three small holes with the screw holes in the base of the OmniPlex vacuum shroud.
   • EM7 base plate only (672-142): Note that the large hole in the base plate for the tail is not centered. The thin section must be on the back side of the OmniPlex (the 4-pin electrical connector faces the back). The 1/4" screw hole farthest from the large center hole must be under the expander side of the OmniPlex (down in the orientation shown in Figure 4-5). Align the three small holes with the screw holes in the base of the OmniPlex vacuum shroud.
   • Use a 3/16" hex wrench to attach the base plate using (3) #1/4"- 28 SHC screws (674-217) and small OD split lock washers (674-218).

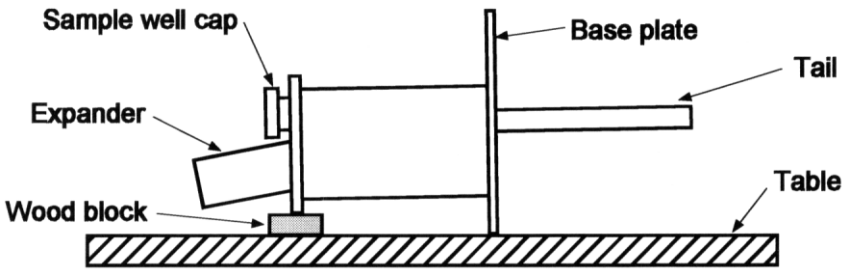


Figure 4-6. OmniPlex Orientation on Table Surface

8. Lift the OmniPlex back on the table and orient as shown in Figure 4-6. Use a wood block to keep the OmniPlex from resting on the expander. A 2 × 4 inch (40 mm thick) block is about right with the EM4 base, but a slightly thicker block is required with the EM7 base.

4.4.3.2 OmniPlex Installation in the Electromagnet

The Model 76014 CCR mounts on top of an electromagnet. Below are directions for mounting to different magnet systems.

Installation on EM4 (4 inch) electromagnet stand:

1. Back out magnet poles to allow plenty of clearance for the cryostat tail. Make sure the path is clear between the location of the 76014 CCR and the magnet stand.
2. Install electromagnet shims (672-137) if it has not been done already. Unbolt electromagnet from stand and raise enough to slip a 3.2 mm (1/8") thick shim under each of the two supports. The shims raise the magnet by the same amount as the base plate attached to the OmniPlex vacuum shroud.
3. Carry the 76014 CCR to the magnet and set in a vertical position with the Base Plate on top of the magnet stand. Be careful not to hit the OmniPlex tail on anything.
4. From the front of the magnet, the Expander should be on the Left and the Flush/Fill box should be facing forward. Align the 3/8" bolt holes in the Base Plate. Note that the head of one screw on the underside of the base plate will drop into one of the left center hole on top of the electromagnet stand.
5. Install the five 3/8"-16 × 1.5" socket head cap screws (654-123) with 3/8" nylon washers (654-148) through the top of the Base Plate. From the bottom side put on a nylon washer and a hex nut (654-166). Do not over-tighten.

Installation on EM7 (7 inch) electromagnet frame only:

1. Back out magnet poles to allow plenty of clearance for the cryostat tail. Make sure the path is clear between the location of the 76014 CCR and the magnet stand.
2. Install plastic guide rails (672-144) on insides of electromagnet coil saddles (672-145L and 672-145R), if it has not been done already. Each guide rail is secured with three shoulder screws 5/16" OD × 3/4" long (674-215) such that the 3/8" holes are aligned with the 3/8" holes in the sides of the coil saddles.
3. Carry the 76014 CCR to the magnet and set in a vertical position with the Base Plate on the plastic guide rails between the saddle sides. Be careful not to hit OmniPlex tail on anything.
4. From the front of the magnet, the Expander should be on the Left and the Flush/Fill box should be facing forward. Align the 3/8" bolt holes in the Base Plate with the holes in the saddle sides.
5. Install the six 3/8"-16 × 1.5" SS SHCS (654-123) with 3/8" nylon washers (654-148) through the saddle sides. Do not over-tighten.

4.4.3.3 Sample Well Helium Purge Gas Connection

The helium exchange gas sample environment requires a source of He gas (standard grade) with delivery pressure of 600-800 kPa (85-115 psig). The customer supplies the helium gas source. A urethane hose 3 m (10 ft.) long and 1/8" ID connects to the Flush/Fill unit. The other end fits a 1/8" barb fitting. Use a 1/8" barb fitting with 1/8" and 1/4" NPTM fittings or a quick disconnect to connect to the helium gas source.

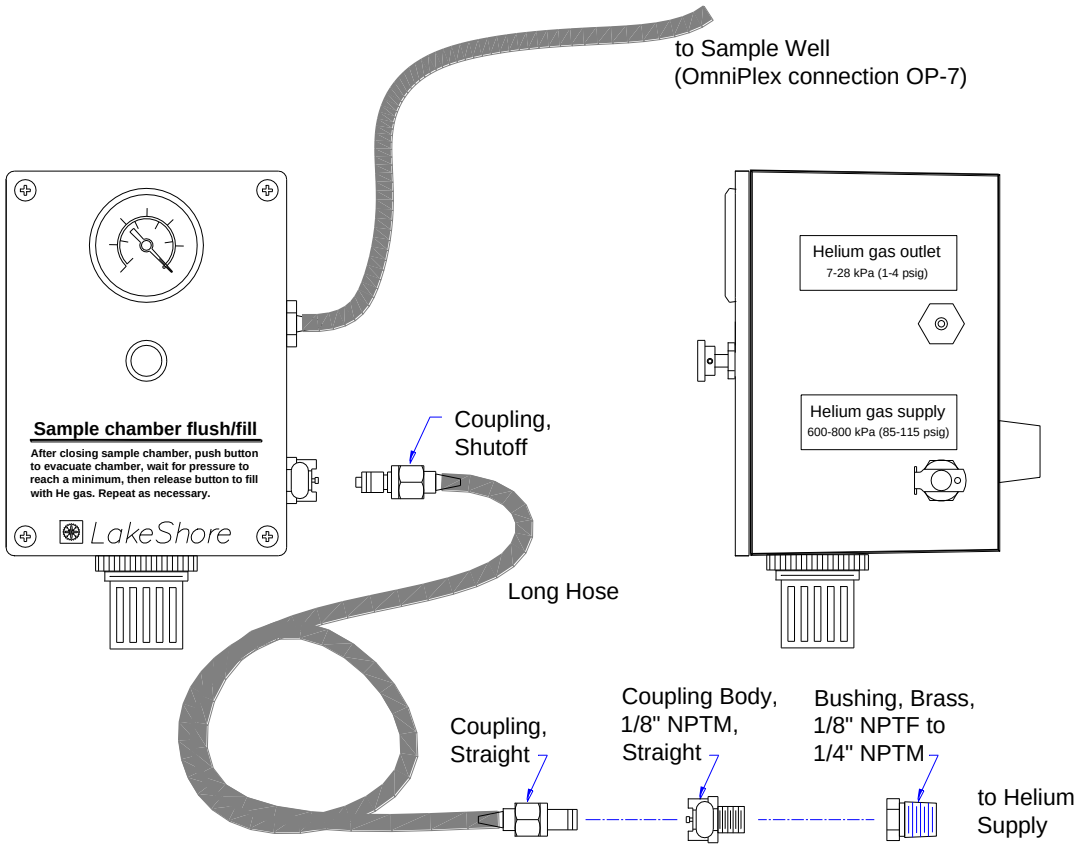


Figure 4-7. Sample Chamber Flush/Fill Unit

1. Attach one end of the 60 cm (24") piece of urethane tubing by pushing onto the Helium Gas Outlet hose barb on the side of the Flush/Fill unit.
2. Install the other end of the urethane hose in the 1/4" ID Swagelok fitting on the sample well manifold.
3. Remove the 0.75 psig relief valve on the sample well manifold and replace with a Relief Valve, 4 psig, 1/4" NPTM (602-611). Use Teflon® tape to seal the threads. The 0.75 psig relief valve can be used in house, but is not needed on the 76014 CCR.
4. Insert the connector end of the long urethane supply hose into the supply inlet port in the side of the Flush/Fill unit.
5. Chain a high pressure helium gas cylinder within reach of the supply hose. The pressure regulator must be capable of supplying helium gas at a regulated gauge pressure of 600-800 kPa (85-115 psi).
6. Connect the free end of the Flush/Fill supply hose to the pressure regulator on the helium cylinder. A 1/8" NPTM hose barb (672-274) is supplied along with a 1/8"NPTF to 1/4"NPTM adapter bushing (209-045), but we more commonly use quick connect fittings in house.
7. Verify that the sample well plug is in place.
8. Set the helium cylinder regulator pressure in the proper 600-800 kPa (85-115 psi) range and open any valves to supply helium to the Flush/Fill unit.
9. Listen for any leaks or hoses popping off. Check for slow leaks by closing the main helium supply tank valve and watching the regulator supply pressure gauge. The pressure should not drop more than 1000 kPa (145 psi) within 10 minutes and is more typically one tenth this leak down rate. Correct any leakage problems and open the main supply valve.
10. Get a balloon and stretch over the Relief Valve on the sample well manifold.

11. Push the valve button on the front of the Flush/Fill unit and check that the pressure drops to about -25 mm Hg (-80 kPa).
12. Release the valve button. The sample well should fill with helium gas until the pressure gauge is pegged. If the balloon fills with gas, the sample well pressure regulator sticking out from the bottom of the Flush/Fill box is set too high. Otherwise, use this regulator to increase the sample well pressure until the balloon just begins to fill, then back off about 1/4 turn.
13. Briefly press the valve button and try to achieve a sample well pressure of -5 mm Hg (-15 kPa). If this pressure can be achieved and the sample well does not refill and pressurize with helium gas, then the sample well regulator is not set high enough. Adjust the regulator setting until a stable pressure of -5 mm Hg is not possible after releasing the valve button, but the balloon does not fill.
14. The Flush/Fill unit is now ready for loading of the Sample Insert.

4.4.3.4 Compressor Set Up and Initial Test

1. Uncrate the compressor.
2. **Connect water to the compressor**. Do not use the supplied hoses for testing prior to shipment to the customer. Note that the compressor must be turned on for the internal solenoid valve to open, so no water will flow until the compressor is turned on.
3. Follow the **Compressor Checkout** instructions in the System section of the APD manual. Note that the helium gas lines are not connected during the checkout. Turn on the compressor and adjust the water flow rate to 3 l/min (0.8 gpm). Run the compressor for one hour.
4. **Turn the compressor OFF**.
5. **Install the helium gas lines**. Follow the instructions under Install Gas Lines in the System section of the APD manual. Verify couplings are clean before making a connection. Use two wrenches when tightening a coupling, as shown in the APD manual.

   Connect helium gas lines to Compressor in the following order: **Supply** (right/red) then **Return** (left/green).

   Connect helium gas lines to the Expander (in 76014 CCR) in the following order: **Return** (bottom/green) then **Supply** (top/red).

   Screw the dust caps together and store in the tool box.
6. **Install Expander Cable**. Connect one end of expander cable to expander receptacle on compressor. Connect the other end of the cable to expander 4-pin circular bulkhead cable plug on OmniPlex expander just above the helium gas line connections (both plug and bulkhead marked **BLUE**).

4.4.3.5 Gaussmeter Probe Installation and Orientation

Operation of the Model 76014 CCR requires a Gaussmeter Probe and Gaussmeter Probe Holder (Figure 3-13).

CAUTION: Exercise care when handling the Gaussmeter Probe. The tip is very fragile. Any excess force can alter the calibration or cause the sensor to break. Broken sensors are not repairable.

WARNING: If electromagnet has been moved and not yet powered to full current, the magnet coils may shift the first time the electromagnet is energized, allowing the Gaussmeter probe holder to fall out and possibly damaging the Gaussmeter probe. After moving the electromagnet , *manually* run the electromagnet to full current before installing the Gaussmeter probe holder.

1. The gap between the tail of the OmniPlex and the right hand electromagnet pole face should be 3-6 mm (1/8 to 1/4 inch). The gap on the left side can be smaller. Lock the electromagnet poles in place.
   NOTE: The Gaussmeter probe tip is to be located between OmniPlex tail and the right hand electromagnet pole face.
2. Insert Gaussmeter probe holder between the coils of the electromagnet. Note that the Probe Mounting Hole can be above or below the threaded rod, as desired. Turn the two knurled end pieces to wedge the assembly in place. Do not overtighten or the threaded rod will bend and buckle.
3. Rotate the mounting block on the threaded rod until it is aligned near the right hand pole face (when viewed from the front of the electromagnet).
4. Tighten the front screw to lock the mounting block against the threaded rod. Do not overtighten.

CAUTION: Exercise care when handling the Gaussmeter probe because the sensor mounted in the tip is fragile. Stressing the probe tip may alter the sensor calibration. Any excess force can easily break the sensor. Broken sensors are not repairable.

5. Insert Gaussmeter probe through Probe Mounting with the Snowflake pattern facing to the *left*. The Top Screw must clamp onto the large diameter portion of the probe handle.

6. Locate Gaussmeter probe in contact with the right side of the OmniPlex tail and with the tip parallel to the electromagnet pole face. The magnetic fields very close to the pole face can be nonuniform, so placement of the tip directly against the electromagnet pole face is not recommended. The location of the mounting block along the threaded rod might require adjustment.
7. Move probe holder assembly forward or backward to position the sensitive portion of probe tip over the center of the electromagnet pole face. The knurled end pieces might need loosened to allow movement, then re-tightened. Verify the probe is straight and properly oriented with snowflake pattern facing to the left so the wide side of the probe tip is parallel to the electromagnet pole face. Adjust as necessary.

CAUTION: A Gaussmeter Probe reversed in orientation reverses the sign of readings (i.e. a positive magnetic field reads as a negative field). Correct sign of readings is critical to magnetic field control.

4.4.3.6 Rotation Stage Alignment

The rotation stage ships mounted on the OmniPlex sample well access port (**OP-1**). Alignment is normally not required unless the rotation stage is removed or rotated for some reason.
Accurate Hall effect measurements require that the sample be perpendicular to the magnetic flux density (field). The rough alignment procedure involves physical alignment of the rotation stage relative to the pole faces, a difficult task to perform accurately and which does not take into account any misalignment contributed by the interface to the Sample Insert or by the Sample Insert itself. The fine alignment procedure involves electrical measurements and is both more accurate and more time consuming.
Below are instructions to install and align the rotation stage. Read the entire procedure before proceeding.

Installation of the rotation stage

1. Start with the plug in the quick connect on top of the rotation stage (i.e., no Sample Insert loaded).
2. Fully loosen the KF-50 quick flange clamp below the rotation stage and open it wide enough to allow rotation of the stage, but do not remove the clamp.

Rough orientation of the rotation stage

The Lake Shore nameplate on the rotation stage should face toward the front of the magnet. The rotation stage should orient the sample perpendicular to the magnetic field and facing the right magnet pole for accurate Hall effect measurements.

1. Orient the rotation stage assembly so the Lake Shore nameplate faces forwards. The fit is tight and requires tipping the rotation stage to rotate it 90 degrees or more.
2. Check orientation relative to the pole faces—the sides of the rotation stage should be parallel to the pole faces—and tighten the clamp. Exact alignment is not easy as the path between the rotation stage and the poles is not clear.

Fine alignment of the rotation stage

1. Mount a sample with a large Hall coefficient on the Sample Insert. The medium resistivity boron doped silicon sample supplied with the system is a good choice if it can be tested near room temperature.
2. Insert Sample Insert into sample well. Face junction box to the right (usual orientation) and lock in place.
3. Connect 25-pin D connector to **Primary** connector on the Sample Insert.
4. Start the Hall System Software program.
5. Activate the Resistance software program, select the menu: Sample Definition, and set up the appropriate sample type for a measurement with the following parameters:
   Hall Resistance
   Current reversal OFF (not selected)
   Two geometries OFF (not selected)
   Settle time = 120 seconds (adjust as needed)
   Excitation current of +100 µA is suggested for the medium resistivity (~10.5 Ω·cm) silicon sample near room temperature
6. Activate the Field Control program. Select the menu: Edit -> Properties and note the maximum magnetic field achievable. Select the menu: Run -> Go To Field and input a field near the maximum to get the largest signal.
7. Verify that the rotation stage is set at 0 degrees rotation.
8. Take a measurement (click on the green TAM button). Repeat as necessary to display the Hall voltage.
9. Rotate the stage about zero to find the orientation where the absolute value of the Hall voltage is maximized. This is the offset angle, Ao. The Hall voltage is displayed on the front panel of the voltmeter. If the voltmeter front panel can not be seen easily, activate the Voltmeter software program, display the front panel, and rotate the monitor for

easy viewing. If the signal is too small to locate the maximal orientation accurately the following corrective actions are suggested:

a) increase the excitation current,
b) increase the magnetic flux density, or
c) use a different sample with smaller sheet charge density.

10. If the offset angle, Ao, is significant - more than a few degrees - rotate the sample stage by the following process:
    a. Set the rotation stage to zero degrees. If desired, use an Allen key to tighten the knob and prevent rotation.
    b. Loosen the KF-50 clamp and rotate the stage and sample insert to maximize the Hall voltage reading (absolute value).
    c. Tighten the KF-50 clamp, being careful not to let the stage rotate during clamping.
    d. Go back to the previous step (15).
11. Record the offset angle, Ao, and note on the Sample Insert. Hall effect measurements using this Sample Insert should be made with the rotation stage set to the offset angle Ao, rather than set to zero. Note that if more than one sample insert is used with this sample module, Ao can change with the sample insert, so each one should be tested.
12. Return the magnetic flux density to zero using the Field Control program menu: Run -> Go To Field.
13. Exit the Hall program when finished.

4.4.3.7 Temperature Controller Setup

The Model 750TC Option adds a Model 336 and is required for operation of the 76014 CCR. This procedure configures the Model 336 inputs for one silicon diode (DT-470) on the cold end of the Expander, one GaAlAs diode (TG-120) at the sample location on the Sample Insert, and two loop temperature control.

A schematic of the control system is shown in Figure 4-1. Temperature sensor and heater physical locations are shown in Figure 4-3.

The first control loop consists of a temperature sensor and heater attached to the cold end of the refrigerator.

The sample is located near the bottom of the copper sample well, separated from the sample well by helium exchange gas, and is a significant distance from the refrigerator cold end. A temperature sensor mounted directly to the sample insert provides a much more accurate measure of the actual sample temperature. Many temperature sensors experience unacceptably large reading errors when operated in high magnetic fields at low temperatures. For this reason a GaAlAs diode temperature sensor is used to monitor the sample temperature. The disadvantage is that each GaAlAs diode must be individually calibrated as a function of temperature and the proper calibration curve must be loaded into the temperature controller and selected for use.

The heater for the second control loop is located on the bottom of the sample well. The temperature sensor on the sample insert is used to control the second loop heater. Refer to the Model 336 manual for further information on dual control loop theory and operation.

Table 4-6. Connection List for Model 336 to Model 76014 CCR

#	*Connection*	*From*	*To*
1	Auxiliary input cable, 655-451 (see Table 4-7)	( ) cable 6-pin circular connector **A** NOT CONNECTED (**G-17**) cable 6-pin circular connector **B** to Model 336 Channel **B** ( ) Cable dual banana connector NOT CONNECTED ( ) Cable single banana connector NOT CONNECTED	(**B-7**) Junction box of Sample Insert, 10-pin circular connector socket (marked BLUE)
2	Loop 1 Control Cable	(**G-16**) cable 10-pin circular connector **A** to Model 336 Channel **A** (**G-5, 6**) Cable dual banana connector to Model 336 Heater Output, gnd tab to LO (**G-7**) Cable single banana connector to Model 336 Heater Output SHIELD	(**OP-10**) 10-pin pin circular connector socket on side of OmniPlex expander (marked RED)
3	Power Booster Coaxial/BNC Heater Input Cable	Power Booster terminals **7**and **14**	(**G-15**) Model 336 Analog Out 2
4	Loop 2 Heater Output Cable: APD Heater Cable (APD part 263316B8) with a 2-pin military socket connector on one end (marked BLUE)	Power Booster terminals **4, 5, 6**	(**OP-8**) 2-pin circular connector socket on rear of OmniPlex (marked BLUE)

Table 4-7. Cable 655-451 Wiring

Connects 76014 Sample Insert 10-pin connector (B-7) to Model 336

Connection	*Pin*	*Use*	*Connection*	*Pin*
B-7	**A**	V– Temperature sensor output voltage (Channel **B**)	(**G-17**) on Model 336	**2**
	B	V+ Temperature sensor output voltage (Channel **B**)		**4**
	C	I– Temperature sensor excitation current (Channel **B**)		**1**
	J	I+ Temperature sensor excitation current (Channel **B**)		**5**
	D	I+ Heater	(NOT USED)	**Hi**
	E	I– Heater		**Lo**
	G	V– Temperature sensor output voltage (Channel **A**)	(NOT USED)	**2**
	H	V+ Temperature sensor output voltage (Channel **A**)		**4**
	F	I– Temperature sensor excitation current (Channel **A**)		**1**
	K	I+ Temperature sensor excitation current (Channel **A**)		**5**

Following is the setup procedure:

1. Connect all cables listed in Table 4-6 (see Figure 4-10).
2. **For Quick setup only**: To determine if a quick setup is possible, check if a configuration file already exists. Use either Windows Explore and look in the Windows directory, or start the Model 336 program and select the menu item: File -> Load. Typical file names relevant to this sample module might look like "76014_S1.34c". Note that some work can be saved by first loading a configuration file similar to one to be set up.
3. Exit any programs using the Model 336. The Model 336 must be in LOCAL mode to change settings through the front panel.
4. Set up the Model 336 through the front panel as specified in the procedure below. For further information, refer to the Model 336 User's Manual and the Model 336 software help files. (For setup of a Model 330 Temperature Controller, refer to the Model 330 User's Manual.)

- **Input Setup** (Model 336 front panel button)

		Input Setup
Input:	**A**	Enter
Enable:	**ON**	^ Enter
Type:	**Silicon Diode**	^ Enter
Curve:	**1 DT-470**	^ Enter
		Save Screen
Input:	**B**	^ Enter
Enable:	**ON**	^ Enter
Type:	**GaAlAs Diode**	^ Enter
Curve:	**21 TG-120SD**	^ Enter

(21 is typical: match the sensor serial number to the calibration curve)

Save Screen, Save Screen

- **Display Format** (Model 336 front panel button)

		Display Format
Input Displays:	**2**	^ Enter
Display 1:	A TEMP K	Enter
Display 2:	B TEMP K	Enter
		Save Screen
		Display Format
		<MORE>
Control Loops:	**BOTH**	^ Enter
Heat Display:	**POWER**	^ Enter
		Save Screen

- **Interface** (Model 336 front panel button)

		Interface
IEEE-488		
Terminator:	CR LF	Enter
EOI:	ON	Enter
Address:	**14**	Enter
		Save Screen

- **Analog Outputs** (Model 336 front panel button)

		Analog Outputs
1:		Enter
Mode:	OFF	Enter
Bipolar:	OFF	Enter
		Save Screen
2:		^ Enter
Mode:	**LOOP**	^ Enter
Bipolar:	OFF	Enter
		Save Screen, Save Screen

- **Loop 1** (Model 336 front panel button)

		Loop 1
		Control Channel
Loop 1 Channel:	**A**	Enter
		Loop 1
		Setpoint
Setpoint:	0.000 K	Enter

- **Loop 2** (Model 336 front panel button)

		Loop 2
		Control Channel
Loop 2 Channel:	**B**	^ Enter
		Loop 2
		Setpoint
Setpoint:	0.000 K	Enter

- **Control Setup** (Model 336 front panel button)

		Control Setup
Loop:	**1** Control Setup	Enter
Enable:	**ON**	Enter
Power Up:	**ON**	Enter
Setup Unit:	TEMP K	Enter
Htr Ω:	**49**	49 Enter
Control Mode:	Manual PID	Enter

Filter:	OFF	Enter
		Save Screen
		<MORE>
Loop:	**1** Control Limits	Enter
Temp:	**350 K**	350 Enter
+slope:	0.0%	Enter
- slope:	0.0%	Enter
Max Htr I:	1.00 A	Enter
Max Range:	49 W	Enter
		Save Screen
		<MORE>
		Control Setup
Loop:	**2** Control Setup	^ Enter
Enable:	**ON**	^ Enter
Power Up:	**ON**	Enter
Setup Unit:	TEMP K	Enter
Control Mode:	Manual PID	Enter
Filter:	OFF	Enter
		Save Screen
		<MORE>
Loop:	**2** Control Limits	Enter
Temp:	**350 K**	350 Enter
+slope:	0.0%	Enter
- slope:	0.0%	Enter
		Save Screen, Save Screen

5. **Start up only the Model 336 software driver program** and display the virtual front panel. The channels should be assigned as follows:
   Control = A
   Sample = B
6. Set up Loop 1 Domains.
   - Close the Model 336 software front panel.
   - Select menu item: Utilities -> Domain File Name and input a file name. A suggested format is: **76014L1A.ini** to indicate **L**oop **1**, set **A**. Change the last letter for variations such as a set of domains with shorter settle times when temperature accuracy is not as important. Note that this temperature control domain file will be located in the Windows directory.
   - Select menu item: Utilities -> Domains and input the data from Table 4-8.

Table 4-8. Model 336 Software Loop 1 Domain Settings for the 76014 CCR

Domain #	*Begin T [K]*	*End T [K]*	*P*	*I*	*D*	*Htr Power (range)*	*Slew rate [K/min]*	*First Wait Time [min]*	*Second: F/C/V*	*Third: Wait Time [min]*
1	0	14	0	0	0	0	20	5	* < 0.05	10
2	14	21	40	0	0	5	20	3	* < 0.05	6
3	21	29	50	0	0	5	20	5	* < 0.05	10
4	29	49	60	0	0	5	20	10	* < 0.1	20
5	49	351	100	0	0	5	20	20	* < 0.1	40
6	351	1000	0	0	0	0	100	0	none	0

* Function (of Function/Condition/Value): **Sample drift** [K/min]

7. Set up Loop 2 Domains.
   - Select menu item: Loop 2 and make sure the Lock Set Point item is checked (select it if it is not checked). This causes the set points of the two temperature control loops to be the same at all times.
     √ Lock Set Point
   - Select menu item: Loop 2 -> Domain File Name and input a file name. A suggested format is: **76014L2A.ini** to indicate **L**oop **2**, set **A**. Change the last letter for variations such as a set of domains with shorter settle times when temperature accuracy is not as important. Note that this temperature control domain file will be located in the Windows directory.
   - Select menu item: Loop 2 -> Domains and input the data from Table 4-9. Note that locking the set point causes the wait times and conditions for Loop 2 to be ignored, but they should be entered anyway.

Table 4-9. Model 336 Software Loop 2 Domain Settings for the 76014 CCR

Domain #	*Begin T [K]*	*End T [K]*	*P*	*I*	*D*	*Htr Power (range)*	*Slew rate [K/min]*	*First: Wait Time [min]*	*Second: F/C/V*	*Third: Wait Time [min]*
1	0	14	10	20	0	1	20	5	* < 0.05	10
2	14	21	5	20	0	1	20	3	* < 0.05	6
3	21	29	10	20	0	1	20	5	* < 0.05	10
4	29	49	20	18	0	1	20	10	* < 0.1	20
5	49	351	40	15	10	1	20	20	* < 0.1	40
6	351	1000	0	0	0	0	100	0	none	0

* Function (of Function/Condition/Value): **Sample drift** [K/min]

8. Close the Model 336 software front panel.
9. Select menu item: File > Save As… and enter a file name. A suggested format is: "**76014_S1.34c**" used here to mean the **76014 S**ample insert number **1**. A unique name must be used if more than one Sample Insert, each with its own calibrated sensor, will be used. If more than one sample insert will be used they can be numbered for identification. The .34c extension indicates that this is a Model 336 configuration file.
10. For each additional sample insert, do the following:
    - Step 3, Exit the Model 336 software program.
    - Step 4, Input Setup, Input B portion only.
    - Step 5, Start up Model 336 software program and check Control and Sample channels.
    - Step 8.
    - Step 9.
11. Check that the configuration files were saved. Select menu item: File -> Load. A dialog box appears with a list of Model 336 configuration files (.34c extensions). Click Cancel, or select a configuration file to load and click OK. This step is performed as part of normal sample module operation.
12. Exit the Model 336 software program.

4.4.3.8 Removal, Storage and Shipping

Removal of the 76014 CCR from an electromagnet platform:

1. Remove Sample Insert from OmniPlex and plug sample well.
2. Remove the Gaussmeter probe from between the electromagnet poles. Store in a safe place where the Gaussmeter probe will not be damaged.
3. Back out the electromagnet poles.
4. Use a 5/16" hex key to remove the 3/8"-16 bolts holding the base plate to the top of the electromagnet stand (EM4) or to the saddle plates (EM7 or EM12).
5. The OmniPlex cryostat (with base plate still attached) is now free of the electromagnet platform and may be removed. Pull the base plate forward. Be careful not to hit the sample module tail on anything.

Storage:

1. Store vertically on a stand.
2. Short term (less than one month) storage on a horizontal surface is also possible. Long term horizontal storage might result in sagging of the copper sample well within the OmniPlex tail. Take the OmniPlex cryostat to a table and lay on its side with the Expander (heavy) down against the table. One end of the base plate will also rest on the table and the tail will stick out and up at an angle.

