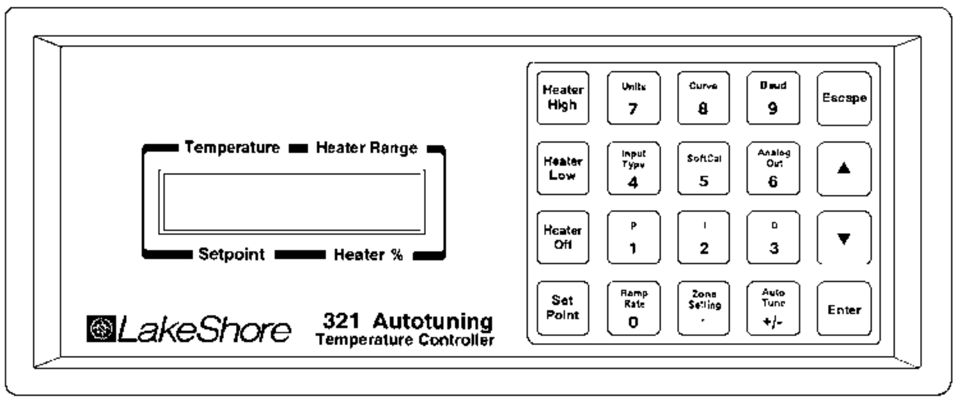
User's Manual

Model 321

Autotuning
Temperature Controller



Includes Coverage For:

Model 321-01 – Silicon Diode
Model 321-02 – Platinum Resistor
Model 321-04 – Thermocouple

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Rev. 1.5 P/N 119-004 **25 March 2004**

LIMITED WARRANTY STATEMENT

WARRANTY PERIOD: ONE (1) YEAR

1. Lake Shore warrants that this Lake Shore product (the "Product") will be free from defects in materials and workmanship for the Warranty Period specified above (the "Warranty Period"). If Lake Shore receives notice of any such defects during the Warranty Period and the Product is shipped freight prepaid, Lake Shore will, at its option, either repair or replace the Product if it is so defective without charge to the owner for parts, service labor or associated customary return shipping cost. Any such replacement for the Product may be either new or equivalent in performance to new. Replacement or repaired parts will be warranted for only the unexpired portion of the original warranty or 90 days (whichever is greater).
2. Lake Shore warrants the Product only if it has been sold by an authorized Lake Shore employee, sales representative, dealer or original equipment manufacturer (OEM).
3. The Product may contain remanufactured parts equivalent to new in performance or may have been subject to incidental use.
4. The Warranty Period begins on the date of delivery of the Product or later on the date of installation of the Product if the Product is installed by Lake Shore, provided that if you schedule or delay the Lake Shore installation for more than 30 days after delivery the Warranty Period begins on the 31st day after delivery.
5. This limited warranty does not apply to defects in the Product resulting from (a) improper or inadequate maintenance, repair or calibration, (b) fuses, software and non-rechargeable batteries, (c) software, interfacing, parts or other supplies not furnished by Lake Shore, (d) unauthorized modification or misuse, (e) operation outside of the published specifications or (f) improper site preparation or maintenance.
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LIMITED WARRANTY STATEMENT (Continued)

9. EXCEPT TO THE EXTENT ALLOWED BY APPLICABLE LAW, THE TERMS OF THIS LIMITED WARRANTY STATEMENT DO NOT EXCLUDE, RESTRICT OR MODIFY, AND ARE IN ADDITION TO, THE MANDATORY STATUTORY RIGHTS APPLICABLE TO THE SALE OF THE PRODUCT TO YOU.

CERTIFICATION

Lake Shore certifies that this product has been inspected and tested in accordance with its published specifications and that this product met its published specifications at the time of shipment. The accuracy and calibration of this product at the time of shipment are traceable to the United States National Institute of Standards and Technology (NIST); formerly known as the National Bureau of Standards (NBS).

FIRMWARE LIMITATIONS

Lake Shore has worked to ensure that the Model 321 firmware is as free of errors as possible, and that the results you obtain from the instrument are accurate and reliable. However, as with any computer-based software, the possibility of errors exists.

In any important research, as when using any laboratory equipment, results should be carefully examined and rechecked before final conclusions are drawn. Neither Lake Shore nor anyone else involved in the creation or production of this firmware can pay for loss of time, inconvenience, loss of use of the product, or property damage caused by this product or its failure to work, or any other incidental or consequential damages. Use of our product implies that you understand the Lake Shore license agreement and statement of limited warranty.

FIRMWARE LICENSE AGREEMENT

The firmware in this instrument is protected by United States copyright law and international treaty provisions. To maintain the warranty, the code contained in the firmware must not be modified. Any changes made to the code is at the user's risk. Lake Shore will assume no responsibility for damage or errors incurred as result of any changes made to the firmware.

Under the terms of this agreement you may only use the Model 321 firmware as physically installed in the instrument. Archival copies are strictly forbidden. You may not decompile, disassemble, or reverse engineer the firmware. If you suspect there are problems with the firmware, return the instrument to Lake Shore for repair under the terms of the Limited Warranty specified above. Any unauthorized duplication or use of the Model 321 firmware in whole or in part, in print, or in any other storage and retrieval system is forbidden.

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF TABLES

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CHAPTER 1

INTRODUCTION

1.0 GENERAL

This chapter provides an introduction to the Model 321 Autotuning Temperature Controller. The Model 321 was designed and manufactured in the United States of America by Lake Shore Cryotronics, Inc. The Model 321 Autotuning Temperature Controller is a microprocessor-based instrument with digital control of a variable current output. The Model 321 features include the following:

- Three Models Available:
  - Model 321-01 – Silicon Diode
  - Model 321-02 – Platinum Resistor 100 Ω
  - Model 321-04 – Thermocouple
- Thermometry:
  - Single Sensor Input
  - Differential Input Allows Four-Lead Sensor Measurement
  - Nonvolatile Memory Space to Store One Precision Calibration Option Curve
  - Nonvolatile Memory Space to Store One SoftCal™ Curve
- Five Tuning Modes:
  - Autotuning P
  - Autotuning PI
  - Autotuning PID
  - Manual
  - Zone (10 Temperature Zones)
- Control:
  - Control Stability to ±0.1 K
  - Three-Term PID Control Loop
  - 25 Watt Heater Power with Two Ranges
  - Setpoint Ramping
- Interface:
  - Backlit 2 Row by 16 Character LCD for High Visibility
  - Display of Sensor Temperature in K, °C, or sensor units in volts, ohms
  - Serial Interface (RS-232C Electrical Format)
  - Analog Output Corresponding to Temperature

If you have just received your new Model 321, please proceed to Chapter 2 and become familiar with the installation instructions. Operation is described in Chapter 3. Remote operation is covered in Chapter 4. Options and accessories are detailed in Chapter 5. Service and calibration procedures are provided in Chapter 6. For reference, various appendices are included.

We welcome your comments concerning this manual. Although every effort has been made to keep it free from errors, some may occur. When reporting a specific problem, please describe it briefly and include the applicable paragraph, figure, table, and page number. Send comments to Lake Shore Cryotronics, Attn: Technical Publications, 575 McCorkle Blvd, Westerville, Ohio 43082-8888. The material in this manual is subject to change without notice.

Due to the Lake Shore commitment to continuous product improvement, it is reasonable to expect that modifications will be made in the Model 321 software with time. Some of these changes are the result of Customer feedback regarding operation on various cryogenic systems. We encourage you to contact us with any observations or suggestions which you have regarding the use of this controller. Also, *please return your warranty card* to ensure that any software updates are sent to you.

1.1 DESCRIPTION

The Model 321 is a microcontroller-based autotuning temperature controller which provides a simple, low-cost answer to basic control needs. There are three models: the 321-01 for Silicon Diode Temperature Sensors, the 321-02 for Platinum Resistors, and the 321-04 for Thermocouples.

The controller displays the temperature in K, °C or sensor units in volts (V), millivolts (mV), or ohms (Ω). The 2 x 16 LCD simultaneously displays temperature, setpoint, heater range, and heater % current.

Precision thermometry is the most basic building block of any digital controller and is necessary for stable, accurate control. Careful analog design provides the Model 321 with stable and repeatable measurements. A differential input allows for a four-lead measurement of the sensor signal. A high resolution A/D converter digitizes the signal for use in thermometry, control, and autotuning.

The control software in the Model 321 compares the measured value of the control sensor to the desired control setpoint and acts with three term (PID) function to minimize the difference. Control parameters can be entered in any one of five tuning modes: Autotuning P, Autotuning PI, Autotuning PID, Manual, and Zone.

Autotuning represents the Lake Shore commitment to bringing convenience and performance to the cryogenic measurement and control market. Autotuning utilizes information gathered during setpoint changes to automatically optimize the control parameters.

The Model 321 allows the user to program up to 10 custom temperature zones where the controller will automatically use pre-programmed PID settings and heater range.

The ramping feature permits the user to set the rate that the setpoint increases or decreases when the setpoint is changed. If this feature is combined with the zone feature, the user could do a ramp through all 10 zones from ≈2 K to room temperature by only changing the setpoint. The controller will change the PID and heater range settings as the temperature setpoint passes through the different zones.

Two heater ranges, with the high providing 25 watts and the low 2.5 watts, accommodate a variety of cryogenic cooling systems. The power output of the Model 321 is a quiet, variable DC current to ensure as little noise coupling as possible between the heater and experiment.

The Serial Interface provides remote access to data from the Model 321 and allows setting of most front panel functions. The Serial Interface is fully compatible with the older Model 320 (with the exception of the added heater range), minimizing the need for reprogramming.

Model 321 thermometry accuracy can be enhanced by using a Lake Shore calibrated sensor and 8000 Series Precision Calibration Option, or by the use of SoftCal™.

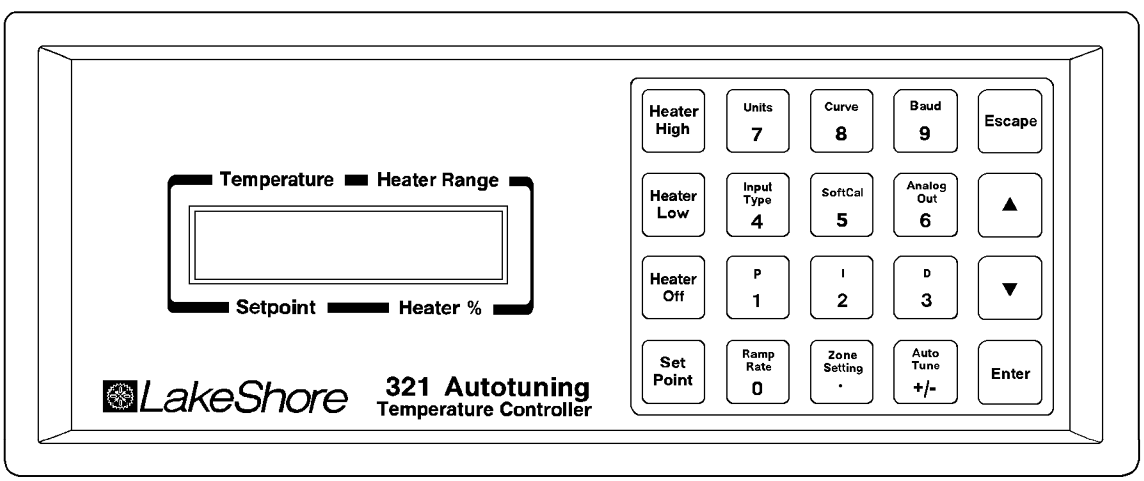

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Figure 1-1. Model 321 Temperature Controller Front Panel

Table 1-1. Electronic Information for Various Sensors and Temperature Ranges

Model No.	321-01	321-02	321-04 *
Sensor Type	Silicon diode	100 Ω Platinum RTD	Thermocouple
Sensor Temp Coefficient	Negative	Positive	Positive
Sensor Units	Volts (V)	Ohms (Ω)	Millivolts (mV)
Controller Temp. Range	1.4 – 475 K †	14 K – 800 K	–273 – 1000 °C †
Input Range	0 – 2.5 V	0 – 300 Ω	±45 mV
Sensor Excitation	10 µA ±0.05% constant current	500 µA ±0.01% constant current	N/A
The following specifications reflect operational characteristics with the specified Lake Shore Sensor.			
Example Lake Shore Sensor	DT-470-C0	PT-103	Ch-AuFe 0.07%
Sensor Temp. Range	1.4 - 475 K	30 - 800 K	1.4 - 325 K
Standard Sensor Curve	Curve 10	DIN 43760	NIST generated
Typical Sensor Sensitivity	–30 mV/K at 4.2 K –1.9 mV/K at 77 K –2.4 mV/K at 300 K –2.2 mV/K at 475 K	0.19 Ω/K at 30 K 0.42 Ω/K at 77 K 0.39 Ω/K at 300 K 0.33 Ω/K at 800 K	16 µV/K at 4.2 K 20 µV/K at 300 K
Measurement Resolution			
Sensor Units	0.04 mV	5 mΩ	1.5 µV
Temperature Equivalence	1.3 mK at 4.2 K 21 mK at 77 K 16 mK at 300 K 18 mK at 475 K	26 mK at 30 K 12 mK at 77 K 13 mK at 300 K 15 mK at 800 K	90 mK at 4.2 K 75 mK at 300 K
Sensor Unit Display Resolution	0.1 mV to 1 mV	0.01 Ω to 0.1 Ω	2 µV
Measurement Accuracy	±0.2 mV ±0.02% RDG	±20 mΩ ±0.05% RDG	±4 µV ±0.05% RDG
Temperature Accuracy with Calibrated Sensor and 8001 Precision Option §	±0.1 K at 4.2 K ±0.3 K at 77 K ±0.2 K at 300 K ±0.2 K at 475 K	±0.2 K at 30 K ±0.2 K at 77 K ±0.3 K at 300 K ±0.6 K at 800 K	±0.8 K at 4.2 K ‡ ±0.4 K at 300 K
Measurement Temp. Coefficient			
Sensor Units (%RDG/°C)	±0.01%	±0.01%	±0.018%
Temperature Equivalence	±8 mK/C° at 4.2 K ±77 mK/°C at 77 K ±33 mK/°C at 300 K ±9 mK/°C at 475 K	±33 mK/°C at 30 K ±22 mK/°C at 77 K ±64 mK/°C at 300 K ±171 mK/°C at 800 K	±200 mK/°C at 4.2 K ±110 mK/°C at 300 K
Setpoint Display Resolution in Sensor Units	0.1 mV to 1 mV	0.01 Ω to 0.1 Ω	2 µV

* Thermocouple data are for uncompensated inputs.

† Dependent on sensor type.

‡ No Model 8001 Precision Calibration Option is available for thermocouples. Error listed is for the controller only.

§ Includes all sensor and controller errors.

Table 1-2. Model 321 Specifications

Thermometry:	
Number of Inputs:	One
Sensor Types:	Model 321-01 – Silicon Diode Model 321-02 – Platinum RTD Model 321-04 – Thermocouple
Accuracy:	Based on Model and Sensor Type (Refer to Table 1-1)
Update Rate:	1 second
Precision Curve Storage:	One 97 point curve entered via Serial Interface
SoftCal™:	Entered in voltage or temperature
Control:	
Control Type:	Digital, three term PID with Autotuning
Automatic Control Mode:	P, PI, or PID control, user selectable
Manual Control Mode:	Gain (**P**roportional) 1-999, Reset (**I**ntegral) 1-999 sec., and Rate (**D**erivative) 0 - 200%
Control Stability:	Better than ±0.1 K in a properly designed system for diode and platinum sensors
Setpoint Resolution:	0.1 K or °C
Heater Output Type:	Analog DC Current Source
Heater Setting Resolution:	15 bit
Heater Ranges:	25 W, 2.5 W
Max Power To Heater:	25 W
Max Current To Heater:	1 A
Heater Output Compliance:	25 V
Heater Load:	25 Ω, 25 W required for full power
Heater Noise:	0.005% of full scale power
Ramp Rate:	0.1 to 99.9 K/min
Analog Output:	
Default Settings:	
Range:	0 to 10 volts at 1 mA max
Default Output:	10 mV/K, 0 – 10 V, 0 – 1000 K
Resolution:	1.22 mV, 0.122 K
Accuracy:	±0.04% of full scale output + measurement accuracy
Programmable Settings:	
Range:	0 V = user defined minimum temperature in kelvin 10 V = user defined maximum temperature in kelvin Minimum temperature resolution is 0.1 K
Front Panel:	
Display:	2 row by 16 character LCD
Display Units:	Temperature in K or °C. Sensor units in volts (321-01), ohms (321-02), or millivolts (321-04)
Temperature Resolution:	0.1 K or °C
Sensor Units Resolution:	5 digits
Keypad:	Numeric keypad
Interface:	
Serial Interface:	300 or 1200 baud, RJ-11 connector (RS-232C electrical standard)
General:	
Ambient Temperature Range:	20 to 30 °C (68 °F to 86 °F), or with reduced accuracy in range 15 °C to 35 °C (59 °F to 95 °F)
Power Requirements:	90 – 110, 105 – 125, or 210 – 250 VAC, 50 or 60 Hz; 65 watts
Size:	217 mm wide × 90 mm high × 317 mm deep (8.5 × 3.5 × 12.5 inches), half-rack package
Weight:	2.7 kilograms (6 pounds)

1.2 CONTROL FUNDAMENTALS AND AUTOTUNE

The Model 321 has several features which aid in temperature control of a cryogenic system. These include standard built-in curves along with the ability to store a single 97 point curve, Serial Interface, a differential input allowing true four-wire sensor readings, 2 row by 16 character LCD for high visibility, 25 Watt DC current output with short circuit protection of the output, and digital filtering. These and other features are discussed in detail throughout this manual.

The immediate predecessor of the Model 321 was the Model 320. The Model 320 (along with the Model 330) were the first cryogenic controllers with an Autotuning feature. The Autotuning algorithm determines the settings of controller gain (**P**roportional), reset (**I**ntegral), and rate (**D**erivative) by observing the time response of the system upon changes in setpoint under either P, PI, or PID control.

Since this is a digital system, there are inherent limitations associated with digital control and Autotuning. First, there is the limitation that any control system is inherently unstable if the sampling rate (frequency) is not greater than twice the system bandwidth (inverse of system time constant). This is known as the Nyquist criterion. With the current technology used in this controller, i.e., sampling frequency, etc., digital control is possible for cryogenic system with time constants near or greater than one second. Fortunately, most cryogenic systems which operate above 1 kelvin will have time constants that meet this criteria.

The Autotuning function requires that the system time response be measured as a result of a change in temperature setpoint. In order to get meaningful data for determining the PID parameters, several points on this response curve must be measured. Consequently, for cryogenic systems where step responses are less than ≈5 seconds (where the number of measured points is small), correct determination of the PID parameters is difficult and better temperature control will normally be achieved by manual selection of gain and reset (rate will not normally be required). Fortunately, fast cryogenic systems are not difficult to tune manually.

For slower systems with longer time constants (which can be very difficult to tune manually), Autotuning can obtain enough information on a step change to characterize the system and determine proper values of gain, reset, and rate.

There may be other conditions where you will prefer to stay with manual settings. For example, when a closed cycle refrigerator has very little mass on its second stage and is near its bottom temperature, attempts at Autotuning may give poor results for control settings due to the large inherent temperature fluctuations associated with the cooling cycle. Adding mass to the second stage smoothes out these fluctuations, but lengthens cool-down time.

Lake Shore has simplified the input of the rate time constant in this controller to correspond to a percentage of the reset time constant, i.e., 0 to 200%. Consequently, if you are in the manual mode and you set RATE at 100%, on any change in RESET, the controller will automatically calculate the RESET time constant (999/RESET) and set the RATE time constant at 1/8 of the RESET time constant. This is one-half the conventional Zeigler-Nichols setting for rate and results in a smaller overshoot of a given setpoint. Therefore, once RATE is set as a percent, you do not have to worry about updating its value with setpoint changes resulting in new PI settings. Obviously, if you prefer less RATE, set the rate setting at something less than 100%. Remember, however, in many cryogenic systems, rate will not be required anyway, and is consequently set at 0%.

An application note titled *Fundamentals for Usage of Cryogenic Temperature Controllers* is included with Appendix D. This application note should be read in detail if you are not familiar with cryogenic temperature controllers.