Shipping:

1. Set OmniPlex on a solid, clean table with the expander lying down against the table surface.

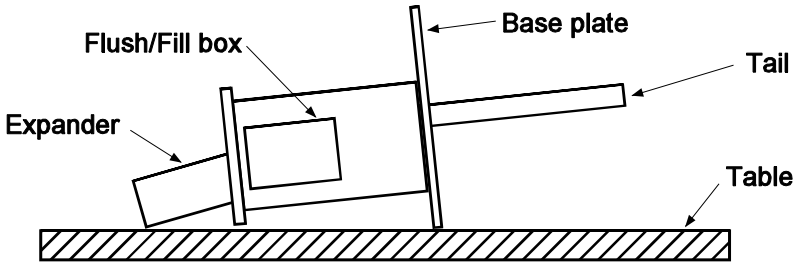


Figure 4-8. OmniPlex Orientation on a Horizontal Surface

2. **Remove Tail Vacuum Shroud**. Use a 5/32" hex wrench to remove the (6) #10-24 × 5/8" SHC screws. Put the screws in a small Ziploc® bag and set aside as they will be used to secure the shipping tail. Wrap/package the tail vacuum shroud with the O-ring for shipping.
3. **Remove Tail Radiation Shield**. Use a 7/64" hex wrench to remove the (6) #6-32 × 3/8" SHC screws. Put the screws in a small Ziploc bag. Carefully peel back any tape holding superinsulation to the tail radiation shield so it can be reused on reassembly. Carefully remove the tail radiation shield. Wrap/package the tail radiation shield with the screws for shipping.
4. **Attach shipping tail.** Find the white PVC shipping tail which should have been kept with the packing materials for the 76014 CCR. The shipping tail should have foam wraps inside. These should slip over the sample well tail (with a screwing motion) and compress enough when inserted into the shipping tail to support the sample well tail during shipping. Secure the shipping tail using the (6) #10-24 × 5/8" SHC screws removed from the tail vacuum shroud.
5. **Remove base plate**. Hang the base plate end over the edge of the table. Use a 3/16" hex wrench to remove the (3) #1/4"- 28 SHC screws and washers. Remove the base plate and return the screws and washers to the holes in the bottom of the vacuum shroud**. Finger tighten ONLY** or the screws will bottom out in these blind tapped holes and the threads will be damaged.
6. **Package 76014 CCR for shipping**. The Flush/Fill unit ships attached to the vacuum shroud. Use the original OmniPlex shipping container or build a suitable replacement. The unit may be shipped in horizontal or vertical orientation.

4.4.4 Sample Mounting with the Model 76014 CCR

Sample mounting is similar to the standard Hall Sample Module with the following exceptions:

1. The sample mounting portion of the Model 76014 Sample Insert is permanently attached, not removable like the Sample Card used in the Model 75013 SCSM.
2. The sample mounts in the center of a sapphire mounting plate centered between solder posts. Glue the sapphire mounting plate to the G-10 plate with rubber cement. Normally, it should not be removed. The solder posts around the sapphire mounting plate are not numbered, but the numbers are shown in Figure 4-4.
3. There is no sample identification space on the Model 76014 Sample Insert sample mounting plate. If desired, attach a removable note to the Sample Insert junction box with the sample identification and other relevant information.

4.4.5 Operation of the Model 76014 CCR

This section provides instructions for the APD Omniplex Top Loading Exchange Gas Cryostat. This module is designed for more sophisticated temperature control.

4.4.5.1 Sample Insert Insertion

Use the procedure below in loading the Sample Insert to avoid contamination or condensation from air (see Figure 4-4).

1. Clean Sample Insert of any dust or dirt accumulated on its surface. Verify that the Sample Insert is completely dry.
2. Ready the Sample Insert, remove Sample Well Plug, and carefully insert the Sample Insert.
3. Twist Sample Insert junction box in the rotation stage to fully engage the bayonet lock.
4. Press valve button on Flush/Fill unit 2 or 3 times. This removes any air from the sample well and backfills with helium gas. Any air in the sample well freezes if the temperature is below about 65 K.
5. Set rotation stage to zero degrees so sample is perpendicular to the applied magnetic field.

4.4.5.2 Sample Insert Cable Connections

The triaxial sample cables should already have a protective sleeve plus a short section of spiral cable wrap and a tie down clamp near the sample end. Bolt the tie down clamp into the right rear bolt hole on top of the saddles. This strain relieves the cables, but positions them close to the sample well where they will be attached to the Sample Insert.

4.4.5.3 Verify Temperature Controller Setup

The temperature controller must be set up for the Sample Module in use. If no temperature controller configuration file exists, create one. Note that there is no indication of the current configuration (unlike the Field Control driver program).

1. Start the Model 336 software driver program on the computer and load the appropriate configuration file. To do this, select the menu item: File -> Load. A dialog box will appear with a list of configuration files (.34c extensions). Select one and click on OK. The Model 336 will be configured, but there is no indication of the current configuration.
2. Open the Front Panel and check that the input channels are reading properly and assigned as follows:
   Control = A
   Sample = B

4.4.5.4 Vacuum Pump Out Procedure

The customer must supply a vacuum pump to evacuate the sample module to a pressure of 100 Pa (0.1 torr) or lower prior to initial operation. Vacuum pressure gauging must be provided or added to the OmniPlex. The OmniPlex can be removed and taken to a vacuum pumping station for pumpout.

Pumpout of the vacuum jacket may be required only every few months if the OmniPlex is kept cold and the lowest possible temperatures are not required. Pumpout of the vacuum space can be performed during operation of the closed cycle refrigerator (CCR) if a turbo, turbomolecular, cryo, diffusion or other very low ultimate pressure (10^{-5} Pa or 10^{-7} torr) dry vacuum pump is used. Pumping during operation might be necessary for long term (several days) operation to the lowest possible temperatures or for repeated ramping from low to high temperature limits.

Initial Pumpout Procedure *(starting from atmospheric pressure)**:***

1. The OmniPlex should be at room temperature for initial vacuum pumpout.
2. Connect vacuum line to Vacuum Valve on OmniPlex Vacuum Pumpout Port (**OP 2**), but **do not open the vacuum valve** yet. The vacuum valve is one of the following two styles:
   a. **Seal-off plug valve**, Cryolab Model SV9-084-5W1 on a KF-25 flange. Remove the retainer ring from inside the vacuum valve body. Push the Cryolab valve operator onto the seal-off valve body and tighten in place with a 1-3/16" (30.2 mm) wrench kept in the OmniPlex tool box. The vacuum hose provided is 13 mm (1/2 inch) ID with KF-16 flange connections. Connect the vacuum hose between the valve operator and the vacuum pump.
   b. **Diaphragm valve** with large black knob and KF-25 flanges. The vacuum hose provided is 25 mm (1 inch) ID with KF-25 flange connections. Connect the vacuum hose between the valve operator and the vacuum pump.
3. Open the vacuum valve:
   a. **Cryolab plug valve**. Push the Cryolab valve handle in and turn clockwise to screw into the plug. Pull out on the handle to remove the valve plug.
   b. **Diaphragm valve**. Turn the large black knob counter clockwise all the way to fully open the valve.
4. Start the vacuum pump and pump out the OmniPlex vacuum space to a pressure less than 1.3 Pa (or 10 millitorr or 10 microns). If using a mechanical vacuum pump which can backstream oil, pump the minimum time necessary to achieve this pressure. Dry pumps can be run longer and the vacuum will be cleaner if the system is pumped for a day or overnight.
5. Close the vacuum valve:
   a. **Cryolab plug valve**. Push in Cryolab valve operator handle to insert valve plug. Rotate handle counter clockwise to unscrew handle from plug. Pull handle back out. Turn off vacuum pump and vent vacuum hose. If desired, remove valve operator from valve and replace retainer ring and dust cap.
   b. **Diaphragm valve**. Turn the large black knob clockwise all the way to fully close the valve. Turn off the vacuum pump and vent the vacuum hose. If desired, remove the vacuum hose.
6. Monitor the pressure on the vacuum gauge. The pressure should rise slowly and level off at a pressure less than about 13 Pa (or 0.1 torr or 100 microns). If the pressure rises rapidly above this pressure level, a leak or contamination may exist. Test the system for leaks to isolate the cause of the problem, and repair it. If everything appears normal, proceed to the next step.

NOTE: Dry vacuum pumping can continue until no longer desired, but if using a mechanical pump stop pumping before starting the CCR compressor.

Vacuum Cleanup Procedure *(starting with vacuum)**:***

1. The OmniPlex can be at any temperature for vacuum cleanup, but a dry vacuum pump with low base pressure is required if the OmniPlex CCR is operating.
2. Connect the vacuum hose between the vacuum pump and the vacuum valve on the OmniPlex (OP 2).
3. Start vacuum pump and pump out vacuum line to a pressure less than 1.3 Pa (or 10 millitorr or 10 microns).
4. Open the vacuum valve:
   a. **Cryolab plug valve**. Push the Cryolab valve handle in and turn clockwise to screw into the plug. Pull out on the handle to remove the valve plug.
   b. **Diaphragm valve**. Turn the large black knob counter clockwise all the way to fully open the valve.
5. Pump out the OmniPlex vacuum space to a pressure less than 1.3 Pa (or 10 millitorr or 10 microns). If using a mechanical vacuum pump which can backstream oil, pump the minimum time necessary to achieve this pressure. Dry pumps can be run longer and the vacuum will be cleaner if the system is pumped for a day or overnight.
6. Close the vacuum valve:
   a. **Cryolab plug valve**. Push in the Cryolab valve operator handle to insert the valve plug. Rotate the handle counter clockwise to unscrew the handle from the plug. Pull the handle back out. Turn off the vacuum pump and vent the vacuum hose. If desired, remove the valve operator from the valve and replace the retainer ring and dust cap.
   b. **Diaphragm valve**. Turn the large black knob clockwise all the way to fully close the valve. Turn off the vacuum pump and vent the vacuum hose. If desired, remove the vacuum hose.
7. Monitor the pressure on the vacuum gauge. The pressure should rise slowly and level off at a pressure less than about 13 Pa (or 0.1 torr or 100 microns). If the pressure rises rapidly above this pressure level, a leak or contamination may exist. Test the system for leaks to isolate the cause of the problem, and repair it. If everything appears normal, proceed to the next step.

NOTE: Dry vacuum pumping can continue until no longer desired, but if using a mechanical pump stop pumping before starting the CCR compressor.

4.4.5.5 Cool Down

1. Optional: Start the Chart Recorder function on the computer:
   Maximize the Model 336 software program.
   Select the menu item: Timing-> Log Time. Set the log time to 5 seconds.
   Select the menu item: Utilities -> Chart Recorder. Select the following items to plot:
   Sample temperature
   Control temperature
   In the plot window, select the menu item: File -> Log…, name the log file and click OK.
2. Start the APD compressor.
3. Verify that the water flow rate is at least 3.0 liters/minute (0.8 gpm).
4. During cooldown, check for condensation on the outside of the OmniPlex tail. Condensation indicates that the vacuum is not good enough and the vacuum pumpout must be repeated.
5. The cooldown to 15 K should take about 1 to 2 hours.
6. Close the Chart Recorder log file when the cooldown is complete.

4.4.5.6 Temperature Control Parameters

Choosing temperature control parameters always requires a compromise between the desires for rapid temperature changes and good stability and accuracy with little temperature overshoot or oscillation.

The temperature control domain parameters suggested in the section on setting up the Model 336 were chosen for slow, controlled temperature changes with little overshoot or oscillation. If faster temperature changes are desired, first try setting the second wait times in the Domains to zero. Additional optimization can be performed by following the procedures described in the Model 336 User's Manual.

4.4.5.7 Sample Insert Removal

Use the procedure below to remove a cold Sample Insert from the Model 76014 CCR (see Figure 4-4).

1. Unplug the 25-pin D connector from the Sample Insert junction box. If desired, leave 10-pin circular connector in place to monitor temperature.
2. Twist Sample Insert junction box in the rotation stage to release the bayonet lock.
3. Remove the Sample Insert quickly from the OmniPlex sample well.
4. Insert the sample well plug and make sure it seals tightly.
5. Press the Flush Fill valve button 2 or 3 times to remove the gas (possibly contaminated with air) from the sample well.
6. Wait until the Sample Insert is dry before removing or mounting samples. Blow dry with a hot air gun, if desired, but do not overheat.

4.4.6 Service and Maintenance for the Model 76014 CCR

4.4.6.1 Leakage Resistance and Shielding

Measurement of very high resistance samples (>10 MΩ) requires very high resistance between all combinations of signal, guard and ground. The following procedure is possible only with measurement instrumentation that drives the guards around the signal lines (-HVWR or -LVWR).

1. Measure the resistance of the Sample Insert without any sample mounted. If necessary, first clean the sample mounting area with isopropyl alcohol and demineralized water, then blow dry with warm air from a heat gun. Install the Sample Insert in the OmniPlex sample well. Measure the resistance (R14,23) in high resistance mode using the Resistance software program.
2. The resistance should be significantly greater than the specified maximum accurately measurable resistance of the measurement system. Note that a leakage resistance of 100 times the maximum sample resistance would lead to a 1% measurement error.

3. If the resistance is low, check the resistance between signal and guard and between guard and ground. A convenient place to do this is at the connectors on the junction box. Likely places to look for shorts are a) the connections between the coaxial cable and the bulkhead connectors, b) the connections to the solder posts, and c) the region between the solder posts. Look for stray wires or improperly cleaned connections.

4.4.6.2 Guide Disk Repair

If the guide disk on the bottom end of Sample Insert falls off, re-epoxy or screw it back on.

4.4.6.3 Sapphire sample plate replacement

Clean sapphire plate and G-10 sample mounting plate region between the solder posts. If the original sapphire plate is cracked or damaged, order a replacement (Lake Shore part number 672-210) or make a similar sample mounting plate from sapphire. Apply a small amount of rubber cement to the rougher side, center between the solder posts, and press down so the rubber cement fills the gap between the sapphire plate and the G-10. Allow to dry, then remove any excess rubber cement.

4.4.6.4 Incorrect Temperature Readings

Check the temperature controller setup for proper sensor type and calibration curve.
Check electrical connections and cables.
Check that the GaAlAs diode temperature sensor on the Sample Insert is epoxied to the back of the sample mounting plate. If the diode temperature sensor has detached, epoxy it back in place using a very small amount of epoxy - the epoxy should not form a fillet on the sides.
If necessary, replace the temperature sensor. Contact Lake Shore to order a replacement and for replacement instructions.

4.4.6.5 Insufficient Heating

Check the heater resistances at the connectors on the OmniPlex and verify that they are correct. A burned out Loop 1 heater (on the cold end of the expander) can be replaced in the field, but will require removal of the tail and vacuum shroud. Contact Lake Shore service for instructions and replacement parts. A burned out Loop 2 heater (sample well) can be replaced in the field more easily. Refer to instructions for Loop 2 Heater Replacement.
Check cables back to the temperature controller and power booster.
Verify output from the temperature controller and power booster.

4.4.6.6 Loop 2 Heater Replacement

Order a replacement heater (Lake Shore part number 673-245 or Minco Products part number H7A10W28).
Remove the tail vacuum shroud and tail radiation shield from the OmniPlex. Be careful to remove tape holding the reflective Mylar® to the radiation shield flange before removing the radiation shield. Follow directions in sections on initial assembly or packing for shipment.
Unsolder old heater leads. Unscrew nut and remove old heater.
If the indium foil gasket must be replaced, make a new one from a piece of indium foil (0.005 inches thick) included with the sample mounting accessories.
Place the new heater over the screw stud and onto the indium foil gasket. Add lock washer and nut, then tighten. Wait one hour for indium to creep, then retighten.
Solder leads and insulate with Teflon or Kynar® heat shrink tubing.
Make sure all leads are secured and will not contact the radiation shield.
Replace tail radiation shield and the tape holding the reflective Mylar in place.
Replace the tail vacuum shroud.
Follow vacuum pumpout procedure.

4.4.6.7 Problems with OmniPlex, Compressor, Hoses, or Expander

Refer to the APD manual for the OmniPlex.

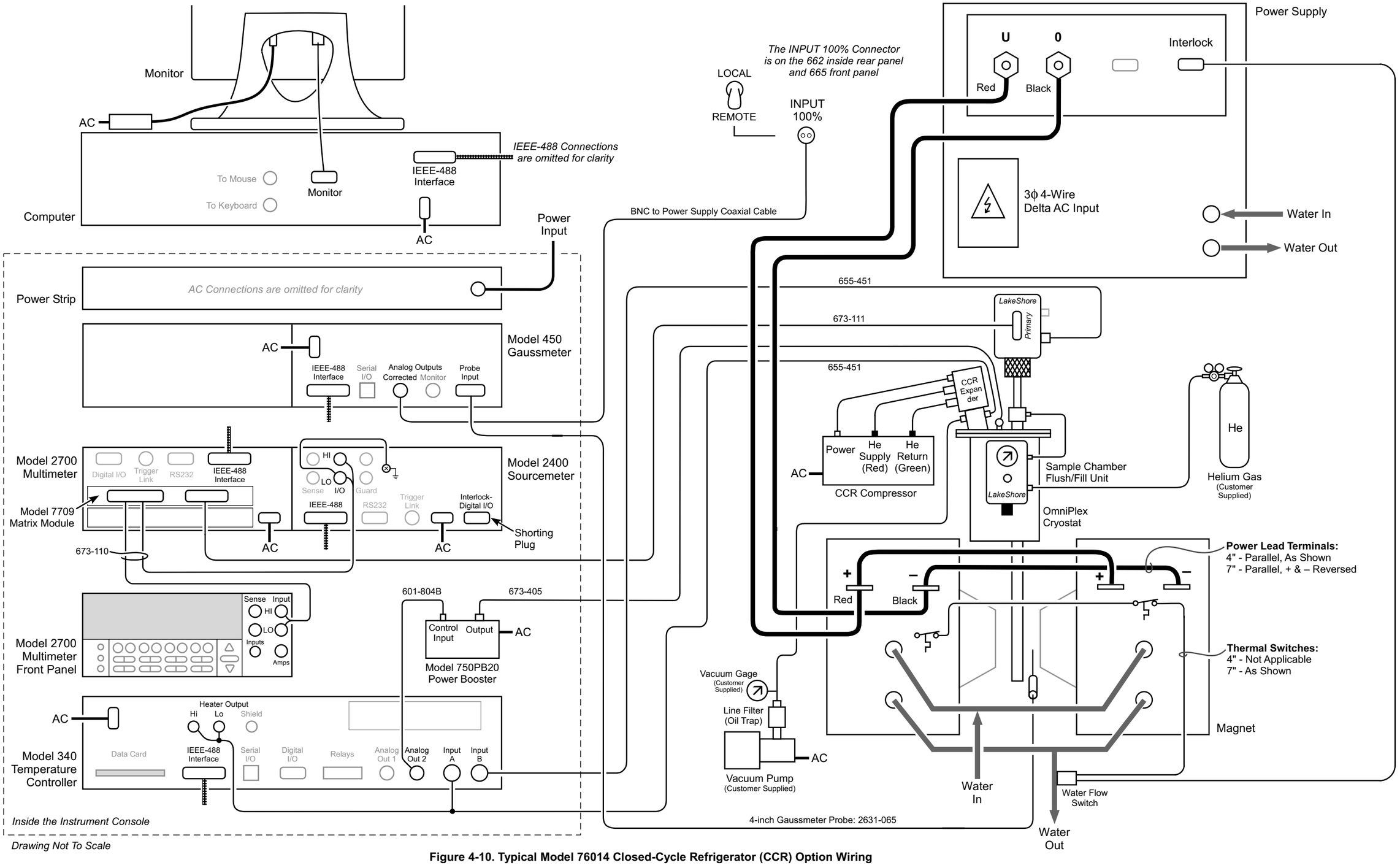


Figure 4-10. Typical Model 76014 Closed-Cycle Refrigerator (CCR) Option Wiring

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4.5 76016 HIGH TEMPERATURE OVEN OPTION

The 76016 High Temperature Oven, also referred to as the Oven Sample Module (OSM), provides for temperature controlled operation from just above ambient to 800 K (527 °C). Stable operation is made possible by balancing the cooling power provided by the ambient environment against two heater circuits powered by a temperature controller. This option also requires the 750TC temperature controller, power booster, and a vacuum pump.

The Oven Sample Module features a heating unit oven body, sample insert, and sample chamber flush/fill unit. The oven body is rigidly mounted to the electromagnet frame and positioned between the electromagnet pole faces. The sample insert attaches through the top of the oven body via a turn locking mechanism. The sample insert makes no contact with the oven body. Since the oven body and sample insert form a vacuum tight enclosure, the sample heating can be done under an inert atmosphere. Argon is recommended. The sample insert has a temperature sensor mounted near the sample location. Electrical contact to the sensor is made through a connector at the top of the sample insert.

4.5.1 Specifications

- **Temperature**: from just above ambient to 800 K (527 °C).
- **Sample Size**: 14 × 17 × 1 mm (W × L × T) maximum.
- **Number of Contacts**: 4 or 6 contacts with independently adjustable tungsten needle probes..
- **Sample Structure**: Hall bar or van der Pauw.
- **Outside Diameter**: 35 mm (1.4 inch) tail.
- **Magnet Air Gap**: 38 mm (1.5 inch) gap.
- **Maximum Field Strength**: 8.5 kG with EM4, 3-inch pole face, 16.4 kG with EM7, 3-inch pole face.
- **Sample Resistances** up to 1 TΩ (1×10^{12} Ω).
- Flush/fill unit can be used to provide an inert atmosphere for the sample.
- Rotation stage for precise sample alignment or study of orientation effects.

NOTE: These specifications are typical results. Specific results may vary somewhat depending upon sample size, geometry, thermal conductivity, and emissivity.

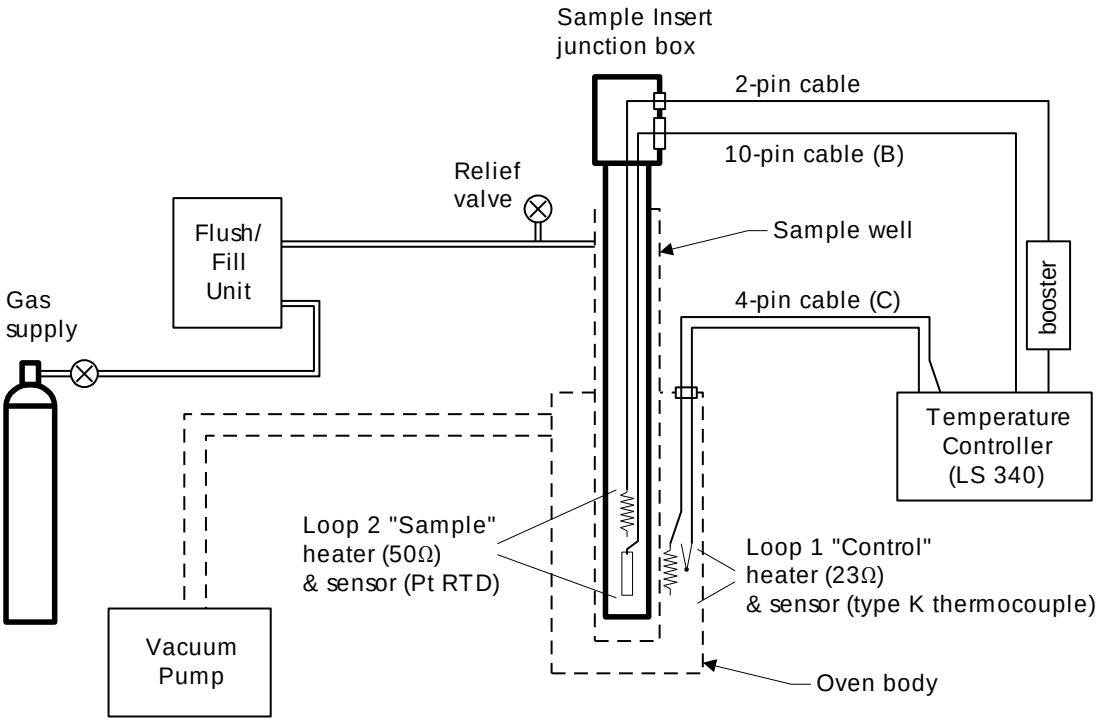


Figure 4-10. Model 76016 OSM Operational Schematic

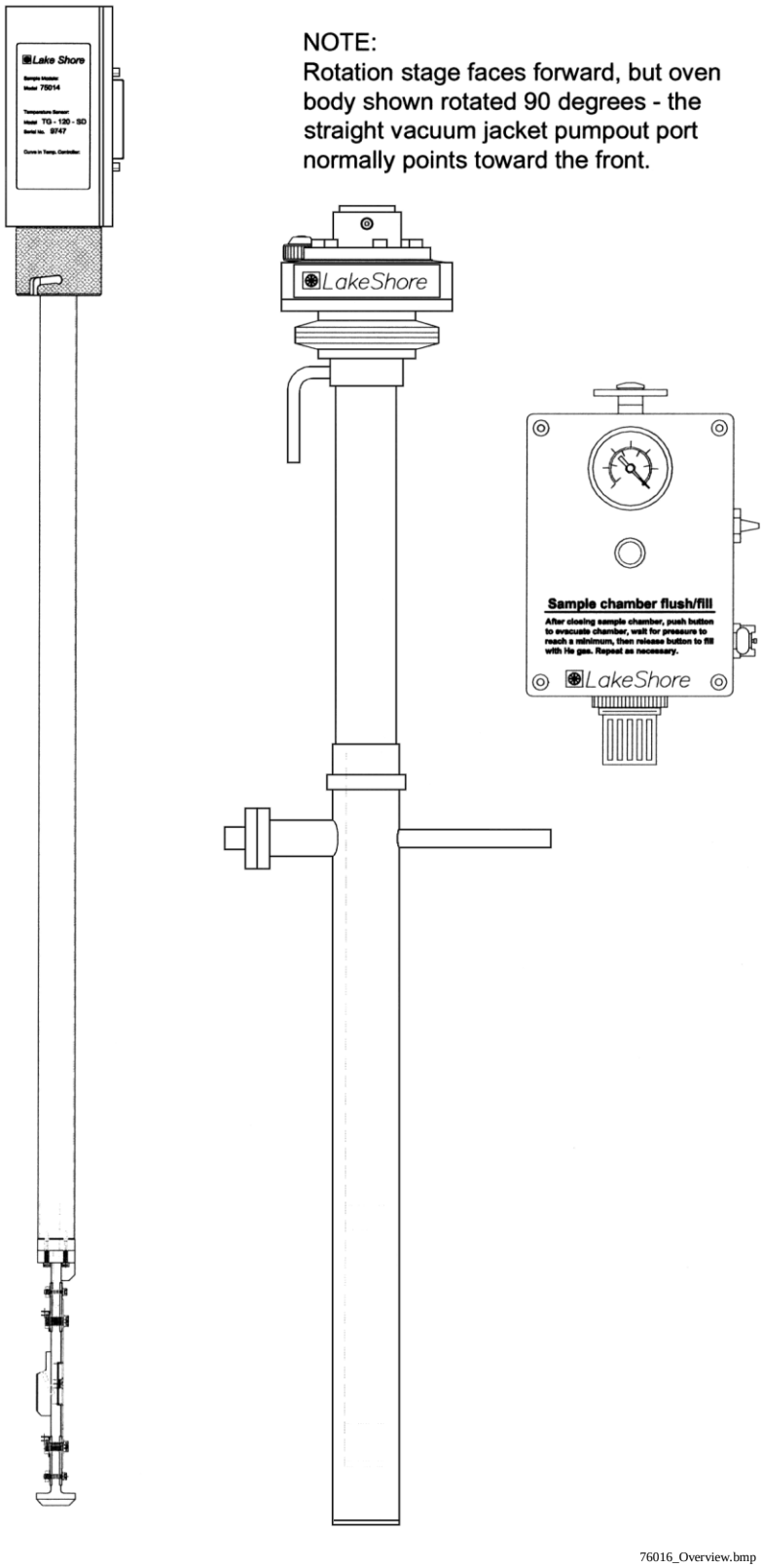


Figure 4-11. Model 76016 OSM Assembly Overview. View from front of electromagnet.

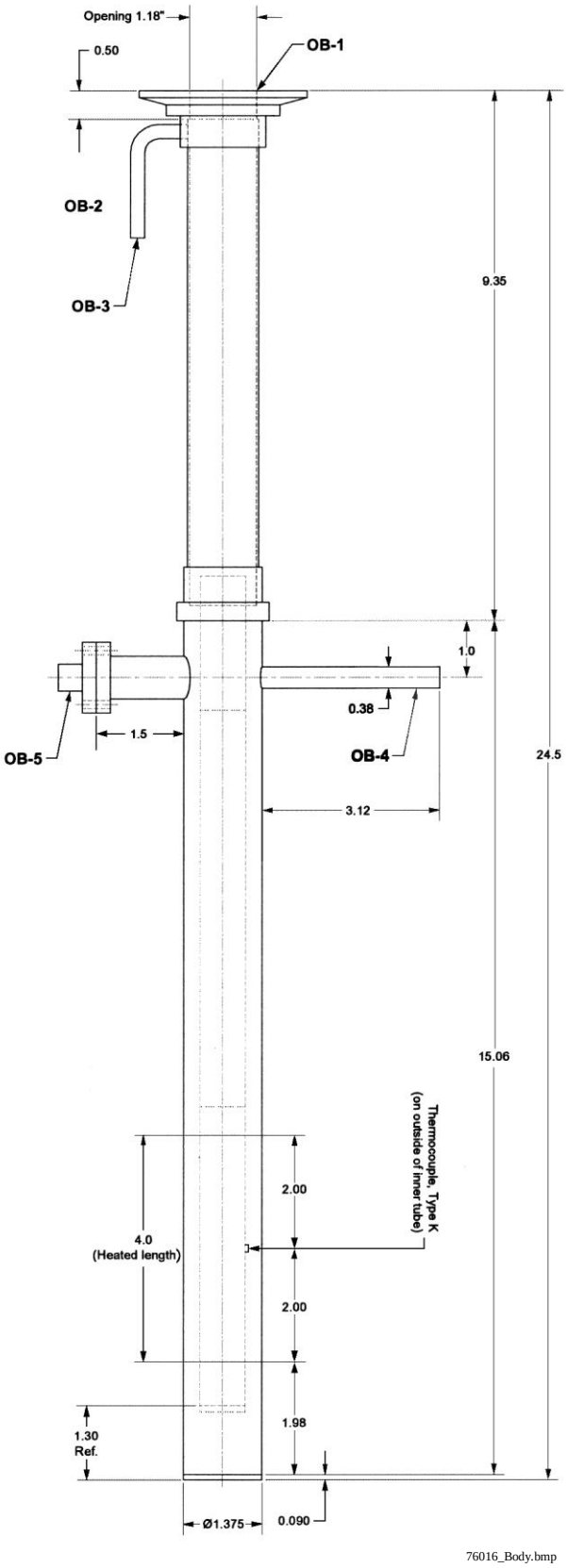


Figure 4-12. Model 76016 Oven Body

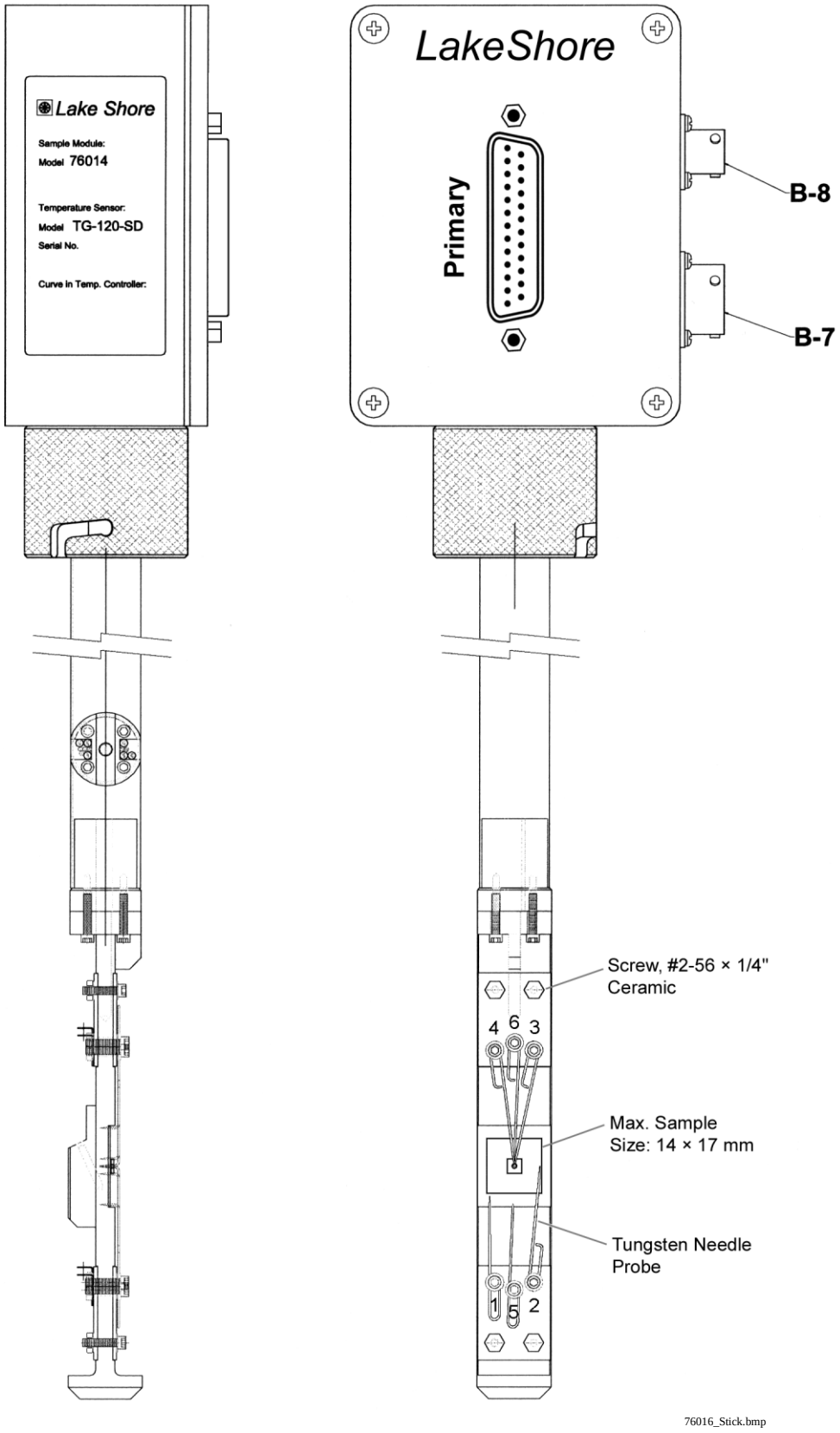


Figure 4-13. Model 76016 Oven Sample Module

Table 4-11. 76016 OSM Oven Body Connection Point and Interface Designations
The locations of the connections listed below are shown in Figure 4-13.

OB-	*Oven Body*
1	Sample well access port, NW-50 flange, 19.1 mm (0.75 inch) clear bore
2	Sample well relief valve, 7 kPa to 14 kPa (1 psig to 2 psig) cracking pressure
3	Sample well exchange gas inlet, Swagelok for 6.35 mm (1/4 inch) OD tube
4	Vacuum pumpout port, 9.52 mm (3/8 inch) OD tube
5	Loop 1 temperature sensor and heater (23 Ω), 4-pin circular connector (RED), see Table 4-13

Table 4-12. Sample Connection Wiring for the 76016 Sample Module
The wire resistance is measured from the connector on the junction box to the needle probe.

Connector	*Pin*	*Use*	*Wire R*
B-1 Primary	**1**	Sample connection # 1	2.5 Ω
	2	Sample connection # 2	
	3	Sample connection # 3	
	5	Sample connection # 4	
	6	Sample connection # 5, I+ for Hall bars	
	8	Sample connection # 6, I– for Hall bars	
B-7	**A**	V– Sample temperature sensor output voltage (Channel **B**)	8 Ω
	B	V+ Sample temperature sensor output voltage (Channel **B**)	
	C	I– Sample temperature sensor excitation current (Channel **B**)	
	J	I+ Sample temperature sensor excitation current (Channel **B**)	
	D	I+ Heater (Loop 2), 50 Ω	
	E	I– Heater (Loop 2)	
	G-K	unused	–
B-8	–	unused	–

Table 4-13. Wiring of 76016 OSM Loop 1 Cable (PN 653-216)
Connects oven body 4-pin connector for Loop 1 heater and temperature sensor (OB-5) to the Model 336.

Connection	*Pin*	*Use*	*Connection*	*Pin*
OB-5	**A**	I+ Heater (Loop 1), 23 Ω	(**G-5**) on Model 336	**Hi**
	B	I– Heater (Loop 1)	(**G-6**) on Model 336	**Lo**
	C	+ Type K thermocouple, Yellow (Channel **C**)	(**G-8**) on Model 336, C+ terminal	**+**
	D	– Type K thermocouple, Red (Channel **C**)	(**G-8**) on Model 336, C– terminal	**–**

Specifications (Continued)

The sample modules available with 7600 Series Hall systems may have additional requirements not provided with the measurement system. Check to make sure these are available when the system arrives.

- Argon gas source (standard grade) with delivery pressure of 600-800 kPa (85-115 psig).
- Vacuum pump with a base pressure of 0.1 Pa ($7x10^{-4}$ torr) or lower. Continuous, oil-free vacuum pumping is required during oven operation. See full discussion in section 4.3. Vacuum hose 1.8 m (6 ft.) long is provided with a KF-25 fitting for connection to the pump.

4.5.2 Setting Up the Model 76016 OSM

Setup must be performed in the following cases:

1. Initial setup following shipping or long term storage.
2. Quick setup following sample module exchange in the electromagnet.

The 76016 OSM can be removed from an electromagnet and stored on a stand without detaching many of the connections, so Case 2 is simpler and often does not require all the steps in the initial setup. Table 4-14 lists the steps required for setup. The table gives an overview and also can be used as a checklist.

Table 4-14. Model 76016 OSM Setup Steps
Reference refers to the relevant section in this manual.
An asterisk (*) indicates the procedure is not always required.

Initial	*Quick*	*Description*	*Reference*
1	–	4.5.2.1 Unpacking and Assembly	4.5.2.1
2	1	4.5.2.2 Oven Installation in the Electromagnet	4.5.2.2
3	2	4.5.2.3 Sample Well Helium Purge Gas Connection	4.5.2.3
4	3	4.5.2.4 Gaussmeter Probe Installation and Orientation	4.5.2.4
5	4	Check oven connections	Table 4-13
6	5*	4.5.2.5 Rotation Stage Alignment	4.5.2.5
7	6*	4.5.2.6 Temperature Controller Setup	4.5.2.6

4.5.2.1 Unpacking and Assembly

1. Unpack the sample module. It ships in a long cardboard box. Set oven assembly on a clean table. Save packaging in case future shipping is required.
2. Assemble mounting collar on the oven neck. When the oven is held vertically, the vacuum pumpout tube and rotation stage name plate should face forward. The two bolts holding the two halves of the mounting collar should face toward the rear.

4.5.2.2 Oven Installation in the Electromagnet

The Model 76016 OSM mounts on top of an electromagnet.

1. Place the sample module assembly so the two holes in the base plate aligns with two corresponding holes on the frame.
2. Install and tighten the two ¼–20×½" socket-head cap screws.
3. Back out magnet poles to allow plenty of clearance for the oven tail. Make sure the path is clear between the location of the 76016 OSM and the magnet stand.
4. Carry the 76016 OSM to the magnet and set in a vertical position so the mounting collar rests on top of the base plate. Be careful not to hit the oven tail on anything.

5. Use a 3/16” hex wrench to attach the mounting collar to the base plate using (2) #1/4”- 20 × 3/4” SHC screws (674-202).
6. Loosen the mounting collar and raise or lower the oven body so the center of the sample mounting space is at the center of the magnet poles. As seen in , the center of the sample mounting space is 51 mm (2 inches) up from the bottom of the oven body.
7. Tighten the mounting collar, making sure the collar is square with the rotation stage.

4.5.2.3 Sample Well Helium Purge Gas Connection

The helium exchange gas sample environment requires a source of He gas (standard grade) with delivery pressure of 600-800 kPa (85-115 psig). The customer supplies the helium gas source. A urethane hose 3 m (10 ft.) long and 1/8” ID connects to the Flush/Fill unit. The other end fits a 1/8" barb fitting. Use a 1/8" barb fitting with 1/8" and 1/4" NPTM fittings or a quick disconnect to connect to the helium gas source.

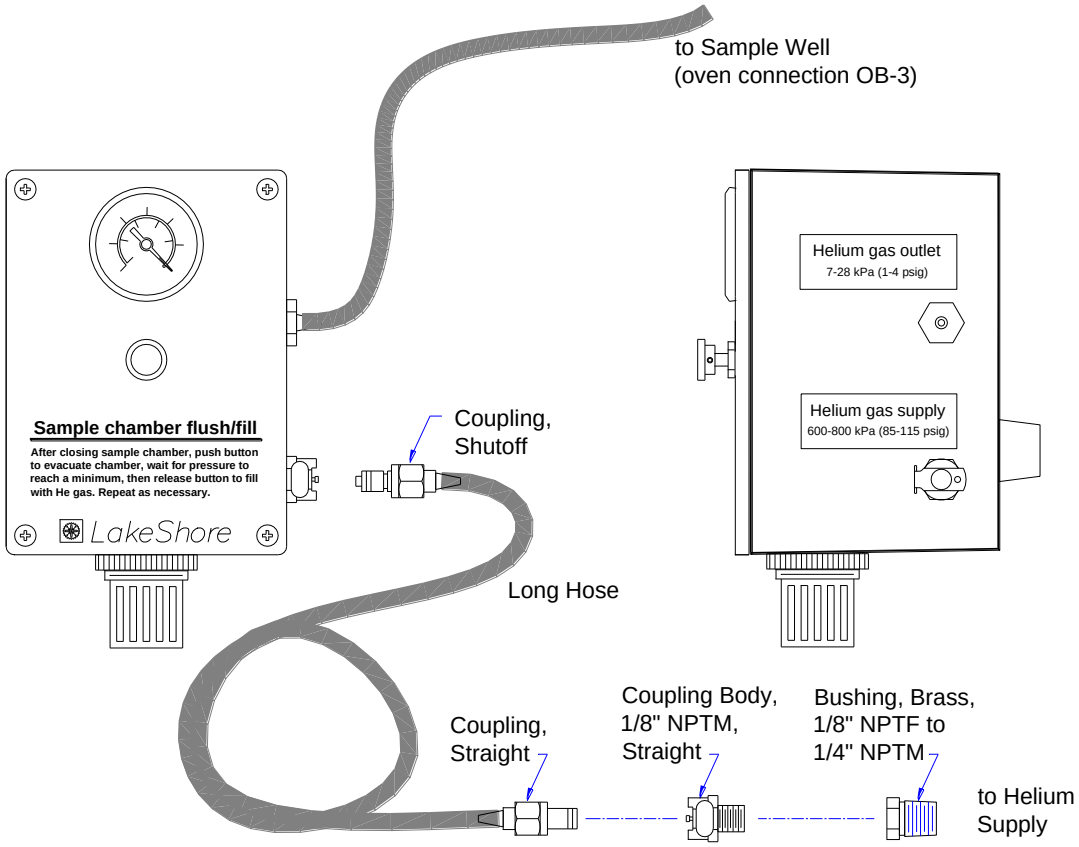


Figure 4-14. Sample Chamber Flush/Fill Unit

1. Mount the Flush/Fill unit in a convenient location.
2. Attach one end of the 60 cm (24”) piece of urethane tubing by pushing onto the Helium Gas Outlet hose barb on the side of the Flush/Fill unit.
3. Install the other end of the urethane hose in the 1/4” ID Swagelok fitting on the sample well manifold.
4. Remove the 0.75 psig relief valve on the sample well manifold and replace with a Relief Valve, 4 psig, 1/4” NPTM (602-611). Use Teflon tape to seal the threads. The 0.75 psig relief valve can be used in house, but is not needed on the 76014 CCR.
5. Insert the connector end of the long urethane supply hose into the supply inlet port in the side of the Flush/Fill unit.
6. Chain a high pressure helium gas cylinder within reach of the supply hose. The pressure regulator must be capable of supplying helium gas at a regulated gauge pressure of 600-800 kPa (85-115 psi).

7. Connect the free end of the Flush/Fill supply hose to the pressure regulator on the helium cylinder. A 1/8" NPTM hose barb (672-274) is supplied along with a 1/8"NPTF to 1/4"NPTM adapter bushing (209-045), but we more commonly use quick connect fittings in house.
8. Verify that the sample well plug is in place.
9. Set the helium cylinder regulator pressure in the proper 600-800 kPa (85-115 psi) range and open any valves to supply helium to the Flush/Fill unit.
10. Listen for any leaks or hoses popping off. Check for slow leaks by closing the main helium supply tank valve and watching the regulator supply pressure gauge. The pressure should not drop more than 1000 kPa (145 psi) within 10 minutes and is more typically one tenth this leak down rate. Correct any leakage problems and open the main supply valve.
11. Get a balloon and stretch over the Relief Valve on the sample well manifold.
12. Push the valve button on the front of the Flush/Fill unit and check that the pressure drops to about –25 mm Hg (–80 kPa).
13. Release the valve button. The sample well should fill with helium gas until the pressure gauge is pegged. If the balloon fills with gas, the sample well pressure regulator sticking out from the bottom of the Flush/Fill box is set too high. Otherwise, use this regulator to increase the sample well pressure until the balloon just begins to fill, then back off about 1/4 turn.
14. Briefly press the valve button and try to achieve a sample well pressure of –5 mm Hg (–15 kPa). If this pressure can be achieved and the sample well does not refill and pressurize with helium gas, then the sample well regulator is not set high enough. Adjust the regulator setting until a stable pressure of –5 mm Hg is not possible after releasing the valve button, but the balloon does not fill.
15. The Flush/Fill unit is now ready for loading of the Sample Insert.

4.5.2.4 Gaussmeter Probe Installation and Orientation

Operation of the Model 76014 CCR requires a Gaussmeter Probe and Gaussmeter Probe Holder (Figure 3-16).

CAUTION: Exercise care when handling the Gaussmeter Probe. The tip is very fragile. Any excess force can alter the calibration or cause the sensor to break. Broken sensors are not repairable.

WARNING: If electromagnet has been moved and not yet powered to full current, the magnet coils may shift the first time the electromagnet is energized, allowing the Gaussmeter probe holder to fall out and possibly damaging the Gaussmeter probe. After moving the electromagnet, *manually* run the electromagnet to full current before installing the Gaussmeter probe holder.

1. The gap between the tail of the oven and the right hand electromagnet pole face should be 3-6 mm (1/8 to 1/4 inch). The gap on the left side can be smaller. Lock the electromagnet poles in place.
   NOTE: The Gaussmeter probe tip is to be located between oven tail and the right hand electromagnet pole face.
2. Insert Gaussmeter probe holder between the coils of the electromagnet. Note that the Probe Mounting Hole can be above or below the threaded rod, as desired. Turn the two knurled end pieces to wedge the assembly in place. Do not overtighten or the threaded rod will bend and buckle.
3. Rotate the mounting block on the threaded rod until it is aligned near the right hand pole face (when viewed from the front of the electromagnet).
4. Tighten the front screw to lock the mounting block against the threaded rod. Do not overtighten.
   CAUTION: Exercise care when handling the Gaussmeter probe because the sensor mounted in the tip is fragile. Stressing the probe tip may alter the sensor calibration. Any excess force can easily break the sensor. Broken sensors are not repairable.
5. Insert Gaussmeter probe through Probe Mounting with the Snowflake pattern facing to the *left*. The Top Screw must clamp onto the large diameter portion of the probe handle.
6. Locate Gaussmeter probe 2-3 mm away from the right side of the oven tail and with the tip parallel to the electromagnet pole face. The oven surface becomes hot to the touch, so direct contact with the Gaussmeter probe is not recommended. The magnetic fields very close to the pole face can be nonuniform, so placement of the tip directly against the electromagnet pole face is not recommended. The location of the mounting block along the threaded rod might require adjustment.
7. Move probe holder assembly forward or backward to position the sensitive portion of probe tip over the center of the electromagnet pole face. The knurled end pieces might need loosened to allow movement, then re-tightened. Verify the probe is straight and properly oriented with snowflake pattern facing to the left so the wide side of the probe tip is parallel to the electromagnet pole face. Adjust as necessary.

CAUTION: A Gaussmeter Probe reversed in orientation reverses the sign of readings (i.e. a positive magnetic field reads as a negative field). Correct sign of readings is critical to magnetic field control.

4.5.2.5 Rotation Stage Alignment

The rotation stage ships mounted on the oven sample well access port (OB-1). Alignment is normally not required unless the rotation stage is removed or rotated for some reason.
Accurate Hall effect measurements require that the sample be perpendicular to the magnetic flux density (field). The rough alignment procedure involves physical alignment of the rotation stage relative to the pole faces, a difficult task to perform accurately and which does not take into account any misalignment contributed by the interface to the Sample Insert or by the Sample Insert itself. The fine alignment procedure involves electrical measurements and is both more accurate and more time consuming.
Below are instructions to install and align the rotation stage. Read the entire procedure before proceeding.

Installation of the rotation stage

1. Start with the plug in the quick connect on top of the rotation stage (i.e. no Sample Insert loaded).
2. Fully loosen the KF-50 quick flange clamp below the rotation stage and open it wide enough to allow rotation of the stage, but do not remove the clamp.

Rough orientation of the rotation stage

The Lake Shore nameplate on the rotation stage should face toward the front of the magnet. The rotation stage should orient the sample perpendicular to the magnetic field and facing the right magnet pole for accurate Hall effect measurements.

1. Orient the rotation stage assembly so the Lake Shore nameplate faces forwards.
2. Check orientation relative to the pole faces - the sides of the rotation stage should be parallel to the pole faces - and tighten the clamp. Exact alignment is not easy as the path between the rotation stage and the poles is not clear.

Fine alignment of the rotation stage

1. Mount a sample with a large Hall coefficient on the Sample Insert. The medium resistivity boron doped silicon sample supplied with the system is a good choice if it can be tested near room temperature.
2. Insert Sample Insert into sample well. Face junction box to the right (usual orientation) and lock in place.
3. Connect triaxial input cables to the junction box on the Sample Insert.
4. Start the Hall System Software program.
5. Activate the Resistance software program, select the menu: Sample Definition, and set up the appropriate sample type for a measurement with the following parameters:
   - Hall Resistance
   - Current reversal OFF (not selected)
   - Two geometries OFF (not selected)
   - Settle time = 120 seconds (adjust as needed)
   - Excitation current of +100 µA is suggested for the medium resistivity (~10.5 Ω·cm) silicon sample near room temperature
6. Activate the Field Control program. Select the menu: Edit -> Properties and note the maximum magnetic field achievable. Select the menu: Run -> Go To Field and input a field near the maximum to get the largest signal.
7. Verify that the rotation stage is set at 0 degrees rotation.
8. Take a measurement (click on the green TAM button). Repeat as necessary to display the Hall voltage.
9. Rotate the stage about zero to find the orientation where the absolute value of the Hall voltage is maximized. This is the offset angle, Ao. The Hall voltage is displayed on the front panel of the voltmeter. If the voltmeter front panel can not be seen easily, activate the Voltmeter software program, display the front panel, and rotate the monitor for easy viewing. If the signal is too small to locate the maximal orientation accurately the following corrective actions are suggested:
   a) increase the excitation current,
   b) increase the magnetic flux density, or
   c) use a different sample with smaller sheet charge density.
10. If the offset angle, Ao, is significant - more than a few degrees - rotate the sample stage by the following process:
    a. Set the rotation stage to zero degrees. If desired, use an Allen key to tighten the knob and prevent rotation.
    b. Loosen the KF-50 clamp and rotate the stage and sample insert to maximize the Hall voltage reading (absolute value).
    c. Tighten the KF-50 clamp, being careful not to let the stage rotate during clamping.
    d. Go back to the previous step (15).

11. Record the offset angle, Ao, and note on the Sample Insert. Hall effect measurements using this Sample Insert should be made with the rotation stage set to the offset angle Ao, rather than set to zero. Note that if more than one sample insert is used with this sample module, Ao can change with the sample insert, so each one should be tested.
12. Return the magnetic flux density to zero using the Field Control program menu: Run -> Go To Field.
13. Exit the Hall program when finished.

4.5.2.6 Temperature Controller Setup

The Model 750TC Option adds a Model 336 and is required for operation of the 76016 OSM. This procedure configures the Model 336 inputs for one thermocouple (Type K) inside the oven jacket, one platinum resistor (PT-103) at the sample location on the Sample Insert, and two loop temperature control.

A schematic of the control system is shown in Figure 4-11. The first control loop consists of a temperature sensor and heater attached inside of the oven body, on the outside of the sample well tube.

The sample is located near the bottom of the sample well and is separated from the sample well walls by helium exchange gas. A temperature sensor mounted directly to the sample insert provides a much more accurate measure of the actual sample temperature. The standard platinum resistor curve can be significantly in error far from the freezing point of water. To reduce the error, the platinum sensor can be individually calibrated as a function of temperature and the calibration curve loaded into the temperature controller and selected for use.

The heater for the second control loop is located in the Sample Insert sample mounting platform. The temperature sensor on the sample insert is used to control the second loop heater. Refer to the Model 336 manual for further information on dual control loop theory and operation.

Table 4-15. Connection List for Model 336 to Model 76016 OSM

#	*Connection*	*From*	*To*
1	Auxiliary input cable, 655-451 (see Table 4-16)	( ) cable 6-pin circular connector **A** NOT CONNECTED (**G-17**) cable 6-pin circular connector **B** to Model 336 Channel **B** (**PB-2**) Cable dual banana connector to Power Booster Output (**PB-3**) Cable single banana connector to Power Booster Shield	(**B-7**) Junction box of Sample Insert, 10-pin circular connector socket (marked BLUE)
2	Loop 1 Control Cable, 653-216	(**G-8**) Yellow wire to Channel **C+** and Red wire to Channel **C-** (**G-5, 6**) Cable dual banana connector to Model 336 Heater Output, gnd tab to LO (**G-7**) Cable single banana connector to Model 336 Heater Output SHIELD	(**OB-5**) 4-pin pin circular connector socket pointing to the rear of the oven (marked RED)
3	Power Booster Coaxial/BNC Heater Input Cable	(**PB-4**) Power Booster Input	(**G-15**) Model 336 Analog Out 2

Table 4-16. Cable 655-451 Wiring. Connects 76016 Sample Insert 10-pin connector (B-7) to Model 336

Connection	*Pin*	*Use*	*Connection*	*Pin*
B-7	**A**	V– Sample temperature sensor output voltage (Channel **B**)	(**G-17**) on Model 336	**2**
	B	V+ Sample temperature sensor output voltage (Channel **B**)		**4**
	C	I– Sample temperature sensor excitation current (Channel **B**)		**1**
	J	I+ Sample temperature sensor excitation current (Channel **B**)		**5**
	D	I+ Heater (Loop 2), 50 Ω	(**PB-2**) Power Booster Output	**Hi**
	E	I– Heater (Loop 2)		**Lo**
	G	V– Temperature sensor output voltage (Channel **A**)	(Not Used)	**2**
	H	V+ Temperature sensor output voltage (Channel **A**)		**4**
	F	I– Temperature sensor excitation current (Channel **A**)		**1**
	K	I+ Temperature sensor excitation current (Channel **A**)		**5**

Following is the setup procedure:

1. Connect all cables listed in Table 4-15. (See Figure 4-16.)
2. **For Quick setup only**: To determine if a quick setup is possible, check if a configuration file already exists. Use either Windows Explore and look in the Windows directory, or start the Model 336 program and select the menu item: File -> Load. Typical file names relevant to this sample module might look like "76016_S1.34c". Note that some work can be saved by first loading a configuration file similar to one to be set up.
3. Exit any programs using the Model 336. The Model 336 must be in LOCAL mode to change settings through the front panel.
4. Set up the Model 336 through the front panel as specified in the procedure below. For further information, refer to the Model 336 User's Manual and the software driver help files. For setup of a Model 330, refer to the Model 330 User's Manual.

- **Input Setup** (Model 336 front panel button)

		Input Setup
Input:	**A**	Enter
Enable:	**OFF**	^ Enter
		Save Screen
Input:	**B**	^ Enter
Enable:	**ON**	^ Enter
Type:	**Plat. 100/500**	^ Enter (500 Ω range to reach 800 K)
Curve:	**4 PT-100**	^ Enter
(or calibration curve, if calibrated)		
		Save Screen
Input:	**C**	^ Enter
Enable:	**ON**	^ Enter
Type:	**Thermocouple**	^ Enter
Room Comp:	**ON**	Enter
Curve:	**6 TYPE K**	^ Enter
		Save Screen
Input:	**D**	^ Enter
Enable:	**OFF**	^ Enter
		Save Screen, Save Screen

- **Display Format** (Model 336 front panel button)

		Display Format
Input Displays:	**2**	^ Enter
Display 1:	C TEMP K	Enter
Display 2:	B TEMP K	Enter
		Save Screen
		Display Format
		<MORE>
Control Loops:	**BOTH**	^ Enter
Heat Display:	**POWER**	^ Enter
		Save Screen

- **Interface** (Model 336 front panel button)

		Interface
IEEE-488		
Terminator:	CR LF	Enter
EOI:	ON	Enter
Address:	**14**	Enter
		Save Screen

- **Analog Outputs** (Model 336 front panel button)

		Analog Outputs
1:		Enter
Mode:	OFF	Enter
Bipolar:	OFF	Enter
		Save Screen
2:		^ Enter
Mode:	**LOOP**	^ Enter
Bipolar:	OFF	Enter
		Save Screen, Save Screen

- **Loop 1** (Model 336 front panel button)

		Loop 1

			Control Channel
	Loop 1 Channel:	**C**	Enter
			Loop 1
			Setpoint
	Setpoint:	0.000 K	Enter
• **Loop 2**			(Model 336 front panel button)
			Loop 2
			Control Channel
	Loop 2 Channel:	**B**	^ Enter
			Loop 2
			Setpoint
	Setpoint:	0.000 K	Enter
• **Control Setup**			(Model 336 front panel button)
			Control Setup
	Loop:	**1** Control Setup	Enter
	Enable:	**ON**	Enter
	Power Up:	OFF	Enter
	Setup Unit:	TEMP K	Enter
	Htr Ω:	**25**	25 Enter
	Control Mode:	Manual PID	Enter
	Filter:	OFF	Enter
			Save Screen
			<MORE>
	Loop:	**1** Control Limits	Enter
	Temp:	**800 K**	800 Enter
	+slope:	0.0%	Enter
	- slope:	0.0%	Enter
	Max Htr I:	2.00 A	2 Enter
	Max Range:	92 W	Enter
			Save Screen
			<MORE>
			Control Setup
	Loop:	**2** Control Setup	^ Enter
	Enable:	**ON**	^ Enter
	Power Up:	OFF	Enter
	Setup Unit:	TEMP K	Enter
	Control Mode:	Manual PID	Enter
	Filter:	OFF	Enter
			Save Screen
			<MORE>
	Loop:	**2** Control Limits	Enter
	Temp:	**800 K**	800 Enter
	+slope:	0.0%	Enter
	- slope:	0.0%	Enter
			Save Screen, Save Screen

5. **Start up only the Model 336 software program** and display the virtual front panel. The channels should be assigned as follows:
   Control = C
   Sample = B
6. Set up Loop 1 Domains.
   - Close the Model 336 software front panel.
   - Select menu item: Utilities -> Domain File Name and input a file name. A suggested format is: **76016L1A.ini** to indicate **L**oop **1**, set **A**. Change the last letter for variations such as a set of domains with shorter settle times when temperature accuracy is not as important. Note that this temperature control domain file will be located in the Windows directory.
   - Select menu item: Utilities -> Domains and input the data from Table 4-17.

Table 4-17. Model 336 Software Loop 1 Domain settings for the 76016 OSM

Domain #	*Begin T [K]*	*End T [K]*	*P*	*I*	*D*	*Htr Power (range)*	*Slew rate [K/min]*	*First: Wait Time [min]*	*Second: F/C/V*	*Third: Wait Time [min]*
1	0	300	0	0	0	0	20	5	* < 0.1	10
2	300	800	100	50	0	5	20	5	* < 0.1	10
3	800	1000	0	0	0	0	100	0	none	0

* Function (of Function/Condition/Value): **Sample drift** [K/min]

7. Set up Loop 2 Domains.
   - Select menu item: Loop 2 and make sure the Lock Set Point item is checked (select it if it is not checked). This causes the set points of the two temperature control loops to be the same at all times.
     √ Lock Set Point
   - Select menu item: Loop 2 -> Domain File Name and input a file name. A suggested format is: **76016L2A.ini** to indicate **L**oop **2**, set **A**. Change the last letter for variations such as a set of domains with shorter settle times when temperature accuracy is not as important. Note that this temperature control domain file will be located in the Windows directory.
   - Select menu item: Loop 2 -> Domains and input the data from Table 4-18. Note that locking the set point causes the wait times and conditions for Loop 2 to be ignored, but they should be entered anyway.