1.3 PRECISION CALIBRATION OPTIONS

The Lake Shore Precision Calibration Option allow the user to convert calibrated sensor data into breakpoint pairs readable by the controller program. The Precision Calibration Option is available in three forms. The Model 8000 loads the breakpoint pairs on a floppy disk in ASCII format for Customer downloading. The Model 8001 puts the breakpoint pairs in a NOVRAM that is installed at the factory. Finally, the Model 80020-05 is a NOVRAM that is installed in the field.

The Precision Calibration Option improves the specified accuracy to 0.1K or better over a given calibration range for DT-400 Series Silicon Diode Sensors. Accuracy for other sensors depends on the sensor type and calibration range.

A copy of the break point information containing sensor type, sensor serial number, maximum allowable error, break point number, voltage (or resistance), temperature and temperature error is supplied. A second sheet containing only the break point temperatures and voltages is also supplied.

The Precision Calibration Option Table is a piecewise linear interpolation based on the sensor calibration. Optimum break points are determined by an iterative procedure using weighted linear least squares defined by either a maximum number of break points allowed or a maximum allowable error. The break point voltages are the values from the least squares linear equations and will therefore differ from the calibration data. Differences between voltages from the input table and the break point voltage are converted to a corresponding error in temperature by dividing the voltage difference by the sensitivity. Temperature errors by this method will be considerably less than by linear interpolation between calibration data points.

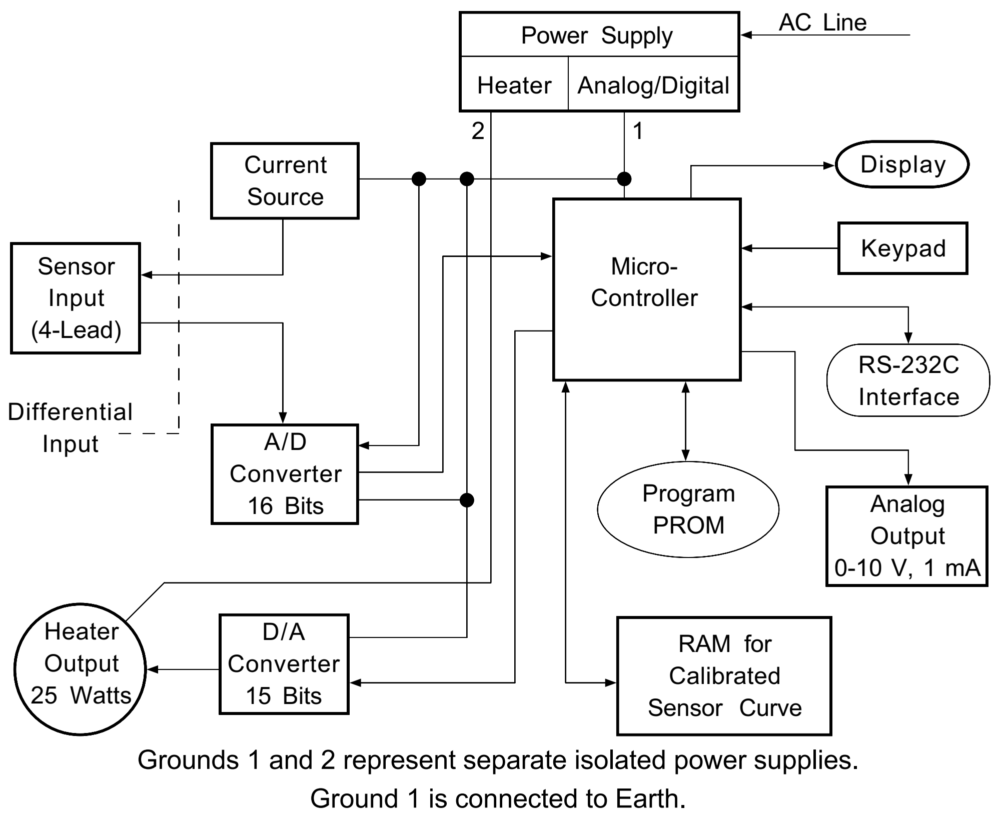


Figure 1-2. Model 321 Block Diagram

1.4 SAFETY SUMMARY

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

The Model 321 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 below may pose a hazard to the operator and surrounding area.

- Temperature: 5° to 40° C.
- Maximum relative humidity: 80% for temperature up to 31° C decreasing linearly to 50% at 40° C.
- Power supply voltage fluctuations not to exceed ±10% of the nominal voltage.

Ground The Instrument
To minimize shock hazard, the instrument chassis and cabinet must be connected to an electrical ground. The instrument is equipped with a three-conductor AC power cable. The power cable must either be plugged into an approved three-contact electrical outlet or used with 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 the instrument in the presence of flammable gases or fumes. Operation of any electrical instrument in such an environment constitutes a definite safety hazard.

Keep Away From Live Circuits
Operating personnel must not remove instrument covers. Component replacement and internal adjustments must be made by 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
Because of the danger of introducing additional hazards, do not install substitute parts or perform any unauthorized modification to the instrument. Return the instrument to an authorized Lake Shore Cryotronics, Inc. representative for service and repair to ensure that safety features are maintained.

1.5 SAFETY SYMBOLS

Direct current (power line).

Alternating current (power line).

Alternating or direct current (power line).

3~ Three-phase alternating current (power line).

Earth (ground) terminal.

Protective conductor terminal.

Frame or chassis terminal.

On (supply)

Off (supply)

Equipment protected throughout by double insulation or reinforced insulation (equivalent to Class II of IEC 536 - see Annex H).

Caution: High voltages; danger of electric shock. Background color: Yellow; Symbol and outline: Black.

Caution or Warning - See instrument documentation. Background color: Yellow; Symbol and outline: Black.

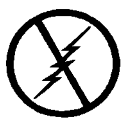
1.6 ELECTROSTATIC DISCHARGE

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.

1.6.1 Identification of Electrostatic Discharge Sensitive Components

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

1.6.2 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. Deenergize 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.

CHAPTER 2

INSTALLATION

2.0 GENERAL

This chapter provides general installation instructions for the Model 321 Autotuning Temperature Controller. Inspection and unpacking instructions are provided in Paragraph 2.1. Repackaging for shipment instructions are provided in Paragraph 2.2. A definition of rear panel controls is provided in Paragraph 2.3. Environmental requirements are detailed in Paragraph 2.4. Grounding and shielding requirements are discussed in Paragraph 2.5. Sensor input settings are detailed in Paragraph 2.6. Sensor installation recommendations are detailed in Paragraph 2.7. Sensor curve selection is detailed in Paragraph 2.8. The Precision Calibration Option is discussed in Paragraph 2.9. Heater setup is detailed in Paragraph 2.10. Rack mounting is discussed in Paragraph 2.11. Finally, the power up sequence, configuration, and errors are provided in Paragraph 2.12.

2.1 INSPECTION AND UNPACKING

Inspect shipping containers for external damage. All claims for damage (apparent or concealed) or partial loss of shipment must be made in writing to Lake Shore within five (5) days from receipt of goods. If damage or loss is apparent, please notify the shipping agent immediately.

Open the shipping containers. A packing list is included with the system to simplify checking that the instrument, sensor, accessories, and manual were received. Please use the packing list and the spaces provided to check off each item as the instrument is unpacked. Inspect for damage. Be sure to inventory all components supplied before discarding any shipping materials. If there is damage to the instrument in transit, be sure to file proper claims promptly with the carrier and insurance company. Please inform Lake Shore of such filings. In case of parts or accessory shortages, advise Lake Shore immediately. Lake Shore cannot be responsible for any missing parts unless notified within 60 days of shipment. The standard Lake Shore Warranty is included on the A Page (immediately behind the title page) of this manual.

2.2 REPACKAGING FOR SHIPMENT

If it is necessary to return the Model 321, sensor, or accessories for repair or replacement, a Return Goods Authorization (RGA) number must be obtained from Technical Service in the United States, or from the authorized sales/service representative from which the product was purchased. Instruments may not be accepted without a RGA number. When returning an instrument for service, the following information must be provided before Lake Shore can attempt any repair.

1. Instrument model and serial number.
2. User name, company, address, and phone number.
3. Malfunction symptoms.
4. Description of system.
5. Returned Goods Authorization (RGA) number.

Wrap instrument in a protective bag and use original spacers to protect controls. Repack the system in the LSCI shipping carton (if available) and seal it with strong paper or nylon tape. Affix shipping labels and FRAGILE warnings. Write the RGA number on the outside of the shipping container or on the packing slip.

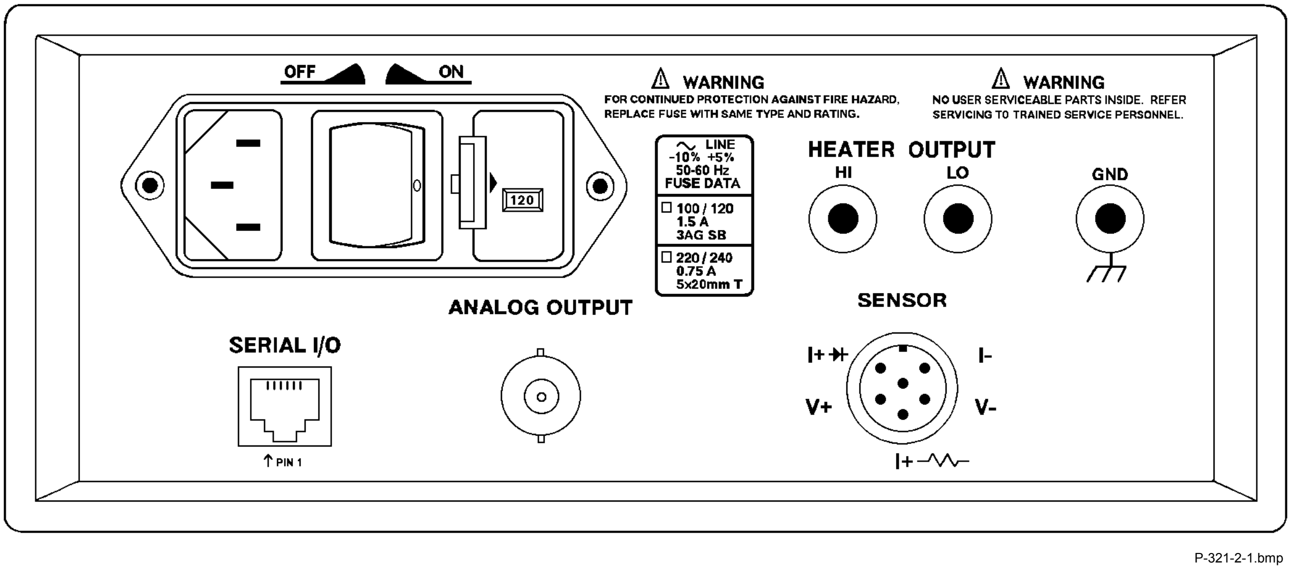


Figure 2-1. Typical Model 321 Rear Panel

2.3 DEFINITION OF REAR PANEL CONNECTIONS

This paragraph provides a description of the Model 321 rear panel connections. The rear panel consists of the power and fuse assembly, Serial I/O Connector, Analog Output Connector, Sensor Input Connector, and Heater Output Connector.

CAUTION: Verify that the AC Line Voltage shown in the window on the fuse drawer corresponds to that marked on the rear panel, and that both these settings are appropriate for the intended AC power input. Also remove and verify the proper fuse is installed before inserting the power cord and turning on the instrument.

CAUTION: Always turn off the instrument before making any rear panel connections. This is especially critical when making sensor to instrument connections.

Power and Fuse Assembly. The power and fuse assembly is the primary entry and control point for AC power to the unit. The assembly consists of two parts: power line jack and the fuse drawer. The line cord is connected to the power line jack. Power to the unit is controlled by the power switch located on the rear panel. Press the right side of the switch for On (**I**) and the left side for Off (**O**). The fuse drawer contains a 1.5 A 3AG Slow Blow fuse for 100 – 120 VAC or a 0.75 A 5×20 mm T fuse for 220 – 240 VAC. Refer to Paragraph 6.2 for changing power settings and fuse rating.

Serial I/O Connector. The Serial I/O (Input/Output) Connector accepts a standard RJ-11 telephone connector. To connect to the User's computer, the optional Model 2001 RJ-11 to RJ-11 10-foot Cable, Model 2002 RJ-11 to DB-25 Adapter, and Model 2003 RJ-11 to DE-9 Adapter are available as accessories from Lake Shore. Refer to Chapter 4 for Serial Interface setup and commands. Refer to Chapter 5 for further information on the serial interface connector accessories.

Analog Output BNC Connector. The analog output is available on one Bayonet Nut Connector (BNC). The signal is on the center conductor while the outer casing is for ground. In the default setting, the analog output provides a 0 – 10 volt output corresponding to 0 – 1000 K (10 mV/K). The user can also redefine the scaling of this output. Refer to Chapter 3 for further information.

Sensor Input Connector. A sensor input connector is provided for attaching temperature sensor to the unit. Always turn off the instrument before connecting the sensor. Refer to Paragraph 2.6 for further information on setting up the sensor input.

Heater Connectors. Banana jacks provide HI, LO, and GND heater connections (25 Ω, 25 W Heater recommended). Refer to Paragraph 2.10 for further information on heater connection setup.

2.4 ENVIRONMENTAL REQUIREMENTS

The Model 321 is intended for laboratory use. In order to meet and maintain specifications, the Model 321 should be operated at an ambient temperature range of 20 to 30 °C (68 to 86 °F). The unit may be operated within the range of 15 to 35 °C (59 to 95 °F) with reduced accuracy.

WARNING: To prevent electrical fire or shock hazards, do not expose this instrument to rain or excess moisture.

2.5 GROUNDING AND SHIELDING

To protect operating personnel, the National Electrical Manufacturer's Association (NEMA) recommends, and some local codes require, instrument panels and cabinets be grounded. This instrument is equipped with a three-conductor power cable which, when plugged into an appropriate receptacle, grounds the instrument.

Grounding and shielding of signal lines are major concerns when setting up any precision instrument or system. The Model 321 allows 4-wire measurement of diode voltage and resistance. To prevent inaccurate measurements, diode and resistive sensor leads must be isolated from earth ground. Thermocouple sensors, however, may be grounded. Shield sensor cables whenever possible. Attach the shields to the shield pin provided in the connector. Do not attach the shield at the sensor end.

The heater output is isolated from earth ground. To prevent heater noise coupling into the measurement, do not allow the heater output to contact earth ground. Earth ground (GND) is provided on the rear panel for shielding purposes only.

Digital logic in the Model 321 is tied directly to earth ground for interface communications. The sensor lines and digital communication lines should be separated whenever possible to prevent excess noise in the measurement.

2.6 SENSOR INPUT SETTINGS

The sensor input type is established at the factory before shipping. Sensor input type is configured by setting DIP switches S1 and S2 on the main PCB inside the unit. If you wish to check the DIP switch settings, the configurations are as follows.

DIP Switch S1 *

	Silicon Diode (Model 321-01)	Platinum (Model 321-02)	Thermocouple (Model 321-04)
S1-1	Closed	Open	Open
S1-2	Open	Closed	Open
S1-3	Open	Open	Closed
S1-4	Open	Open	Closed

DIP Switch S2 *

	Silicon Diode (Model 321-01)	Platinum (Model 321-02)	Thermocouple (Model 321-04)
S2-1	Closed	Open	Open
S2-2	Open	Closed	Open
S2-3	Open	Open	Closed
S2-4	Open	Open	Closed

**To change sensor input type, DIP switches on S1 and S2 must be switched identically.*

To change the DIP Switch settings, refer to Paragraph 6.7. The Model 321 must be recalibrated when switched between sensor input types.

Diode and Platinum connections are defined in Paragraph 2.7.1. Thermocouple connections are described in Paragraph 2.7.2. Finally, thermocouple compensation is discussed in Paragraph 2.7.2.1.

2.7 SENSOR INSTALLATION

Abbreviated sensor installation recommendations for the Model 321 are included in this paragraph. Please refer to the Lake Shore Product Catalog or Sensor Guide for installation details and sensor specifications. Call Lake Shore for copies of application notes or with questions or comments concerning sensor installation. The following are general recommendations on sensor installation:

1. Do not ground the sensor.
2. Shield the leads and connect the shield wire to SHIELD on the screw terminal connector only. Do not connect shield at the other end of the cable.
3. Keep leads as short as possible.
4. Use twisted-pair wire. Use of Lake Shore Duo-Twist™ wire (or equivalent) for two-wire, or Quad-Twist™ wire (or equivalent) for four-wire applications, is strongly recommended.
5. Lead wires should be thermally anchored.

Sensor installation is provided in two parts. Diode (Model 321-01) and Platinum (Model 321-02) sensor connections are detailed in Paragraph 2.7.1. Thermocouple (Model 321-04) sensor connections are detailed in Paragraph 2.7.2. Finally, sensor input error messages are described in Paragraph 2.7.3.

2.7.1 Diode (Model 321-01) and Platinum (Model 321-02) Connections

The Model 321 has a rear panel 6-pin input connector for silicon diode (Model 321-01) or platinum resistance (Model 321-02) sensors. The lead connections are defined in Table 2-1.

Table 2-1. Diode or Platinum Input Connections

Terminal	Description
1	– Current
2	– Voltage
3	+ Current 500 µA (platinum)
4	+ Voltage
5	+ Current 10 µA (diodes)
6	Shield

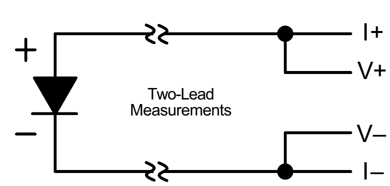
Paragraph 2.7.1.1 discusses two-lead versus four-lead measurements. Paragraph 2.7.1.2 discusses connecting leads. Sensor mounting is covered in Paragraph 2.7.1.3. Finally, Paragraph 2.7.1.4 describes the effect of measurement errors due to AC noise.

2.7.1.1 Two-Lead Versus Four-Lead Measurements

The use of a four-lead connection is highly recommended for two lead resistive elements and diodes to avoid introducing current/resistive (IR) drops in the voltage sensing pair which translates into a temperature measurement error. In the two lead measurement scheme, the leads used to measure the sensor voltage are also the current carrying leads. The resultant voltage measured at the instrument is the sum of the temperature sensor voltage and the IR voltage drop within the two current leads. Since in a cryogenic environment, the flow of heat down the leads can be of critical concern, normally wire of small diameter and significant resistance per foot is preferred to minimize this heat flow. Consequently, a voltage drop within the leads can be present.

1. Two-Lead Measurements

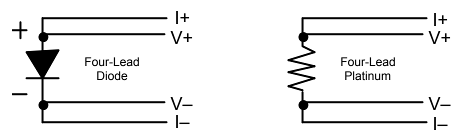
Sometimes system constraints dictate the use of two-lead measurements. Connect the positive terminals (V+ and I+) together and the negative terminals (V– and I–) together at the instrument, then run two leads to the sensor.



Some loss in accuracy can be expected since the voltage measured at the voltmeter becomes the sum of the sensor voltage and the voltage drop across the connecting leads. The exact measurement error will depend on sensor sensitivity and variations resulting from changing temperature. For example, a 10 Ω lead resistance will result in a 0.1 mV voltage error. The resultant temperature error at liquid helium temperature is only 3 mK, but, because of the diode's lower sensitivity (dV/dT) at higher temperatures, it becomes 10 mK at liquid nitrogen temperature.

2. Four-Lead Measurements

All sensors, including both two-lead and four-lead devices, can be measured in a four-lead configuration to eliminate the effects of lead resistance. The exact point at which the connecting leads are soldered to the two-lead sensor normally results in a negligible temperature uncertainty.



The four-lead measurement configuration should always be used with Series PT-100 Platinum Sensors being attached to the Model 321-02.

2.7.1.2 Connecting Leads To The Sensor

An excessive heat flow through the connecting leads to any temperature sensor can create a situation where the active sensing element is at a different temperature than the sample to which the sensor is mounted. This is then reflected as a real temperature offset between what is measured and the true sample temperature. Such temperature errors can be eliminated by proper selection and installation of the connecting leads.

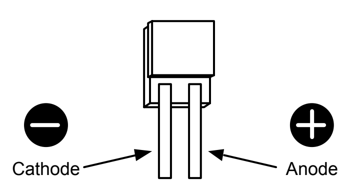
In order to minimize any heat flow through the leads, the leads should be of small diameter and low thermal conductivity. Phosphor-bronze or Manganin wire is commonly used in sizes 32 or 36 AWG. These wires have a fairly low thermal conductivity yet the electrical resistivities are not so large as to create any problems in measurements.

Lead wires should also be thermally anchored at several temperatures between room temperature and cryogenic temperatures to guarantee that heat is not being conducted through the leads to the sensor.

2.7.1.3 Sensor Mounting

Before installing a diode sensor, identify which lead is the anode and which is the cathode. When viewed with the base down and with the leads towards the observer, the positive lead (anode) is on the right and the negative lead (cathode) is on the left. The Lake Shore DT-470-SD silicon diode sensor lead configuration is shown below. For other sensors, read the accompanying literature or consult the manufacturer to ensure positive identification of sensor leads. Be sure the lead identification remains clear even after installation of the sensor. It is also a good idea to record the serial number and location of the sensor.

DT-470-SD
Diode Sensor Leads



On the DT-470-SD, the base is the largest flat surface. It is sapphire with gold metallization over a nickel buffer layer. The base is electrically isolated from the sensing element and leads, and all thermal contact to the sensor should be made through the base. A thin braze joint around the sides of the SD package is electrically connected to the sensing element. Contact to the sides with any electrically conductive material must be avoided.

When installing the sensor, verify there are no electrical shorts or current leakage paths between the leads or between the leads and ground. If IMI-7031 varnish or epoxy is used, it may soften varnish-type lead insulations so that high resistance shunts appear between wires if *sufficient time for curing is not allowed*. Teflon® spaghetti tubing is useful for sliding over bare leads when the possibility of shorting exists. Also, avoid putting stress on the device leads and allow for the thermal contractions that occur during cooling which could fracture a solder joint or lead if installed under tension at room temperature.

For temporary mounting in cold temperature applications, a thin layer of Apiezon® N Grease may be used between the sensor and sample to enhance the thermal contact under slight pressure. The preferred method for mounting the DT-470-SD sensor is the Lake Shore CO Adapter.

CAUTION: Lake Shore will not warranty replace any device damaged by a user-designed clamp or damaged by solder mounting.

If semi-permanent mountings are desired, the use of Stycast® epoxy can replace the use of Apiezon® N Grease. (Note: Do not apply Stycast epoxy over the DT-470-SD package. Stress on the sensor can cause shifts in the readings.) In all cases, the mounting of the sensor should be periodically inspected to verify that good thermal contact to the mounting surface is maintained.

For the Model 321-02, Series PT-100 Platinum Sensors follow the same procedures for diode type sensors. The difference is Platinum sensors have no lead polarity and some of the materials used at cold temperatures will not tolerate the high temperature range of the Platinum sensor.

2.7.1.4 Measurement Errors Due To AC Noise

Poorly shielded leads or improperly grounded measurement systems can introduce AC noise into the sensor leads. For diode sensors, the effect of the AC noise appears as a shift in the DC voltage measurement due to the non-linear current/voltage characteristics of the diode. When this occurs, the DC voltage measured will be too low and the corresponding temperature indication will be high. The resulting measurement error can approach several tenths of a kelvin.

For Series PT-100 Platinum Sensors, the noise will not cause a DC shift, but it can still degrade the accuracy of the measurement. To determine if this is a problem in your measurement system, perform either of the two following procedures.

1. Place a capacitor across the diode to shunt the induced AC currents. The size of the capacitor will depend on the frequency of the noise. If the noise is related to the power line frequency, use a 10 μF capacitor. If AC-coupled digital noise is suspected (digital circuits or interfaces), then use a capacitor between 0.1 to 1 μF. In either case, if the resultant DC voltage measured is observed to increase, there is induced noise in your measurement system.
2. Measure the AC voltage across the diode with an AC voltmeter or oscilloscope. Note that most voltmeters will not have the frequency response to measure noise associated with digital circuits or interfaces (which operate in the MHz range). A thorough discussion of this potential problem, and the magnitude of error which may result, is given in the paper "Measurement System-Induced Errors In Diode Thermometry," J.K. Krause and B.C. Dodrill, Rev. Sci. Instr. 57 (4), 661, April, 1986; which is available from Lake Shore upon request.

The potential for this type of error can be greatly reduced by connecting twisted leads (pairs) between the controller and the diode sensors when an AC noise environment exists. We recommend the use of Duo-Twist™ Cryogenic Wire, which features phosphor bronze wire, 32 or 36 AWG, twisted at 3.15 twists per centimeter (8 twists per inch). Duo-Twist wire is available from Lake Shore. Refer to the Lake Shore Product Catalog or contact Lake Shore for further information.

2.7.2 Thermocouple (Model 321-04) Connections

The thermocouple input has a thermal block for connecting thermocouple wires. The positive and negative terminals correspond to V+ and V– and should match the polarity of the thermocouple used. Be sure to tighten the screw terminals carefully. Loose connections will result in unstable readings and control. For additional information on thermocouple operation, refer to Paragraph 3.5.

2.7.2.1 Thermocouple Compensation

The thermocouple input has a thermal block for connecting thermocouple wires and for temperature compensation. The thermocouple response curve tables within the instrument are normalized to the ice point of water. Consequently, accurate readings can be obtained by one of two methods. An ice bath with a reference junction can be used with the internal room temperature compensation turned OFF. The more convenient method is to eliminate the reference junction with its associated ice bath and use the internal electronic room temperature compensation by turning the internal compensation ON.

2.7.2.2 Thermocouple Wire Types at Cryogenic Temperatures

Below are recommended thermocouple wire types for cryogenic temperatures. The ANSI color code for thermocouples is red for the negative lead, while the type of thermocouple determines the positive lead color: purple (Type E), black (Type J), yellow (Type K), and blue (Type T). For details on thermocouples or other sensors, see the Lake Shore Temperature Sensor Guide.

Chromel™ vs. Gold with 0.03% or 0.07% Atomic Iron (0.03% not currently sold by Lake Shore)

Consists of Gold (Au) doped with 0.03* or 0.07 atomic percent Iron (Fe) as the negative thermoelement and a Ni-Cr alloy (Chromel™) as the positive thermoelement. This thermocouple has relatively high temperature sensitivity below 25 K, and usable sensitivity below 10 K. It is widely used in cryogenic applications due to its relatively high thermoelectric sensitivity (>15 µV/K above 10K). Recommended useful temperature range for the 0.03% Fe is 4 K to 325 K, and for the 0.07% Fe is 1.4 K.

Type E (Chromel™-Constantan)

Type E is a thermocouple pair consisting of a Ni-Cr alloy (Chromel™) as the positive thermoelement and a Cu-Ni alloy (Constantan) as the negative thermoelement. It has the highest sensitivity of the three standard thermocouples (E, K and T) typically used for low temperature applications: 8.5 µV/K at 20K. This thermocouple is best for temperatures down to 40 K. It is recommended for oxidizing or inert environments. Do not use it in sulfurous or reducing atmospheres, or environments that promote corrosion. Recommended useful temperature range is 3 K to 475 K.

Type K (Chromel™-Alumel™)

Type K is a thermocouple pair consisting of a Ni-Cr alloy (Chromel™) as the positive thermoelement and a Cu-Al alloy (Alumel™) as the negative thermoelement. It may be used in inert environments, but not in sulfurous or reducing atmospheres, or environments that promote corrosion. Sensitivity at 20K: 4.1 µV/K. Recommended useful temperature range is 3 K to 575 K.

Type T (Copper-Constantan)

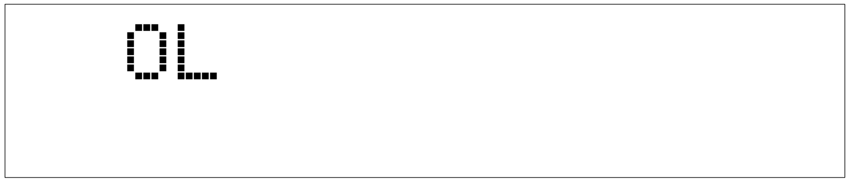
Type T is a thermocouple pair consisting of Cu (Copper) as the positive thermoelement and a Cu-Ni alloy (Constantan) as the negative element. It may be used in a vacuum as well as oxidizing, reducing or inert environments down to 90 K. At temperatures below 80 K, the thermoelectric properties of the positive thermoelement depend largely on the impurity of iron. The high thermal conductivity of the copper element makes this thermocouple the least usable for cryogenic applications. Sensitivity at 20 K: 4.6 µV/K.

Chromel™-CuFe (0.15%)

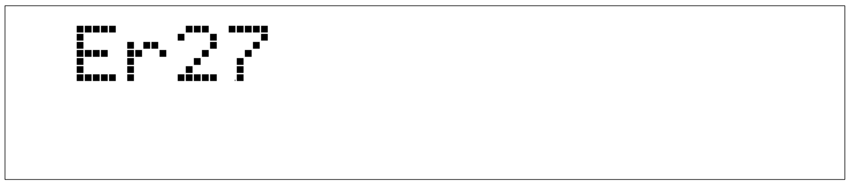
The Chromel™-Copper/Iron thermocouple consists of a Ni-Cr alloy (Chromel™) as the positive thermoelement and a Copper/0.15% Iron alloy as the negative thermoelement. Sensitivity at 4.2K: >11 µV/K. Less expensive than Gold-Chromel™ thermocouples and physically stronger. Recommended useful temperature range is 4 K to 300 K.

2.7.3 Sensor Input Error Messages

If an input signal from the sensor exceeding full scale is applied to the input leads, an overload condition is present and is indicated by "OL" on the display, as shown below.

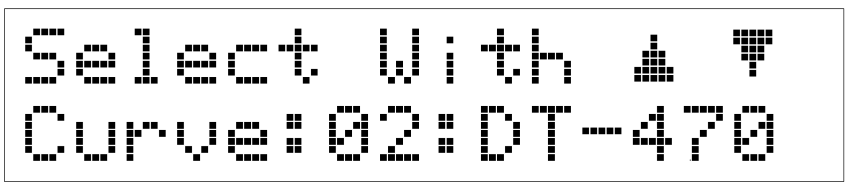


If no signal or a signal of the wrong polarity is present at the input leads, a Zero Error is indicated by "Er27" on the display, as shown below.

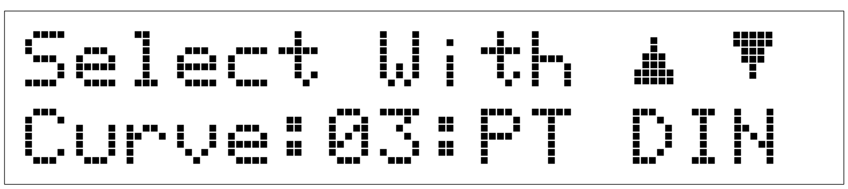


2.8 SENSOR CURVE SELECTION

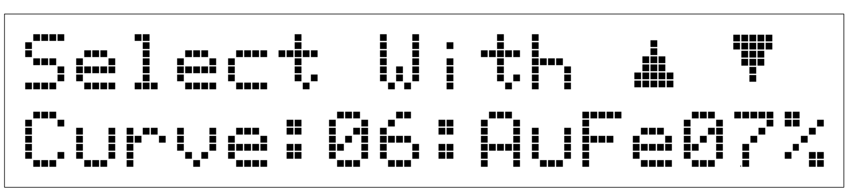
In order for the instrument to provide accurate temperature readings, it is necessary to select the response curve that matches the sensor being used. To determine which curve is selected, press the Curve key. The default curve for the Model 321-01 is DT-470 Curve 10, being the second selection in the curve list built into the unit (refer to Table 2-2). This display is shown below.



The default curve for the Model 321-02 is Curve DIN-PT, being the third selection in the curve list built into the unit (refer to Table 2-2). This display is shown below.



The default curve for the Model 321-04 is Curve AuFe07%, being the sixth selection in the curve list built into the unit (refer to Table 2-2). This display is shown below.



To change the curve, press the Curve key, then press either the ▲ (up) or ▼ (down) key to increment or decrement through the available curve selections. The curve numbers available are 0 through 12. To accept a new curve number, press the Enter key, or press the Escape key to cancel. The standard curves, with their curve number and temperature range, are given in Table 2-2. If a curve with the wrong temperature coefficient slope is selected, the Model 321 will default to the lowest order curve of the correct type.

Table 2-2. Sensor Curves

Curve No.	Number of Lines	Range (K)	Abbreviation	Description
00	31	1 – 325	DRC D	DT-500 DRC Curve D
01	31	1 – 325	DRC E1	DT-500 DRC Curve E1
02	31	1 – 325	DT-470	DT-400 Series Sensors Curve 10
03	31	14 – 800	Plat.	Platinum DIN Curve
04	88	2 - 475	DT-470 *	DT-400 Series Sensors Curve 10
05	31			Reserved
06	31	1.4 – 325 *	AuFe07%	AuFe 0.07% vs. Chromel
07	31	4 – 325 *	AuFe03%	AuFe 0.03% vs. Chromel
08	31	3 – 850 *	Type E	Type E
09	31	3 – 1272 * †	Type K	Type K
10	31	3 – 670 *	Type T	Type T
11			User	User Curve or Precision Option
12			SoftCal	SoftCal™ Curve

* Values are for thermocouples with compensation. Uncompensated, the thermocouple can use the full ±45 mV range.
† Display reading is limited to 999.9 in K. For higher readings, change units to °C.

Sensor curves available with the Model 321 include D Curve, E1 Curve, Curve 10, Platinum Curve (DIN 43760), various thermocouple curves, and a factory installed Precision Calibration Option for a calibrated sensor.

D and E1 Curve. Users of older Lake Shore DT-500 Series Diode Sensors can still use the Model 321 when set to D-Curve (Domestic) or E1-Curve (Export).

Curve 10. The Lake Shore DT-470 Series silicon diodes follow the same standard temperature response Curve 10. Consequently, all of the sensors in this series can be routinely interchanged with one another. Curve 10 is programmed into all Lake Shore Temperature Controllers, Digital Thermometers, and Temperature Transmitters. DT-470 Series silicon diode sensors are offered in five bands of tracking accuracy, enabling sensors to be selected on the basis of both technical performance and budgetary requirements.

Platinum Curve. Users of the Model 321-02 have the option of the standard platinum curve, or the precision option. The standard platinum curve, which is detailed in Appendix C, conforms to DIN 43760:1980; IEC 751:1983; and 1904:1984.

Thermocouple Curves. The curve selected should match the type of thermocouple being used.

User Curve. In addition to the standard curves, the Model 321 provides space for one user-defined curve. Space for this user curve is provided as Curve Number 11 in the Model 321 (refer to Table 2-2). This curve can be a custom curve developed by the Customer, a Precision Calibration Option Curve purchased from Lake Shore (refer to Paragraph 2.9), or a curve purchased from another vendor. The user defined curve can have up to 97 points plus two end points. The points can be loaded into the controller using the serial interface, or if the Precision Calibration Option Curve is purchased from Lake Shore, the curve can be entered at the factory. Chapter 4 of this manual describes user curve entry using the serial interface.

SoftCal™ Curve. If the SoftCal™ feature of the Model 321 is used, the resulting SoftCal™ curve is stored in curve location number 12. Refer to Table 2-2 and Paragraph 3.2.6 to use SoftCal™.

2.9 PRECISION CALIBRATION OPTION

The Precision Calibration Option is the easiest way to combine the additional performance of a Lake Shore calibrated sensor with the Model 321 Temperature Transmitter. The Precision Calibration Option is a read-only memory chip (PROM) with specific sensor calibration stored on it. The Precision Calibration Option improves combined sensor/instrument accuracy to within ±0.25 K or better over the calibrated temperature range of the sensor.

There are three types of precision options available for the Model 321. The Model 8000 Precision Calibration Option generates the data table from a Lake Shore calibrated sensor. The maximum number of data points is 99. A typical calibration precision option ranges between 30 and 40 points depending on the sensor type and temperature range of the calibration. The data and accuracy of the fit is supplied to the user as a separate document. This information can be entered by the user over the serial interface.

Prior to shipment, Lake Shore can also generate a custom sensor response curve from the individual sensor calibration as indicated in the above paragraph and store it in the Model 321 via the Model 8001 Precision Calibration Option. The data and accuracy of the fit is then supplied to the user as a supplement to this manual.

The Model 8002 Precision Calibration Option is used when the customer already owns a Model 321 and wants the additional sensor calibration stored in the instrument. Lake Shore stores the calibration data in a NOVRAM and sends the programmed IC to the customer. The IC is then installed in the instrument by the customer. The user should be prepared to supply the Model 321 serial number at the time of order.

The 8001-321 Precision Calibration Option is installed at Lake Shore when you order your instrument with a calibrated sensor. If you order the instrument to be used with a Lake Shore calibrated sensor that you already own, Lake Shore will need to know the model number and serial number of your sensor at the time of order. The Model 8002-321 is for field installations of the Precision Calibration Option in an existing Model 321.

2.10 HEATER SETUP

The heater output of the Model 321 is brought out the back panel as a Dual Banana Jack. A mating connector is supplied. Current is driven from the HEATER (HI) connection to the HEATER (LO) connection. A resistive heater load of 25Ω, 25 W should be connected between these two points.

The heater output is a 1 A on High range, 0.31 A on Low range, and does not have to be fused. The Model 321 is designed to power a 25 Ω heater for maximum heater output. A larger heater resistance may also be used but will result in a lower maximum power output. For example, the output compliance voltage is 25 volts so that a 100 Ω heater resistance allows a maximum power output of 6.25 watts [$(25V)^2/100\ \Omega$].

If the heater load drops below ≈21 Ω, the output current will limit to prevent the instrument from overheating. The maximum output current will drop with the heater resistance when the resistance is below 21 Ω. The heater output is isolated from earth ground. To prevent heater noise coupling into the measurement, do not allow the heater output to contact earth ground. For example, if the heater load is 20 Ω, the maximum output current is ≈0.90 A. If the heater output is shorted, the maximum output current is ≈0.30 A.

NOTE: The front panel Heater % display is calculated, not measured. If heater resistance is not 25 Ω, the display may not indicate actual heater output.

NOTE: The heater output is isolated from earth ground. To prevent heater noise coupling into the measurement, do not allow the heater output to contact earth ground. Earth ground is provided on the back panel for shielding purposes only.

NOTE: If the heater leads must be close to the sensor leads, wind (twist) them in such a manner that they cross each other at ninety degrees.

Within a cryostat, 30 gauge stranded copper lead wire (ND-30) is recommended for connection to the heater. The heater leads should not run coincident with the sensor leads due to the possibility of capacitive pick-up between the two sets of leads. If the heater leads must be close to the sensor leads, wind (twist) them in such a manner that they cross at ninety degrees.

2.11 RACK MOUNTING

The Model 321 is shipped with plastic "feet" and is ready for use as a bench instrument. As an option, the Model 321 can be installed in a standard 19 inch instrument rack. For information on the optional Model 3022 Half-Rack Mounting Kit for a single controller, refer to Paragraph 5.3 and see Figure 5-4. For information on the optional Model 3026 Dual Mounting Shelf for side-by-side mounting of two controllers, refer to Paragraph 5.3 and see Figure 5-5.

2.12 POWER UP

The power up paragraph consists of a power up sequence in Paragraph 2.8.1. Power up (PUP) Configuration is defined in Paragraph 2.8.2. Power up errors are explained in Paragraph 2.8.3.

2.12.1 Power Up Sequence

The following power up sequence occurs at power up.

1. The first display gives the name of the unit.

```
Autotuning Temp.
   Controller
```

2. Next, the unit displays the current RS-232C Baud rate setting. The default setting is 300 Baud.

```
Baud Rate:   300
```

3. The temperature sensor input type is then displayed. The type of sensor depends on the model of the instrument. A Model 321-01 will display the following message.

```
Input Type:
Silicon Diode
```

A Model 321-02 will display the following message.

```
Input Type:
Plat. Resistor
```

A Model 321-04 will display the following message.

```
Input Type:
Thermocouple
```

4. The Model 321 then goes into normal operation showing the Temperature and Heater Range (High, Low, or Off) setting on the first line and the Setpoint and Heater % power on the second line. Refer to Chapter 3 for Model 321 operation.

2.12.2 Power Up (PUP) Configuration

A provision has been made to store a Power Up (PUP) configuration for the Model 321. This ensures that it will power up to a user-defined state after power down. Parameters including heater range, setpoint, gain, reset, units, and curve number are stored in non-volatile memory and preserved even when the line cord is disconnected.

To view PUP status, press and hold the Enter key for ≈5 seconds. You will see the following display.

```
Select With ▲ ▼
PUP: →On   Off
```

"On" indicates that the power up settings will change when settings on the instrument are made via the front panel or over the remote interface. "On" is the default PUP condition.

"Off" indicates that updates to the power up memory are disabled and the instrument will power up in the configuration it was in when the power up feature was turned off.