Table 4-18. Model 336 Software Loop 2 Domain settings for the 76016 OSM

Domain #	*Begin T [K]*	*End T [K]*	*P*	*I*	*D*	*Htr Power (range)*	*Slew rate [K/min]*	*First: Wait Time [min]*	*Second: F/C/V*	*Third: Wait Time [min]*
1	0	300	100	50	10	1	20	5	* < 0.1	10
2	300	800	100	50	10	1	20	5	* < 0.1	10
6	800	1000	0	0	0	0	100	0	none	0

* Function (of Function/Condition/Value): **Sample drift** [K/min]

8. Close the Model 336 software front panel.
9. Select menu item: File > Save As… and enter a file name. A suggested format is: "**76016_S1.34c**" used here to mean the **76016 S**ample insert number **1**. A unique name must be used if more than one Sample Insert, each with its own calibrated platinum sensor, will be used. If more than one sample insert will be used they can be numbered for identification. The .34c extension indicates that this is a Model 336 temperature controller configuration file.
10. For each additional sample insert, do the following:
    - Step 3, Exit the Model 336 software program.
    - Step 4, Input Setup, Input B portion only.
    - Step 5, Start up Model 336 software program and check Control and Sample channels.
    - Step 8.
    - Step 9.
11. Check that the configuration files were saved. Select menu item: File -> Load. A dialog box appears with a list of Model 336 configuration files (.34c extensions). Click Cancel, or select a configuration file to load and click OK. This step is performed as part of normal sample module operation.
12. Exit the Model 336 software program.

4.5.2.7 Removal, Storage and Shipping

Removal of the 76016 OSM from an electromagnet platform:

1. Exit from all computer programs.
2. Remove Sample Insert from oven and plug sample well.
3. Remove the Gaussmeter probe from between the electromagnet poles. Store in a safe place where the Gaussmeter probe will not be damaged.
4. Back out the electromagnet poles.
5. Use a 5/16" hex key to remove the 3/8"-16 bolts holding the base plate to the top of the electromagnet stand (EM4) or to the saddle plates (EM7 or EM12).
6. The oven (with base plate still attached) is now free of the electromagnet platform and may be removed. Pull the base plate forward. Be careful not to hit the sample module tail on anything.

Storage:

1. Store vertically on a stand.
2. Short term (less than one month) storage on a horizontal surface is also possible. Long term horizontal storage might result in sagging of the sample well within the oven tail.

Shipping:

1. **Remove base plate**. Use a 3/16" hex wrench to remove the (3) #1/4"- 28 SHC screws and washers. Remove the base plate and return the screws and washers to the holes in the bottom of the collar.
2. **Package 76016 OSM for shipping**. The Flush/Fill unit ships detached. Use the original shipping container or build a suitable replacement. The unit may be shipped in horizontal or vertical orientation.

4.5.3 Sample Mounting with the Model 76016 OSM

Mount samples by following the Model 75013 SCSM Prober Sample Card sample mounting instructions given in Section 4.1.2.2 with the following exceptions:

1. The sample mounting portion of the Model 76016 Sample Insert is permanently attached, not removable like the Prober Sample Card used in the Model 75013 SCSM.
2. The sample mounts in the center of a sapphire mounting plate centered between solder posts. Glue the sapphire mounting plate to the G-10 plate with rubber cement. Normally, it should not be removed. The solder posts around the sapphire mounting plate are not numbered, but are laid out in the same pattern and orientation as the numbered triaxial bulkhead connectors on the Sample Insert junction box.
3. There is no sample identification space on the Model 76016 Sample Insert sample mounting plate. If desired, attach a removable note to the Sample Insert junction box with the sample identification and other relevant information.

4.5.4 Operation of the Model 76016 OSM

This section provides instructions for the APD Omniplex™ Top Loading Exchange Gas Cryostat. This module is designed for more sophisticated temperature control.

4.5.4.1 Sample Insert Insertion

Use the procedure below in loading the Sample Insert to avoid contamination or condensation from air.

1. Clean Sample Insert of any dust or dirt accumulated on its surface. Verify that the Sample Insert is dry.
2. Ready the Sample Insert, remove Sample Well Plug, and carefully insert the Sample Insert.
3. Twist Sample Insert junction box in the rotation stage to fully engage the bayonet lock.
4. Press valve button on Flush/Fill unit 2 or 3 times. This removes any air from the sample well and backfills with helium gas. Any air remaining in the sample well will drop to the bottom of the sample well, near the sample, if a lighter purge gas such as helium is used.
5. Set rotation stage to zero degrees so sample is perpendicular to the applied magnetic field.

4.5.4.2 Sample Insert Cable Connections

The 4 or 6 triaxial sample cables should already have a protective sleeve plus a short section of spiral cable wrap and a tie down clamp near the sample end. Bolt the tie down clamp into the right rear bolt hole on top of the saddles. This strain relieves the cables, but positions them close to the sample well where they will be attached to the Sample Insert.

4.5.4.3 Verify Temperature Controller Setup

The temperature controller must be set up for the Sample Module in use. If no temperature controller configuration file exists, create one (see section 0). Note that there is no indication of the current configuration (unlike the Field Control driver program).

1. Start the Model 336 software driver program on the computer and load the appropriate configuration file. To do this, select the menu item: File -> Load. A dialog box will appear with a list of configuration files (.34c extensions). Select one and click on OK. The Model 336 will be configured, but there is no indication of the current configuration.
2. Open the Front Panel and check that the input channels are reading properly and assigned as follows:
   Control = C
   Sample = B

4.5.4.4 Vacuum Pump Out Procedure

The customer must supply a vacuum pump to evacuate the sample module to a pressure of 0.1 Pa ($7x10^{-4}$ torr) or lower prior to initial operation. Vacuum pressure gauging must be provided or added to the oven. The oven must be pumped continuously during operation.

1. The oven should be at room temperature for initial vacuum pumpout.
2. Connect vacuum line to the oven Vacuum Pumpout Port (**OB-4**).
3. The other end of the vacuum line has a KF-25 flange attached. Connect the flanged end to a vacuum pump.
4. Start the vacuum pump and pump out the oven vacuum space to a pressure less than 1 Pa ($7x10^{-3}$ torr). If using a mechanical vacuum pump which can backstream oil, a trap must be used. Dry pumps can be run longer and the vacuum will be cleaner.

4.5.4.5 Temperature Control Parameters

Choosing temperature control parameters always requires a compromise between the desires for rapid temperature changes and good stability and accuracy with little temperature overshoot or oscillation.
The temperature control domain parameters suggested in the section on setting up the Model 336 temperature controller were chosen for slow, controlled temperature changes with little overshoot or oscillation. If faster temperature changes are desired, first try setting the second wait times in the Domains to zero. Additional optimization can be performed by following the procedures described in the Model 336 User's Manual.

4.5.4.6 Sample Insert Removal

Use the procedure below to remove a Sample Insert from the Model 76016 OSM.

1. Wait until the Sample Insert temperature is below 350 K before removal.
2. Unplug the triaxial BNC cables from the Sample Insert junction box. If desired, leave 10-pin circular connector in place to monitor temperature.
3. Twist Sample Insert junction box in the rotation stage to release the bayonet lock.
4. Remove the Sample Insert from the oven sample well.
5. Insert the sample well plug and make sure it seals tightly.
6. Press the Flush Fill valve button 2 or 3 times to remove the gas (possibly contaminated with air) from the sample well.

4.5.5 Service and Maintenance for the Model 76016 OSM

4.5.5.1 Leakage Resistance and Shielding

Measurement of very high resistance samples (>10 MΩ) requires very high resistance between all combinations of signal, guard and ground. The following procedure is possible only with measurement instrumentation that drives the guards around the signal lines (-HVWR or -LVWR).

1. Measure the resistance of the Sample Insert without any sample mounted. If necessary, first clean the sample mounting area with isopropyl alcohol and demineralized water, then blow dry with warm air from a heat gun. Install the Sample Insert in the oven sample well. Measure the resistance (R14,23) in high resistance mode using the Resistance software program.
2. The resistance should be significantly greater than the specified maximum accurately measurable resistance of the measurement system. Note that a leakage resistance of 100 times the maximum sample resistance would lead to a 1% measurement error.
3. If the resistance is low, check the resistance between signal and guard and between guard and ground. A convenient place to do this is at the connectors on the junction box. Likely places to look for shorts are a) the connections between the coaxial cable and the bulkhead connectors, b) the connections to the solder posts, and c) the region between the solder posts. Look for stray wires or improperly cleaned connections.

4.5.5.2 Needle Probe Replacement

Contact Lake Shore for replacement needle probes (Lake Shore P/N 673-207) and bending instructions.

4.5.5.3 Sapphire sample plate replacement

Clean sapphire plate and copper sample mounting plate region between the needle probes. If the original sapphire plate is cracked or damaged, order a replacement (Lake Shore part number 672-528) or make a similar sample mounting plate from sapphire. Hold the sapphire plate in place with two wires tied around the sample mounting plate. The wires must lay in the edge grooves or they will rub against the sides of the sample well and break.

4.5.5.4 Incorrect Temperature Readings

Check the temperature controller setup for proper sensor type and calibration curve.
Check electrical connections and cables.
Check that the platinum temperature sensor on the Sample Insert is firmly attached to the back of the sample mounting plate. If the temperature sensor has detached, paste it back in place using a very small amount of ceramic paste.
If necessary, replace the temperature sensor. Contact Lake Shore to order a replacement and for replacement instructions.

4.5.5.5 Insufficient Heating

Check the heater resistances at the connectors on the oven body and Sample Insert junction box and verify that they are correct. A burned out Loop 1 heater (in the oven body) must be replaced at the factory. Contact Lake Shore to schedule service. A burned out Loop 2 heater (Sample Insert) can be replaced in the field. Refer to instructions for Loop 2 Heater Replacement.
Check cables back to the temperature controller and power booster.
Verify output from the temperature controller and power booster.

4.5.5.6 Loop 2 Heater Replacement

Order a replacement heater (Lake Shore part number 672-529).
Remove the copper sample mounting platform from the end of the Sample Insert tube by removing the four #4-40 screws.

Separate the sample mounting platform from the tube, exposing the end of the heater.

Detach old heater leads and remove the heater.

Spot weld or braze the new heater to the lead wires and insulate with fiberglass tubing rated to at least 850 K.

Insert the new heater in the hole in the sample mounting platform.

Screw the sample mounting platform back onto the end of the Sample Insert tube. The sample space must face in the same direction as the cover of the junction box.

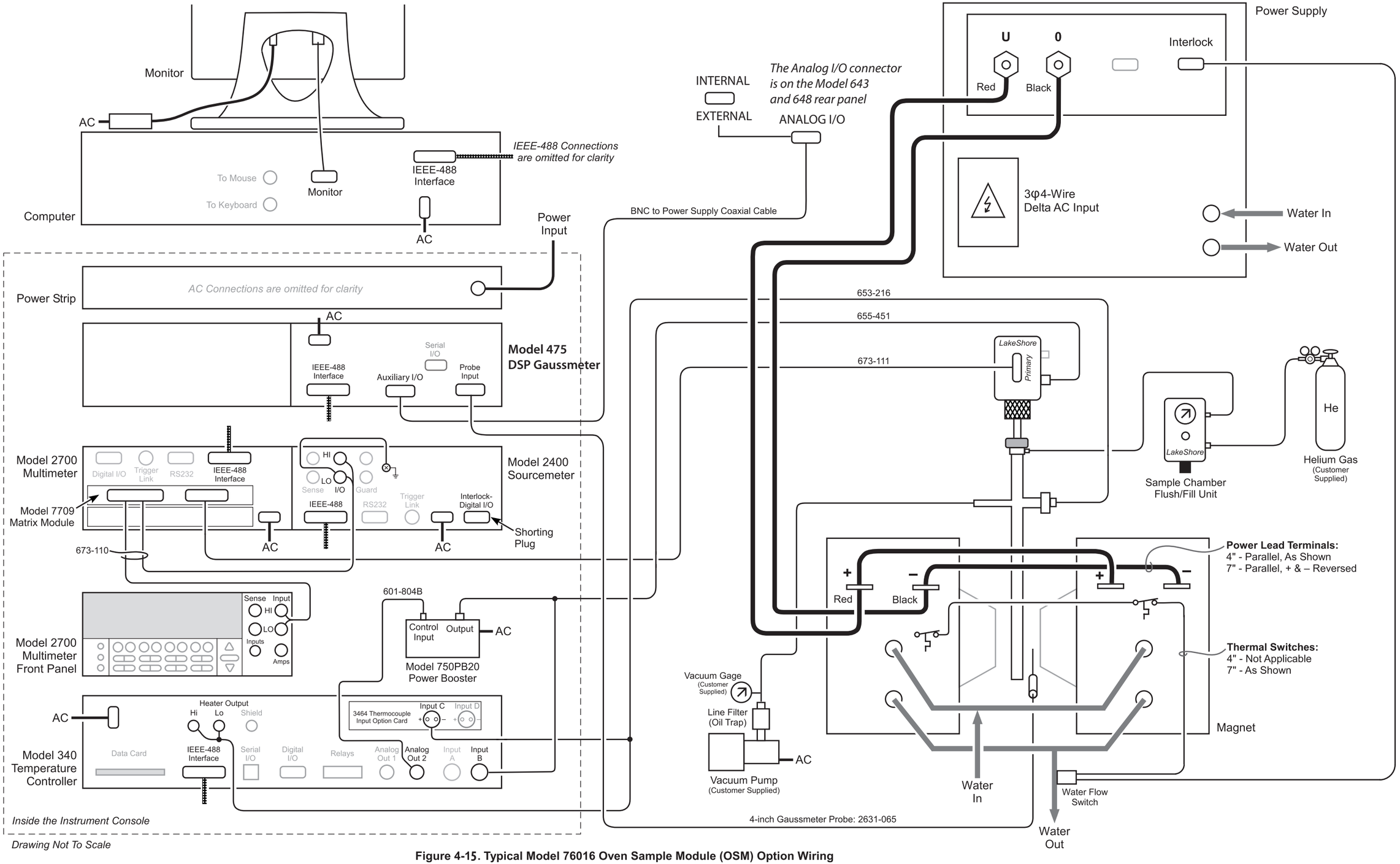


Figure 4-15. Typical Model 76016 Oven Sample Module (OSM) Option Wiring

Truly Blank Page

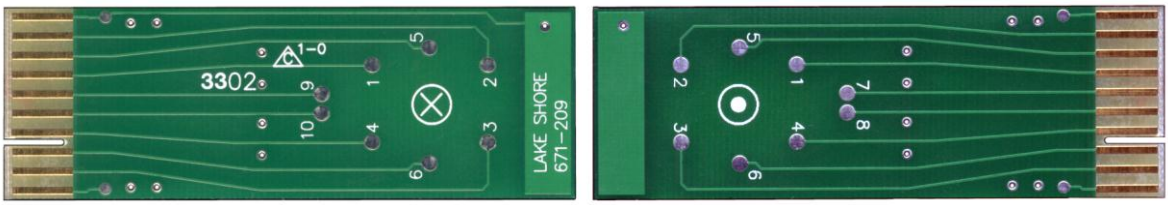
4.6 SMALL SAMPLE CARDS (1 × 1 cm)

The sample mounting cards have solder pads where wires from the sample are connected to the card. Soldered contacts are the most reliable, but take more time and effort to make.

Note that contact size and metallurgy can have a significant impact on measurement accuracy. Sample preparation and contacting is the user's responsibility. Refer to Appendix A for general Hall effect measurement theory and a discussion of Hall sample geometries. Refer to Appendix B for references to literature on contact formation.

4.6.1 Dual Sample Card (671-209)

The dual sample card is designed specifically for use with the 7600 Series Hall System. The standard Hall System can measure two 1 × 1 cm samples simultaneously, mounted on the "A" side of two sample cards. The optional 7600-4 Hall System can measure four samples, with the samples mounted on both the "A" and "B" sides of the two sample cards. See Figure 4-17.



Back View **Front View**

671-201.bmp

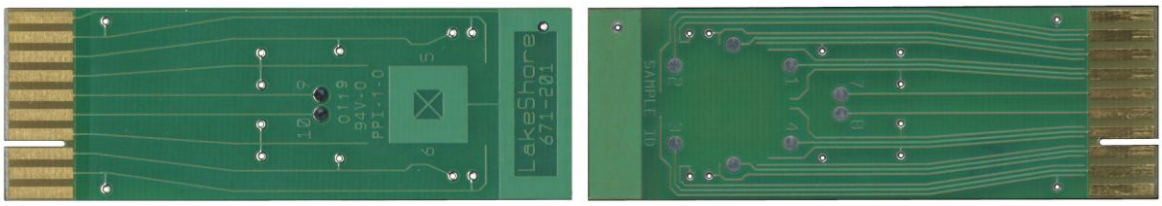
Figure 4-16. Typical Small Sample Card, Dual 1 × 1 cm Samples

4.6.2 Single Sample Card (671-201)

The single-sample cards from the Lake Shore 75/77/95/9700 Series Hall Measurement Systems can also be used. Each sample card has 20 gold-plated contact fingers. The contact fingers on the front side connect to sample contact pads 1 thru 6 and auxiliary contact pads 7 and 8. The contact fingers on the back side connect to auxiliary contact pads 9 and 10 and to the driven shields for signal lines 1 thru 6. Routing the driven shields onto the card minimizes leakage currents, allowing more accurate measurements on very high resistance samples. See Figure 4-18.

Standard sample mounting cards have solder pads where wires from the sample are connected to the card. Soldered contacts are the most reliable, but take more time and effort to make. Card mounted samples can be stored for rapid insertion and measurement in the Hall Sample Module.

The auxiliary contacts are available for a temperature sensor, heater, light source, sample bias, additional sample contacts, or other use. The auxiliary contacts are not guarded and their use may not be directly supported by the hardware or software supplied. Sample cards are reusable. Do not use permanent adhesive if sample is to be removed from sample card.



Back View **Front View**

671-209.bmp

Figure 4-17. Typical Small Sample Card, Single 1 × 1 cm Sample

4.7 LARGE SAMPLE CARDS (5 ×5 CM)

The sample mounting cards have solder pads where wires from the sample are connected to the card. Soldered contacts are the most reliable, but take more time and effort to make.

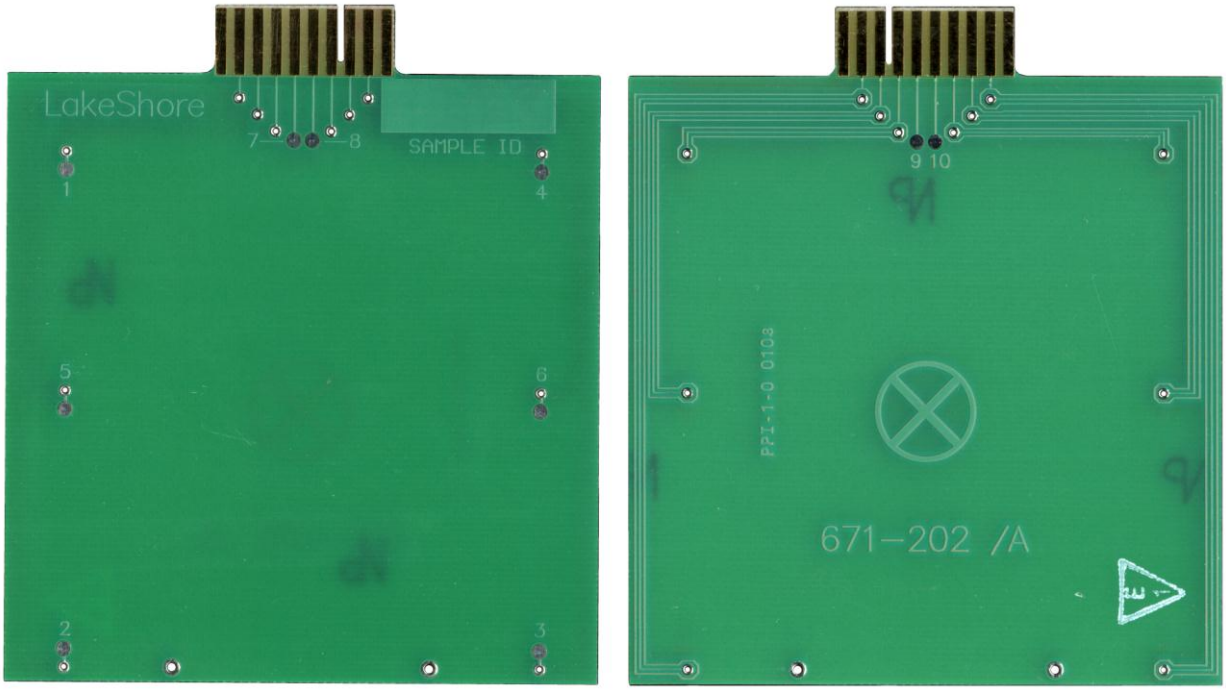
Note that contact size and metallurgy can have a significant impact on measurement accuracy. Sample preparation and contacting is the user's responsibility. Refer to Appendix A for general Hall effect measurement theory and a discussion of Hall sample geometries. Refer to Appendix B for references to literature on contact formation.

4.7.1 Large Sample Card (671-202)

The large single-sample cards from the Lake Shore 75/77/95/9700 Series Hall Measurement Systems can also be used. Each sample card has 20 gold-plated contact fingers. The contact fingers on the front side connect to sample contact pads 1 thru 6 and auxiliary contact pads 7 and 8. The contact fingers on the back side connect to auxiliary contact pads 9 and 10 and to the driven shields for signal lines 1 thru 6. Routing the driven shields onto the card minimizes leakage currents, allowing more accurate measurements on very high resistance samples. See Figure 4-19.

Standard sample mounting cards have solder pads where wires from the sample are connected to the card. Soldered contacts are the most reliable, but take more time and effort to make. Card mounted samples can be stored for rapid insertion and measurement in the Hall Sample Module.

The auxiliary contacts are available for a temperature sensor, heater, light source, sample bias, additional sample contacts, or other use. The auxiliary contacts are not guarded and their use may not be directly supported by the hardware or software supplied. Sample cards are reusable. Do not use permanent adhesive if sample is to be removed from sample card.



Front View **Rear View**

Large Sample Card.bmp

Figure 4-18. Typical Large Sample Card, Single 5 × 5 cm Sample

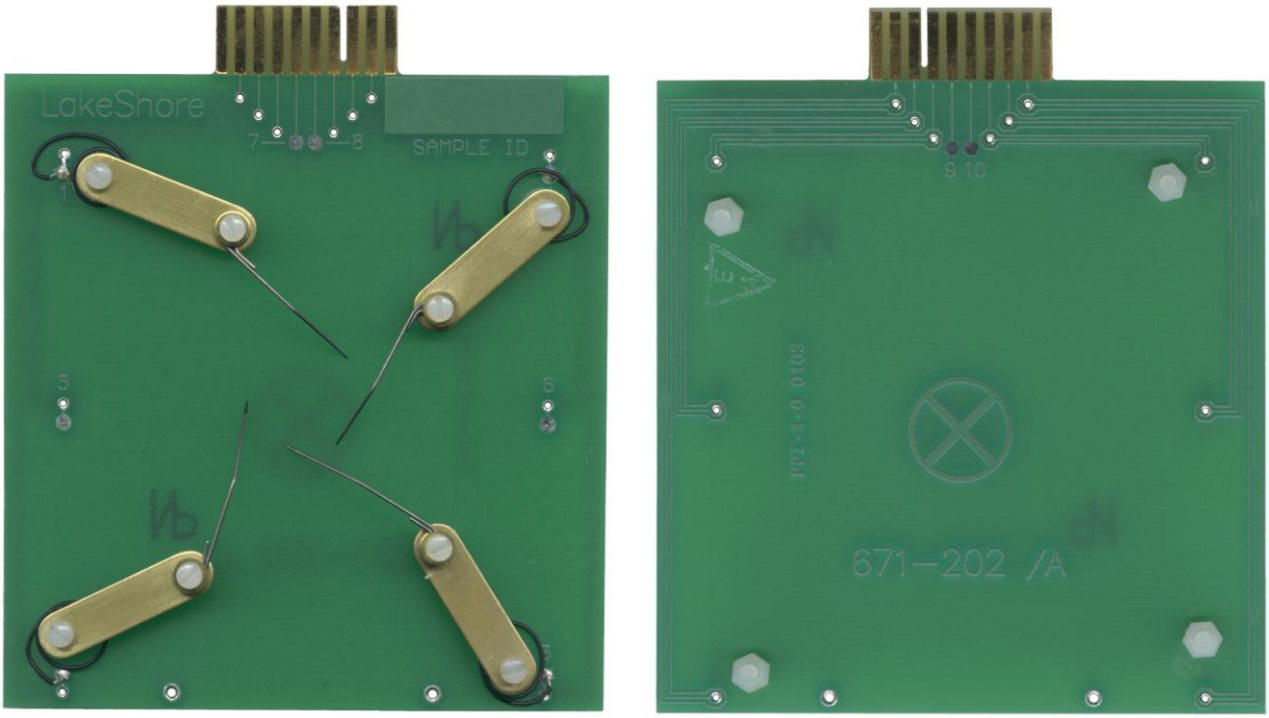
4.7.2 Prober Sample Card (671-205)

The Prober Sample card has four tungsten needle probes to contact the sample. Samples contactable with the needle probes can be rapidly mounted and demounted. The card is designed to accommodate a 5 × 5 cm sample. Nothing (sample, arms, or probers) should extend beyond the edges of the prober card or they might contact the inside of the sample enclosure. See Figure 4-20.

The force required to move the prober arms can be changed by tightening or loosening the nylon screws and nuts. The force of the prober on the sample can be adjusted by swinging the probe tip over the edge of the card and then bending the probe needle up or down as required.

Heavy samples might require additional support. A small amount of temporary adhesive such as rubber cement could be used. The two nylon screw heads at the bottom of the prober sample card can be used as rests for 75 mm (3 inch) diameter wafers. Similar rests could be added as needed.

Accurate van der Pauw measurements require the probes to be as near a sample edge as possible. Some compromise might be necessary if the edge of the sample is not uniform. Symmetrically placed probes on a symmetrical sample generally improve measurement accuracy by minimizing misalignment voltages. For further discussion of this subject, see Appendix A – Hall Effect Measurement Theory and Practice.



Prober Card – Front View

Prober_Front.bmp

Prober Card – Rear View

Prober_Back.bmp

Figure 4-19. Typical Prober Sample Card, Single 5 × 5 cm Sample

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APPENDIX A

HALL EFFECT MEASUREMENTS

A.1 GENERAL

The model Hall effect system consists of a uniform slab of electrically conducting material through which a uniform current density flows in the presence of a perpendicular applied magnetic field. The Lorentz force deflects moving charge carriers to one side of the sample and generates an electric field perpendicular to both the current density and the applied magnetic field. The Hall coefficient is the ratio of the perpendicular electric field to the product of current density and magnetic field, while the resistivity is the ratio of the parallel electric field to the current density.

Experimental determination of a real material's transport properties requires some significant departures from the ideal model. To begin with, one cannot directly measure the electric field or current density inside a sample. Current density is determined from the total excitation current and the sample's geometry. Electric fields are determined by measuring voltage differences between electrical contacts on the sample surface.

Electrical contacts are made of conductive material, and usually have a higher conductivity than the sample material itself. Electric current therefore tends to flow through the contacts rather than the sample, distorting the current density and electric field in the sample from the ideal. Excitation current flowing through the contacts used to measure voltage differences reduces both current density in the vicinity and the Hall field. If a contact extends across the sample in the same direction as the Hall field, it can conduct current from one side of the sample to the other, shorting out the Hall voltage and leading to an underestimate of the Hall coefficient. Finally, if pairs of contacts used in a voltage measurement are not aligned properly either perpendicular or parallel to the excitation current density, then the voltages measured will not correctly determine the perpendicular or parallel component of the electric field. To minimize these geometrical problems, one must take care with the size and placement of electrical contacts to the sample.

There are also many intrinsic physical mechanisms that alter current density and electric field behavior in a real material. Most of these relate to the thermoelectric behavior of the material in or out of a magnetic field. Some of these effects can be minimized by controlling temperature in the sample's vicinity to minimize thermal gradients across it. In addition, most errors introduced by intrinsic physical mechanisms can be canceled by reversing either the excitation current or the magnetic field and averaging measurements.

A.2 HALL EFFECT MEASUREMENT THEORY

Hall effect measurements commonly use two sample geometries: (1) long, narrow Hall bar geometries and (2) nearly square or circular van der Pauw geometries. Each has advantages and disadvantages. In both types of samples, a Hall voltage is developed perpendicular to a current and an applied magnetic flux. The following is an introduction to the Hall effect and its use in materials characterization. A number of other sources are available for further information[1,2,3,4].

Hall bar geometry: Some common Hall bar geometries are shown in Figure A-1. The Hall voltage developed across an 8-contact Hall bar sample with contacts numbered as in Figure A-1 is:

$$V_H = V_{24} = \frac{R_H B I}{t}$$

where V_{24} is the voltage measured between the opposing contacts numbered 2 and 4, R_H is the Hall coefficient of the material, *B* is the applied magnetic flux density, *I* is the current, and *t* is the thickness of the sample (in the direction parallel to *B*). This section assumes SI units. For a given material, increase the Hall voltage by increasing *B* and *I* and by decreasing sample thickness.