2.12.3 Power Up Errors

On power up, the Model 321 does a check of the internal memory. There are two potential error messages. The first is usually recoverable, the second is not. The first error display is shown below.

```
RAMnotRecog.Er#2
Escape to Init.
```

This indicates than an attempt to read the internal non-volatile RAM for the Model ID was unsuccessful. In some situations, this error can be corrected by the user by initializing the Model 321 memory. There are three methods that can be used to reinitialize the instrument: (1) Press the Escape key when the error message is being displayed, (2) hold the Escape key down when the instrument is off and then turning the instrument on, or (3) holding the Escape key down for more than 5 seconds. Wait until a message is given before releasing the key.

The second error display is shown below.

```
RAM Rd/Wr    Er#1
Escape to Retry.
```

This error message indicates that an attempt to write and then read the internal non-volatile RAM was unsuccessful. This error is not correctable by the user. Please consult the factory.

CHAPTER 3

OPERATION

3.0 GENERAL

This chapter describes Model 321 Temperature Controller operation. A definition of front panel controls is provided in Paragraph 3.1. Thermometry related functions are described in Paragraph 3.2. Control functions are described in Paragraph 3.3. Interface and miscellaneous functions are described in Paragraph 3.4. Finally, thermocouple controller operation (Model 321-04 only) is described in Paragraph 3.5.

3.1 DEFINITION OF FRONT PANEL CONTROLS

This paragraph provides a description of the front panel controls on the Model 321. The front panel consists of two major sections: a description of the 20 front panel buttons in Paragraph 3.1.1, and a description of the 2 row by 16 character LCD in Paragraph 3.1.2.

3.1.1 Front Panel Keypad Definitions

The buttons on the front panel are defined as follows. Note the following are abbreviated descriptions of each button. A more detailed description of each function is provided in subsequent paragraphs.

Heater High Turns the heater on high: 25 Watts (maximum). Refer to Paragraph 3.3.1.

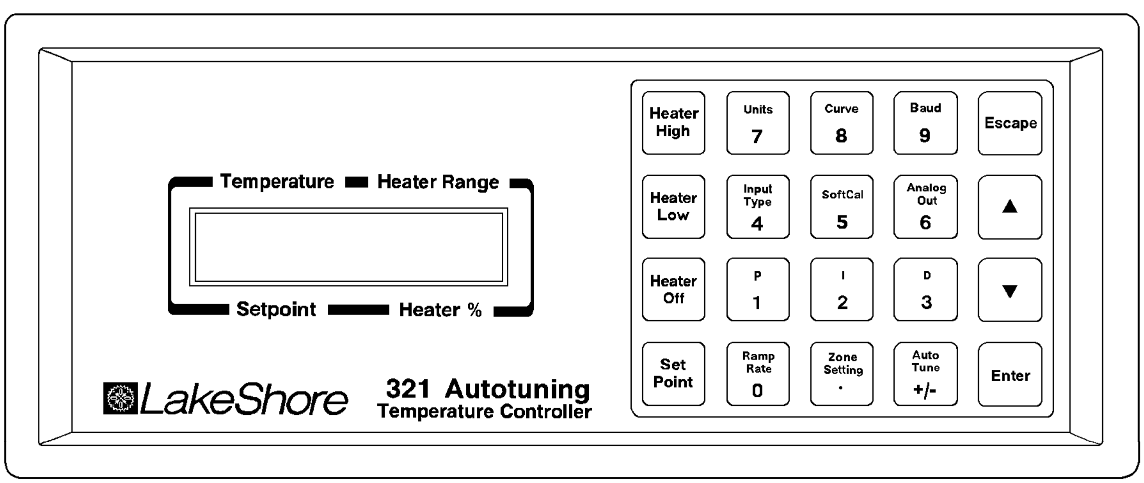
Heater Low Turns the heater on low: 2.5 Watts (maximum). Refer to Paragraph 3.3.1.

Heater Off Turns the heater off. Refer to Paragraph 3.3.1.

Set Point Permits the user to adjust the temperature setpoint. Refer to Paragraph 3.3.2.

Units Sets the controller to display temperature units in degrees kelvin (K) or Celsius (C), or sensor units in volts (V), millivolts (mV), or ohms (Ω), depending on Model number. Refer to Paragraph 3.2.2.

Input Type Displays the currently selected sensor input type. Refer to Paragraph 3.2.1. This is a display only. To change the sensor input, refer to Paragraph 6.7. (The controller must be recalibrated after changing the input type.) This button also has two press and hold functions: Thermocouple Compensation and Display Filter. Refer to Paragraphs 3.2.3 and 3.2.4 respectively.



P-321-1-1.bmp

Figure 3-1. Model 321 Front Panel

Ramp Rate Allows the user to set the rate at which the temperature setpoint increases or decreases when the user changes the setpoint value. Refer to Paragraph 3.3.3.

Curve Used to select the sensor response curve. Refer to Paragraph 3.2.5.

SoftCal™ Permits the user to improve the accuracy of the silicon diode sensor by setting up a special modification to the Standard Curve 10. Refer to Paragraph 3.2.6.

Zone Setting The user is able to enter up to 10 temperature zones where the controller will automatically use preprogrammed PID settings and Heater Ranges. Refer to Paragraph 3.3.6.

Baud If the Serial Interface is being used, the Baud Rate of the Model 321 may be selected from 300 or 1200 by pressing this button. Refer to Paragraph 3.4.1.

Analog Out Use this button to set the scaling of the analog output. The default is 0 to 10 volts corresponding to 0 to 1000 K. A user defined output scaling can also be specified. Refer to Paragraph 3.4.2.

AutoTune The controller has the capability of automatically setting P, PI, or PID values. Refer to Paragraph 3.3.4.

P For manual adjustment of controller gain (**P**roportional). Refer to Paragraph 3.3.5.1.

I For manual adjustment of reset (**I**ntegral). Refer to Paragraph 3.3.5.2.

D For manual adjustment of rate (**D**erivative). Refer to Paragraph 3.3.5.3.

Escape The **Escape** button is used to terminate a function without making changes to the existing settings. Pressing and holding the **Escape** button for ≈5 seconds resets the controller, returning most parameters to factory default values. Refer to Paragraph 3.4.3.

▲ The up triangle (▲) serves two functions. The first is to toggle between various settings shown in the display. The second is to increment a numerical display.

▲ The down triangle (▼) serves two functions. The first is to toggle between various settings shown in the display. The second is to decrement a numerical display.

Enter The **Enter** button is used to accept changes made in the field display. Press and hold the **Enter** button to gain access to the Power Up (PUP) configuration setup display. Refer to Paragraph 3.4.4.

3.1.2 Two Row by Sixteen Character Liquid Crystal Display (LCD)

In normal operation, the two row by sixteen character display provides a temperature reading and heater status on the top row and the current temperature setpoint and heater output status on the bottom row. Other information is displayed when using the various functions on the keypad. Each character is comprised of a 5 by 7 dot matrix. See Figure 3-2.

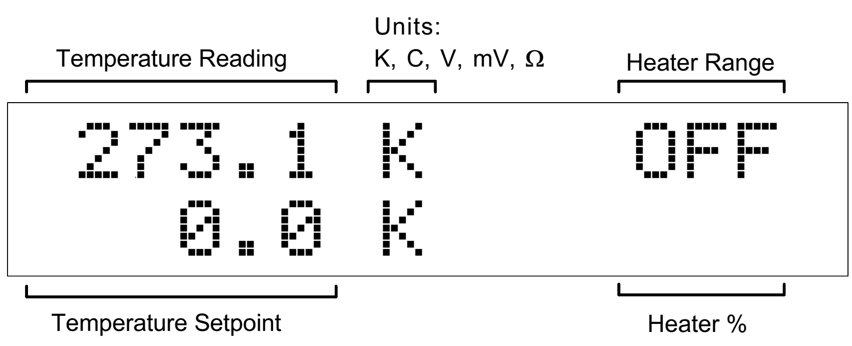


Figure 3-2. Definition of 2 by 16 Display

3.2 THERMOMETRY FUNCTIONS

The following front panel keyboard function are related to the thermometry or temperature control aspects of the Model 321.

Function	Paragraph
Input Type	3.2.1
Units	3.2.2
Temp. Compensation	3.2.3
Display Filter	3.2.4
Curve	3.2.5
SoftCal	3.2.6

3.2.1 Input Type

The **Input Type** button has been included to permit the user to ascertain the internal DIP switch setting configuration that determines the type of sensor input. When first configured at the factory, the Model number will correspond the type of sensor to be used with the controller. A Model 321-01 will display the following message.

```
Input Type:
Silicon Diode
```

A Model 321-02 will display the following message.

```
Input Type:
Plat. Resistor
```

A Model 321-04 will display the following message.

```
Input Type:
Thermocouple
```

The Input Type display is for information only; no user changes are available. The display will remain visible for 3 seconds and then will return to the normal display.

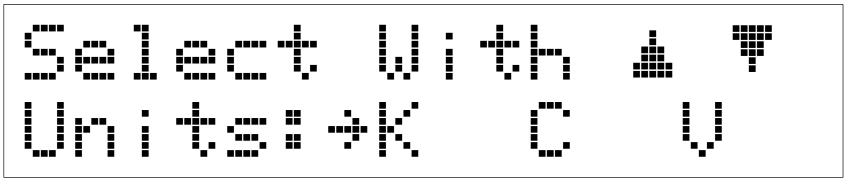
In addition to showing input sensor type, pressing and holding **Input Type** has the function of turning the Display Filter on or off. Refer to Paragraph 3.2.4. For thermocouple units only, the extra Input Type display is Temperature Compensation. Refer to Paragraph 3.2.3.

3.2.2 Units

The **Units** button gives a slightly different display depending on the sensor input and model number. All three models permit selection of temperature displays in kelvin (K) or degrees Celsius (°C). The difference is in the selection of sensor output. For the silicon diode used with the Model 321-01, the additional units selection is Volts (V). Refer to Paragraph 3.2.2.1. For the platinum resistor used with the Model 321-02, the additional units selection is ohms (Ω). Refer to Paragraph 3.2.2.2. For the thermocouple used with the Model 321-04, the additional units selection is millivolts (mV). Refer to Paragraph 3.2.2.3. Units in K is the default for all models.

3.2.2.1 Units for Silicon Diode Input (Model 321-01)

To select the display units for a silicon diode input (Model 321-01), press the **Units** button.

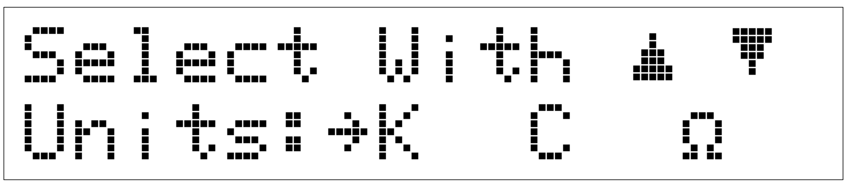


Use the ▲, ▼, or **Units** button to cycle the selector arrow (→) between choices. The available selections are K (kelvin), C (Celsius), and V (Volts). Display in K is the default value. Press **Enter** to accept the new units or **Escape** to return the normal display and retain the old setting.

NOTE: If the display is set to read in V (Volts) and Ramp Rate or Zone Setting are selected, the controller will request the user to return the display to K or C before proceeding.

3.2.2.2 Units for Platinum Resistor Input (Model 321-02)

To select the display units for a platinum resistor input (Model 321-02), press the **Units** button.

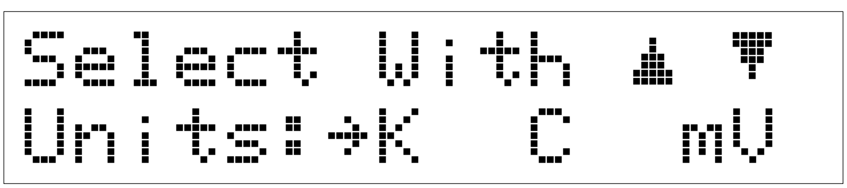


Use the ▲, ▼, or **Units** button to cycle the selector arrow (→) between choices. The available selections are K (kelvin), C (Celsius), and Ω (ohms). Display in K is the default value. Press **Enter** to accept the new units or **Escape** to return the normal display and retain the old setting.

NOTE: If the display is set to read in Ω (ohms) and Ramp Rate or Zone Setting are selected, the controller will request the user to return the display to K or C before proceeding.

3.2.2.3 Units for Thermocouple Input (Model 321-04)

To select the display units for a thermocouple input (Model 321-04), press the **Units** button.



Use the ▲, ▼, or **Units** button to cycle the selector arrow (→) between choices. The available selections are K (kelvin), C (Celsius), and mV (millivolts). Display in K is the default value. Press **Enter** to accept the new units or **Escape** to return the normal display and retain the old setting.

NOTE: If the display is set to read in mV (millivolts) and Ramp Rate or Zone Setting are selected, the controller will request the user to return the display to K before proceeding.

3.2.3 Thermocouple Temperature Compensation (Model 321-04 Only)

For thermocouple sensors only (Model 321-04), the temperature compensation display is shown after the Input Type display has timed out (≈3 seconds). The display appears as follows:

```
Select With ▲ ▼
TempComp: On→Off
```

Use either the ▲, ▼, or **Input Type** button to cycle the selector arrow (→) between choices. The available selections are On and Off, with Off being the default. Press **Enter** to retain the selected setting or **Escape** to return to the normal display and retain the old setting. Also refer to Paragraph 2.7.2.1.

3.2.4 Display Filter

The filter function reads 8 sequential temperature readings and displays the average. It is used to quiet the display, making it more readable when the sensor is exposed to fluctuating conditions. Filter affect the display only and does *not* affect any other control functions. Filter has the effect of slowing the display, and therefore should not be used when ramping. To turn the filter on, press and hold the **Input Type** button (for ≈5 seconds) until you see the following display.

```
Select With ▲ ▼
Filter:  On →Off
```

Use either the ▲, ▼, or **Input Type** button to cycle the selector arrow (→) between choices. The available selections are On and Off, with Off being the default. Press **Enter** to turn the filter on or **Escape** to return the normal display and retain the old setting.

3.2.5 Curve

In order for the controller to provide accurate temperature readings, it is necessary to select the response curve that matches the sensor being used. To determine which curve is selected, press the **Curve** button. The default curve for the Model 321-01 is Curve 10, being the second selection in the curve list built into the unit. Refer to Table 3-1. The default display is shown below.

```
Select With ▲ ▼
Curve:02:DT-470
```

The default curve for the Model 321-02 is Curve DIN-PT, being the third selection in the curve list built into the unit. Refer to Table 3-1. The default display is shown below.

```
Select With ▲ ▼
Curve:03:PT DIN
```

The default curve for the Model 321-04 is Curve AuFe07%, being the sixth selection in the curve list built into the unit. Refer to Table 3-1.

The default display is shown below.

```
Select With ▲ ▼
Curve:06:AuFe07%
```

To change the curve, press the **Curve** button, then press either the ▲, ▼, or **Curve** button to increment or decrement through the available curve selections. The curve numbers available are 0 through 12. When cycling through the displays, only the curves appropriate for the specified sensor type will be displayed. To accept a new curve number, press the **Enter** button, or press the **Escape** button to cancel. The standard curves, with their curve number and temperature range, are given in Table 3-1.

Table 3-1. Sensor Curves

Curve No.	Number of Lines	Range (K)	Abbreviation	Description
00	31	1 – 325	DRC D	DT-500 DRC Curve D
01	31	1 – 325	DRC E1	DT-500 DRC Curve E1
02	31	1 – 325	DT-470	DT-400 Series Sensors Curve 10
03	31	14 – 800	Plat.	Platinum DIN Curve
04	88	2 - 475	DT-470 *	DT-400 Series Sensors Curve 10
05	31			Reserved
06	31	1.4 – 325 *	AuFe07%	AuFe 0.07% vs. Chromel
07	31	4 – 325 *	AuFe03%	AuFe 0.03% vs. Chromel
08	31	3 – 850 *	Type E	Type E
09	31	3 – 1272 * †	Type K	Type K
10	31	3 – 670 *	Type T	Type T
11			User	User Curve or Precision Option
12			SoftCal	SoftCal Curve

* Values are for thermocouples with compensation. Uncompensated, the thermocouple can use the full ±45 mV range.

† Display reading is limited to 999.9 in K. For higher readings, change units to °C.

3.2.6 SoftCal

SoftCal is used to improve the accuracy of a DT-400 Series Silicon Diode Sensor. The SoftCal feature enables the user to reduce the error between a silicon diode and the Standard Curve 10 used by the controller to convert the input voltage from the diode to a corresponding temperature. In short, SoftCal provides the means to generate inexpensive calibrations for DT-400 Series sensors used with the Model 321 Temperature Controller.

The Lake Shore DT-400 Series Sensors incorporate remarkably uniform sensing elements that exhibit precise, monotonic, and repeatable temperature response in the range from 2 K to 475 K. Temperature characteristics are extremely stable and predictable, and exhibit excellent uniformity from device to device. As a result, these sensors can be routinely interchanged with one another. It is this diode feature that makes the use of SoftCal possible.

For the DT-400 Series diodes, five tolerance bands of tracking accuracy are available. See Figure 3-3. Band 11 sensors offer absolute accuracy to within ±0.25 K at low temperature, and to within ±0.5 K at room temperature. At the other end of the spectrum, Band 13 sensors are accurate to within ±1.0 K a low temperature, and to within ±1.0% of temperature or better from 100 K to 475 K. If better accuracy is required, SoftCal can be employed with the Model 321 to improve the absolute accuracy of the sensor.

SoftCal can be implemented in one of two ways: as a method or a service.

1. The Customer may perform the SoftCal procedure. This would involve using the Model 321 and the silicon diode sensor to sense either two or three sources of a stable temperature. For a 3 point SoftCal, the Customer must provide stable temperatures of 4.2 K (Liquid Helium), 77.35 K (Liquid Nitrogen), and 295 K (Room Temperature). For a 2 point SoftCal, the Customer must provide stable temperatures of 77.35 K and 295 K. The procedure to follow is provided in Paragraph 3.2.6.2. User performed SoftCal has the advantage of nulling both sensor and controller inaccuracies.

2. Lake Shore provides an inexpensive SoftCal Calibration Service. This service will provide the Customer with the voltages corresponding to the 2 or 3 point calibrations. The calibration consists of a modified (T vs. V) Curve 10 Table for a specific DT-400 Series Sensor. A SoftCal Report is generated that includes the voltages for data points and a unique sensor curve table interpolated from these 2 or 3 points. The procedure for entering these voltages is provided in Paragraph 3.2.6.3.

Using either method, the Model 321 will create a new curve for this specific diode, which is stored as Curve 12 in the controller memory. This procedure can make an inexpensive Band 13 diode more accurate than our tightest Band 11 diode (but, of course, with the interchangeability).

3.2.6.1 SoftCal Errors

The calibration cannot be transferred from one sensor to another. A SoftCal calibration will compensate for some of the temperature error of the controller if an instrument is used to do the calibration. If the sensor is calibrated outside the instrument, the specified accuracy of the instrument must be added to the sensor accuracy.

SoftCal accuracy also depends on the precision of the setting points. An error in the setting temperature can actually degrade the sensor performance beyond the normal tolerance bands. For example, the boiling point of nitrogen at standard pressure is near 77.4 K. During a storm, this can change as much as 0.2 K because of the change in atmospheric pressure. These types of errors must be added to the sensor accuracy specification.

3.2.6.2 Customer Performed SoftCal

The Customer may locally perform the SoftCal procedure using their own controller and silicon diode sensor. Although not as convenient as obtaining a Lake Shore SoftCal Report, it has the advantage of nulling the error of both the sensor and the controller as a system, thereby eliminating much of the controller error. Depending on the temperature range of interest, the Customer has the option of doing a 2 point or 3 point SoftCal. This example will assume a 3 point SoftCal. If only 2 points are required, then omit the steps associated with reading the voltage at 4.2 K. Requirements are a stable temperature source at three temperatures: 4.2 K (Liquid Helium), 77.35 K (Liquid Nitrogen), and <300 K (room temperature). It does not matter in which order the SoftCal data are taken.

NOTE: Allow the instrument to warm up for ≈1 hour before beginning the SoftCal procedure.