The relationship between the Hall coefficient and the type and density of charge carriers can be complex, but useful insight can be developed by examining the limit $B \to \infty$, when:

$$R_H = \frac{r}{q(p-n)}$$

where r is the Hall scattering factor, q is the fundamental electric charge, p is the density of positive and n the density of negative charge carriers in the material. For the case of a material with one dominant carrier, the Hall coefficient is inversely proportional to the carrier density. The measurement implication is that the greater the density of dominant charge carriers, the smaller the Hall coefficient and the smaller the Hall voltage which must be measured. The scattering factor r depends on the scattering mechanisms in the material and typically lies between 1 and 2.[1,5]

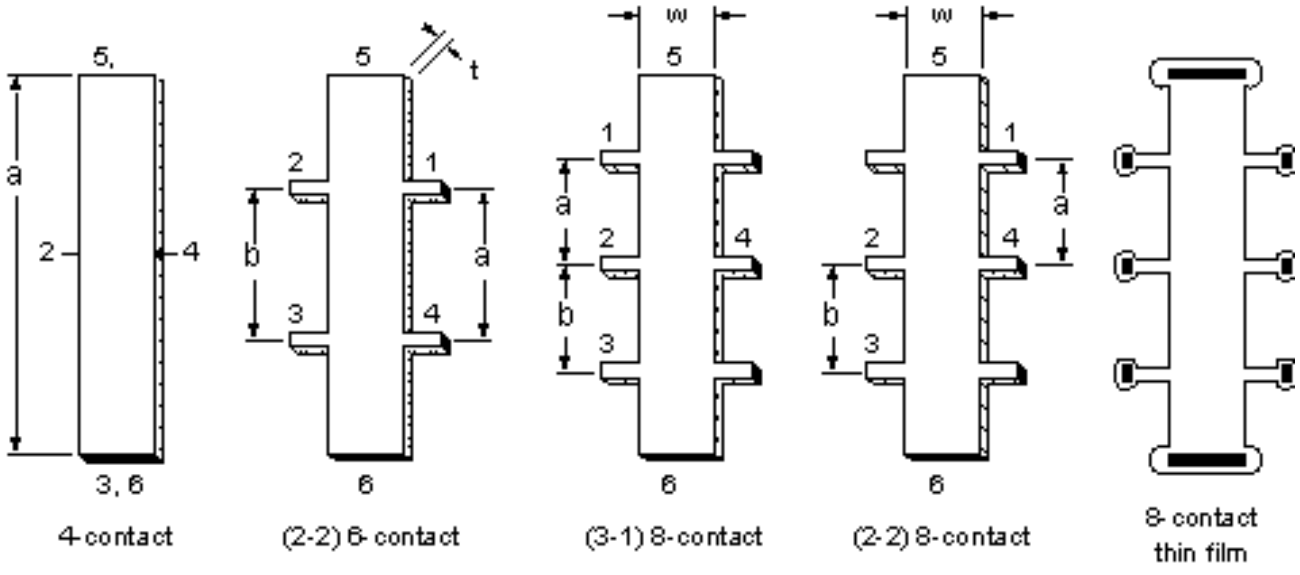
Another quantity frequently of interest is the carrier mobility, defined as: $\mu_H = \frac{|R_H|}{\rho}$

where μ_H is the Hall mobility and ρ is the electrical resistivity at zero magnetic flux density. The electrical resistivity can be measured by applying a current between contacts 5 and 6 of the sample shown in Figure A-1 and measuring the voltage between contacts 1 and 3, then using the formula:

$$\rho(B) = \frac{V_{13}}{I_{56}} \frac{wt}{b}$$

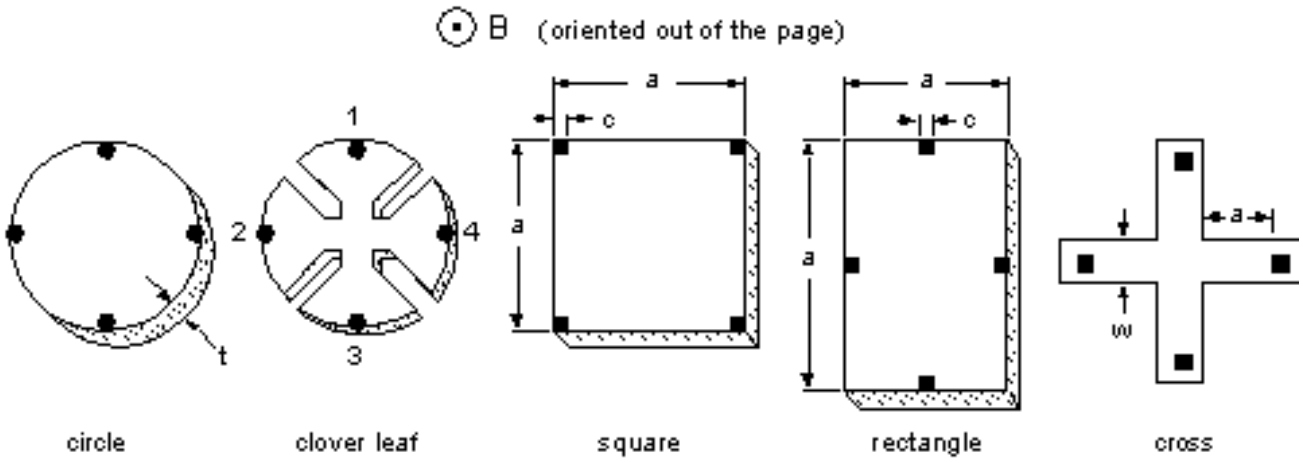
where w is the width and t is the thickness of the Hall bar, b is the distance between contacts 1-3, and B is the magnetic flux density at which the measurement is taken. The Hall bar is a good geometry for making resistance measurements since about half of the voltage applied across the sample appears between the voltage measurement contacts. For this reason, Hall bars of similar geometries are commonly used when measuring magnetoresistance or Hall mobility on samples with low resistances.

Disadvantages of Hall bar geometries include the following: A minimum of six contacts to make mobility measurements; accuracy of resistivity measurements is sensitive to the geometry of the sample; Hall bar width and the distance between the side contacts can be especially difficult to measure accurately. The accuracy can be increased by making contact to the sides of the bar at the end of extended arms as shown in Figure A-2. Creating such patterns can be difficult and can result in fragile samples.



Common Hall bar sample geometries. The sample thickness, t, of a thin film sample is equal to the diffusion depth or layer thickness. Contacts are shown in black and are numbered according to the standard for mounting in Lake Shore sample holders.

Figure A-1. Common Hall Bar Geometries.



Common van der Pauw sample geometries. The cross is shown as a thin film pattern and the others are shown as bulk samples. Contacts are shown in black.

Figure A-2. Common van der Pauw Sample Geometries.

van der Pauw geometry: Some disadvantages of Hall bar geometries can be avoided with van der Pauw sample geometries (see Figure A-2). Van der Pauw 5,6 showed how to calculate the resistivity, carrier concentration, and mobility of an arbitrary, flat sample if the following conditions are met:

1. The contacts are on the circumference of the sample.
2. The contacts are sufficiently small.
3. The sample is of uniform thickness, and:
4. The sample is singly connected (contains no isolated holes).

The resistivity of a van der Pauw sample is given by the expression:

$$\rho = \frac{\pi t}{\ln(2)} \frac{V_{43}}{I_{12}} + \frac{V_{14}}{I_{23}}$$

where V_{23} is defined as V_2 - V_3 and I_{12} indicates the current enters the sample through contact 1 and leaves through contact 2. Two voltage readings are required with the van der Pauw sample, whereas the resistivity measurement on a Hall bar requires only one. This same requirement applies to Hall coefficient measurement as well, so equivalent measurements take twice as long with van der Pauw samples.

The quantity F is a transcendental function of the ratio R_r, defined as:

$$R_r \equiv \frac{V_{43}}{I_{12}} \frac{I_{23}}{V_{14}} \equiv \frac{R_{12,43}}{R_{23,14}} \text{ or } R_r \equiv \frac{I_{12}}{V_{43}} \frac{V_{14}}{I_{23}} \equiv \frac{R_{23,14}}{R_{12,43}}$$

whichever is **greater**, and F is found by solving the equation:

$$\frac{R_r - 1}{R_r + 1} = \frac{F}{\ln(2)} \operatorname{arcosh}\left\{\frac{\exp[\ln(2)/F]}{2}\right\}$$

F=1 when R_r=1, which occurs with symmetrical samples like circles or squares when the contacts are equally spaced and symmetrical. The best measurement accuracy is also obtained when R_r =1.

Squares and circles are the most common van der Pauw geometries, but contact size and placement can significantly effect measurement accuracy. A few simple cases were treated by van der Pauw. Others have shown that for square samples with sides of length *a* and square or triangular contacts of size δ in the four corners, if $\delta/a < 0.1$, then the measurement error is less than 10%[6]. The error is reduced by placing the contacts on square samples at the midpoint of the sides rather than in the corners[7]. The Greek cross shown in Figure A-2 has arms which serve to isolate the contacts from the active region. When using the Greek cross sample geometry with a/w > 1.02, less than 1% error is introduced[8]. A cloverleaf shaped structure like the one shown in Figure A-2 is often used for a patternable thin film on a substrate. The active area in the center is connected by four pathways to four connection pads around its perimeter. This shape makes the measurement much less sensitive to contact size, allowing for larger contact areas.

The contact size affects voltage required to pass a current between two contacts. Ideal point contacts would produce no error due to contact size, but require an enormous voltage to force the current through the infinitesimal contact area. Even with square contacts in the corners of a square sample with $\delta/a < 0.1$, the ratio of the output to input voltage V_{43}, V_{12} is on the order of 1/10. Van der Pauw sample geometries are thus much less efficient at using the available excitation voltage than Hall bars.

Advantages of van der Pauw samples: Only four contacts required. No need to measure sample widths or distances between contacts. Simple geometries can be used.

Disadvantages: Measurements take about twice as long. Errors due to contact size and placement can be significant when using simple geometries.

Mobility spectra: Hall effect measurements are usually performed at just one magnetic flux density, although polarity is reversed and the voltage readings averaged to remove some sources or error. The resulting single mobility calculated from the measurements is a weighted average of the mobilities of all carriers present in the sample. Beck and Anderson[9] developed a technique for interpreting magnetic flux-dependent Hall data which generates a mobility spectrum. The result is a plot of the carrier concentration of conductivity as a function of the mobility. The number of peaks appearing in a mobility spectrum indicates the number of distinct charge carriers active in the material. This powerful technique has virtually eliminated the need for destructive testing techniques such as differential profiling. An example mobility spectrum analysis performed on a GaAs/AlGaAs five-quantum-well heterostructure is shown in Figure 2-9 of their paper.

A technique combining mobility spectrum analysis and multi-carrier fitting was developed by Brugger and Kosser[10], yielding some improvement. The development of quantitative mobility spectrum analysis by Antoszewski et al.[2,11,12,13] has produced even greater improvements in capability.

A.3 SAMPLE GEOMETRIES AND MEASUREMENTS SUPPORTED BY HALL SOFTWARE

This section describes common sample geometries useful in the Lake Shore 7600 Series Hall Measurement System and formulas used to calculate resistivities, Hall coefficients, carrier concentrations, and mobilities.

A.3.1 System of Units

Hall effect and magnetoresistance measurements commonly use two systems of units: the SI system and the so-called "laboratory" system. The laboratory system is a hybrid, combining elements of the SI, emu, and esu unit systems. Table A-1 lists the most common quantities, their symbols, their units in both systems, and the conversion factor between them.

Table A-1. Unit Systems and Conversions

Quantity	*Symbol*	*SI*	*= Factor x*	*Laboratory*
Capacitance	C	farad	1	farad
Carrier concentration	c,n,p	m^{-3}	10^{-6}	cm^{-3}
Charge	q,e	coulomb	1	coulomb
Conductivity (volume)	σ	(ohm m)-1	10-2	$(ohm\ cm)^{-1}$
Current	I	ampere	1	ampere
Current density	j	$ampere/m^2$	10^{-4}	$ampere/cm^2$
Electric field intensity	E	volt/m	10^{-2}	volt/cm
Hall coefficient	R_H	m^3/coulomb	10^6	cm^3/coulomb
Magnetic induction	B	tesla (= V s/m2)	10^4	gauss
Mobility	μ_H	m^2/V s	10^4	cm^2/V s
Electric potential	V	volt	1	volt
Resistivity	ρ	ohm m	10^2	ohm cm

To use this table, 1 SI unit = (factor) × 1 laboratory unit. For example, 1 tesla = 10^4 gauss.

A.3.2 Nomenclature

The equations below appear twice - once in SI units, once in laboratory units. In all cases, voltages are measured in volts, electric currents are measured in amperes, and resistances are measured in ohms. All other measured quantities appear

with their respective unit in brackets. For example, the width of a sample in SI units appears as $w\ m$. The equations below indicate voltages and currents as follows:

Voltage Nomenclature
$V^{\pm}_{ij,kl}(\pm B)$ indicates a voltage difference $V_k - V_l$ measured between terminals *k* and *l*. Terminal *i* is connected to the excitation current source and terminal *j* is connected to the current sink. The superscript ±. Indicates the sign of the excitation current supplied by the current source. ±B indicates the sign of the applied magnetic induction *B*, measured in the direction shown on the drawings. *Example*: $V^{-}_{56,12}(+B)$ indicates a voltage difference $V_1 - V_2$ measured while a negative current was supplied by a current source at terminal 5 and flowed to terminal 6, in the presence of a positive applied magnetic induction.
Current Nomenclature
$I^{\pm}_{ij}(\pm B)$ indicates a current flowing from terminal *i* to terminal *j* of polarity given by the superscript ± and with the indicated magnetic field polarity.

A.3.3 Van der Pauw Measurements

The van der Pauw structure is probably the most popular Hall measurement geometry, primarily because it requires fewer geometrical measurements of the sample. In 1958, van der Pauw[13] solved the general problem of the potential in a thin conducting layer of arbitrary shape. His solution allowed Hall and resistivity measurements to be made on any sample of uniform thickness, provided that the sample was homogeneous and there were no holes in it. All that is needed to calculate *sheet* resistivity or carrier concentration is four point contacts on the edge of the surface (or four line contacts on the periphery); an additional measurement of sample thickness allows calculation of *volume* resistivity and carrier concentration. These relaxed requirements on sample shape simplify fabrication and measurement in comparison to Hall bar techniques.

On the other hand, the van der Pauw structure is more susceptible to errors caused by the finite size of the contacts than the Hall bar. It is also impossible to accurately measure magnetoresistance with the van der Pauw geometry, so both Hall effect and magnetoresistance (i.e. the whole conductivity tensor) measurements must be done with a Hall bar geometry.

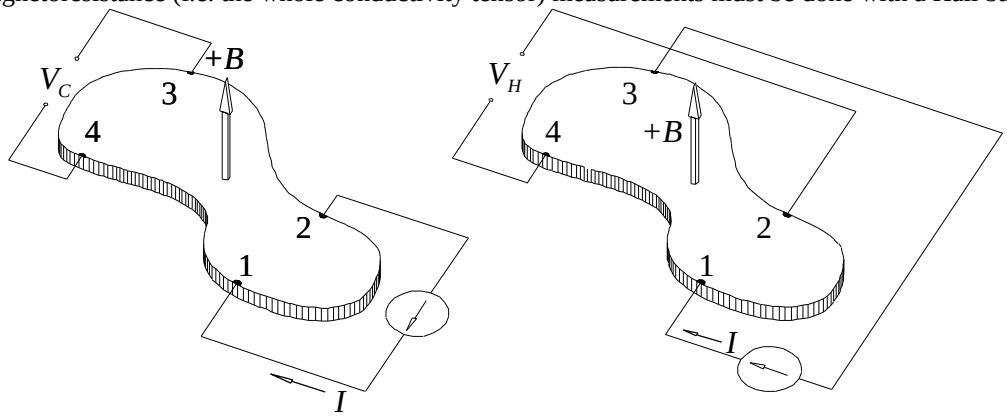


Figure A-3 **Measuring Resistivity and Hall Coefficient Using a van der Pauw Geometry.**
In the basic van der Pauw contact arrangement, the four contacts made to the sample are numbered counter-clockwise in ascending order when the sample is viewed from above with the magnetic field perpendicular to the sample and pointing toward the observer. The sample interior should contain no contacts or holes. The sample must be homogeneous and of uniform thickness.

Resistivity
Again, let V^{+}_{ijkl} indicate a voltage measured across terminals *k* and *l*, with *k* positive, while a positive current flows into terminal *i* and out of terminal *j*. In a similar fashion, let R^{+}_{ijkl} indicate a resistance $R^{+}_{ijkl} = V_{kl} / I_{ij}$, with the voltage measured across terminals *k* and *l*, while a positive current flows into *i* and out of *j*. First calculate the two resistivities:

$$\rho_A = \frac{\pi\, f_A\, t[m,cm]}{\ln(2)} \left\{ \frac{V^+_{12,43} - V^-_{12,43} + V^+_{23,14} - V^-_{23,14}}{I^+_{12} - I^-_{12} + I^+_{23} - I^-_{23}} \right\} \quad [\Omega\cdot\mathrm{m}, \Omega\cdot\mathrm{cm}],$$

and

$$\rho_B = \frac{\pi\, f_B\, t[m,cm]}{\ln(2)} \left\{ \frac{V^+_{34,21} - V^-_{34,21} + V^+_{41,23} - V^-_{41,23}}{I^+_{34} - I^-_{34} + I^+_{41} - I^-_{41}} \right\} \quad [\Omega\cdot\mathrm{m}, \Omega\cdot\mathrm{cm}].$$

Geometrical factors f_A and f_B are functions of resistance ratios Q_A and Q_B, respectively, given by:

$$Q_A = \left(\frac{R^+_{12,43} - R^-_{12,43}}{R^+_{23,14} - R^-_{23,14}} \right) = \left(\frac{V^+_{12,43} - V^-_{12,43}}{I^+_{12} - I^-_{12}} \right) \left(\frac{I^+_{23} - I^-_{23}}{V^+_{23,14} - V^-_{23,14}} \right),$$

and

$$Q_B = \left(\frac{R^+_{34,21} - R^-_{34,21}}{R^+_{41,23} - R^-_{41,23}} \right) = \left(\frac{V^+_{34,21} - V^-_{34,21}}{I^+_{34} - I^-_{34}} \right) \left(\frac{I^+_{41} - I^-_{41}}{V^+_{41,23} - V^-_{41,23}} \right).$$

If either Q_A or Q_B is greater than one, then use the reciprocal instead. The relationship between f and Q is expressed by the transcendental equation

$$\frac{Q-1}{Q+1} = \frac{f}{\ln 2} \cosh^{-1}\left\{ \frac{1}{2} \exp\left[\frac{\ln 2}{f} \right] \right\},$$

which can be solved numerically.

The two resistivities ρ_A and ρ_B should agree to within ±10%. If they do not, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do agree, the average resistivity is given by

$$\rho_{av} = \frac{\rho_A + \rho_B}{2} \quad [\Omega\cdot\mathrm{m}, \Omega\cdot\mathrm{cm}].$$

Magnetoresistivity

If desired, calculate the magnetoresistivity as

$$\rho_A(B) = \frac{\pi\, f_A\, t[m,cm]}{\ln(2)} \left\{ \frac{V^+_{12,43}(+B) - V^-_{12,43}(+B) + V^+_{23,41}(+B) - V^-_{23,41}(+B)}{I^+_{12}(+B) - I^-_{12}(+B) + I^+_{23}(+B) - I^-_{23}(+B)} \cdots \right.$$
$$\left. \frac{+ V^+_{12,43}(-B) - V^-_{12,43}(-B) + V^+_{23,41}(-B) - V^-_{23,41}(-B)}{+ I^+_{12}(-B) - I^-_{12}(-B) + I^+_{23}(-B) - I^-_{23}(-B)} \right\} \quad [\Omega\cdot\mathrm{m}, \Omega\cdot\mathrm{cm}],$$

and

$$\rho_B(B) = \frac{\pi\, f_B\, t[m,cm]}{\ln(2)} \left\{ \frac{V^+_{34,21}(+B) - V^-_{34,21}(+B) + V^+_{41,23}(+B) - V^-_{41,23}(+B)}{I^+_{34}(+B) - I^-_{34}(+B) + I^+_{41}(+B) - I^-_{41}(+B)} \cdots \right.$$
$$\left. \frac{+ V^+_{34,21}(-B) - V^-_{34,21}(-B) + V^+_{41,23}(-B) - V^-_{41,23}(-B)}{+ I^+_{34}(-B) - I^-_{34}(-B) + I^+_{41}(-B) - I^-_{41}(-B)} \right\} \quad [\Omega\cdot\mathrm{m}, \Omega\cdot\mathrm{cm}].$$

Calculate factors f_A and f_B the same way as at zero magnetic field, and the average magnetoresistivity is:

$$\rho_{av}(B) = \frac{\rho_A(B) + \rho_B(B)}{2} \quad [\Omega\cdot\mathrm{m}], [\Omega\cdot\mathrm{cm}].$$

This measurement does not give the true magnetoresistance, as defined in terms of the material's conductivity tensor. Van der Pauw's calculation of resistivity is invalid in the presence of a magnetic field, since the magnetic field alters the

current density vector field inside the sample. On the other hand, magnetoresistance measurements are routinely performed on van der Pauw samples anyway.

Hall Coefficient

Calculate two values of the Hall coefficient by the following:

$$R_{HC} = \frac{t[\mathrm{m}]}{B[\mathrm{T}]} \frac{V^{+}_{31,42}(+B) - V^{-}_{31,42}(+B) + V^{-}_{31,42}(-B) - V^{+}_{31,42}(-B)}{I^{+}_{31}(+B) - I^{-}_{31}(+B) + I^{-}_{31}(-B) - I^{+}_{31}(-B)} \quad \left[\mathrm{m}^3 \cdot C^{-1}\right]$$

$$= 10^8 \frac{t[\mathrm{cm}]}{B[\mathrm{gauss}]} \frac{V^{+}_{31,42}(+B) - V^{-}_{31,42}(+B) + V^{-}_{31,42}(-B) - V^{+}_{31,42}(-B)}{I^{+}_{31}(+B) - I^{-}_{31}(+B) + I^{-}_{31}(-B) - I^{+}_{31}(-B)} \quad \left[\mathrm{cm}^3 \cdot C^{-1}\right],$$

and

$$R_{HD} = \frac{t[\mathrm{m}]}{B[\mathrm{T}]} \frac{V^{+}_{42,13}(+B) - V^{-}_{42,13}(+B) + V^{-}_{42,13}(-B) - V^{+}_{42,13}(-B)}{I^{+}_{42}(+B) - I^{-}_{42}(+B) + I^{-}_{42}(-B) - I^{+}_{42}(-B)} \quad \left[\mathrm{m}^3 \cdot \mathrm{C}^{-1}\right]$$

$$= 10^8 \frac{t[\mathrm{cm}]}{B[\mathrm{gauss}]} \frac{V^{+}_{42,13}(+B) - V^{-}_{42,13}(+B) + V^{-}_{42,13}(-B) - V^{+}_{42,13}(-B)}{I^{+}_{42}(+B) - I^{-}_{42}(+B) + I^{-}_{42}(-B) - I^{+}_{42}(-B)} \quad \left[\mathrm{cm}^3 \cdot \mathrm{C}^{-1}\right].$$

These two should agree to within ±10%. If they do not, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do, then the average Hall coefficient can be calculated by

$$R_{Hav} = \frac{R_{HC} + R_{HD}}{2} \quad \left[\mathrm{m}^3 \cdot \mathrm{C}^{-1}, \mathrm{cm}^3 \cdot \mathrm{C}^{-1}\right]$$

Hall Mobility

The Hall mobility is given by

$$\mu_H = \frac{|R_{Hav}|}{\rho_{av}} \quad \left[\mathrm{m}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}, \mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}\right],$$

where ρ_{av} is the magnetoresistivity if it was measured, and the zero-field resistivity if it was not.

A.3.4 Hall Bar Measurements

Hall bars approximate the ideal geometry for measuring the Hall effect, in which a constant current density flows along the long axis of a rectangular solid, perpendicular to an applied external magnetic field.

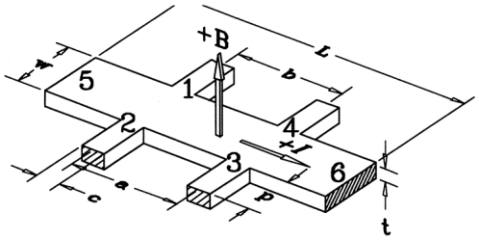


Figure A-4 Six-Contact 1-2-2-1 Hall Bar Geometry

A.3.4.1 Six-Contact 1-2-2-1 Hall Bar

An ideal six-contact 1-2-2-1 Hall bar geometry is symmetrical. Contact separations *a* and *b* on either side of the sample are equal, with contacts located opposite one another. Contact pairs are placed symmetrically about the midpoint of the long axis of the sample.

This geometry allows two equivalent measurement sets to check for sample homogeneity in both resistivity and Hall coefficient. However, the close location of the Hall voltage contacts to the sample ends may cause the end contacts to short out the Hall voltage, leading to an underestimate of the actual Hall coefficient. While the 1-2-2-1 Hall bar geometry is included in ASTM Standard F76, the contact numbering given here differs from the standard.

Resistivity

To calculate resistivity at zero field, first calculate

$$\rho_A = \frac{V^+_{56,23}(B=0) - V^-_{56,23}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{a[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^+_{56,23}(B=0) - V^-_{56,23}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{a[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}],$$

and

$$\rho_B = \frac{V^+_{56,14}(B=0) - V^-_{56,14}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{b[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^+_{56,14}(B=0) - V^-_{56,14}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{b[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}].$$

These two resistivities should agree to within ±10%. If they do not, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do, then the average resistivity is given by

$$\rho_{av} = \frac{\rho_A + \rho_B}{2} \quad [\Omega \cdot \mathrm{m}, \Omega \cdot \mathrm{cm}] .$$

Magnetoresistivity

Magnetoresistivity is typically used in mobility spectrum calculations, but not in Hall mobility calculations. To calculate magnetoresistivity, first calculate

$$\rho_A(B) = \frac{V^+_{56,23}(+B) - V^-_{56,23}(+B) + V^+_{56,23}(-B) - V^-_{56,23}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{a[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^+_{56,23}(+B) - V^-_{56,23}(+B) + V^+_{56,23}(-B) - V^-_{56,23}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{a[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}],$$

and

$$\rho_B(B) = \frac{V^+_{56,14}(+B) - V^-_{56,14}(+B) + V^+_{56,14}(-B) - V^-_{56,14}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{b[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^+_{56,14}(+B) - V^-_{56,14}(+B) + V^+_{56,14}(-B) - V^-_{56,14}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{b[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}].$$

These two resistivities should agree to within ±10%. If they do not, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do, then the average magnetoresistivity is given by

$$\rho_{av}(B) = \frac{\rho_A(B) + \rho_B(B)}{2} \quad [\Omega \cdot \mathrm{m}, \Omega \cdot \mathrm{cm}].$$

Hall Coefficient

First, calculate the individual Hall coefficients

$$R_{HA} = \frac{t[\mathrm{m}]}{B[\mathrm{T}]} \frac{V^+_{56,34}(+B) - V^-_{56,34}(+B) + V^-_{56,34}(-B) - V^+_{56,34}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)} \quad [\mathrm{m}^3 \cdot C^{-1}]$$

$$= 10^8 \frac{t[\mathrm{cm}]}{B[\mathrm{gauss}]} \frac{V^+_{56,34}(+B) - V^-_{56,34}(+B) + V^-_{56,34}(-B) - V^+_{56,34}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)} \quad [\mathrm{cm}^3 \cdot C^{-1}],$$

and

$$R_{HA} = \frac{t[\mathrm{m}]}{B[\mathrm{T}]} \frac{V^+_{56,21}(+B) - V^-_{56,21}(+B) + V^-_{56,21}(-B) - V^+_{56,21}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)} \quad [\mathrm{m}^3 \cdot \mathrm{C}^{-1}]$$

$$= 10^8 \frac{t[\mathrm{cm}]}{B[\mathrm{gauss}]} \frac{V^+_{56,21}(+B) - V^-_{56,21}(+B) + V^-_{56,21}(-B) - V^+_{56,21}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)} \quad [\mathrm{cm}^3 \cdot \mathrm{C}^{-1}].$$

If R_{HA} and R_{HB} do not agree to within ±10%, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do agree, then the average Hall Coefficient is given by

$$R_{Hav} = \frac{R_{HA} + R_{HB}}{2} \quad [\mathrm{m}^3 \cdot \mathrm{C}^{-1}, \mathrm{cm}^3 \cdot \mathrm{C}^{-1}].$$

Hall Mobility

$\mu_H = \frac{|R_{Hav}|}{\rho_{av}}$ $[\mathrm{m}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}, \mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}]$ gives the Hall mobility where ρ_{av} is the zero-field resistivity.

A.3.4.2 Six-contact 1-3-1-1 Hall Bar

The ideal 1-3-1-1 Hall bar geometry places contacts 2 and 4 directly across from one another in the exact middle of the sample's length and contacts 1 and 3 symmetrically on either side of contact 2.
This geometry allows no homogeneity checks, but measuring the Hall voltage in the exact center of the sample's length helps minimize the shorting of the Hall voltage via the end contacts. The 1-3-1-1 Hall bar is not included in ASTM Standard F76.

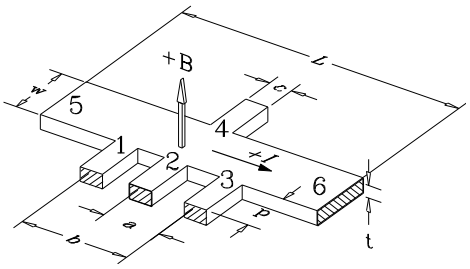


Figure A-5 **Six-Contact** 1-3-1-1 Hall Bar Geometry

Resistivity

Calculate the resistivity at zero field by

$$\rho = \frac{V^+_{56,13}(B=0) - V^-_{56,13}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{b[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^+_{56,13}(B=0) - V^-_{56,13}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{b[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}].$$

Magnetoresistivity

If desired, calculate the magnetoresistivity by

$$\rho(B) = \frac{V^{+}_{56,13}(+B) - V^{-}_{56,13}(+B) + V^{+}_{56,13}(-B) - V^{-}_{56,13}(-B)}{I^{+}_{56}(+B) - I^{-}_{56}(+B) + I^{+}_{56}(-B) - I^{-}_{56}(-B)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{b[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^{+}_{56,13}(+B) - V^{-}_{56,13}(+B) + V^{+}_{56,13}(-B) - V^{-}_{56,13}(-B)}{I^{+}_{56}(+B) - I^{-}_{56}(+B) + I^{+}_{56}(-B) - I^{-}_{56}(-B)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{b[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}].$$

Hall Coefficient
Calculate the Hall coefficient by

$$R_H = \frac{t[\mathrm{m}]}{B[\mathrm{T}]} \frac{V^{+}_{56,24}(+B) - V^{-}_{56,24}(+B) + V^{-}_{56,24}(-B) - V^{+}_{56,24}(-B)}{I^{+}_{56}(+B) - I^{-}_{56}(+B) + I^{-}_{56}(-B) - I^{+}_{56}(-B)} \quad [\mathrm{m}^3 \cdot \mathrm{C}^{-1}]$$

$$= 10^8 \frac{t[\mathrm{cm}]}{B[\mathrm{gauss}]} \frac{V^{+}_{56,24}(+B) - V^{-}_{56,24}(+B) + V^{-}_{56,24}(-B) - V^{+}_{56,24}(-B)}{I^{+}_{56}(+B) - I^{-}_{56}(+B) + I^{-}_{56}(-B) - I^{+}_{56}(-B)} \quad [\mathrm{cm}^3 \cdot \mathrm{C}^{-1}].$$

Hall Mobility

The Hall mobility is given by $\mu_H = \frac{|R_H|}{\rho} \quad [\mathrm{m}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}, \mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}]$,

where ρ is the magnetoresistivity if it was measured, and the zero-field resistivity if it was not.

A.3.4.3 Eight-contact 1-3-3-1 Hall Bar

The eight contact 1-3-3-1 Hall bar geometry is ideally the most symmetrical of the Hall bars. Two sets of three equally-spaced contacts lie directly opposite one another on either side of the sample with center contacts (numbers 2 and 4) located at the exact center of the sample's length. Voltage measurement connections are made to contacts 1 through 4, while current flows from contact 5 to contact 6. Only six of the eight contacts are used in this measuring procedure. The remaining two (unnumbered) contacts are included to keep the sample completely symmetrical.

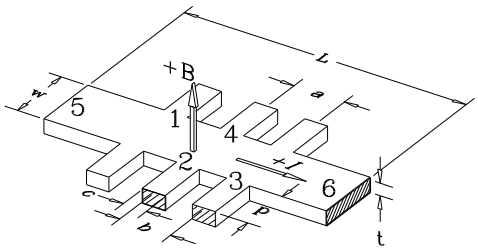


Figure A-6 **Eight-Contact** 1-3-3-1 Hall Bar Geometry

The eight-contact Hall bar attempts to combine the homogeneity checks possible with the 1-2-2-1 six-contact geometry and the benefit of measuring the Hall voltage in the center of the sample. It allows two resistivity measurements compare for homogeneity, but only one Hall voltage measurement. Either the 1-2-2-1 or 1-3-1-1 six-contact measurements can be made using an eight-contact Hall bar, simply by moving the electrical connections to the appropriate points. The eight-contact Hall bar geometry is included in ASTM Standard F76, but the contact numbering given here differs from the standard.

Resistivity
First calculate the two resistivities

$$\rho_A = \frac{V^{+}_{56,23}(B=0) - V^{-}_{56,23}(B=0)}{I^{+}_{56}(B=0) - I^{-}_{56}(B=0)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{b[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^{+}_{56,23}(B=0) - V^{-}_{56,23}(B=0)}{I^{+}_{56}(B=0) - I^{-}_{56}(B=0)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{b[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}],$$

and

$$\rho_B = \frac{V^+_{56,14}(B=0) - V^-_{56,14}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{b[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^+_{56,14}(B=0) - V^-_{56,14}(B=0)}{I^+_{56}(B=0) - I^-_{56}(B=0)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{b[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}]$$

at zero magnetic field.
If these two values disagree by more than ±10%, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do agree, then the average resistivity is given by

$$\rho_{av} = \frac{\rho_A + \rho_B}{2} \quad [\Omega \cdot \mathrm{m}], [\Omega \cdot \mathrm{cm}] \,.$$

Magnetoresistivity
If desired, calculate the two magnetoresistivities

$$\rho_A = \frac{V^+_{56,23}(+B) - V^-_{56,23}(+B) + V^+_{56,23}(-B) - V^-_{56,23}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{b[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^+_{56,23}(+B) - V^-_{56,23}(+B) + V^+_{56,23}(-B) - V^-_{56,23}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{b[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}],$$

and

$$\rho_B = \frac{V^+_{56,14}(+B) - V^-_{56,14}(+B) + V^+_{56,14}(-B) - V^-_{56,14}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[\mathrm{m}]\, t[\mathrm{m}]}{b[\mathrm{m}]} \quad [\Omega \cdot \mathrm{m}]$$

$$= \frac{V^+_{56,14}(+B) - V^-_{56,14}(+B) + V^+_{56,14}(-B) - V^-_{56,14}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^+_{56}(-B) - I^-_{56}(-B)} \frac{w[\mathrm{cm}]\, t[\mathrm{cm}]}{b[\mathrm{cm}]} \quad [\Omega \cdot \mathrm{cm}].$$

If these two values disagree by more than ±10%, then the sample is too inhomogeneous, or anisotropic, or has some other problem. If they do agree, then the average magnetoresistivity is given by

$$\rho_{av}(B) = \frac{\rho_A(B) + \rho_B(B)}{2} \quad [\Omega \cdot \mathrm{m}, \Omega \cdot \mathrm{cm}].$$

Hall Coefficient
Calculate the Hall coefficient by

$$R_H = \frac{t[\mathrm{m}]}{B[\mathrm{T}]} \frac{V^+_{56,24}(+B) - V^-_{56,24}(+B) + V^-_{56,24}(-B) - V^+_{56,24}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)} \quad [\mathrm{m}^3 \cdot \mathrm{C}^{-1}]$$

$$= 10^8 \frac{t[\mathrm{cm}]}{B[\mathrm{gauss}]} \frac{V^+_{56,24}(+B) - V^-_{56,24}(+B) + V^-_{56,24}(-B) - V^+_{56,24}(-B)}{I^+_{56}(+B) - I^-_{56}(+B) + I^-_{56}(-B) - I^+_{56}(-B)} \quad [\mathrm{cm}^3 \cdot \mathrm{C}^{-1}].$$

Hall Mobility
The Hall mobility is given by

$$\mu_H = \frac{|R_{Hav}|}{\rho_{av}} \quad [\mathrm{m}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}, \mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}],$$

where ρ_{av} is the magnetoresistivity if it was measured, and the zero-field resistivity if it was not.

A.4 COMPARISON TO ASTM STANDARD

The contact numbering and voltage measurement indexing given above differ in several ways from that given in the ASTM Standard F76[15].

To begin, the ASTM contact numbering schemes for the van der Pauw and Hall Bar geometries are incompatible with one another. To allow either sample type to be mounted using the same set of contacts, the Lake Shore numbering scheme for Hall bar samples differs from the ASTM scheme.

Second, the ASTM standard is inconsistent with the "handedness" of the van der Pauw contact numbering order with respect to the applied magnetic field. Lake Shore numbered the contacts counter-clockwise in ascending order when the sample is viewed from above with the magnetic field perpendicular to the sample and pointing toward the observer, as shown in Figure A-3 **Measuring Resistivity and Hall Coefficient Using a van der Pauw Geometry.**

Finally, the ASTM assumes that the direction of the excitation current is to be changed by physically reversing the current connections. This technique is not well suited to high-resistance samples using a programmable current source like the Keithley Model 220. This current source (and others like it) has a guarded "high" current output, and an unguarded "low" current return. For proper current source operation, the "high" output lead should be farther from common ground than the "low" return lead, a condition violated half of the time when physically reversing the high and low current leads to the sample. When this condition is violated, leakage current can flow through the voltmeter, leading to possibly serious measurement errors.

To avoid this difficulty, Lake Shore reversed the sign of the programmed current source, while leaving the contacts alone. This requires a more sophisticated notation for voltage measurements:

$$V^{\pm}_{ij,kl}\left(\pm B\right)$$

In this notation, terminal i refers to the contact to which the current source output attaches, terminal j is the current return contact, terminal k is the positive voltmeter terminal, and terminal l is the negative voltmeter terminal. The superscript ± refers to the sign of the programmed current, while $\pm B$ refers to the sign of the applied magnetic field relative to the positive direction indicated in the figures.

A.5 SOURCES OF MEASUREMENT ERROR

David C. Look gives a good treatment of systematic error sources in Hall effect measurements in the first chapter of his book.[2] There are two kinds of error sources: intrinsic and geometrical.

A.5.1 Intrinsic Error Sources

The apparent Hall voltage, V_{Ha}, measured with a single reading can include several spurious voltages. These spurious error sources include the following:

1. **Voltmeter offset (V_o):** An improperly zeroed voltmeter adds a voltage V_o to every measurement. The offset does not change with sample current or magnetic field direction.
2. **Current meter offset (I_o):** An improperly zeroed current meter adds a current I_o to every measurement. The offset does not change with sample current or magnetic field direction.
3. **Thermoelectric voltages (V_S):** A temperature gradient across the sample allows two contacts to function as a pair of thermocouple junctions. The resulting thermoelectric voltage due to the Seebeck effect is designated V_s. Portions of wiring to the sensor can also produce thermoelectric voltages in response to temperature gradients. These thermoelectric voltages are not affected by current or magnetic field, to first order.
4. **Ettingshausen effect voltage (V_E):** Even if no external transverse temperature gradient exists, the sample can set up its own. The e**v**×**B** force shunts slow (cool) and fast (hot) electrons to the sides in different numbers and causes an internally generated Seebeck effect. This phenomenon is known as the Ettingshausen effect. Unlike the Seebeck effect, V_E is proportional to both current and magnetic field.
5. **Nernst effect voltage (V_N):** If a longitudinal temperature gradient exists across the sample, then electrons tend to diffuse from the hot end of the sample to the cold end and this diffusion current is affected by a magnetic field, producing a Hall voltage. The phenomenon is known as the Nernst or Nernst-Ettingshausen effect. The resulting voltage is designated V_N and is proportional to magnetic field, but not to external current. This is the one intrinsic error source which can not be eliminated from a Hall voltage measurement by field or current reversal.
6. **Righi-Leduc voltage (V_R):** The Nernst (diffusion) electrons also experience an Ettingshausen-type effect since their spread of velocities result in hot and cold sides and thus again set up a transverse Seebeck voltage, known as the Righi-Leduc voltage, V_R. The Righi-Leduc voltage is also proportional to magnetic field, but not to external current.

7. **Misalignment voltage (V_M):** The excitation current flowing through the sample produces a voltage gradient parallel to the current flow. Even in zero magnetic field, a voltage appears between the two contacts used to measure the Hall voltage if they are not electrically opposite each other. Voltage contacts are difficult to align exactly. The misalignment voltage is frequently the largest spurious contribution to the apparent Hall voltage.

   The apparent Hall voltage, V_{Ha}, measured with a single reading contains all of the above spurious voltages: $V_{Ha} = V_H + V_o + V_S + V_E + V_N + V_R + V_M$.

   All but the Hall and Ettingshausen voltages can be eliminated by combining measurements, as shown in Table A-2. Measurements taken at a single magnetic field polarity still have the misalignment voltage, frequently the most significant unwanted contribution to the measurement signal. Comparing values of Rh(+B) and Rh(-B) reveals the significance of the misalignment voltage relative to the signal voltage.

   A Hall measurement is fundamentally a voltage divided by a current, so excitation current errors are equally as important. Current offsets, I_o, are canceled by combining the current measurements, then dividing the combined Hall voltage by the combined excitation current.

Table A-2. Hall effect measurement voltages showing the elimination of all but the Hall and Ettingshausen voltages by combining readings with different current and magnetic field polarities.

	I	B	V_H	V_M	V_S	V_E	V_N	V_R	V_O
V_1	+	+	+	+	+	+	+	+	+
V_2	–	+	–	–	+	–	+	+	+
$(V_1 – V_2)$			$2V_H$	$-2V_M$	0	$2V_E$	0	0	0
V_3	+	–	–	+	+	–	–	–	+
V_4	–	–	+	–	+	+	–	–	+
$(– V_3 + V_4)$			$2V_H$	$- 2V_M$	0	$2V_E$	0	0	0
$(V_1 – V_2 – V_3 + V_4)$			$4V_H$	0	0	$4V_E$	0	0	0

A.5.2 Geometrical Errors in Hall Bar Samples

Geometrical error sources in the Hall bar arrangement are caused by deviations of the actual measurement geometry from the ideal of a rectangular solid with constant current density and point-like voltage contacts.

The first geometrical consideration with the Hall bar is the tendency of the end contacts to short out the Hall voltage. If the aspect ratio of sample length to width $l / w = 3$, then this error is less than 1%.[15] Therefore, it's important $l / w \geq 3$.

The finite size of the contacts affects both the current density and electric potential in their vicinity, and may lead to fairly large errors. The errors are larger for a simple rectangular Hall bar than for one in which the contacts are placed at the end of arms.

For a simple rectangle, the error in the Hall mobility can be approximated (when μB << 1) by[16]

$$\frac{\Delta\mu_H}{\mu_H} = 1 - (1 - e^{-\pi l/2w})(1 - 2c/\pi w).$$

Here, $\Delta\mu_H$ is the amount μ_H must *increase* to obtain a true value.

If *l*/*w* = 3, and *c*/*w* = 0.2, then $\Delta\mu_H / \mu_H = 0.13$, which is certainly a significant error.

Reduce the contact-size error to acceptable levels by placing contacts at the ends of contact arms.[17] The following aspect ratios yield small deviations from the ideal: $p \approx c, c \leq w/3, l \geq 4w$.

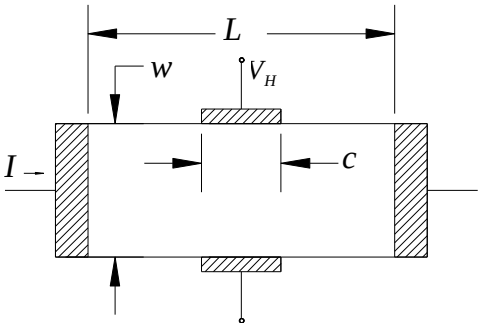


Figure A-7 Hall Bar
With Finite Voltage Contacts

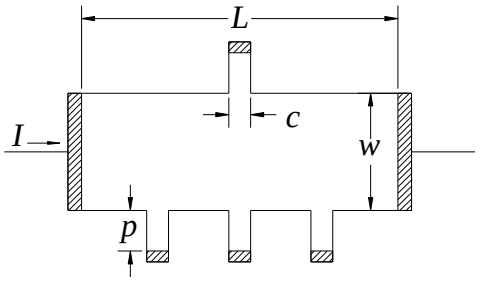


Figure A-8 Hall Bar With Contact Arms

A.5.3 Geometrical Errors in van der Pauw Structures

Van der Pauw's analysis of resistivity and Hall effect in arbitrary structures assumes point-like electrical connections to the sample. In practice, this ideal can be difficult or impossible to achieve, especially for small samples. The finite-contact size corrections depend on the particular sample geometry, and, for Hall voltages, the Hall angle θ (defined by $\tan\theta \cong \mu B$, where μ is the mobility). Look[2] presents the results of both theoretical and experimental determinations of the correction factors for some of the most common geometries. We summarize these results here, and compare the correction factors for a 1:6 aspect ratio of contact size to sample size.

A.5.3.1 Square Structures

The resistivity correction factor $\Delta\rho/\rho$ for a square van der Pauw structure is roughly proportional to$(c / l)^2$ for both square and triangular contacts. At $(c / l) = 1/6$, $\Delta\rho/\rho = 2\%$ for identical square contacts, and $\Delta\rho/\rho < 1\%$ for identical triangular contacts[18]. Hall voltage measurement error is much worse, unfortunately. The correction factor $\Delta R_H / R_H$ is proportional to (c / l), and is about 15% for triangular contacts when $(c / l) = 1/6$. The correction factor also increases by about 3% at this aspect ratio as the Hall angle increases from $\tan\theta = 0.1$ to $\tan\theta = 0.5$.

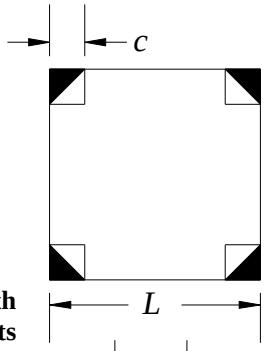


Figure A-9 **Square van der Pauw Structure with Either Square or Triangular Contacts**

A.5.3.2 Circular Structures

Circular van der Pauw structures fare slightly better. van der Pauw[14] gives a correction factor for circular contacts of

$$\frac{\Delta\rho}{\rho} \cong -\frac{1}{16\ln 2}\left(\frac{c}{l}\right)^2 \qquad \text{(per contact)},$$

which results in a correction of $\Delta\rho/\rho = -1\%$ for $(c / l) = 1/6$ for four contacts. For the Hall coefficient, van der Pauw gives the correction

$$\frac{\Delta R_H}{R_H} \cong \frac{2}{\pi^2}\frac{c}{l} \qquad \text{(per contact)}.$$

At $(c / l) = 1/6$, this results in a correction of 13% for four contacts.
van Daal[19] reduced these errors considerably (by a factor of 10 to 20 for resistivity, and 3 to 5 for Hall coefficient) by cutting slots to turn the sample into a cloverleaf.
The clover leaf structure is mechanically weaker than the square and round samples unless it is patterned as a thin film on a thicker substrate. Another disadvantage is that the "active" area of the cloverleaf is much smaller than the actual sample.

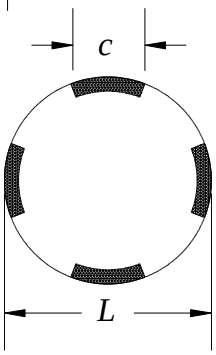


Figure A-10 **Circular** van der Pauw Structure

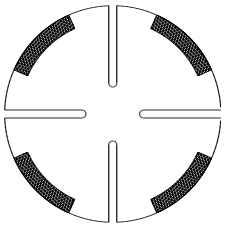


Figure A-11 **Cloverleaf** van der Pauw Structure

A.4.3.3 Greek Cross Structures

The Greek cross is one of the best van der Pauw geometries to minimize finite contact errors. Its advantage over simpler van der Pauw structures is similar to placing Hall bar contacts at the ends of arms. David and Beuhler[20] analyzed this structure numerically. They found that the deviation of the actual resistivity ρ from the measured value ρ_m obeyed

$$E = 1 - \frac{\rho}{\rho_m} = (0.59 \pm 0.006) \exp\left[-(6.23 \pm 0.02) \frac{a}{c} \right].$$

This is a very small error: for $c/(c + 2a) = 1/6$, where $c + 2a$ corresponds to the total dimension of the contact arm, $E \cong 10^{-7}$.

Hall coefficient results are substantially better. De Mey[21,22] has shown that

$$\frac{\mu_H - \mu_{Hm}}{\mu_H} = \frac{\Delta\mu_H}{\mu_H} \cong 1.045 e^{-\pi a/c} \quad \text{(four contacts)},$$

where μ_H and μ_{Hm} are the actual and measured Hall mobilities, respectively. For $c / (c + 2a) = 1/6$, this results in $\Delta\mu_H / \mu_H \cong 0.04\%$, which is quite respectable.

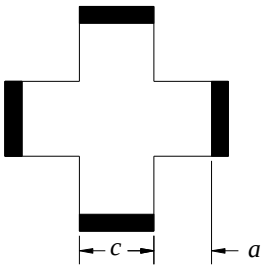


Figure A-12. Greek Cross van der Pauw Structure

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APPENDIX B

ELECTRICAL CONTACTS TO SEMICONDUCTORS

B.1 GENERAL

All direct measurements of the electronic transport properties of a material require adequate electrical contacts between the sample and the measuring instrument. Adequacy depends on the particular measurement performed. Generally, low resistance "ohmic" contacts are desired.

The word "ohmic" ideally means "obeying Ohm's Law", a condition that is technically impossible to achieve in a metal-semiconductor interface1. "Ohmic" usually means a contact with a small resistance compared to the resistance of the sample being studied, and therefore insignificant non-linear current-voltage characteristics.

Several parameters describe electrical contacts to semiconductors. The quantity of greatest interest is the contact resistivity or specific contact resistance, denoted by ρ_c and usually measured in Ω cm^2. Contact resistivity is the product of the contact resistance R_c and the area A of the contact. Other common contact parameters include the barrier height Φ_B, measured in eV, and the semiconductor doping concentration, measured in cm^{-3}.

Three primary mechanisms govern current transport across a metal-to-semiconductor interface: Thermionic emission, field emission, and thermionic-field emission2. They differ mainly by the interface potential barrier height and width as determined by the work function of the metal, the semiconductor electron affinity, and the semiconductor doping concentration near the interface.

Thermionic emission is important when both the barrier and doping concentration are low. In thermionic emission, electrons thermally excited to energies above the barrier, pass directly over it. As a result, contact resistance where thermionic emission dominates depends strongly on temperature.

Field emission is important when both the barrier and doping concentration are high. A high doping concentration reduces the width of the carrier depletion region near the semiconductor's surface. This in turn produces a thin barrier that electrons tunnel through directly. A field emission is only weakly dependent on temperature.

Thermionic-field emission is important when both barrier and doping concentration are moderate. In thermionic-field emission, electrons are thermally excited part way up the potential barrier, at which point they tunnel the rest of the way through. Thermionic-field emission is moderately temperature-dependent. Typically, some sort of thermionic-field emission is the most likely transport mechanism.

There are several methods of contact deposition: applying metal-bearing paints and pastes, melting metals directly on the semiconductor surface, evaporation, sputtering, molecular beam epitaxy, ion-implantation, and others. Once deposited on the semiconductor, the contact may be thermally annealed by conventional oven, laser or electron beam, or rapid thermal annealing/processing (RTA or RTP), in which halogen lamps rapidly heat the semiconductor to the annealing temperature, and hold it there for a short time (typically 10 to 30 seconds).

This appendix discusses methods of making electrical contacts to a variety of semiconductor materials. In most cases, it indicates contact materials, method of deposition and annealing, contact resistivity and doping concentration, and references to original publications.

B.2 SILICON

Much effort has been made to produce reliable, small, low-resistance contacts to silicon for VLSI electronics. Gildenblat and Cohen[3] give an excellent review of the art and include the following reference table for silicon contacts. Cooke gives an additional review of LPCVD metallization techniques.

Table B-1. Making Electrical Contacts to Silicon

Contact resistivities are minimum values reported in the references. Usually, these were obtained with the highest dopant concentration employed. Conventional sintering typically involves a furnace anneal at 400–450 °C for 30–60 minutes. All surfaces are assumed to be ⟨100⟩ unless indicated otherwise.[3]

Metallization	Semicon-ductor Type	Sintering Conditions	$\rho_c(\Omega \cdot \mu m^2)$	Comments	Reference
Aluminum	p^+	Conventional	3700	⟨111⟩ Si	4
	p^+	Conventional	26	⟨111⟩ Si	5
	n^-	Conventional	410000	⟨111⟩ Si	4
	n^+	Conventional	100	⟨111⟩ Si , High Doping	6
	n^+	Conventional	<120	⟨111⟩ Si	7
	n^+	Conventional	100	⟨111⟩ Si	8
	n^+	Conventional	400	---	9
	n^+	Conventional	<60	---	10
	n^+	E-beam	310	---	11
	n^+	Laser,e-beam	104-1000	---	12,13,14
	n^+	Conventional	100	Polysilicon	15
	p^+	Conventional	300	⟨111⟩ Si	7
	p^+	Conventional	<100	Ion Beam Deposition	16
	p^+	Halogen Lamp	15	---	17
	p^+	E-beam	110	---	11
	p^+	Conventional	20	Polysilicon	15
Al-Si Alloys	p^+	Conventional	15	0.9% Si in alloy	18
	n^+	Conventional	90	---	18
	n^+	Conventional	70	1-2% Si	10,19
	n^+	Conventional	<200	1% Si	19
	p^+	Conventional	<500	---	10,19
PtSi	n^+	Conventional	5000	Al Overlayer	20
	n^+	Conventional	20	Al Overlayer	21
	n^+	Conventional	4	Al Overlayer	22
	n^+	Conventional	5	Mo Overlayer	23
	n^+	CW Laser	<100	Ti Overlayer	24
	p^+	Conventional	10000	Al Overlayer	20
	p^+	Conventional	7	Al Overlayer	22
	p^+	Conventional	10	Patterning by Liftoff	25
	p^+	Conventional	7	Mo Overlayer	5

Table B-1. Making Electrical Contacts to Silicon (Continued)

Metallization	Semicon-ductor Type	Sintering Conditions	$\rho_c(\Omega \cdot \mu m^2)$	Comments	References
Pd_2Si	n^-	Conventional	400	---	26
	n^-, p^+	Conventional	63,68	Both $\langle 111 \rangle$ and $\langle 100 \rangle$	5
$MoSi_2$	n^-	Laser	100	---	27
$CoSi_2$	n^-	Laser	<50	---	28
	p^+	Laser	700	---	29
$TiSi_2$	n^-	Laser	100	---	30
	n^-	Laser	<150	---	31
	n^-	Laser	15	---	32
	p^+	Laser	<40	---	31
	p^+	Laser	100	---	32
$TiSi_{1.86}$	p^+	Laser	<50	---	31
	n^-	Laser	<30	---	31
Tungsten	n^-	Laser	20	Selective Deposition	33
	p^+	Laser	25	Selective Deposition	33
WTi	p^+	Laser	20	Al overlayer	34
	n^-	Laser	7	Al overlayer	34
	n^-	E-beam	17	---	11
	p^+	E-beam	13	---	11
Molybdenum	p^+	Conventional	440	---	4
	p^+	Conventional	600	---	35
	p^+	Conventional	5	Sintered at 650 °C	36
	n^-	Conventional	8000	---	4
	n^-	Conventional	800	---	35
	n^-	Conventional	<100	---	37
	n^-	Conventional	2	Sintered at 650 °C	36
Mo_xNi_{1-x}	n^-	Conventional	<350	---	38
	p^+	Conventional	<150	---	38
$Fe_{45}W_{36}$	p^+	Conventional	110	---	39
	n^-	Conventional	10	---	39
Nickel	n^-, p^+	Conventional	200	---	35
Vanadium	p^+	Conventional	520	---	4
	n^-	Conventional	7300	---	4
Cobalt	n^-	Conventional	14000	---	4
	p	Conventional	780	---	4
Chromium	p	Conventional	400	---	35
	n^-	Conventional	300	---	35
TiN,HfN	p	Conventional	<10	Solar cell type Si	40

B.3 GALLIUM ARSENIDE AND OTHER III-V COMPOUNDS

Electrical contact to gallium arsenide has grown due to the popularity of GaAs in the electronic industry, particularly for electro-optical and high-speed digital applications which exploit other III-V compounds as well. In his book, David Look reviews a variety of techniques to contact GaAs and closely related compounds4[1]. A more recent article by T. C. Shen, G. B. Gao, and H. Morkoç[2] discusses the emerging role of rapid thermal annealing/processing in contacting GaAs, and electrical contacts to several other III-V compounds.

Table B-2. Electrical Contacts to III-V Compound Semiconductors

Semicon-ductor	Carrier Conc. (10^{18} cm^{-3})	Metallization	Preparation	ρ_c (10^{-6} $\Omega \cdot cm^2$)	Ref.
n-GaAs	2.2	Au/Pd/Ge	evap. surf. heater, 450 °C, 30 s	0.5	42
	2.2	Au/Ge/Ni	evap. surf. heater, 450 °C, 30 s	0.4	42
	5	Ni/AuGe	evap., laser, 40 ns	56	43
	5	Ni/AgGe	evap., laser, 40 ns	95	43
	1	Au/Ni/AuGe	evap. surf. heater, 320 °C, 60 s	15	44
	10	Ni/Au/Ge	evap. no alloying	0.2	45
	1.8	AuGe/Ni	evap., laser, 20 ns	1.5	46
	2	Au/Pd	electroless dep., furnace, 350°C, 2 min	8	47
	100	Au/Cr	evap. no alloying	2.5	48
	0.5	WSi_x	evap. RTA, 800°C, few s	1	49
	0.3	In	evap. surf. heater, 350°C, 15 s	12	50
	0.15	In/Pt	evap. surf. heater, 400°C	2	51
	2	Au/In	electroless dep., furnace, 350°C, 2 min	15	47
	low 10^{18}	Ge/Pd, Pd/Ge	furnace, 325-375°C, up to 30 min, or RTP	~1	42,52
	low 10^{18}	Si/Pd	RTP	~1	53,54
	1	MoGeW	RTP	0.3 Ω mm1	55
	4	MoGeW	RTP	0.4	56
	3.5×10^{13} cm^{-2}2	MoGeInW	RTP	0.5 Ω mm	57
	3.5×10^{13} cm^{-2}	GeInW	RTP	0.5 Ω mm	58
	3.5×10^{13} cm^{-2}	NiInW	RTP	0.3 Ω mm	58
	6.6×10^{13} cm^{-2}	NiInW(Si)	RTP	0.1 Ω mm	59
	6.6×10^{13} cm^{-2}	NiInW(Ge)	RTP	0.3 Ω mm	59
	3.5×10^{13} cm^{-2}	NiInW	RTP	---	60
	0.01	Au/WSi_2/Ge Au/$W_{40}N_{40}$ Ge/Ni	RTP	50	61
	0.1	Au/W/Pd/Ge	RTP	~5	62
	0.1	Au/W/Mo/ Ge	RTP	~5	62

[1] Ω mm can convert to Ω cm^2 if the contact width is known[2] [2] Layer doping in units of cm^{-2} is the dose obtained by ion implantation[2].