In this example, we will take our first SoftCal measurement around 4.2 K. Immerse the temperature sensor in Liquid Helium and allow the controller temperature reading to stabilize. Press the **SoftCal** button. Use either the ▲, ▼, or **SoftCal** button to cycle the selector arrow (→) to T (Temperature). You will see the following display.

```
Select With ▲ ▼
Cal: V →T  Erase
```

Press **Enter**. Use the numeric keypad to enter your actual reading (we will use 4.20 K). Be sure to enter the reading as accurately as possible. You will see the following display.

```
Enter Temp in
     +004.20 K
```

Once your observed temperature is entered, press the **Enter** button. The display will read "Processing..." for a couple of seconds, and then will return to the Enter Temperature display. If you attempt to enter a temperature that is too far out of tolerance, you will see the following message.

```
Temperature diff
too large.
```

To take the second SoftCal measurement near 77.35 K, immerse the sensor in liquid nitrogen and allow the reading to stabilize. Press the **SoftCal** button. Use either the ▲, ▼, or **SoftCal** button to cycle the selector arrow (→) to T (Temperature). Press the **Enter** button. Use the numeric keypad to enter your actual reading (we will use 77.35 K). You will see the following display.

```
Enter Temp in
     +077.35 K
```

Once your observed temperature is entered, press the **Enter** button. The display will read "Processing..." for a couple of seconds, and then will return to the Enter Temperature display.

To take the third SoftCal measurement, allow the temperature sensor to stabilize at ambient temperature. Take an independent temperature measurement of the air at the location of the temperature sensor. Press the **SoftCal** button. Use either the ▲, ▼, or **SoftCal** button to cycle the selector arrow (→) to T (Temperature). Press the **Enter** button. Use the numeric keypad to enter your room temperature measurement (we will use 295 K). You will see the following display.

```
Enter Temp in
     +295.00 K
```

Once the proper temperature is entered, press the **Enter** button. The display will read "Processing..." for a couple of seconds, and then will return to the Enter Temperature display. This completes the temperature entry procedure.

To use the newly calculated SoftCal curve, press the **Curve** button, and press either the ▲, ▼, or **Curve** button to increment or decrement until you get to Curve 12:SoftCal, as shown below.

```
Select With ▲ ▼
Curve:12:SoftCal
```

Press the **Enter** button. The controller will now use the new SoftCal curve to interpret the silicon diode sensor voltages to the corresponding temperature reading.

3.2.6.3 Entering Voltage Values from a Lake Shore SoftCal Report

If a Lake Shore SoftCal Report was purchased, the voltage values for the 2 or 3 point calibration can be entered and the resulting modified Standard Curve 10 stored as Curve 12 in the controller. To enter the voltages, pressing the **SoftCal** button. Use either the ▲, ▼, or **SoftCal** button to cycle the selector arrow (→) to V (Voltage). You will see the following display.

```
Select With ▲ ▼
Cal:→V  T  Erase
```

Press **Enter**. You will see the following display.

```
Select With ▲ ▼
→4.2K 77.3K 305K
```

This procedure will assume a 3 point SoftCal was obtained. The Customer will now enter the 3 voltages corresponding to the temperature points on the report. (A 2 point SoftCal uses the same procedure, but skips the 4.2 K entry.) With the selector arrow (→) pointing to 4.2 K, press the **Enter** button.

NOTE: In this example, we will be using voltages taken from a sample Lake Shore SoftCal Report. These values are *for example only*. Since voltage values are unique to individual silicon diode sensors, the Customer should substitute the values from their report when following this procedure.

For this example, the Lake Shore SoftCal Report provided a reading of 1.6339 V corresponding to 4.2 K. For the Model 321, you must round the provided voltage to four places. Use the numeric keypad to enter the voltage. You will see the following display.

```
Enter V for 4.2K
    +1.6339 V
```

If you attempt to enter a value that is ±10° from the Standard Curve 10, you will see the following error message.

```
Voltage out of
range for 4.2K
```

A similar message will be displayed if entering an incorrect value for 77.3 K or 305 K.

Once the proper voltage value is entered, press the **Enter** button. The display will read "Processing..." for a couple of seconds, and then will return to the temperature selection display. Use the ▲, ▼, or **SoftCal** button to cycle the selector arrow (→) to 77.3 K and press the **Enter** button. Again look at the SoftCal Report and enter the voltage corresponding to 77.35 K. In this example, the report provided a value of 1.0215. You will see the following display.

```
Enter V for 77.3
   +1.0215 V
```

Once the proper voltage value is entered, press the **Enter** button. The display will read "Processing..." for a couple of seconds, and then will return to the temperature selection display. Use the ▲, ▼, or **SoftCal** button to cycle the selector arrow (→) to 305 K and press the **Enter** button. Again look at the SoftCal Report and enter the voltage corresponding to 305 K. In this example, the report provided a value of 0.5126. You will see the following display.

```
Enter V for 305K
   +0.5126 V
```

Once the proper voltage value is entered, press the **Enter** button. The display will read "Processing..." for a couple of seconds, and then will return to the temperature selection display. This completes the voltage entry procedure.

To use the newly calculated SoftCal curve, press the **Curve** button, and press either the ▲, ▼, or **Curve** button to increment or decrement until you get to Curve 12:SoftCal, as shown below.

```
Select With ▲ ▼
Curve:12:SoftCal
```

Press the **Enter** button. The controller will now use the new SoftCal curve to interpret the silicon diode sensor voltages to the corresponding temperature reading.

3.2.6.4 Erasing the SoftCal Curve

To erase an existing SoftCal curve, press the **SoftCal** button. Use the ▲, ▼, or **SoftCal** button to cycle the selector arrow (→) to Erase. You will see the following display.

```
Select With ▲ ▼
Cal: V  T →Erase
```

Press **Enter**. Use the ▲, ▼, or **SoftCal** button to cycle the selector arrow (→) to Yes. You will see the following display.

```
Select With ▲ ▼
Erase:  →Yes  No
```

Press Enter. You will briefly see the "Erasing SoftCal Values & Curve" message. The old SoftCal curve is now erased.

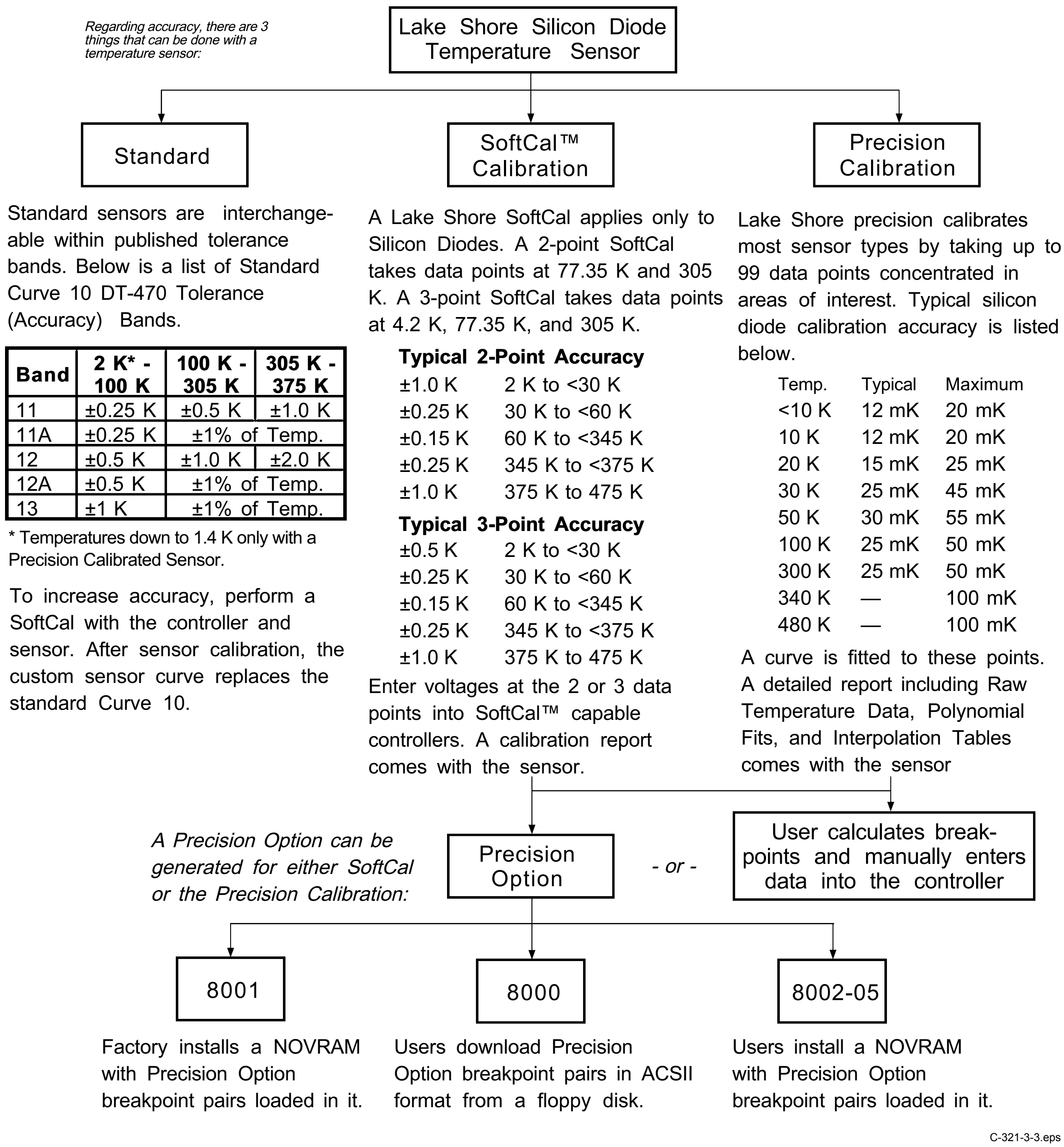


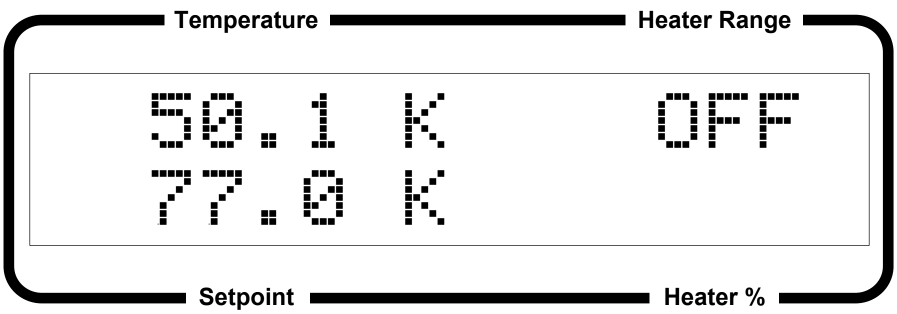
Figure 3-3. Sensor Calibrations and Precision Options

3.3 CONTROL FUNCTIONS

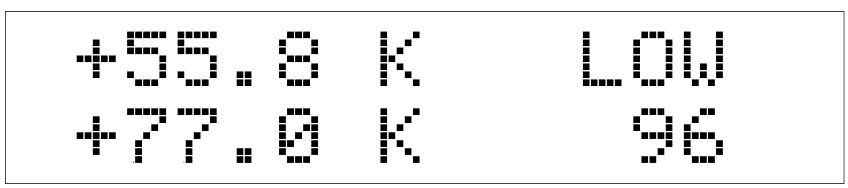
The following front panel keyboard function are related to the control aspects of the Model 321.

3.3.1 Heater High, Low, and Off

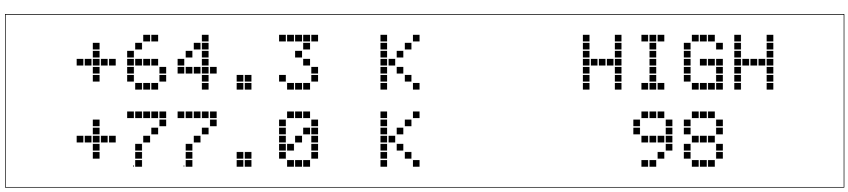
There are three buttons and two portions of the display to control and indicate heater operations. The three buttons are **Heater High**, **Heater Low**, and **Heater Off**. The two display areas are **Heater Range** in the top line and **Heater %** in the lower line. When the user presses **Heater High**, **Heater Low**, or **Heater Off**, the selection is reflected in the **Heater Range** portion of the display. The Heater Off condition is shown in the following display.



When the heater is on, **Heater %** will reflect the percentage of current being applied to the heater. The heater low output is 2.5 Watts maximum into 25 Ω. A typical **Heater Low** display is shown as follows.



The heater high output is 25 Watts maximum into 25 Ω. A typical **Heater High** display is shown as follows.



The percentage of current reflects the percentage of full scale current being applied to the heater output, and will change automatically according to control parameters.

NOTE: If the heater load drops below ≈20 Ω, the output power will reduce. However, the display may still show the Heater % reading of a 25 Ω load.

A 25 Ω load is required to get a full 25 Watt power output. Refer to Paragraph 2.10 for heater setup and power considerations.

3.3.2 Setpoint

To change the setpoint, press the **Setpoint** button. You will see the following display.

```
Enter Setpoint:
    +077.0  K
```

Use the numeric keypad to enter a new setpoint, press **Enter** to accept the new setpoint or **Escape** to return the normal display and retain the old setting. You may also use either ▲ or ▼ to increment or decrement the display in tenths of a degree. The setpoint can be set as follows: for a Model 321-01, the available selections are K (kelvin), C (Celsius), and V (Volts). For a Model 321-02, the available selections are K (kelvin), C (Celsius), and Ω (ohms). For a Model 321-04, the available selections are K (kelvin), C (Celsius), and mV (millivolts). Display in K is the default value for all three models.

The setpoint is limited in temperature to the range of the curve being used for control. Table 3-1 gives these limitations in kelvin for curves 00 through 04 and 06 thru 10. The setpoint resolution in temperature is 0.1 degrees.

3.3.2.1 Voltage Resolution (Models 321-01 and 321-04 Only)

Voltage mode is used for the Silicon Diode Input. In voltage mode, the display has a resolution of 0.0001 Volt (V). For thermocouple input, the display is in millivolts. The millivolt display resolution is 1 microvolt.

3.3.2.2 Resistance Resolution (Model 321-02 Only)

The Resistance mode is allowed for the Platinum Resistor input configuration. The display resolution, in resistance, is 0.01 Ω below 200 Ω and 0.1 Ω above 200 Ω.

3.3.3 Ramp

The Model 321 has a programmable ramp feature with a programmable rate. This feature allows the user to set the rate at which the temperature setpoint increases or decreases when the user changes the setpoint value. The ramp rate range is from 0.1 to 99.9 degrees per minute. Ramp will only work if the controller is reading in temperature units (K or °C). An example of ramp rate is as follows. Given a starting setpoint is 50 K, the user would see the following normal display.

```
 +50.1 K    OFF
 +50.0 K
```

In this example, the user wants to change the setpoint from 50 K to 100 K at a rate of 1 k/min. To set this up, the user begins by pressing the **Ramp Rate** button. Then press the either the ▲, ▼, or **Ramp Rate** button to cycle the selector arrow (→) between choices. The available selections are On and Off, with Off being the default. See the following display.

```
Select With ▲ ▼
Ramping:→On  Off
```

With the arrow pointing to On, pressing the **Enter** button will bring up the Enter Ramp Rate display. Using the numeric keypad, press the number 1. You should see the following display.

```
Enter Ramp Rate
      01.0  K/min
```

Press **Enter** to accept the new ramp rate. You will now return to the normal display. Now press the **Setpoint** button and use the numeric keypad to enter 100 K. You should see the following display.

```
Enter Setpoint:
     +0100.0 K
```

The normal display returns showing the old setpoint of 50 K. The display slowly begin to change to 100 K at a rate of 1 K per minute, reaching 100 K in 50 minutes. The ramp can be stopped at the current setpoint by pressing **Setpoint** and then **Enter**. To turn off the ramping feature, press the **Ramp Rate** button and use either the ▲, ▼, or **Ramp Rate** button to cycle the selector arrow (→) to no, then push **Enter**.

3.3.4 Autotune

There are five tuning modes on the Model 321: Auto P, Auto PI, Auto PID, Manual, and Zone. This paragraph will discuss the three Autotune modes. The Autotuning algorithm determines the proper settings for Gain (**P**roportional), Reset (**I**ntegral) and Rate (**D**erivative) by observing the time response of the system upon changes in setpoint under either P, PI or PID control.

Adaptation of an autotuning algorithm for use at cryogenic temperatures is a more complex issue than for more stable, well-behaved, high-temperature loads. For example, over its useful temperature range a single cryogenic load may exhibit thermal property variations of three orders of magnitude or greater.

The Autotuning function is initiated with a change in temperature setpoint. The controller automatically gathers data to determine optimum control parameters. No more tuning will be done until the next change in setpoint. The controller will never disturb the system. It tunes only on user setpoint changes.

System design is also a factor. Under some circumstances, very fast cryogenic systems may not provide sufficient data points on step changes to accurately predict the proper control settings. Unusually large thermal lags, caused by poor placement and mounting relative to the heater, can obstruct the correlation between the heater and the system necessary to tune properly.

For slower systems with longer time constants, which are very difficult to tune manually, Autotuning can obtain enough information on a step change to characterize the system and determine proper values for Gain, Reset, and Rate.

To put the controller in Autotune PID mode, press the **AutoTune** button, and press either the ▲, ▼, or **AutoTune** button to cycle the selector arrow (→) to Auto PID. You should see the following display.

```
Select With ▲ ▼
Tune: Auto PID
```

Press the **Enter** button. The controller is now in Autotuning PID mode. The method for setting the controller to Auto P or Auto PI modes is the same as just explained. Further information on Auto P, I, and D settings are provided in the following paragraphs.

3.3.4.1 Initial Values of PID Parameters In Autotune Mode

The initial values of the PID parameters in the Autotune mode are set when the controller is changed from Manual to either P, PI or PID control. The initial PID factory settings are 50 and 20 with the controller set for PI control.

3.3.4.2 Minimum Overshoot

The full three function PID control algorithm is designed to minimize overshoot. It uses Gain (P), Reset (I), and Rate (D) to bring the system to the control temperature as smoothly as possible. To select the PID tuning algorithm, press the **AutoTune** button.

3.3.4.3 Minimum Time To Setpoint

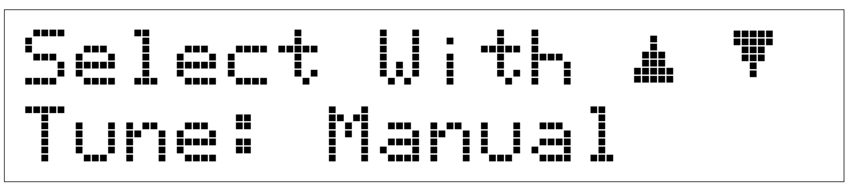
The two function PI control algorithm minimizes the time it takes for the system to first reach the setpoint. Some of the damping used in PID control is not present so more overshoot should be expected. To select the PI tuning algorithm, press the **AutoTune** button.

3.3.4.4 Gain Only

The third control algorithm available on the Model 321 is Gain (P) only. No time dependent control parameters (other than digital sampling rate) will be initiated by the controller. In this mode, thermal characteristics of the system being controlled are more apparent but there will be a temperature offset below the setpoint. To select the P tuning algorithm, press the **AutoTune** button.

3.3.5 Manual Control Settings (PID)

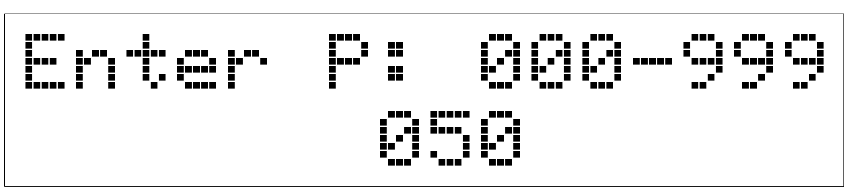
There are five tuning modes on the Model 321: Auto P, Auto PI, Auto PID, Manual, and Zone. This paragraph will discuss the Manual mode. In manual mode, the controller will accept Gain, Reset and Rate parameters from the user to provide three term PID control. To put the controller in Manual mode, press the **AutoTune** button, and press either the ▲, ▼, or **AutoTune** button to cycle the selector arrow (→) to Manual. You should see the following display.



Press the **Enter** button. The controller is now in Manual mode. Further information on setting gain (Proportional), refer to Paragraph 3.3.5.1. Setting reset (Integral) is discussed in Paragraph 3.3.5.2. Setting rate (Derivative) is discussed in Paragraph 3.3.5.3. Finally, the effect of temperature on tuning parameters is discussed in Paragraph 3.3.5.4.

3.3.5.1 Setting Gain (Proportional)

Adjustment of the gain (Proportional) part of the control function gives the controller an overall range of 000 to 999. To enter a gain value, press the **P** button. You will see the following display.



This display shows the current Proportional setting (the default setting is 50). Use the numeric keypad to enter a new setting. Press **Enter** to accept the new Proportional setting or **Escape** to return the normal display and retain the old setting.

To experimentally determine the proper gain setting, use the following procedure. Set Autotune to Manual, then turn off both Reset (I) and Rate (D). Set in a nominal gain setting of 50. Make sure that the heater turns on; if not, increase the gain setting until the heater turns on. Let the system stabilize. Note that it will stabilize at some point below the setpoint (typically 2 to 3 K below). Keep increasing the controller gain by factors of two until the system temperature begins to oscillate. Adjust the gain for small sustained oscillations. Measure the period of these oscillations for determining the correct setting for reset. Reduce the gain by a factor of two to three until the temperature again becomes stable with time. Be sure that you allow time at each setting for the system to stabilize (if it will). For some systems and cryogenic sensors with low sensitivity, the maximum gain is required.

3.3.5.2 Setting Reset (Integral)

Adjusts the reset time constant of reset (Integral) in the control function. Effective reset time constants, between 1 and 999 seconds can be achieved by entering reset settings of 1 - 999. Reset time in seconds is (999/Value Entered). A reset of zero will make the controller proportional only. To enter a reset value, press the **I** button. You will see the following display.

```
Enter I: 000-999
       020
```

This display shows the current Integral setting (the default setting is 20). Use the numeric keypad to enter a new setting. Press **Enter** to accept the new Proportional setting or **Escape** to return the normal display and retain the old setting. For example, if the Reset setting is 20 the reset time in seconds is approximately 50 (999/20=50).

The reset number is an industrial control term which in the Model 321 corresponds to the number of repeats (or time constants) per 1000 seconds. The time constant is 1000 divided by this number in seconds. Consequently, a reset number setting of 20 corresponds to a time constant of 50 seconds. A system will normally take several time constants to settle into the set point, e.g. the 50 second time constant, if correct for the system being controlled, would result in a stable set point in a time frame between 5 and 10 minutes.

The oscillation period which you measured in determining the appropriate gain setting is equal to the reset time constant which is desired. Divide this number in seconds into 1000 and set the result into the RESET register. This result is the number of repeats per 1000 seconds. If the system did not oscillate at the highest gain setting, use the following procedure. Stabilize the temperature at a high gain setting. Change the set point downward by one or two degrees and observe the time that it takes for the temperature to change 60% of this excursion. Use this number as the reset time constant; divide it into 1000 and set in the result as the RESET value.

3.3.5.3 Setting Rate (Derivative)

This adjusts rate time constant of derivative (D) in the control function. Effective settings are between 0 seconds and 200% of 1/4 the reset time. In manual mode, rate is normally set at 1/4 the reset time in seconds (100%), because larger values may cause system instability. To enter a rate value, press the **D** button. You will see the following display.

```
Enter D: 000-200
       100
```

This display shows the current Derivative setting (the default setting is 100). Use the numeric keypad to enter a new setting. Press **Enter** to accept the new Proportional setting or **Escape** to return the normal display and retain the old setting.

The rate time constant should normally be somewhere between 1/4 and 1/8 the reset time constant, if it is used at all. Consequently, you can set it between 0 and 200% of 1/4 the reset time constant. Start with settings of either 0, 50 or 100% and determine which setting gives you the type of control which you desire. Don't be surprised if for your system, the setting you prefer is 0 (OFF). Note that by using a percent of reset time constant, rate scales automatically with changes in the reset value and does not have to be revisited frequently.

3.3.5.4 Effect of Temperature on Tuning Parameters

As the temperature increases, the system gain normally increases. Consequently, if the sensor sensitivity is relatively constant, you can normally increase the controller gain with increasing temperature.

The system gain is a product of the controller gain and the sensor gain. For example, for a silicon diode at 25 K the sensor sensitivity (dV/dT) is approximately an order of magnitude larger than it is at 35 K. If the load parameters have not changed greatly, neither will the system gain. Therefore, the controller gain should be increased to compensate for the reduction in sensor sensitivity.

Concerning Reset (I) change with temperature, in a normal cryogenic system, the time response of the system slows down as the temperature increases. Consequently, as the temperature rises the time constant will become longer as well. Therefore, if you have determined a valid value of reset at a particular temperature, increasing the temperature will result in a decrease in the reset number, i.e., a longer time constant; conversely decreasing temperature will demand a shorter time constant, i.e., an increase in the reset setting.

3.3.6 Zone Setting

There are five tuning modes on the Model 321: Auto P, Auto PI, Auto PID, Manual, and Zone. This paragraph will discuss Zone. The Model 321 allows the user to establish up to 10 custom contiguous temperature zones where the controller will automatically use pre-programmed PID settings and heater range. The user should configure the zones using 01 as the lowest to 10 as the highest zone in K. Make a copy of Figure 3-4 to plan your zones, then use the manual to record final zone settings.

If this feature is combined with the ramp rate feature, the user could do a ramp through all 10 zones from 1.4 K to room temperature by only changing the setpoint. The controller will automatically change the PID and heater range settings as the temperature setpoint passes through the different zones.

To setup a zone, ensure the units are set to K, then press the **Zone Setting** button. Use the numeric keypad to enter the number 1. You will see the following display.

```
Enter Zone 01-10
       01
```

Press the **Enter** button. The Enter Setpoint display will then appear. Use the numeric keypad to enter this setpoint. You should see the following display.

```
Enter Setpoint:
     +077.0  K
```

Press the **Enter** button. The Heater Range display will then appear as follows.

```
Select With ▲ ▼
Rg:→Off Low High
```

Use the ▲ or ▼ button to cycle the selector arrow (→) through Heater Range selections of Off, Low, and High. For this example, we will select Low. Press the **Enter** button. The Gain (Proportional) display is next as follows.

```
Enter P: 000-999
       050
```

The user may select a gain setting from 000 to 999. For this example, we have entered a setting of 50. Press the **Enter** button. The Reset (Integral) display is next as follows.

```
Enter I: 000-999
       020
```

The user may select a reset setting from 000 to 999. For this example, we have entered a setting of 20. Press the **Enter** button. The final entry is the Rate (Derivative) display as follows.

```
Enter D: 000-200
       100
```

The user may select a rate setting from 000 to 999. For this example, we have entered a setting of 100. Press the **Enter** button. This completes the setting of a typical zone. Repeat this same procedure for other zones as necessary.

Once the number of zones required have been programmed, you need to place the controller in zone mode. To do this, press the **AutoTune** button. Use the ▲ or ▼ button to select Zone. Then press **Enter** to accept the new tuning mode. Once zone is turned on, the instrument will update the control settings each time the setpoint is changed to a new zone. If the settings are changed manually, the controller will use the new setting while it is in the same zone and update to the zone table settings when the setpoint is hanged to a value outside that zone.

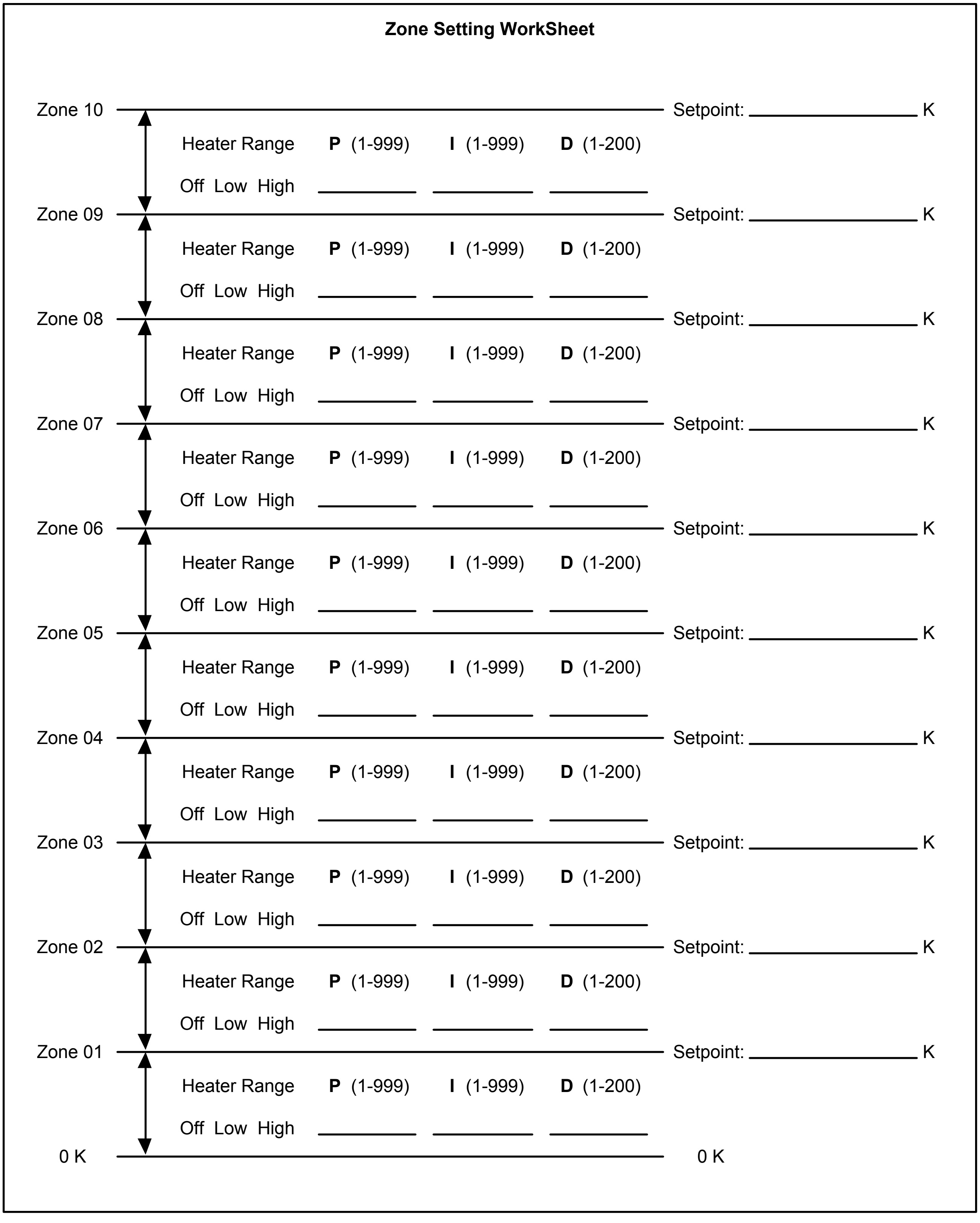


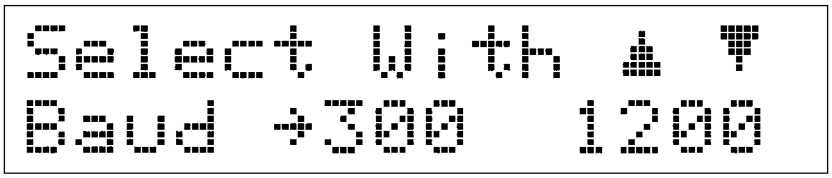
Figure 3-4. Record of Zone Settings

3.4 INTERFACE AND MISCELLANEOUS FUNCTIONS

The following front panel keyboard function are related to the thermometry or temperature control aspects of the Model 321.

3.4.1 Baud

If using the Serial Interface, the use must set the Baud rate. Pressing the **Baud** button brings up the following display.

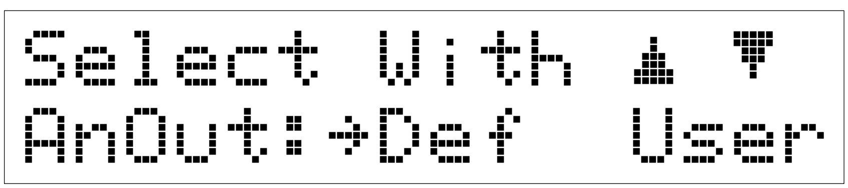


Use either the ▲, ▼, or **Baud** button to cycle the selector arrow (→) between choices. The available selections are 300 or 1200 Baud, with 300 being the default. Press **Enter** to accept the new Baud rate or **Escape** to return the normal display and retain the old setting. Other communication parameters are fixed as listed in Table 4-1.

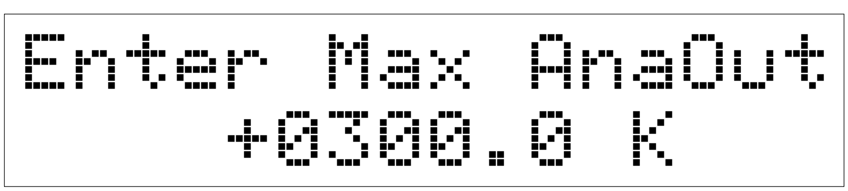
3.4.2 Analog Out

The Analog Output provides a 0 to 10 volt (1 mA max) output that corresponds to the temperature reading. The default analog output has the 0 to 10 volts corresponding to 0 to 1000 K. The resolution is 1.22 mV (0.122 K) and the accuracy is ±0.04% of full scale output + measurement accuracy. The user also has the option to rescale the analog output; assigning new temperatures (in kelvin) to correspond to 0 and 10 V (minimum temperature resolution is 0.1 K).

To program the analog output, press the **Analog Out** button. You will see the following display.



The default selection is default, where the 1 to 10 volt output will correspond to 1 to 1000 K. A different (narrower) temperature range may be selected by using either the ▲, ▼, or **Analog Out** button to cycle the selector arrow (→) to User. Upon pressing the **Enter** button, you will see the Enter Maximum display. For this example, we will use the numeric keypad to enter a maximum temperature of 300 K. After making this entry, you should see the following display.



Press the **Enter** button. The Enter Minimum display will now appear. For this example, we will use the numeric keypad to enter a minimum temperature of 2 K. After making this entry, you should see the following display.

```
Enter Min AnaOut
    +0002.0 K
```

Press the **Enter** button. This completes the definition of the analog output. The 0 to 10 volt output will now correspond to 2 K to 300 K.

3.4.3 Factory Default Settings

The controller can be reset to factory default settings by pressing and holding the **Escape** button for ≈5 seconds. An alternate method is to turn off the unit, and press and hold the **Escape** button while turning the controller on. In either case, the user will see the following display.

CAUTION: Any User or SoftCal Curves and Zone Settings are erased when the controller is initialized.

```
Select With ▲ ▼
Init RAM:→Yes No
```

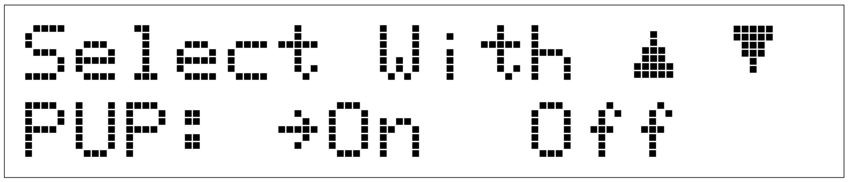
Use either the ▲ or ▼ button to cycle the selector arrow (→) between choices. Select No followed by the **Enter** button if you do not wish to reinitialize the memory. Select Yes followed by the **Enter** button if you do wish to initialize the memory. After briefly flashing a "RAM Initialized" message, the controller will then be returned to factory settings as follows.

Heater ....Off
Setpoint................0.0
Units.....................K
Input Type............Determined by Model Number
Filter.....................Off
TempComp ....Off
Ramp Rate...........Off
Curve ....Determined by Model Number; User and SoftCal Curves erased
SoftCal ....V selected but not implemented
Zone Settings.......Erased
Baud 300
Analog Out...........Default (0 V = 0 K, 10 V = 1000 K)
AutoTune ....Auto PID selected
P 50
I............................20
D 100

3.4.4 Power Up (PUP) Configuration

A provision has been made to store a Power Up (PUP) configuration for the Model 321. This ensures that it will power up to a user-defined state after power down. Parameters including heater range, setpoint, gain, reset, units, and curve number are stored in non-volatile memory and preserved even when the line cord is disconnected.

To view PUP status, press and hold the Enter key for ≈5 seconds. You will see the following display.



"On" indicates that the power up settings will change when settings on the instrument are made via the front panel or over the remote interface. "On" is the default PUP condition.

"Off" indicates that updates to the power up memory are disabled and the instrument will power up in the configuration it was in when the power up feature was turned off.

3.5 THERMOCOUPLE CONTROLLER OPERATION (MODEL 321-04 ONLY)

The thermocouple input option is designed for thermocouple sensors. Chromel-AuFe (0.07%), Chromel-AuFe (0.03%), E, K, and T thermocouples are supported with internal curves that enable the controller to operate in temperature units (°C and K) as well as voltage in millivolts.

The thermocouple input utilizes a secondary temperature sensor to monitor the Reference Junction (room) temperature and provide curve compensation. Thermocouple (Reference Junction) Compensation can be disabled in order for the Model 321 to be used with external compensation techniques.

3.5.1 Sensor Attachment

Thermocouple leads are attached to the terminal block by aluminum screws. Be sure to tighten the terminal screws carefully. Loose connections will result in unstable readings and control. The leads must be connected with the proper polarity or the input option will not operate properly. The positive terminal of the terminal block is on the side of the V+ label on the back panel and should correspond with the positive thermoelement listed for each type of thermocouple.

3.5.2 Thermocouple Curve Selection

To choose a thermocouple curve listed in Table 2-3. Refer to the instructions for curve selection in Paragraph 3.2.5.

3.5.3 Thermocouple Compensation From Front Panel

To determine whether thermocouple compensation is selected or not, refer to Paragraph 3.2.3.

3.5.4 Thermocouple Compensation From Remote Interface

To select or prevent thermocouple compensation over the remote interface, use the ACOMP command described in Chapter 4 - Remote Operation.

3.5.5 Internal Offset Adjustment

When a new or different thermocouple is attached to the controller, you must adjust the offset to compensate for discrepancies in thermocouple material, leads, and connections. Offset adjustment trimpots are provided inside the Model 321 to allow offset calibration of the thermocouple.

1. Place the thermocouple in a reference bath of known temperature (liquid nitrogen, ice, etc.). Allow the system to stabilize to the reference temperature.
2. On the front panel, select the thermocouple input and the desired temperature units.
3. Turn on thermocouple compensation.
4. Remove the controller cover.
5. Adjust the offset adjustment trimpot (R60) so that the displays read the reference temperature.

NOTE: The offset adjustment compensates for the thermocouple used in the calibration. If another thermocouple is attached, or the thermocouple has aged, or the configuration of the system is changed, then the offset adjustment must be repeated.

3.5.6 Curve Format

The input is hardware limited to reading input between -45 mV and +45mV. All curves should be limited in temperature so not to exceed these values. If thermocouple compensation is desired, the thermocouple curve must be normalized to zero in degrees Celsius. Compensation also limits the practical range of the card by approximately the room temperature voltage of the thermocouple used.

The Model 321 is designed to operate on sensor curve data in the range of 0.00000 to 9.00000 volts so thermocouple voltage must be converted to this range before it is entered into a curve table. To obtain the proper table value from a thermocouple voltage, it must be summed with 45 millivolts to make it positive and multiplied by one hundred to shift the resolution.

A -45.0000 millivolt thermocouple voltage will result in a 0.00000 volt table value and +45.0000 millivolts will result in 9.00000 volts.

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CHAPTER 4

REMOTE OPERATION

4.0 GENERAL

The Model 321 is equipped with an RS-232C serial computer interface. The interface allows computer automation of instrument setup and field measurement data collection. Nearly every feature of the instrument can be accessed through the computer interface. Interface capabilities including setup information and Basic programs are provided in Paragraph 4.1. Interface commands including a command summary are detailed in Paragraph 4.2.

4.1 SERIAL INTERFACE OVERVIEW

The serial interface used in the Model 321 is commonly referred to as an RS-232C interface. RS-232C is a standard of the Electronics Industries Association (EIA) that describes one of the most common interfaces between computers and electronic equipment. The RS-232C standard is quite flexible and allows many different configurations. However, any two devices claiming RS-232C compatibility cannot necessarily be plugged together without interface setup. The remainder of this paragraph briefly describes the key features of a serial interface that are supported by the instrument. A customer supplied computer with similarly configured interface port is required to enable communication.