Table B-2. Electrical Contacts to III-V Compound Semiconductors (Continued)

Semiconductor	Carrier Conc. (10^{18} cm^{-3})	Metallization	Preparation	ρ_c (10^{-6} $\Omega \cdot cm^2$)	Ref.
n-GaAs (continued)	1	W-In	RTP	3	63
	1	NiGe(Au)W	RTP	0.16 Ω mm	64
	3.5×10^{13} cm^{-2}	W/Ni/InAs	RTP	0.4 Ω mm	65
	6×10^{13} cm^{-2}	WInTe		5	66
	3.5×10^{13} cm^{-2}	W/Ni/InAs /Ni	RTP	0.4 Ω mm	65
	---	Pd/In	RTP	~2	67
p-GaAs	4	Au/Pd	electroless dep., furnace, 250°C, 2 min	200	47
	2	Ag/TiN/Pt/ Mg	evap., furnace, 450°C, 30 min	100	68
	1	Ag/W/Pt	evap., furnace, 400°C, 30 min	300	69
	100	Ni/AuZn	evap., furnace, 450°C, 2.5 min	10	70
	---	Si/Ni/Mg/Ni	RTP	0.7	71
p-AlGaAs	10-100	AuBe, Pt/Ti	RTP	---	72
n-InGaAs	---	Au/Cr	evap., no alloying	2.2	73
	15	Au/Pt/Ti	evap., no alloying	0.05	74
	1.8	Al	evap., no alloying	0.5	75
	1	Ni/Au-Sn/Ni	---	0.04	76
	30	Al	---	0.48	75
p-InGaAs	---	Au/Cr	evap., no alloying	82	73
	1	Ni/AgZn/Ti	evap. furnace, 400°C, 2 min	11	77
	1	Ni/Au-Zn/Ni	---	20	76
n-InAlAs/ InGaAs	1	Au/Ag/Au/ Ge/Ni	evap., furnace, 480°C, 60 s	0.8	78
n-AlGaAs /GaAs	3	Au/Ni/AuGe	evap. 500°C, 50 s	0.1	79
p-InGaAsP	5	AuBe	---	0.49	80
	20	Pt/Ti	---	1	80
	23	Pd/Ge	Solid-phase epitaxy	2.3	81
p-GaSb	1	Au-Zn	furnace	10	82

Table B-2. Electrical Contacts to III-V Compound Semiconductors (Continued)

Semiconductor	Carrier Conc. (10^{18} cm^{-3})	Metallization	Preparation	ρ_c (10^{-6} $\Omega \cdot cm^2$)	Ref.
n-InP	---	Ni/Zn/Au, Ni/Hg/Au, InPd	electroless dep.	---	83
	2	AuGe/Ni/Au	Si-implanted, RTP	0.2	84
	---	Pt/Ti	RTP >400°C	0.8	85
	0.8	Au/Sn/In	400°C, 2 min	300	86
	0.8	Ni/AuGe/Ni	350°C 2 min after AuGe, 400°C 1 min after Ni	2.3	86
p-InP	1	Au/Cr/AuBe	RTP	10	87
	0.9	Au/Zn 90/10	400°C, 2 min	110	86
p-InAs	10	Pt/Ti	Zn-doped, RTP, 450°C, 30 s	0.099	88
n-GaN	---	Al	evap. no annealing	0.01-0.1	89
n-GaN		Au	evap. 575°C, 10 min	0.01-0.1	89
	0.1	Al/Ti	evap., RTA 900°C, 30 s	8	90
	5	InN/GaN	superlattice, InN cap, no annealing	60	91
n- & p- AlN	---	Al, Pt, Au	sputtering	---	92

B.4 DIAMOND (CARBON)

Semiconducting diamond is gaining popularity thanks to its unique combination of electronic and physical properties, including high breakdown voltage, high thermal conductivity, low dielectric constant, and radiation hardness. Tachibana and Glass9[3] and by Das *et al.*9[4] review the art of making both ohmic and Schottky contacts to diamond.

There are several methods to produce ohmic contacts on diamond: roughening or damaging the surface, welding noble metal/transition metal alloys, ion implantation, *in situ* doping with B during CVD film growth, solid-state diffusion doping, and deposition of carbide-forming metals.

Table B-3. Electrical Contacts to Diamond

Metallization	Doping	Preparation	*A*	Ref.
Ag Paint	natural	Mechanical Roughening	---	95
Colloidal Graphite	natural	Mechanical Roughening	---	96
W point probes	natural	Mechanical Roughening	---	97
Au(99%)-Ta(1%)	natural	Welding: E-Beam and Joule Heating	---	95-97
Au(90%)-Ta(9%)-Al(1%)	natural	Welding: E-Beam and Joule Heating	---	95-97
Pd-Ta	natural	Vacuum Brazing	---	98
Pt-Au-Ta	natural	Vacuum Brazing	---	98
Au, Ag, Cu	B, 3×10^{16} cm^{-3}	35 keV Ion Implantation at 200°C, Annealed at 1200°C, Etched	36 Ω cm	99
Au/Ti	B, 10^{20} cm^{-3}	Ion Implantation at 200°C	10^{-5} — 10^{-6} Ω cm^2	100
---	B, 3×10^{20} cm^{-3}	In Situ Vapor-Phase Doping	10^{-4} Ω cm^2	101
Ti	B, 10^{19} cm^{-3}	Solid State Diffusion, cBN at 1400°C, 20-60 s in Ar	---	102,103
Ti, Mo, Ta	natural	Carbide Formation, Annealing at >400°C	10^{-5} Ω cm^2	96, 104-108
Al/Si	B, 4.9×10^{21} cm^{-3}	Annealed 450°C	2.3×10^{-7} Ω cm^2	109
Ti-Au	B, 4.9×10^{20} cm^{-3}	Annealed 450°C	14×10^{-5} Ω cm^2	109
TiWN-Au	B, 4.9×10^{20} cm^{-3}	Annealed 450°C	6.6×10^{-5} Ω cm^2	109

B.5 II-VI MATERIALS

Wide and narrow bandgap II-VI compounds are increasingly sought for optoelectronic applications ranging from IR to UV wavelengths. HgCdTe is a "gapless" semiconductor used in IR detectors. ZnTe is a wide bandgap semiconductor that can be heavily doped with N, making it a potentially attractive material for blue and UV optoelectronics. ZnSe is the focus of considerable effort in the area of blue and UV semiconductor lasers, but it is extremely difficult to produce ohmic contacts to this material1[10].

Table B-4. Electrical Contacts to II-VI Compound Semiconductors

Material	Carrier Concentration (cm^{-3})	Metallization	Process	ρ_c ($\Omega \cdot cm^2$)	Ref.
HgCdTe	$\sim 10^{15}$	Au	Ar presputter, evap.	$\sim 1 \times 10^{-4}$	111
	4×10^{14}	Sn/In	evap.	1×10^{-5} - 1×10^{-5}	112
p-ZnTe	3×10^{19}	Au/Pt/Ti/N	e-beam evap., 120°C	1.1×10^{-6}	113

B.6 SILICON CARBIDE

Like diamond, silicon carbide is potentially useful for high-power, high-speed, and high-frequency devices, due to its large bandgap, high breakdown field and high thermal conductivity. However, ohmic contacts to this material have not been studied extensively.

Table B-5. Electrical Contacts to Silicon Carbide.

Material	Metallization	Process	ρ_c ($\Omega \cdot cm^2$)	Reference
SiC	Cr and alloys	ohmic to p-type	---	114
	Al	---	---	115
	Ti	sputter, 300°C, 30 min	9.2×10^{-3}	116
	$TiSi_2$	450°C, 390 min	1×10^{-4}	116
	WSi_2	450°C, 120 min	3×10^{-4}	116

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APPENDIX C

GLOSSARY OF TERMINOLOGY

absolute zero. The temperature of –273.16 °C, or –459.69 °F, or 0 K, thought to be the temperature at which molecular motion vanishes and a body would have no heat energy.[1]

accuracy. The degree of correctness with which a measured value agrees with the true value.[2]

electronic accuracy. The accuracy of an instrument independent of the sensor.

sensor accuracy. The accuracy of a temperature sensor and its associated calibration or its ability to match a standard curve.

algorithm. A set of well-defined rules for the solution of a problem in a finite number of steps.[1]

American Standard Code for Information Exchange (ASCII). A standard code used in data transmission, in which 128 numerals, letters, symbols, and special control codes are represented by a 7-bit binary number as follows:

Bits b_7 b_6 b_5 / b_4 b_3 b_2 b_1	Col. / Row	0 0 0	0 0 1	0 1 0	0 1 1	1 0 0	1 0 1	1 1 0	1 1 1
		0	1	2	3	4	5	6	7
0 0 0 0	0	NUL	DLE	SP	0	@	P	`	p
0 0 0 1	1	SOH	DC1	!	1	A	Q	a	q
0 0 1 0	2	STX	DC2	"	2	B	R	b	r
0 0 1 1	3	ETX	DC3	#	3	C	S	c	s
0 1 0 0	4	EOT	DC4	$	4	D	T	d	t
0 1 0 1	5	ENG	NAK	%	5	E	U	e	u
0 1 1 0	6	ACK	SYN	&	6	F	V	f	v
0 1 1 1	7	BEL	ETB	'	7	G	W	g	w
1 0 0 0	8	BS	CAN	(	8	H	X	h	x
1 0 0 1	9	HT	EM	)	9	I	Y	i	y
1 0 1 0	10	LF	SS	*	:	J	Z	j	z
1 0 1 1	11	VT	ESC	+	;	K	[	k	{
1 1 0 0	12	FF	FS	,	<	L	~	l	|
1 1 0 1	13	CR	GS	–	=	M	]	m	}
1 1 1 0	14	SO	RS	.	>	N	^	n	~
1 1 1 1	15	SI	US	/	?	O	_	o	DEL

American Wire Gage (AWG). Wiring sizes are defined as diameters in inches and millimeters as follows:

AWG	Dia. In.	Dia. mm	AWG	Dia. In.	Dia. mm	AWG	Dia. In.	Dia. mm	AWG	Dia. In.	Dia. mm
1	0.2893	7.348	11	0.0907	2.304	21	0.0285	0.7230	31	0.0089	0.2268
2	0.2576	6.544	12	0.0808	2.053	22	0.0253	0.6438	32	0.0080	0.2019
3	0.2294	5.827	13	0.0720	1.829	23	0.0226	0.5733	33	0.00708	0.178
4	0.2043	5.189	14	0.0641	1.628	24	0.0207	0.5106	34	0.00630	0.152
5	0.1819	4.621	15	0.0571	1.450	25	0.0179	0.4547	35	0.00561	0.138
6	0.1620	4.115	16	0.0508	1.291	26	0.0159	0.4049	36	0.00500	0.127
7	0.1443	3.665	17	0.0453	1.150	27	0.0142	0.3606	37	0.00445	0.1131
8	0.1285	3.264	18	0.0403	1.024	28	0.0126	0.3211	38	0.00397	0.1007
9	0.1144	2.906	19	0.0359	0.9116	29	0.0113	0.2859	39	0.00353	0.08969
10	0.1019	2.588	20	0.0338	0.8118	30	0.0100	0.2546	40	0.00314	0.07987

ambient temperature. The temperature of the surrounding medium, such as gas or liquid, which comes into contact with the apparatus.[1]

ampere. The constant current that, if maintained in two straight parallel conductors of infinite length, of negligible circular cross section, and placed one meter apart in a vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length.[2] This is one of the base units of the SI.

ampere-turn. A MKS unit of magnetomotive force equal to the magnetomotive force around a path linking one turn of a conducting loop carrying a current of one ampere; or 1.26 gilberts.

ampere/meter (A/m). The SI unit for magnetic field strength (H). 1 ampere/meter = $4\pi/1000$ oersted ≈ 0.01257 oersted.

analog controller. A feedback control system where there is an unbroken path of analog processing between the feedback device (sensor) and control actuator (heater).

analog data. Data represented in a continuous form, as contrasted with digital data having discrete values.[1]

analog output. A voltage output from an instrument that is proportional to its input. From an instrument such as a digital voltmeter, the output voltage is generated by a digital-to-analog converter with a discrete number of voltage levels.

anode. The terminal that is positive with respect to the other terminal when the diode is biased in the forward direction.[2]



area. A measure of the size of a two-dimensional surface, or of a region on such a surface.[1]

area·turns. A coil parameter produced by the multiplication of a magnet's area and number of turns. Gives an indication of the sensitivity of a coil.

asphyxiant gas. A gas which has little or no positive toxic effect but which can bring about unconsciousness and death by displacing air and thus depriving an organism of oxygen.

autotuning. In Lake Shore Temperature Controllers, the Autotuning algorithm automatically determines the proper settings for Gain (Proportional), Reset (Integral), and Rate (Derivative) by observing the time response of the system upon changes in setpoint.

B. Symbol for magnetic flux density. *See* Magnetic Flux Density.

bar. Unit of pressure equal to 10^5 pascal, or 0.98697 standard atmosphere.

baud. A unit of signaling speed equal to the number of discrete conditions or signal events per second, or the reciprocal of the time of the shortest signal element in a character.[2]

bel. A dimensionless unit expressing the ration of two powers or intensities, or the ratio of a power to a reference power, such that the number of bels is the common logarithm of this ratio.[1]

bipolar magnet. A permanent magnet that has been magnetized in two different field directions, with one side being designated north and the other south.

bit. A contraction of the term "binary digit"; a unit of information represented by either a zero or a one.[2]

BNC. Bayonet Nut Connector.

boiling point. The temperature at which a substance in the liquid phase transforms to the gaseous phase; commonly refers to the boiling point at sea level and standard atmospheric pressure.

CalCurve™ Service. The service of storing a mathematical representation of a calibration curve on an EEEPROM or installed in a Lake Shore instrument. Previously called Precision Option.

calibration. To determine, by measurement or comparison with a standard, the correct (accurate) value of each scale reading on a meter or other device, or the correct value for each setting of a control knob.[1]

cathode. The terminal from which forward current flows to the external circuit.[2]



Celsius (°C) Scale. A temperature scale that registers the freezing point of water as 0 °C and the boiling point as 100 °C under normal atmospheric pressure. Celsius degrees are purely derived units, calculated from the Kelvin Thermodynamic Scale. Formerly known as "centigrade." *See* Temperature for conversions.

cgs system of units. A system in which the basic units are the centimeter, gram, and second.[2]

Chebychev polynomials. A family of orthogonal polynomials which solve Chebychev's differential equation.[1]

Chebychev differential equation. A special case of Gauss' hypergeometric second-order differential equation: $(1 - x^2)\, f''(x) - xf'(x) + n^2 f(x) = 0$.[1]

closed-loop. *See* feedback control system.

coercive force (coercive field). The magnetic field strength (H) required to reduce the magnetic induction (B) in a magnetic material to zero.

coercivity. generally used to designate the magnetic field strength (H) required to reduce the magnetic induction (B) in a magnetic material to zero from saturation. The coercivity would be the upper limit to the coercive force.

compliance voltage. *See* current source.

cryogen. *See* cryogenic fluid.[1]

cryogenic. Refers to the field of low temperatures, usually –130 °F or below, as defined by 173.300(f) of Title 49 of the Code of Federal Regulations.

cryogenic fluid. A liquid that boils at temperatures of less than about 110 K at atmospheric pressure, such as hydrogen, helium, nitrogen, oxygen, air, or methane. Also known as cryogen.[1]

cryostat. An apparatus used to provide low-temperature environments in which operations may be carried out under controlled conditions.[1]

cryotronics. The branch of electronics that deals with the design, construction, and use of cryogenic devices.[1]

Curie temperature (Tc). Temperature at which a magnetized sample is completely demagnetized due to thermal agitation. Named for Pierre Curie (1859 – 1906), a French chemist.

current source. A type of power supply that supplies a constant current through a variable load resistance by automatically varying its compliance voltage. A single specification given as "compliance voltage" means the output current is within specification when the compliance voltage is between zero and the specified voltage.

curve. A set of data that defines the temperature response of a temperature sensor. It is used to convert the signal from the sensor to temperature.

decibels (dB). A unit for describing the ratio of two powers or intensities, or the ratio of a power to a reference power; equal to one-tenth bel; if P_1 and P_2 are two amounts of power, the first is said to be *n* decibels greater, where $n = 10 \log_{10} (P_1/P_2)$.[1]

degree. An incremental value in the temperature scale, i.e., there are 100 degrees between the ice point and the boiling point of water in the Celsius scale and 180 degrees between the same two points in the Fahrenheit scale.

demagnetization. when a sample is exposed to an applied field (H_a), poles are induced on the surface of the sample. Some of the returned flux from these poles is inside of the sample. This returned flux tends to decrease the net magnetic field strength internal to the sample yielding a true internal field (H_{int}) given by: $H_{int} = H_a - DM$,where M is the volume magnetization and D is the demagnetization factor. D is dependent on the sample geometry and orientation with respect to the field.

deviation. The difference between the actual value of a controlled variable and the desired value corresponding to the setpoint.[1]

Dewar flask. A vessel having double walls, the space between being evacuated to prevent the transfer of heat and the surfaces facing the vacuum being heat-reflective; used to hold liquid gases and to study low-temperature phenomena.[1] Invented by Sir James Dewar (1842 – 1923), a Scottish physical chemist.

differential permeability. The slope of a B versus H curve: $\mu_d = dB/dH$.

differential susceptibility. The slope of a M versus H curve: $\chi_d = dM/dH$.

digital controller. A feedback control system where the feedback device (sensor) and control actuator (heater) are joined by a digital processor. In Lake Shore controllers the heater output is maintained as a variable DC current source.

digital data. Pertaining to data in the form of digits or interval quantities. Contrast with analog data.[2]

dimensionless sensitivity. Sensitivity of a physical quantity to a stimulus, expressed in dimensionless terms. The dimensionless temperature sensitivity of a resistance temperature sensor is expressed as $S_d = (T/R)(dR/dT)$ which is also equal to the slope of R versus T on a log-log plot, that is $S_d = d\ lnR/d\ lnT$. Note that absolute temperature (in Kelvin) must be used in these expressions.

drift, instrument. An undesired but relatively slow change in output over a period of time, with a fixed reference input. *Note:* Drift is usually expressed in percent of the maximum rated value of the variable being measured.[2]

electromagnet. A device in which a magnetic field is generated as the result of electrical current passing through a helical conducting coil. It can be configured as an iron-free solenoid in which the field is produced along the axis of the coil, or an iron-cored structure in which the field is produced in an air gap between pole faces. The coil can be water cooled copper or aluminum, or superconductive.

electron. An elementary particle containing the smallest negative electric charge. *Note:* The mass of the electron is approximately equal to 1/1837 of the mass of the hydrogen atom.[2]

electrostatic discharge (ESD). A transfer of electrostatic charge between bodies at different electrostatic potentials caused by direct contact or induced by an electrostatic field.

error. Any discrepancy between a computed, observed, or measured quantity and the true, specified, or theoretically correct value or condition.[2]

excitation. Either an AC or DC input to a sensor used to produce an output signal. Common excitations include: constant current, constant voltage, or constant power.

extrema. Mathematical term that defines the two extremes of a measurement: maxima and minima. Extrema can be either be relative or absolute, where relative is in relation to other nearby (local) maxima and minima and absolute represents the overall maxima and minima for the entire measurement.

Fahrenheit (°F) Scale. A temperature scale that registers the freezing point of water as 32 °F and the boiling point as 212 °F under normal atmospheric pressure. *See* Temperature for conversions.

feedback control system. A system in which the value of some output quantity is controlled by feeding back the value of the controlled quantity and using it to manipulate an input quantity so as to bring the value of the controlled quantity closer to a desired value. Also known as closed-loop control system.[1]

flux (ϕ). The electric or magnetic lines of force in a region.[1]

flux density (B). Any vector field whose flux is a significant physical quantity; examples are magnetic flux density, electric displacement, and gravitational field.[1]

four-lead. measurement technique where one pair of excitation leads and an independent pair of measurement leads are used to measure a sensor. This method reduces the effect of lead resistance on the measurement.

gamma. A cgs unit of low-level flux density, where 100,000 gamma equals one oersted, or 1 gamma equals 10^{-5} oersted.

gauss (G). The cgs unit for magnetic flux density (B). 1 gauss = 10^{-4} tesla = 1 Mx/cm^2 = $line/cm^2$. Named for Karl Fredrich Gauss (1777 – 1855) a German mathematician, astronomer, and physicist.

gaussian system (units). A system in which centimeter-gram-second units are used for electric and magnetic qualities.

general purpose interface bus (GPIB). Another term for the IEEE-488 bus.

gilbert (Gb). A cgs electromagnetic unit of the magnetomotive force required to produce one maxwell of magnetic flux in a magnetic circuit of unit reluctance. One gilbert is equal to $10/4\pi$ ampere-turn. Named for William Gilbert (1540 – 1603), an English physicist; hypothesized that the earth is a magnet.

gilbert per centimeter. Practical cgs unit of magnet intensity. Gilberts per cm are the same as oersteds.

Greek alphabet. The Greek alphabet is defined as follows:

Alpha	α	A	Iota	ι	I	Rho	ρ	P
Beta	β	B	Kappa	κ	K	Sigma	σ	Σ
Gamma	γ	Γ	Lambda	λ	Λ	Tau	τ	T
Delta	δ	Δ	Mu	μ	M	Upsilon	υ	Y
Epsilon	ε	E	Nu	ν	N	Phi	ϕ	Φ
Zeta	ζ	Z	Xi	ξ	Ξ	Chi	χ	X
Eta	η	H	Omicron	ο	O	Psi	ψ	Ψ
Theta	θ	Θ	Pi	π	Π	Omega	ω	Ω

ground. A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth, or to some conducting body of large extent that serves in place of the earth. *Note:* It is used for establishing and maintaining the potential of the earth (or of the conducting body) or approximately that potential, on conductors connected to it, and for conducting ground current to and from the earth (or of the conducting body).[2]

H. Symbol for magnetic field strength. *See* Magnetic Field Strength.

Hall effect. The generation of an electric potential perpendicular to both an electric current flowing along a thin conducting material and an external magnetic field applied at right angles to the current. Named for Edwin H. Hall (1855 – 1938), American physicist.

Hall mobility. The quantity μH in the relation $\mu H = R\sigma$, where R = Hall coefficient and σ = conductivity.[2]

hazard communication standard (HCS). The OSHA standard cited in 29 CFR 1910.1200 requiring communication of risks from hazardous substances to workers in regulated facilities.

Helmholtz coils. A pair of flat, circular coils having equal numbers of turns and equal diameters, arranged with a common axis, and connected in series; used to obtain a magnetic field more nearly uniform than that of a single coil.[1]

hertz (Hz). A unit of frequency equal to one cycle per second.

hole. A mobile vacancy in the electronic valence structure of a semiconductor that acts like a positive electron charge with a positive mass.[2]

hysteresis. The dependence of the state of a system on its previous history, generally in the form of a lagging of a physical effect behind its cause.[1] Also *see* magnetic hysteresis.

IEEE. Institute of Electrical and Electronics Engineers.

IEEE-488. An instrumentation bus with hardware and programming standards designed to simplify instrument interfacing. The addressable, parallel bus specification is defined by the IEEE.

Indium (In). Ductile, shiny, silver-white metal, softer than lead. Soluble in acids. In-soluble in alkalies. Corrosion-resistant at room temperatures but oxidizes readily at higher temperatures. Nontoxic. Atomic Number: 49; Atomic Weight: 114.82; Density: 7.31 gm/cc; Melting Point: 156.61 °C; Boiling Point: 2080 °C; Thermal Conductivity: 0.818 W/cm/K @ 298.2 K; Electrical Resistivity: 8.37 microhm-cm @ 20 °C; Electronegativity: 1.7 Paulings; Specific Heat: 0.056 Cal/g/K @ 25 °C; Heat of Vaporization: 53.7 K-Cal/gm atom at 2080 °C; Heat of Fusion: 0.781 Cal/gm mole.

initial permeability. The permeability determined at H = 0 and B = 0.

initial susceptibility. The susceptibility determined at H = 0 and M = 0.

integrator. A circuit or network whose output waveform is the time integral of its input waveform.[1]

international system of units (SI). A universal coherent system of units in which the following seven units are considered basic: meter, kilogram, second, ampere, kelvin, mole, and candela. The International System of Units, or Système International d'Unités (SI), was promulgated in 1960 by the Eleventh General Conference on Weights and Measures. For definition, spelling, and protocols, *see* Reference 3 for a short, convenient guide.

interpolation table. A table listing the output and sensitivity of a sensor at regular or defined points which may be different from the points at which calibration data was taken.

intrinsic coercivity. The magnetic field strength (H) required to reduce the magnetization (M) or intrinsic induction in a magnetic material to zero.

intrinsic induction. The contribution of the magnetic material (B_i) to the total magnetic induction (B).

$B_i = B - \mu_o H$ (SI) $\qquad B_i = B - H$ (cgs)

isolated (neutral system). A system that has no intentional connection to ground except through indicating, measuring, or protective devices of very-high impedance.[2]

ITS-90. International Temperature Scale of 1990. Also abbreviated as T_{90}. This scale was designed to bring into as close a coincidence with thermodynamic temperatures as the best estimates in 1989 allowed.

Kelvin (K). The unit of temperature on the Kelvin Scale. It is one of the base units of SI. The word "degree" and its symbol (°) are omitted from this unit. *See* Temperature Scale for conversions.

Kelvin Scale. The Kelvin Thermodynamic Temperature Scale is the basis for all international scales, including the ITS-90. It is fixed at two points: the absolute zero of temperature (0 K), and the triple point of water (273.16 K), the equilibrium temperature that pure water reaches in the presence of ice and its own vapor.

line regulation. The maximum steady-state amount that the output voltage or current will change as the result of a specified change in input line voltage (usually for a step change between 105 – 125 or 210 – 250 volts, unless otherwise specified).

line of flux. An imaginary line in a magnetic field of force whose tangent at any point gives the direction of the field at that point; the lines are spaced so that the number through a unit area perpendicular to the field represents the intensity of the field. Also know as a Maxwell in the cgs system of units.

line voltage. The RMS voltage of the primary power source to an instrument.

line voltage. The RMS voltage of the primary power source to an instrument.

liquid helium (LHe). Used for low temperature and superconductivity research: minimum purity 99.998%. Boiling point at 1 atm = 4.2 K. Latent heat of vaporization = 2.6 kilojoules per liter. Liquid density = 0.125 kilograms per liter.

EPA Hazard Categories: Immediate (Acute) Health and Sudden Release of Pressure Hazards
DOT Name: Helium, Refrigerated Liquid
DOT Label: Nonflammable Gas
DOT Class: Nonflammable Gas
DOT ID No.: UN 1963

liquid nitrogen (LN_2). Also used for low temperature and superconductivity research and for its refrigeration properties such as in freezing tissue cultures: minimum purity 99.998%, O_2 8 ppm max. Boiling point at 1 atm = 77.4 K. Latent heat of vaporization = 160 kilojoules per liter. Liquid density = 0.81 kilograms per liter.

EPA Hazard Categories: Immediate (Acute) Health and Sudden Release of Pressure Hazards
DOT Name: Nitrogen, Refrigerated Liquid
DOT Label: Nonflammable Gas
DOT Class: Nonflammable Gas
DOT ID No.: UN 1977

load regulation. A steady-state decrease of the value of the specified variable resulting from a specified increase in load, generally from no-load to full-load unless otherwise specified.

M. Symbol for magnetization. *See* magnetization.

magnetic air gap. The air space, or non-magnetic portion, of a magnetic circuit.

magnetic field strength (H). The magnetizing force generated by currents and magnetic poles. For most applications, the magnetic field strength can be thought of as the applied field generated, for example, by a superconducting magnet. The magnetic field strength is not a property of materials. Measure in SI units of A/m or cgs units of oersted.

magnetic flux density (B). Also referred to as magnetic induction. This is the net magnetic response of a medium to an applied field, H. The relationship is given by the following equation: $B = \mu_o (H + M)$ for SI, and $B = H + 4\pi M$ for cgs, where H = magnetic field strength, M = magnetization, and μ_o = permeability of free space = $4\pi \times 10^{-7}$ H/m.

magnetic hysteresis. The property of a magnetic material where the magnetic induction (B) for a given magnetic field strength (H) depends upon the past history of the samples magnetization.

magnetic induction (B). *See* magnetic flux density.

magnetic moment (m). This is the fundamental magnetic property measured with DC magnetic measurements systems such as a vibrating sample magnetometer, extraction magnetometer, SQUID magnetometer, etc. The exact technical definition relates to the torque exerted on a magnetized sample when placed in a magnetic field. Note that the moment is a total attribute of a sample and alone does not necessarily supply sufficient information in understanding material properties. A small highly magnetic sample can have exactly the same moment as a larger weakly magnetic sample (*see* Magnetization). Measured in SI units as $A \cdot m^2$ and in cgs units as emu. 1 emu = 10^{-3} $A \cdot m^2$.

magnetic scalar potential. The work which must be done against a magnetic field to bring a magnetic pole of unit strength from a reference point (usually at infinity) to the point in question. Also know as magnetic potential.[1]

magnetic units. Units used in measuring magnetic quantities. Includes ampere-turn, gauss, gilbert, line of force, maxwell, oersted, and unit magnetic pole.

magnetization (M). This is a material specific property defined as the magnetic moment (m) per unit volume (V). M = m/V. Measured in SI units as A/m and in cgs units as emu/cm^3. 1 $emu/cm^3 = 10^3$ A/m. Since the mass of a sample is generally much easier to determine than the volume, magnetization is often alternately expressed as a mass magnetization defined as the moment per unit mass.

magnetostatic. Pertaining to magnetic properties that do not depend upon the motion of magnetic fields.[1]

material safety data sheet (MSDS). OSHA Form 20 contains descriptive information on hazardous chemicals under the OSHA Hazard Communication Standard (HCS). These data sheets also provide precautionary information on the safe handling of the gas as well as emergency and first aid procedures.

Maxwell (Mx). A cgs electromagnetic unit of magnetic flux, equal to the magnetic flux which produces an electromotive force of 1 abvolt in a circuit of one turn link the flux, as the flux is reduced to zero in 1 second at a uniform rate.[1]

neutral zone. The area of transition located between areas of a permanent magnet which have been magnetized in opposite directions.

MKSA System of Units. A system in which the basic units are the meter, kilogram, and second, and the ampere is a derived unit defined by assigning the magnitude $4\pi \times 10^{-7}$ to the rationalized magnetic constant (sometimes called the permeability of space).

NBS. National Bureau of Standards. Now referred to as NIST.