4.1.1 Physical Connection

The Model 321 has an RJ-11 connector on the rear panel for serial communication. The original RS-232C standard specifies 25 pins, but 9-pin, 25-pin, and RJ-11 connectors are commonly used in the computer industry. For you convenience, Lake Shore offers a Model 2001 RJ-11 Cable. When combined with either the Model 2002 DB-25 Adapter or Model 2003 DE-9 Adapter, this cable assembly can be used to connect the instrument to a computer with the corresponding connector type (See Figure 4-1). These adapters are described in Chapter 5 – Options and Accessories and are schematically diagramed in Figures 6-6 thru 6-8.

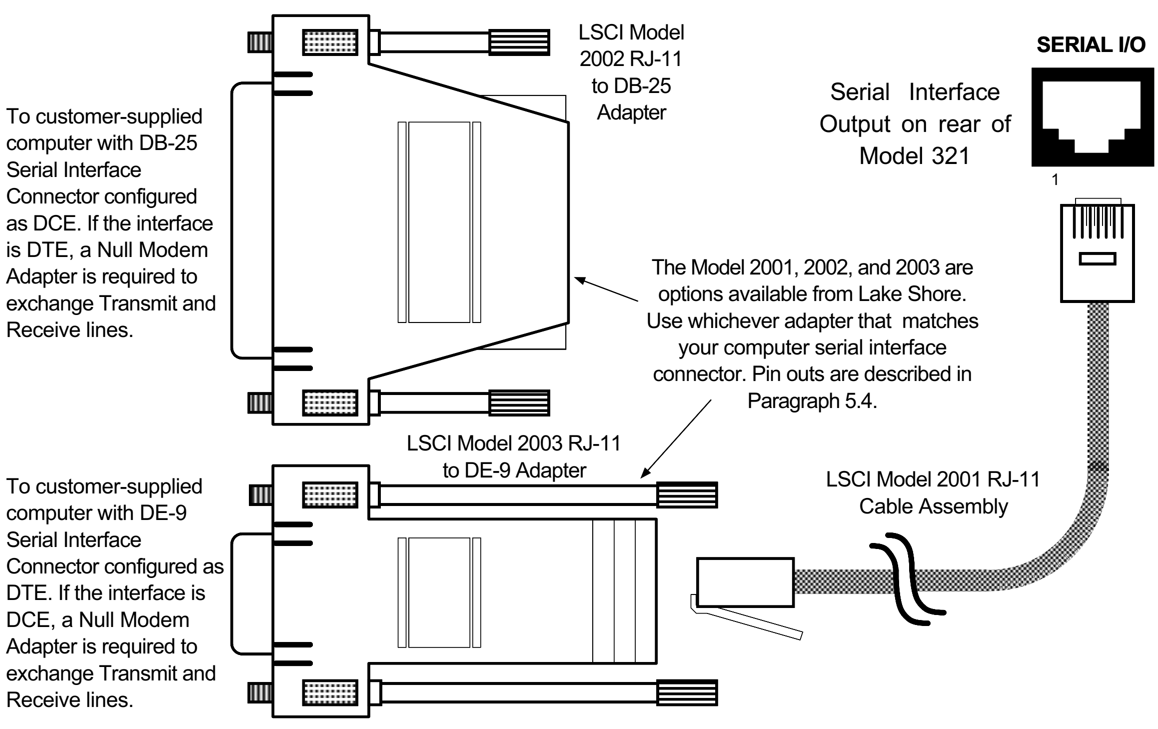


Figure 4-1. Optional Serial Interface Connections

Physical Connection (Continued)

Equipment with Data Communications Equipment (DCE) wiring can be connected to the instrument with a straight through cable. However, if the interface is for Data Terminal Equipment (DTE), a Null Modem Adapter is required to exchange the transmit (TxD) and receive (RxD) lines.

The instrument uses drivers to generate the transmission voltage levels required by the RS-232C standard. These voltages are considered safe under normal operating conditions because of their relatively low voltage and current limits. The drivers are designed to work with cables up to 50 feet in length.

4.1.2 Hardware Support

The Model 321 interface hardware supports the following features. Asynchronous timing is used for the individual bit data within a character. This timing requires start and stop bits as part of each character so the transmitter and receiver can resynchronized between each character. Half duplex transmission allows the instrument to be either a transmitter or a receiver of data but not at the same time. Communication speeds of 300 or 1200 baud are supported. The Baud rate is the only interface parameter that can be changed by the user.

Hardware handshaking is not supported by the instrument. Handshaking is often used to guarantee that data message strings do not collide and that no data is transmitted before the receiver is ready. In this instrument appropriate software timing substitutes for hardware handshaking. User programs must take full responsibility for flow control and timing as described in Paragraph 4.1.5.

4.1.3 Character Format

A character is the smallest piece of information that can be transmitted by the interface. Each character is 10 bits long and contains data bits, bits for character timing and an error detection bit. The instrument uses 7 bits for data in the ASCII format. One start bit and one stop bit are necessary to synchronize consecutive characters. Parity is a method of error detection. One parity bit configured for odd parity is included in each character.

ASCII letter and number characters are used most often as character data. Punctuation characters are used as delimiters to separate different commands or pieces of data. Two special ASCII characters, carriage return (CR 0DH) and line feed (LF 0AH), are used to indicate the end of a message string.

Table 4-1. Serial Interface Specifications

Connector Type:	RJ-11 Connector
Connector Wiring:	DTE
Voltage Levels:	EIA RS-232C Specified
Transmission Distance:	50 feet maximum
Timing Format:	Asynchronous
Transmission Mode:	Half Duplex
Baud Rate:	300, 1200
Handshake:	Software timing
Character Bits:	1 Start, 7 Data, 1 Parity, 1 Stop
Parity:	Odd
Terminators:	CR(0DH) LF(0AH)
Command Rate:	20 commands per second maximum

4.1.4 Message Strings

A message string is a group of characters assembled to perform an interface function. There are three types of message strings commands, queries and responses. The computer issues command and query strings through user programs, the instrument issues responses. Two or more command strings can be chained together in one communication but they must be separated by a semi-colon (;). Only one query is permitted per communication but it can be chained to the end of a command. The total communication string must not exceed 64 characters in length.

Message Strings (Continued)

A command string is issued by the computer and instructs the instrument to perform a function or change a parameter setting. The format is <command mnemonic><space><parameter data><terminators>. Command mnemonics are listed in Paragraph 4.2. Parameter data necessary for each one is described in Paragraph 4.2.1. Terminators must be sent with every message string.

A query string is issued by the computer and instructs the instrument to send a response. The query format is <query mnemonic><?><space><parameter data><terminators>. Query mnemonics are often the same as commands with the addition of a question mark. Parameter data is often unnecessary when sending queries. Query mnemonics are listed in Paragraph 4.2. Parameter data if necessary is described in Paragraph 4.2.1. Terminators must be sent with every message string. The computer should expect a response very soon after a query is sent.

A response string is the instruments response or answer to a query string. The instrument will respond only to the last query it receives. The response can be a reading value, status report or the present value of a parameter. Response data formats are listed along with the associated queries in Paragraph 4.2.1. The response is sent as soon as possible after the instrument receives the query. Typically it takes 10 ms for the instrument to begin the response. Some responses take longer.

4.1.5 Message Flow Control

It is important to remember that the user program is in charge of the serial communication at all times. The instrument can not initiate communication, determine which device should be transmitting at a given time or guarantee timing between messages. All of this is the responsibility of the user program.

When issuing commands only the user program should:

- Properly format and transmit the command including terminators as one string.
- Guarantee that no other communication is started for 50 ms after the last character is transmitted.
- Not initiate communication more than 20 times per second.

When issuing queries or queries and commands together the user program should:

- Properly format and transmit the query including terminators as one string.
- Prepare to receive a response immediately.
- Receive the entire response from the instrument including the terminators.
- Guarantee that no other communication is started during the response or for 50 ms after it completes.
- Not initiate communication more than 20 times per second.

Failure to follow these simple rules will result in inability to establish communication with the instrument or intermittent failures in communication.

4.1.6 Changing Baud Rate

To use the Serial Interface, you must first set the Baud rate. Press **Interface** key to display the following screen.

```
Select With ▲ ▼
Baud →300  1200
```

Press the ▲ or ▼ keys to cycle through the choices of 300 or 1200 Baud. The rate selected will have a right pointing arrow (→) immediately to the left. Press **Enter** to accept the new number.

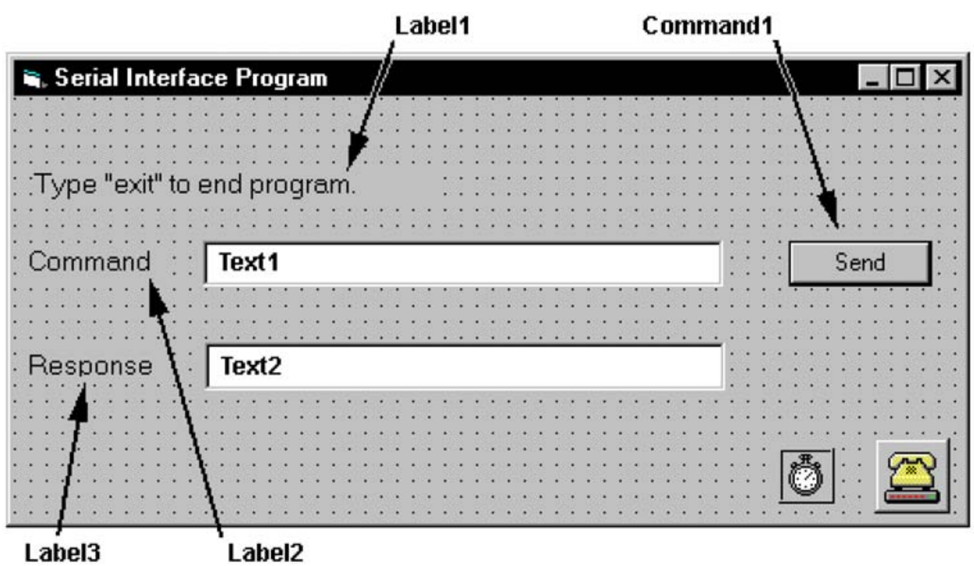
4.1.7 Serial Interface Basic Programs

Two BASIC programs are included to illustrate the serial communication functions of the instrument. The first program was written in Visual Basic. Refer to Paragraph 4.1.7.1 for instructions on how to setup the program. The Visual Basic code is provided in Table 4-3. The second program was written in Quick Basic. Refer to Paragraph 4.1.7.2 for instructions on how to setup the program. The Quick Basic code is provided in Table 4-4. Finally, a description of operation common to both programs is provided in Paragraph 4.1.7.3. While the hardware and software required to produce and implement these programs not included with the instrument, the concepts illustrated apply to almost any application where these tools are available.

4.1.7.1 Visual Basic Serial Interface Program Setup

The serial interface program (Table 4-3) works with Visual Basic 6.0 (VB6) on an IBM PC (or compatible) with a Pentium-class processor. A Pentium 90 or higher is recommended, running Windows 95 or better, with a serial interface. It uses the COM1 communications port at 9600 Baud. Use the following procedure to develop the Serial Interface Program in Visual Basic.

1. Start VB6.
2. Choose Standard EXE and select Open.
3. Resize form window to desired size.
4. On the Project Menu, click Components to bring up a list of additional controls available in VB6.
5. Scroll through the controls and select Microsoft Comm Control 6.0. Select OK. In the toolbar at the left of the screen, the Comm Control will have appeared as a telephone icon.
6. Select the Comm control and add it to the form.
7. Add controls to form:
   a. Add three Label controls to the form.
   b. Add two TextBox controls to the form.
   c. Add one CommandButton control to the form.
   d. Add one Timer control to the form.
8. On the View Menu, select Properties Window.
9. In the Properties window, use the dropdown list to select between the different controls of the current project.

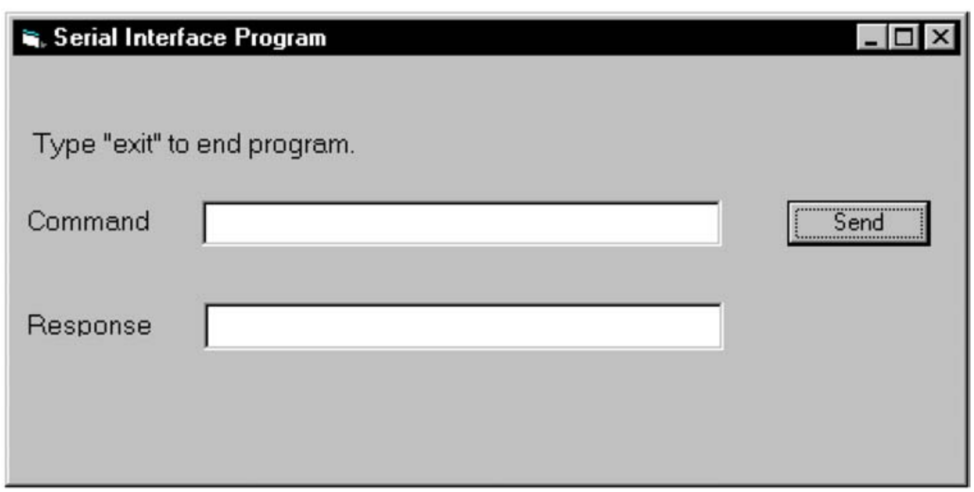


10. Set the properties of the controls as defined in Table 4-2.
11. Save the program.

Table 4-2. Serial Interface Program Control Properties

Current Name	Property	New Value
Label1	Name Caption	lblExitProgram Type “exit” to end program.
Label2	Name Caption	lblCommand Command
Label3	Name Caption	lblResponse Response
Text1	Name Text	txtCommand <blank>
Text2	Name Text	txtResponse <blank>
Command1	Name Caption Default	cmdSend Send True
Form1	Name Caption	frmSerial Serial Interface Program
Timer1	Enabled Interval	False 10

12. Add code (provided in Table 4-3).
    a. In the Code Editor window, under the Object dropdown list, select (General). Add the statement: Public gSend as Boolean
    b. Double Click on cmdSend. Add code segment under Private Sub cmdSend_Click( ) as shown in Table 4-3.
    c. In the Code Editor window, under the Object dropdown list, select Form. Make sure the Procedure dropdown list is set at Load. The Code window should have written the segment of code: Private Sub Form_Load( ). Add the code to this subroutine as shown in Table 4-3.
    d. Double Click on the Timer control. Add code segment under Private Sub Timer1_Timer() as shown in Table 4-3.
    e. Make adjustments to code if different Com port settings are being used.
13. Save the program.
14. Run the program. The program should resemble the following.



15. Type in a command or query in the Command box as described in Paragraph 4.1.7.3.
16. Press Enter or select the Send button with the mouse to send command.
17. Type Exit and press Enter to quit.

Table 4-3. Visual Basic Serial Interface Program

```
Public gSend As Boolean                                   'Global used for Send button state

Private Sub cmdSend_Click()                               'Routine to handle Send button press
    gSend = True                                          'Set Flag to True
End Sub

Private Sub Form_Load()                                   'Main code section
    Dim strReturn As String                               'Used to return response
    Dim strHold As String                                 'Temporary character space
    Dim Term As String                                    'Terminators
    Dim ZeroCount As Integer                              'Counter used for Timing out
    Dim strCommand As String                              'Data string sent to instrument

    frmSerial.Show                                        'Show main window
    Term = Chr(13) & Chr(10)                              'Terminators are <CR><LF>
    ZeroCount = 0                                         'Initialize counter
    strReturn = ""                                        'Clear return string
    strHold = ""                                          'Clear holding string
    If frmSerial.MSComm1.PortOpen = True Then             'Close serial port to change settings
        frmSerial.MSComm1.PortOpen = False
    End If
    frmSerial.MSComm1.CommPort = 1                        'Example of Comm 1
    frmSerial.MSComm1.Settings = "9600,o,7,1"             'Example of 9600 Baud,Parity,Data,Stop
    frmSerial.MSComm1.InputLen = 1                        'Read one character at a time
    frmSerial.MSComm1.PortOpen = True                     'Open port

  Do
    Do                                                    'Wait loop
    DoEvents                                              'Give up processor to other events
    Loop Until gSend = True                               'Loop until Send button pressed
    gSend = False                                         'Set Flag as false

    strCommand = frmSerial.txtCommand.Text                'Get Command
    strReturn = ""                                        'Clear response display

    strCommand = UCase(strCommand)                        'Set all characters to upper case
    If strCommand = "EXIT" Then                           'Get out on EXIT
        End
    End If

    frmSerial.MSComm1.Output = strCommand & Term          'Send command to instrument
    If InStr(strCommand, "?") <> 0 Then                   'Check to see if query
        While (ZeroCount < 20) And (strHold <> Chr$(10))  'Wait for response
            If frmSerial.MSComm1.InBufferCount = 0 Then   'Add 1 to timeout if no character
                frmSerial.Timer1.Enabled = True
                Do
                DoEvents                                  'Wait for 10 millisecond timer
                Loop Until frmSerial.Timer1.Enabled = False
                ZeroCount = ZeroCount + 1                 'Timeout at 2 seconds
            Else
                ZeroCount = 0                             'Reset timeout for each character
                strHold = frmSerial.MSComm1.Input         'Read in one character
                strReturn = strReturn + strHold           'Add next character to string
            End If
        Wend                                              'Get characters until terminators

        If strReturn <> "" Then                           'Check if string empty
            strReturn = Mid(strReturn, 1, InStr(strReturn, Term) - 1)  'Strip terminators
        Else
            strReturn = "No Response"                     'Send No Response
        End If
        frmSerial.txtResponse.Text = strReturn            'Put response in textbox on main form
        strHold = ""                                      'Reset holding string
        ZeroCount = 0                                     'Reset timeout counter
    End If
  Loop
End Sub

Private Sub Timer1_Timer()                                'Routine to handle Timer interrupt
    frmSerial.Timer1.Enabled = False                      'Turn off timer
End Sub
```

4.1.7.2 Quick Basic Serial Interface Program Setup

The serial interface program (Table 4-4) works with QuickBasic 4.0/4.5 or Qbasic on an IBM PC (or compatible) running DOS or in a DOS window with a serial interface. It uses the COM1 communication port at 9600 Baud. Use the following procedure to develop the Serial Interface Program in Quick Basic.

1. Start the Basic program.
2. Enter the program exactly as presented in Table 4-4.
3. Adjust the Com port and Baud rate in the program as necessary.
4. Lengthen the "TIMEOUT" count if necessary.
5. Save the program.
6. Run the program.
7. Type a command query as described in Paragraph 4.1.7.3.
8. Type "EXIT" to quit the program.

Table 4-4. Quick Basic Serial Interface Program

```
       CLS                                                'Clear screen
       PRINT " SERIAL COMMUNICATION PROGRAM"
       PRINT
       TIMEOUT = 2000                                     'Read timeout (may need more)
       BAUD$ = "9600"
       TERM$ = CHR$(13) + CHR$(10)                        'Terminators are <CR><LF>
       OPEN "COM1:" + BAUD$ + ",O,7,1,RS" FOR RANDOM AS #1 LEN = 256

LOOP1: LINE INPUT "ENTER COMMAND (or EXIT):"; CMD$        'Get command from keyboard
       CMD$ = UCASE$(CMD$)                                'Change input to upper case
         IF CMD$ = "EXIT" THEN CLOSE #1: END              'Get out on Exit
       CMD$ = CMD$ + TERM$
       PRINT #1, CMD$;                                    'Send command to instrument

       IF INSTR(CMD$, "?") <> 0 THEN                      'Test for query
         RS$ = ""                                         'If query, read response
         N = 0                                            'Clr return string and count

         WHILE (N < TIMEOUT) AND (INSTR(RS$, TERM$) = 0)    'Wait for response
           IN$ = INPUT$(LOC(1), #1)                       'Get one character at a time
           IF IN$ = "" THEN N = N + 1 ELSE N = 0          'Add 1 to timeout if no chr
           RS$ = RS$ + IN$                                'Add next chr to string
         WEND                                             'Get chrs until terminators

         IF RS$ <> "" THEN                                'See if return string is empty
           RS$ = MID$(RS$, 1, (INSTR(RS$, TERM$) - 1))'Strip off terminators
           PRINT "RESPONSE:"; RS$                         'Print response to query
         ELSE
           PRINT "NO RESPONSE"                            'No response to query
         END IF
       END IF                                             'Get next command
       GOTO LOOP1
```

4.1.7.3 Program Operation

Once either program is running, try the following commands and observe the response of the instrument. Input from the user is shown in **bold** and terminators are added by the program. The word [term] indicates the required terminators included with the response.