National Institute of Standards and Technology (NIST). Government agency located in Gaithersburg, Maryland and Boulder, Colorado, that defines measurement standards in the United States. *See* Standards Laboratories for an international listing.

negative temperature coefficient (NTC). Refers to the sign of the temperature sensitivity. For example, the resistance of a NTC sensor decreases with increasing temperature.

noise (electrical). Unwanted electrical signals that produce undesirable effects in circuits of control systems in which they occur.[2]

normalized sensitivity. For resistors, signal sensitivity (dR/dT) is geometry dependent; i.e., dR/dT scales directly with R; consequently, very often this sensitivity is normalized by dividing by the measured resistance to give a sensitivity, s_T, in percent change per kelvin. $s_T = (100/R)\ (dR/dT)$ %K, where T is the temperature in kelvin and R is the resistance in ohms.

normally closed (N.C.). A term used for switches and relay contacts. Provides a closed circuit when actuator is in the free (unenergized) position.

normally open (N.O.). A term used for switches and relay contacts. Provides an open circuit when actuator is in the free (unenergized) position.

oersted (Oe). The cgs unit for the magnetic field strength (H). 1 oersted = $10^3/4\pi$ ampere/meter ≈ 79.58 ampere/meter.

ohm (Ω). The SI unit of resistance (and of impedance). The ohm is the resistance of a conductor such that a constant current of one ampere in it produces a voltage of one volt between its ends.[2]

open-loop. A control system in which the system outputs are controlled by system inputs only, and no account is taken of actual system output.[1]

pascal (Pa). The SI unit of pressure equal to 1 N/m^2. Equal to 1.45×10^{-4} psi, 1.0197×10^{-5} kg_f/cm^2, 7.5×10^{-3} torr, 4.191×10^{-3} inches of water, or 1×10^{-5} bar.

permeability. Material parameter which is the ratio of the magnetic induction (B) to the magnetic field strength (H): $\mu = B/H$. Also *see* Initial Permeability and Differential Permeability.

platinum (Pt). A common temperature sensing material fabricated from pure platinum to make the Lake Shore PT family of resistance temperature sensor elements.

polynomial fit. A mathematical equation used to fit calibration data. Polynomials are constructed of finite sums of terms of the form $a_i x_i$, where a_i is the i^{th} fit coefficient and x_i is some function of the dependent variable.

positive temperature coefficient (PTC). Refers to the sign of the temperature sensitivity. For example, the resistance of a PTC sensor increases with increasing temperature.

pounds per square inch (psi). A unit of pressure. 1 psi = 6.89473 kPa. Variations include psi absolute (psia) measured relative to vacuum (zero pressure) where one atmosphere pressure equals 14.696 psia and psi gauge (psig) where gauge measured relative to atmospheric or some other reference pressure.

ppm. Parts per million, e.g., 4×10^{-6} is four parts per million.

precision. Careful measurement under controlled conditions which can be repeated with similar results. *See* repeatability. Also means that small differences can be detected and measured with confidence. *See* resolution.

prefixes. SI prefixes used throughout this manual are as follows:

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	da	10^{-24}	yocto	y

probe. A long, thin body containing a sensing element which can be inserted into a system in order to make measurements. Typically, the measurement is localized to the region near the tip of the probe.

proportional, integral, derivative (PID). A control function where output is related to the error signal in three ways. Proportional (gain) acts on the instantaneous error as a multiplier. Integral (reset) acts on the area of error with respect to time and can eliminate control offset or droop. Derivative (rate) acts on the rate of change in error to dampen the system, reducing overshoot.

quench. A condition where the superconducting magnet goes "normal," i.e., becomes non-superconductive. When this happens, the magnet becomes resistive, heat is generated, liquid cryogen is boiled off, and the magnet power supply is shut down due to the sudden increase in current demand.

rack mount. An instrument is rack mountable when it has permanent or detachable brackets that allow it to be securely mounted in an instrument rack. The standard rack-mount is 19 inches wide. A full-rack instrument requires the entire width of the rack. Two half-rack instruments fit horizontally in one rack width.

relief valve. A type of pressure relief device which is designed to relieve excessive pressure, and to reclose and reseal to prevent further flow of gas from the cylinder after reseating pressure has been achieved.

remanence. The remaining magnetic induction in a magnetic material when the material is first saturated and then the applied field is reduced to zero. The remanence would be the upper limit to values for the remanent induction. Note that no strict convention exists for the use of remanent induction and remanence and in some contexts the two terms may be used interchangeably.

remanent induction. The remaining magnetic induction in a magnetic material after an applied field is reduced to zero. Also *see* remanence.

repeatability. The closeness of agreement among repeated measurements of the same variable under the same conditions.[2]

resistance temperature detector (RTD). Resistive sensors whose electrical resistance is a known function of the temperature, made of, e.g., carbon-glass, germanium, platinum, or rhodium-iron.

resolution. The degree to which nearly equal values of a quantity can be discriminated.[2]

display resolution. The resolution of the physical display of an instrument. This is not always the same as the measurement resolution of the instrument. Decimal display resolution specified as "*n* digits" has 10^n possible display values. A resolution of *n* and one-half digits has 2×10^n possible values.

measurement resolution. The ability of an instrument to resolve a measured quantity. For digital instrumentation this is often defined by the analog-to-digital converter being used. A n-bit converter can resolve one part in 2^n. The smallest signal change that can be measured is the full scale input divided by 2^n for any given range. Resolution should not be confused with accuracy.

root mean square (RMS). The square root of the time average of the square of a quantity; for a periodic quantity the average is taken over one complete cycle. Also known as effective value.[1]

scalar. A quantity which has magnitude only and no direction, in contrast to a vector.[1]

semiconducting material. A conducting medium in which the conduction is by electrons, and holes, and whose temperature coefficient of resistivity is negative over some temperature range below the melting point.[2]

semiconductor. An electronic conductor, with resistivity in the range between metals and insulators, in which the electric charge carrier concentration increases with increasing temperature over some temperature range. Note: Certain semiconductors possess two types of carriers, namely, negative electrons and positive holes.[2]

sensitivity. The ratio of the response or change induced in the output to a stimulus or change in the input. Temperature sensitivity of a resistance temperature detector is expressed as S = dR/dT.

setpoint. The value selected to be maintained by an automatic controller.[1]

SI. Système International d'Unités. *See* International System of Units.

stability. The ability of an instrument or sensor to maintain a constant output given a constant input.

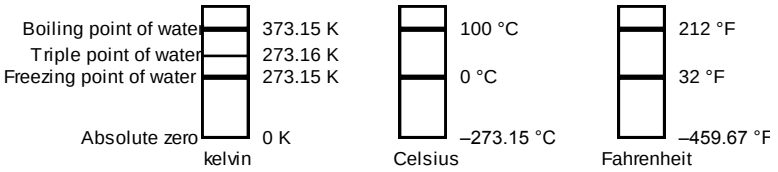
strain relief. A predetermined amount of slack to relieve tension in component or lead wires. Also called stress relief.

superconducting magnet. An electromagnet whose coils are made of a type II superconductor with a high transition temperature and extremely high critical field, such as niobium-tin, Nb_3Sn; it is capable of generating magnetic fields of 100,000 oersteds and more with no steady power dissipation.[1] *See* electromagnet.

susceptance. In electrical terms, susceptance is defined as the reciprocal of reactance and the imaginary part of the complex representation of admittance: [suscept(ibility) + (conduct)ance].

susceptibility (χ). Parameter giving an indication of the response of a material to an applied magnetic field. The susceptibility is the ratio of the magnetization (M) to the applied field (H). χ = M/H. In both SI units and cgs units the volume susceptibility is a dimensionless parameter. Multiply the cgs susceptibility by 4π to yield the SI susceptibility. *See* also Initial Susceptibility and Differential Susceptibility. As in the case of magnetization, the susceptibility is often seen expressed as a mass susceptibility or a molar susceptibility depending upon how M is expressed.

temperature scales. *See* Kelvin Scale, Celsius Scale, and ITS-90. Proper metric usage requires that only kelvin and degrees Celsius be used. However, since degrees Fahrenheit is in such common use, all three scales are delineated as follows:



To convert kelvin to Celsius, subtract 273.15.
To convert Celsius to Fahrenheit: multiply °C by 1.8 then add 32, or: °F = (1.8 × °C) + 32.
To convert Fahrenheit to Celsius: subtract 32 from °F then divide by 1.8, or: °C = (°F – 32)/1.8.

temperature coefficient, measurement. The measurement accuracy of an instrument is affected by changes in ambient temperature. The error is specified as an amount of change (usually in percent) for every one degree change in ambient temperature.

tesla (T). The SI unit for magnetic flux density (B). 1 tesla = 10^4 gauss

thermal emf. An electromotive force arising from a difference in temperature at two points along a circuit, as in the Seebeck effect.[1]

tolerance. The range between allowable maximum and minimum values.

torque. For a single force, the cross product of a vector from some reference point to the point of application of the force with the force itself. Also known as moment of force and rotation moment.[1]

torque constant (K_t). The ratio of the torque delivered by a motor to the current supplied to it. K_t = N·m/A.

torr. Unit of pressure. 1 torr ≈ 1 mm of mercury. 1 atmosphere = 760 torr.

turns (N). One complete loop of wire.

two-lead. Measurement technique where one pair of leads is used for both excitation and measurement of a sensor. This method will not reduce the effect of lead resistance on the measurement.

Underwriters Laboratories (UL). An independent laboratory that establishes standards for commercial and industrial products.

unit magnetic pole. A pole with a strength such that when placed 1 cm away from a like pole, the force between the two is 1 dyne.

vector. A quantity that has both magnitude and direction, and whose components transform from one coordinate system to another in the same manner as the components of a displacement. Also known as a polar vector.[1]

volt (V). The difference of electric potential between two points of a conductor carrying a constant current of one ampere, when the power dissipated between these points is equal to one watt.[2]

volt-ampere (VA). The SI unit of apparent power. The volt-ampere is the apparent power at the points of entry of a single-phase, two-wire system when the product of the RMS value in amperes of the current by the RMS value in volts of the voltage is equal to one.[2]

watt (W). The SI unit of power. The watt is the power required to do work at the rate of 1 joule per second.[2]

weber (Wb). The unit of magnetic flux in the mks system, equal to the magnetic flux which, linking a circuit of one turn, produces in it an electromotive force of 1 volt as it is reduced to zero at a uniform rate in 1 second.[1]

References:

1 Sybil P. Parker, Editor. *Dictionary of Scientific and Technical Terms: Fifth Edition*. New York: McGraw Hill, 1994 (IBSN 0-07-113584-7)

2 Christopher J. Booth, Editor. *The New IEEE Standard Dictionary of Electrical and Electronic Terms: IEEE Std 100-1992, Fifth Edition*. New York: Institute of Electrical and Electronics Engineers, 1993 (IBSN 1-55937-240-0). Definitions printed with permission of the IEEE.

3 Nelson, Robert A. *Guide For Metric Practice*, Page BG7 – 8, Physics Today, Eleventh Annual Buyer's Guide, August 1994 (ISSN 0031-9228 coden PHTOAD)

APPENDIX D

REFERENCE INFORMATION

Table D-1. Conversion from CGS to SI Units

Quantity	Symbol	Gaussian & CGS emu[a]	Conversion Factor, C[b]	SI & Rationalized mks[c]
Magnetic flux density, Magnetic induction	B	gauss (G)[d]	10^{-4}	tesla (T), Wb/m^2
Magnetic Flux	ϕ	maxwell (Mx), $G \cdot cm^2$	10-8	weber (Wb), volt second (V·s)
Magnetic potential difference, magnetomotive force	U, F	gilbert (Gb)	$10/4\pi$	ampere (A)
Magnetic field strength, magnetizing force	H	oersted (Oe),[e] Gb/cm	$10^3/4\pi$	A/m[f]
(Volume) magnetization[g]	M	emu/cm^{3h}	10^3	A/m
(Volume) magnetization	$4\pi M$	G	$10^3/4\pi$	A/m
Magnetic polarization, intensity of magnetization	J, I	emu/cm^3	$4\pi \times 10^{-4}$	T, Wb/m^{2i}
(Mass) magnetization	σ, M	emu/g	1 $4\pi \times 10^{-7}$	$A \cdot m^2/kg$ Wb·m/kg
Magnetic moment	m	emu, erg/G	10^{-3}	$A \cdot m^2$, joule per tesla (J/T)
Magnetic dipole moment	j	emu, erg/G	$4\pi \times 10^{-10}$	$Wb \cdot m^i$
(Volume) susceptibility	χ, κ	dimensionless emu/cm^3	- $(4\pi)^2 \times 10^{-7}$	Henry per meter (H/m), Wb/(A·m)
(Mass) susceptibility	χ_ρ, κ_ρ	cm^3/g, emu/g	$4\pi \times 10^{-3}$ $(4\pi)2 \times 10^{-10}$	m^3/kg $H \cdot m^2/kg$
(Molar) susceptibility	χ_{mol}, κ_{mol}	cm^3/mol, emu/mol	$4\pi \times 10^{-6}$ $(4\pi)^2 \times 10^{-13}$	m^3/mol $H \cdot m^2/mol$
Permeability	μ	dimensionless	$4\pi \times 10^{-7}$	H/m, Wb/(A·m)
Relative permeability[j]	μ_r	not defined	-	dimensionless
(Volume) energy density, energy product[k]	W	erg/cm^3	10^{-1}	J/m^3
Demagnetization factor	D, N	dimensionless	$1/4\pi$	dimensionless

NOTES:

a. Gaussian units and cgs emu are the same for magnetic properties. The defining relation is $B = H + 4\pi M$.

b. Multiply a number in Gaussian units by C to convert it to SI (e.g. $1\ G \times 10^{-4} T/G = 10^{-4} T$).

c. SI (Système International d'Unités) has been adopted by the National Bureau of Standards. Where two conversion factors are given, the upper one is recognized under, or consistent with, SI and is based on the definition $B = \mu_0(H + M)$, where to $\mu_0 = 4\pi \times 10^{-7} H/m$. The lower one is not recognized under SI and is based on the definition $B = \mu_0 H + J$, where the symbol I is often used in place of J.

d. 1 gauss = 10^5 gamma (γ).

e. Both oersted and gauss are expressed as $cm^{-½} \cdot g^{½} \cdot s^{-1}$ in terms of base units.

f. A/m was often expressed as "ampere-turn per meter" when used for magnetic field strength.

g. Magnetic moment per unit volume.

h. The designation "emu" is not a unit.

i. Recognized under SI, even though based on the definition $B = \mu_0 H + J$. See footnote c.

j. $\mu_r = \mu/\mu_0 = 1 + \chi$, all in SI. μ_r is equal to Gaussian μ.

k. B H and $\mu_0 M \cdot H$ have SI units J/m^3, M H and B H/4π have Gaussian units erg/cm^3.

R.B. Goldfarb and F.R. Fickett, U.S. Department of Commerce, National Bureau of Standards, Bolder, Colorado 80303, March 1985, NBS Special Publication 696. For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

Table D-2. Recommended SI Values for Physical Constants

Quantity	Symbol	Value (SI units)
Permeability of Vacuum	μ_0	$4\pi \times 10^{-7}$ H m^{-1}
Speed of Light in Vacuum	c	2.9979×10^{8} m s^{-1}
Permitivity of Vacuum	$\varepsilon_0 = (\mu_0 c^2)^{-1}$	8.8542×10^{-12} F m^{-1}
Fine Structure Constant, μ0ce2/2h	α α^{-1}	0.0073 137.0360
Elementary Charge	e	1.6022×10^{-19} C
Plank's Constant	h $h = h/2\pi$	6.6262×10^{-34} J Hz^{-1} 1.0546×10^{-34} J s
Avogadro's Constant	N_A	6.0220×10^{23} mol^{-1}
Atomic Mass Unit	$lu = (10^{-3}$ kg mol^{-1}/N_A	1.6605×10^{-27} kg
Electron Rest Mass	m_e	0.9109×10^{-30} kg 5.4858×10^{-4} u
Proton Rest Mass	m_p	1.6726×10^{-27} kg 1.0073 u
Neutron Rest Mass	m_n	1.6749×10^{-27} kg 1.0087 u
Magnetic Flux Quantum	$\phi = h/2e$ h/e	2.0679×10^{-15} Wb 4.1357×10^{-15} J Hz^{-1} C^{-1}
Josephson Frequency-Voltage Ratio	2e/h	483.5939 THz V^{-1}
Quantum of Circulation	$h/2m_e$ h/m_e	3.6369×10^{-4} J Hz^{-1} kg^{-1} 7.2739×10^{-4} J Hz^{-1} C^{-1}
Rydberg Constant	R_∞	1.0974×10^{7} m-1
Proton Moment in Nuclear Magnetons	μ_p/μ_N	2.7928
Bohr Magneton	$\mu_B = eh/2m_e$	9.2741×10^{-24} J T^{-1}
Proton Gyromagnetic Ratio	γ_p	2.6752×10^{8} s^{-1} T^{-1}
Diamagnetic Shielding Factor, Spherical H_2O Sample	$1 + \sigma(H_2O)$	1.0000
Molar Mass Constant	R	8.3144 J mol^{-1} K^{-1}
Molar Volume, Ideal Gas (T_0 = 273.15K, p_0 = 1 atm)	$V_m = RT_0/p_0$	0,0224 m^3 mol^{-1}
Boltzman Constant	$k = R/N_A$	1.3807×10^{-23} J K^{-1}
Stefan-Boltzman Constant	$\sigma = (\pi^2/60)\ k^4/h^3\ c^2$	5.6703×10^{-8} W m^{-2} K^{-4}
First Radiation Constant	$c_1 = 2\pi hc^2$	3.7418×10^{-16} W m^{-2}
Second Radiation Constant	$c_2 = hc/k$	0.0144 mK
Gravitation Constant	G	6.6720×10^{-11} N m^2 kg^{-2}

Data (abbreviated to 4 decimal places) from CODATA Bulletin No. 11, ICSU CODATA Central Office, 19 Westendstrasse, 6 Frankfurt/Main, Germany. Copies of this bulletin are available from this office.

APPENDIX E

TEMPERATURE SCALES

E1.0 DEFINITION

Temperature is a fundamental unit of measurement which describes the kinetic and potential energies of the atoms and molecules of bodies. When the energies and velocities of the molecules in a body are increased, the temperature is increased whether the body is a solid, liquid, or gas. Thermometers are used to measure temperature. The temperature scale is based on the temperature at which ice, liquid water, and water vapor are all in equilibrium. This temperature is called the triple point of water and is assigned the value 0 °C, 32 °F, and 273.15 K. These three temperature scales are defined as follows:

Celsius. Abbreviation: °C. A temperature scale that registers the freezing point of water as 0 °C and the boiling point as 100 °C under normal atmospheric pressure. Formerly known as "Centigrade." Originally devised by Anders Celsius (1701–1744), a Swedish astronomer.

Fahrenheit. Abbreviation: °F. A temperature scale that registers the freezing point of water as 32 °F and the boiling point as 212 °F under normal atmospheric pressure. Originally devised by Gabriel Fahrenheit (1686–1736), a German physicist residing in Holland; developed use of mercury in thermometry.

Kelvin. Abbreviation: K. An absolute scale of temperature, the zero point of which is approximately –273.15°C. Scale units are equal in magnitude to Celsius degrees. Originally devised by Lord Kelvin, William Thompson, (1824–1907), a British physicist, mathematician, and inventor.

E2.0 COMPARISON

The three temperature scales are graphically compared in Figure E-1.

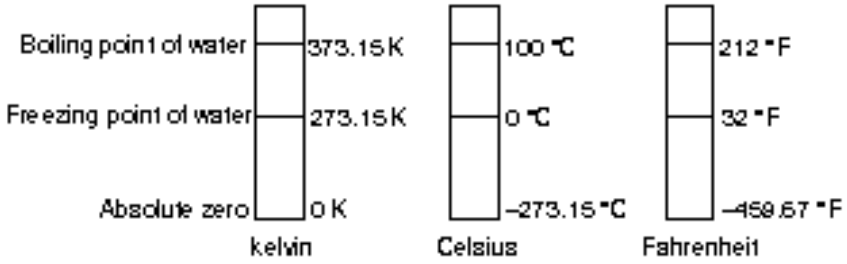


Figure E-1. Temperature Scale Comparison

E3.0 CONVERSIONS

To convert Fahrenheit to Celsius: subtract 32 from °F then divide by 1.8, or:

$$°C = (°F - 32) \div 1.8$$

To convert Celsius to Fahrenheit: multiply °C by 1.8 then add 32, or:

$$°F = (1.8 \times °C) + 32$$

To convert Fahrenheit to kelvin, first convert °F to °C, then add 273.15.

To convert Celsius to kelvin, add 273.15.

Table E-1. Temperature Conversion Table

°F	°C	K	°F	°C	K	°F	°C	K
-459.67	-273.15	0	-292	-180	93.15	-129.67	-89.82	183.33
-454	-270	3.15	-290	-178.89	94.26	-120	-84.44	188.71
-450	-267.78	5.37	-289.67	-178.71	94.44	-119.67	-84.26	188.89
-449.67	-267.59	5.56	-280	-173.33	99.82	-117.67	-83.15	190
-441.67	-263.15	10	-279.67	-173.15	100	-112	-80	193.15
-440	-262.22	10.93	-274	-170	103.15	-110	-78.89	194.26
-439.67	-262.04	11.11	-270	-167.78	105.57	-109.67	-78.71	194.44
-436	-260	13.15	-269.67	-167.59	105.56	-100	-73.33	199.82
-430	-256.67	16.48	-261.67	-163.15	110	-99.67	-73.15	200
-429.67	-256.48	16.67	-260	-162.22	110.93	-94	-70	203.15
-423.67	-253.15	20	-259.67	-162.04	111.11	-90	-67.78	205.37
-420	-251.11	22.04	-256	-160	113.15	-89.67	-67.59	205.56
-419.67	-250.93	22.22	-250	-156.67	116.48	-81.67	-63.15	210
-418.00	-250	23.15	-249.67	-156.48	116.67	-80	-62.22	210.93
-410	-245.56	27.59	-243.67	-153.15	120	-79.67	-62.04	211.11
-409.67	-245.37	27.78	-240	-151.11	122.04	-76	-60	213.15
-405.67	-243.15	30	-239.67	-150.93	122.22	-70	-56.67	216.48
-400	-240	33.15	-238	-150	123.15	-69.67	-56.48	216.67
-399.67	-239.82	33.33	-230	-145.56	127.59	-63.67	-53.15	220
-390	-234.44	38.71	-229.67	-145.37	127.78	-60	-51.11	222.04
-389.67	-234.26	38.89	-225.67	-143.15	130	-59.67	-50.93	222.22
-387.67	-233.15	40	-220	-140	133.15	-58	-50	223.15
-382	-230	43.15	-219.67	-139.82	133.33	-50	-45.56	227.59
-380	-228.89	44.26	-210	-134.44	138.71	-49.67	-45.37	227.78
-379.67	-228.71	44.44	-209.67	-134.26	138.89	-45.67	-43.15	230
-370	-223.33	49.82	-207.67	-133.15	140	-40	-40	233.15
369.67	-223.15	50	-202	-130	143.15	-39.67	-39.82	233.33
-364	-220	53.15	-200	-128.89	144.26	-30	-34.44	238.71
-360	-217.78	55.37	-199.67	-128.71	144.44	-29.67	-34.26	238.89
-359.67	-217.59	55.56	-190	-123.33	149.82	-27.67	-33.15	240
-351.67	-213.15	60	189.67	-123.15	150	-22	-30	243.15
-350	-212.22	60.93	-184	-120	153.15	-20	-28.89	244.26
-349.67	-212.04	61.11	-180	-117.78	155.37	-19.67	-28.71	244.44
-346	-210	63.15	-179.67	-117.59	155.56	-10	-23.33	249.82
-340	-206.67	66.48	-171.67	-113.15	160	-9.67	-23.15	250
-339.67	-206.48	66.67	-170	-112.22	160.93	-4	-20	253.15
-333.67	-203.15	70	-169.67	-112.04	161.11	0	-17.78	255.37
-330	-201.11	72.04	-166	-110	163.15	+0.33	-17.59	255.56
-329.67	-200.93	72.22	-160	-106.67	166.48	8.33	-13.15	260
-328	-200	73.15	-159.67	-106.48	166.67	10	-12.22	260.93
-320	-195.56	77.59	-153.67	103.15	170	10.33	-12.04	261.11
-319.67	-195.37	77.78	-150	-101.11	172.04	14	-10	263.15
-315.67	-193.15	80	-149.67	-100.93	172.22	20	-6.67	266.48
-310	-190	83.15	-148	-100	173.15	20.33	-6.48	266.67
-309.67	-189.82	83.33	-140	-95.96	177.59	26.33	-3.15	270
-300	-184.44	88.71	-139.67	-95.37	177.78	30	-1.11	272.04
-299.67	-184.26	88.89	-135.67	-93.15	180	30.33	-0.93	272.22
-297.67	-183.15	90	-130	-90	183.15	32	0	273.15

APPENDIX F

HANDLING LIQUID HELIUM AND NITROGEN

F1.0 GENERAL

Use of liquid helium (LHe) and liquid nitrogen (LN_2) is often associated with the Hall Measurement System. Although not explosive, there are a number of safety considerations to keep in mind in the handling of LHe and LN_2.

F2.0 PROPERTIES

LHe and LN_2 are colorless, odorless, and tasteless gases. Gaseous nitrogen makes up about 78 percent of the Earth's atmosphere, while helium comprises only about 5 ppm. Most helium is recovered from natural gas deposits. Once collected and isolated, the gases will liquefy when properly cooled. A quick comparison between LHe and LN_2 is provided in Table F-1.

Table F-1. Comparison of Liquid Helium and Liquid Nitrogen

Property	*Liquid Helium*	*Liquid Nitrogen*
Boiling Point @1 atm, in K	4.2	77
Thermal Conductivity (Gas), w/cm–K	0.083	0.013
Latent Heat of Vaporization, Btu/liter	2.4	152
Liquid Density, pounds/liter	0.275	0.78

F3.0 HANDLING CRYOGENIC STORAGE DEWARS

Cryogenic containers (dewars) must be operated in accordance with the manufacturer's instructions. Safety instructions will also be posted on the side of each dewar. Cryogenic dewars must be kept in a well-ventilated place where they are protected from the weather and away from any sources of heat. A typical cryogenic dewar is shown in Figure F-1.

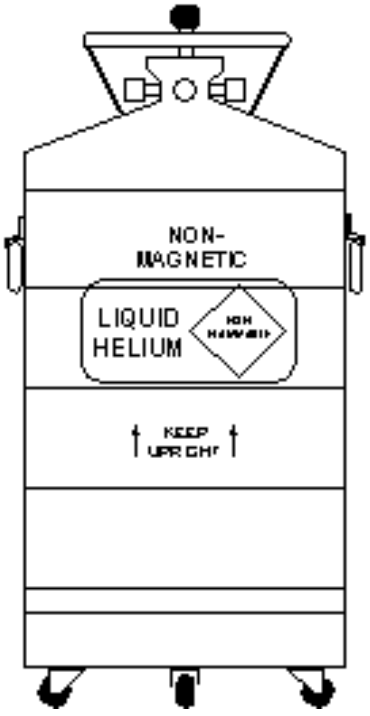


Figure F-1. Typical Cryogenic Storage Dewar

F4.0 LIQUID HELIUM AND NITROGEN SAFETY PRECAUTIONS

Transferring LHe and LN_2 and operation of the storage dewar controls should be in accordance with the manufacturer/supplier's instructions. During this transfer, it is important that all safety precautions written on the storage dewar and recommended by the manufacturer be followed.

WARNING: Liquid helium and liquid nitrogen are potential asphyxiants and can cause rapid suffocation without warning. Store and use in area with adequate ventilation. DO NOT vent container in confined spaces. DO NOT enter confined spaces where gas may be present unless area has been well ventilated. If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical help.

WARNING: Liquid helium and liquid nitrogen can cause severe frostbite to the eyes or skin. DO NOT touch frosted pipes or valves. In case of frostbite, consult a physician at once. If a physician is not readily available, warm the affected areas with water that is near body temperature.

The two most important safety aspects to consider when handling LHe and LN_2 are adequate ventilation and eye and skin protection. Although helium and nitrogen gases are non-toxic, they are dangerous in that they replace the air in a normal breathing atmosphere. Liquid products are of an even greater threat since a small amount of liquid evaporates to create a large amount of gas. Therefore, it is imperative that cryogenic dewars be stored and the MTD System be operated in open and well ventilated areas.

Persons transferring LHe and LN_2 should make every effort to protect eyes and skin from accidental contact with liquid or the cold gas issuing from it. Protect your eyes with full face shield or chemical splash goggles. Safety glasses (even with side shields) are not adequate. Always wear special cryogenic gloves (Tempshield Cryo-Gloves™ or equivalent) when handling anything that is, or may have been, in contact with the liquid or cold gas, or with cold pipes or equipment. Long sleeve shirts and cuffless trousers that are of sufficient length to prevent liquid from entering the shoes are recommended.

F5.0 RECOMMENDED FIRST AID

Every site that stores and uses LHe and LN_2 should have an appropriate Material Safety Data Sheet (MSDS) present. The MSDS may be obtained from the manufacturer/distributor. The MSDS will specify the symptoms of overexposure and the first aid to be used. A typical summary of these instructions is provided as follows.

If symptoms of asphyxia such as headache, drowsiness, dizziness, excitation, excess salivation, vomiting, or unconsciousness are observed, remove the victim to fresh air. If breathing is difficult, give oxygen. If breathing has stopped, give artificial respiration. Call a physician immediately.

If exposure to cryogenic liquids or cold gases occurs, restore tissue to normal body temperature (98.6°F) as rapidly as possible, then protect the injured tissue from further damage and infection. Call a physician immediately. Rapid warming of the affected parts is best achieved by bathing it in warm water. The water temperature should not exceed 105 °F (40 °C), and under no circumstances should the frozen part be rubbed, either before or after rewarming. If the eyes are involved, flush them thoroughly with warm water for at least 15 minutes. In case of massive exposure, remove clothing while showering with warm water. The patient should not drink alcohol or smoke. Keep warm and rest. Call a physician immediately.