`ENTER COMMAND?` **`CUNI K`**	Set Control Units. Instrument will set unit to kelvin units.
`ENTER COMMAND?` **`CUNI?`**	Control Units Query. Instrument will return appropriate unit, where K = kelvin.
`K`	
`ENTER COMMAND?` **`CDAT?`**	Sensor Data Query. Instrument will return appropriate sensor reading.
`+77.6`	
`ENTER COMMAND?` **`TUNE 3`**	Set Autotuning Status. Instrument will set Autotuning to PID.
`ENTER COMMAND?` **`TUNE?`**	Autotuning Status Query. Instrument will return appropriate setting, where 0 = Manual, 1 = P, 2 = PI, and 3 = PID.
`3`	
`ENTER COMMAND?` **`RANG 0;RANG?`**	Combination command of setting the heater to off and requesting heater status; where 0 = off and 1 = on.
`0`	
`ENTER COMMAND?`	

The following are additional notes on using either Serial Interface program.

- If you enter a correctly spelled query without a "**?**," nothing will be returned. Incorrectly spelled commands and queries are ignored. Commands and queries and should have a space separating the command and associated parameters.
- Leading zeros and zeros following a decimal point are not needed in a command string, but they will be sent in response to a query. A leading "**+**" is not required but a leading "**–**" *is* required.

4.1.8 Trouble Shooting

New Installation

1. Check instrument baud rate
2. Make sure transmit (TD) signal line from the instrument is routed to receive (RD) on the computer and vice versa. (Use a null modem adapter if not).
3. Always send terminators
4. Send entire message string at one time including terminators. (Many terminal emulation programs do not.)
5. Send only one simple command at a time until communication is established.
6. Be sure to spell commands correctly and use proper syntax.

Old Installation No Longer Working

1. Power instrument off then on again to see if it is a soft failure.
2. Power computer off then on again to see if communication port is locked up.
3. Verify that baud rate has not been changed on the instrument during a memory reset.
4. Check all cable connections.

Intermittent Lockups

1. Check cable connections and length.
2. Increase delay between all commands to 100 ms to make sure instrument is not being over loaded.

4.2 SERIAL INTERFACE COMMANDS

This paragraph provides a summary of the Serial Interface Commands. The summary is divided into four command groups: Display, Control Process, Curve Commands, and Analog Output Commands. A detailed list of Display Commands is provided in Paragraph 4.2.1. A detailed list of Control Process Commands is provided in Paragraph 4.2.2. A detailed list of Curve Commands is provided in Paragraph 4.2.3. Finally, a detailed list of Analog Output Commands is provided in Paragraph 4.2.4.The commands are presented in the same order presented in Table 4-5.

Table 4-5. Serial Interface Command Summary

Display Commands

Command	Function	Page
∗IDN	Identification Query	10
CDAT?	Control Sensor Data Query	10
CUNI	Set Control Units	10
CUNI?	Control Units Query	11
FILT	Set Display Filter	11
FILT?	Display Filter Query	11

Control Process Commands

Command	Function	Page
TUNE	Tune Status	12
TUNE?	Tune Query	12
SETP	Set Setpoint	12
SETP?	Setpoint Query	12
GAIN	Set Gain	13
GAIN?	Gain Query	13
RSET	Set Reset	13
RSET?	Reset Query	13
RATE	Set Rate	13
RATE?	Rate Query	13
RANG	Set Range	14
RANG?	Range Query	14
HEAT?	Heater Query	14
ZONE	Store Zone	14
ZONE?	Zone Query	14
RAMP	Enable/Disable Ramping	15
RAMP?	Ramping Enable/Disable Query	15
RAMPR	Set Ramp Rate in K/min.	15
RAMPR?	Ramp Rate Query	15
RAMPS?	Ramping Status Query	15

Curve Commands

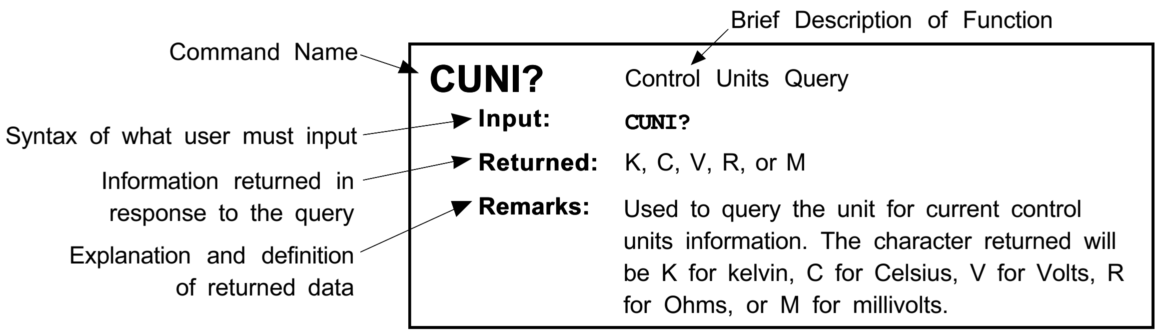
Command	Function	Page
ACUR	Set Curve for A	16
ACUR?	Curve A Query	16
ACOMP	Set A Compensation	16
ACOMP?	A Compensation Query	16
ATYPE?	A Input Type Query	16
CUID?	Curve Identification Query	17
CURV11	Enter User Curve 11	17
CURV?	Curve No. Information Query	18
ECUR11	Edit User Curve 11	19
KCUR11	Delete User Curve 11	19
SCAL	SoftCal™ Entry	19

Analog Output Commands

Command	Function	Page
ANOD	Set Analog Output Default	20
ANOD?	Analog Default Query	20
ANOH	Set Analog Output Max. (High)	20
ANOH?	Analog Max. (High) Query	20
ANOL	Set Analog Output Min. (Low)	20
ANOL?	Analog Min. (Low) Query	20

4.2.1 Display Commands

This paragraph provides a detailed description of each Display Command. The display commands allow the interface to act as a virtual display. Display data, as well as format, can be transferred. An explanation of the command structure is shown below.



∗IDN? — Identification Query.

Input: `∗IDN?`

Returned: Manufacturer,model number,0,firmware date

Remarks: Identifies the instrument model and software level. "0" in the returned syntax is in place of the serial number.

Example: `LSCI,MODEL321,0,121393[term]`

CDAT? — Sensor Data Query.

Input: `CDAT?`

Returned: `+/- 000.0`

Remarks: A free field is active here. The value returned is 7 characters: a sign, 5 digits and a decimal point. The last digit may be a null.

Example:
`+1.2345[term]` Typical response for a voltage query.
`-123.4 [term]` Typical response for a degrees Celsius query.
`+234.5 [term]` Typical response for a kelvin or degrees Celsius query.

CUNI — Set Control Units Status.

Input: `CUNI K`, `CUNI C`, or `CUNI S`

Returned: Nothing

Remarks: Set units parameter with K for kelvin, C for Celsius, or S for the appropriate sensor units (volts, ohms, or millivolts).

Example: If operating in kelvin with a Model 321-01, CUNI S[term] makes the units volts; being the sensor units for a diode sensor. The Model 321-02 platinum controller has sensor units of ohms, and the Model 321-04 thermocouple controller has sensor units of millivolts.

Display Commands (Continued)

CUNI?

Control Units Query.

Input: `CUNI?`

Returned: **K**, **C**, **V**, **R**, or **M**

Remarks: Returns current control units setting. The character returned will be K for kelvin, C for Celsius, V for volts, R for Ohms or M for millivolts.

FILT

Set Display Filter.

Input: **FILT 0**, or **FILT 1**

Returned: Nothing

Remarks: Used to turn the display filter on or off, where 0 = Off and 1 = On. Quiets the display by taking a running average of 10 readings.

FILT?

Display Filter Query.

Input: `FILT?`

Returned: **0** or **1**

Remarks: Returns the display filter setting, where 0 = Off and 1 = On.

4.2.2 Control Process Commands

This paragraph provides a detailed description of each Control Process Command. These commands allow the interface to change any of the control parameters of the Model 321. Manual mode PID parameters are accessible as well as Autotuning status.

TUNE

Sets Autotuning Status.

Input: **`TUNE X`**

Returned: Nothing

Remarks: Set Autotuning status as follows: 0 = Manual, 1 = P, 2 = PI, and 3 = PID. Refer to Paragraph 4.1 for further information on Autotuning settings.

TUNE?

Autotuning Query.

Input: **`TUNE?`**

Returned: **`X`**

Remarks: Returns current Autotuning status where 0 = Manual, 1 = P, 2 = PI, and 3 = PID. Refer to Paragraph 4.1 for further information on Autotuning settings.

SETP

Sets Setpoint In Units Chosen For Control.

Input: **`SETP XXX.X`** for temperature, or **`SETP X.XXXX`** for voltage

Returned: Nothing

Remarks: Fill in the setpoint parameter with a value from 0 through 999.9 for temperature or 0 through 2.499 for voltage. Utilizes the free field format for the decimal point.

Example: If in kelvin:

1. **`SETP 77.2[term]`** will result in the display showing 77.2 K.
2. **`SETP 123[term]`** will result in the display showing 123.0 K.

If in Celsius:

3. **`SETP -123[term]`** will result in the display showing –123.0 C.
4. **`SETP 123.456[term]`** will result in the display showing 123.4 C.

SETP?

Setpoint Status Query.

Input: **`SETP?`**

Returned: **`±XXX.X`** for temperature, or **`±X.XXXX`** for voltage

Remarks: Returns current set point setting. The value returned will be 6 digits (a sign, 4 digits, and a decimal point).

Example: If using the examples above in the SETP command discussion—if in kelvin:

1. **`SETP?[term]`** will return **`+077.2 [term]`**.
2. **`SETP?[term]`** will return **`+123.0 [term]`**.

If in Celsius:

3. **`SETP?[term]`** will return **`-123.0 [term]`**.
4. **`SETP?[term]`** will return **`+123.4 [term]`**.

Control Process Commands (Continued)

GAIN

Set Gain While In Manual Control Mode.

Input: `GAIN XXX`

Returned: Nothing

Remarks: The gain parameter can be filled in with an integer of 0 through 999.

Example: `GAIN 65 [term]` instructs the Model 321 to set a control gain of 65. Gain corresponds to the Proportional (P) portion of the PID Autotuning control algorithm.

GAIN?

Gain Query.

Input: `GAIN?`

Returned: `XXX`

Remarks: Returns current gain setting in manual or AutoTune mode. The value returned is an integer from 000 through 999. Gain corresponds to the Proportional (P) portion of the PID Autotuning control algorithm.

RSET

Manual Mode Reset Setting.

Input: `RSET XXX`

Returned: Nothing

Remarks: The reset parameter can be filled in with an integer from 0 through 999. Reset corresponds to the Integral (I) portion of the PID Autotuning control algorithm.

RSET?

Reset Query.

Input: `RSET?`

Returned: `XXX`

Remarks: Returns current reset setting. The value returned is an integer from 000 through 999. Reset corresponds to the Integral (I) portion of the PID Autotuning control algorithm.

RATE

Manual Mode Rate Setting.

Input: `RATE XXX`

Returned: Nothing

Remarks: The rate parameter can be filled in with an integer from 0 through 200. Rate corresponds to the Differential (D) portion of the PID Autotuning control algorithm.

RATE?

Rate Query.

Input: `RATE?`

Returned: `XXX`

Remarks: Returns current rate setting. The value returned is an integer from 0 through 200. Rate corresponds to the Differential (D) portion of the PID Autotuning control algorithm.

Control Process Commands (Continued)

RANG
Set Heater Status.

Input: `RANG 0`, `RANG 2` or `RANG 3`

Returned: Nothing

Remarks: Sets heater status where 0 = off, 2 = low, and 3 = high.

RANG?
Heater Status Query.

Input: `RANG?`

Returned: `0`, `2` or `3`

Remarks: Returns current heater status where 0 = off, 2 = low, and 3 = high.
NOTE: To maintain software compatibility with the Model 320, RANG 1 will be interpreted as 3 (high).

HEAT?
Heater Power Status Query.

Input: `HEAT?`

Returned: `XXX`

Remarks: Returns the percent of full scale heater current, where the returned number represents one percent increments up to 100.

ZONE
Zone Storage.

Input: `ZONE XX,±SSS.S,R,PPP,III,DDD`

Returned: Nothing

Remarks: Stores the stated values of Setpoint, Heater Range, Gain, Rate, and Reset. Zone XX is between 01 and 10. ±SSS.S is the setpoint in kelvin, R is the heater range, PPP is the gain, III is the Reset, and DDD is the Rate. The heater Range is 0 for Heater off, 2 for Heater Low, and 3 for Heater High.

Example: `ZONE 1,100.0,2,100.0,100,20[term]` instructs the Model 321 to store in Zone 1 a setpoint of 100.0 K, a Heater Range of 2 (Low), a Gain of 100, a Reset of 100, and a Rate of 20%.

ZONE?
Zone Storage Query.

Input: `ZONE?XX`

Returned: `±SSS.S,R,PPP,III,DDD`

Remarks: When entering the zone command, XX defines the zone between 01 and 10. Returned information is in the following format: ±SSS.S is the setpoint in kelvin, R is the heater range, PPP is the gain, III is the Reset, and DDD is the Rate. The heater Range is 0 for Heater off, 2 for Heater Low, and 3 for Heater High.

Control Process Commands (Continued)

RAMP

Enable/Disable Ramp Function.

Input: `RAMP 0` or `RAMP 1`

Returned: Nothing

Remarks: RAMP 0 disables the ramping function while RAMP 1 enables ramping.

RAMP?

Ramping Enable/Disable Status Query.

Input: `RAMP?`

Returned: `0` or `1`

Remarks: Returns a 0 if the ramping function is disabled or a 1 if the ramping function is enabled.

RAMPR

Set Ramp Rate in Kelvin per Minute.

Input: `RAMPR XX.X`

Returned: Nothing

Remarks: XX.X is the ramp rate in Kelvin per minute between 0 and 99.9.

Example: `RAMP 10[term]` instructs the Model 321 to make the ramp rate equal to 10 K/Min.

RAMPR?

Ramp Rate Query.

Input: `RAMPR?`

Returned: `XX.X`

Remarks: Returns the current value of the ramp rate.

RAMPS?

Ramping Status Query.

Input: `RAMPS?`

Returned: `0` or `1`

Remarks: Returns a 1 if the instrument is in the process of ramping or a 0 if not ramping.

4.2.3 Curve Commands

This paragraph provides a detailed description of each Curve Command. The commands allow the user to verify existing curves added at the factory or enter and delete the user defined curve over the interface.

ACUR

Assign Curve Number.

Input: `ACUR XX`

Returned: Nothing

Remarks: Fill in curve parameter with an integer from 0 through 12. Refer to Table 2-2 for a listing of sensor curve numbers.

ACUR?

Curve Number Query.

Input: `ACUR?`

Returned: `XX`

Remarks: Value returned is an integer from 00 through 12, corresponding to the currently selected sensor curve number. Refer to Table 2-2 for a listing of sensor curve numbers.

ACOMP

Set Room Temperature Compensation **(Model 321-04 Thermocouple Only).**

Input: `ACOMP 0` or `ACOMP 1`

Returned: Nothing

Remarks: Select temperature compensation parameter with 0 for off or 1 for on.

ACOMP?

Room Temperature Compensation Query **(Model 321-04 Thermocouple Only).**

Input: `ACOMP?`

Returned: `0` or `1`

Remarks: Returns current room temperature compensation status where 0 = off and 1 = on

---

ATYPE?

Input Type Query.

Input: `ATYPE?`

Returned: `SI`, `PT`, `TC`, or `ER`

Remarks: Returns input type where SI = silicon diode, PT = platinum, TC = thermocouple, and ER = error (improper switch setting).

Curve Commands (Continued)

CUID?

Curve Identification Query.

Input: `CUID?`

Returned: `WW,XXXXXXXXXXXXXXXXXX,Y,ZZ,...`

Remarks: Returns the header lines that identify the curves (standard sensor and user curve) loaded into each curve location. The information lines for the user curve will only be available if it is actually present. Information returned is defined as follows:

W = Curve number:	The value given here will be 00 through 11.
X = Curve description:	18 character information line. All 18 character spaces do not have to be used.
Y = Temp. coefficient:	N represents a negative temperature coefficient, while P represents a positive one.
Z = Number of points:	This value will be the number of points for that particular curve (usually 31, but can be up to 99).

Example:

```
00, STANDARD DRC-D ,N,31,
01, STANDARD DRC-E1,N,31,
02, STANDARD CRV 10,N,31,
03, STANDARD DIN-PT,P,31,
```

etc.

CURV11

Initiate User Curve.

Input: `CURV 11,SB0CCCCCCCCCCCCCCC,D.DDDDD,EEE.E,Y.YYYYY,ZZZ.Z*`

Returned: Nothing

Note: Due to the limited 256 character buffer used by the serial interface, an entire curve cannot be loaded at once. The CURV11 command should be used to enter the first two points and then the ECUR11 command to add the remaining points one at a time up to a maximum of 97 points.

Remarks: This command is used to establish and enter the first two points of the user curve in the following format:

S	=	For the Model 330, the first character must be the letter "S."
B	=	Setpoint Limit, where 0 = 325 K, 1 = 375 K, 2 = 475 K, 3 = 800 K, and 9 = 999 K. The 9 should be used for all thermocouples.
0	=	For the Model 321, the third character should be the number "0" for all sensors except thermocouples where the number should be "9.'
C	=	15 characters for curve description. Must be at least 1 character. More than 15 characters will be ignored.
D	=	First voltage or resistance (lowest units value).
E	=	First temperature.
Y	=	Last voltage or resistance (highest units value).
Z	=	Last temperature.

The data points are input with the units value first. This value will be voltage or R_{equiv}. The value will have one character before the decimal place and five after it (0.00000). The table below gives the conversion of raw units into the format required. The Model 321 automatically fills in leading and trailing zeros.

The second value is the temperature. It has three character spaces before the decimal point and one after it (000.0). After both points are input, placement of an "*" terminates the sensor curve input.

(Continued on next page)

Curve Commands (Continued)

CURV11 (Continued)

To view a typical output after using this command, refer to the example under the CURV? command. When entering, omit the temperature coefficient, number of points, and endpoints.

The Model 321 determines and stores whether the curve is a positive or negative coefficient curve. Based on temperature coefficient, the Model 321 then stores the curve end points and also adds the number of points.

INPUT TYPE	UNITS	CONVERSION
Silicon Diode	Voltage	Input range is 0.00000 to 6.00000.
Platinum	Resistance	Input range is 0.00 to 299.99 Ω. 0.00 Ω looks like 0.00000 and 299.99 Ω looks like 2.99990 (0.01 times R).
Thermocouple	Millivolts	Input range is –45 to +45. Add 45 mV to make all positive 0–90 mV and multiply by 100 to make look like 0–9.00000 V. For example, a thermocouple voltage of 0.0000 mV would be entered as 4.50000 V. Temperature should be stored as K÷2.

To aid in the automated loading of the User Curve, a QuickBASIC Curve Loading Program is provided in Paragraph 4.3.

CURV?

Curve Number Information Query.

Input: `CURV? XX`

Returned: `AA,SB0CCCCCCCCCCCCCCC,D,XX,Y.YYYYY,ZZZ.Z`

Remarks: User must provide curve number (00 thru 12) with query. The instrument will return header line and all point information for that curve. Information returned is defined as follows:

A = Curve number: The value will be from 00 to 11.
B = Setpoint Limit 0 = 325 K, 1 = 375 K, 2 = 475 K, 3 = 800 K, and 9 = 999 K. The 9 should be used for all thermocouples.
0 = For the Model 321, the third character should be the number "0" for all sensors except thermocouples where the number should be "9.'
C = Curve description: 15 character information line. You do not have to use all 15 characters, but there must be at least 1 character.
D = Temp. coefficient: N represents negative temperature coefficient, while P represents positive.
X = Number of points: The number of data points for that particular curve (usually 31, but can be up to 99).
Y = Units: The value will be voltage or R_{equiv}. (Refer to CURV Command). The value will have 1 character before the decimal place and 5 after it (0.00000).
Z = Temperature: The value will have 3 places before the decimal point and one after it (000.0).

Curve Commands (Continued)

Example:

```
00, STANDARD DRC-D ,N,31,
0.00000,499.9,0.19083,365.0,
0.24739,345.0,0.36397,305.0,
0.42019,285.0,0.47403,265.0,
0.53960,240.0,0.59455,220.0,
0.73582,170.0,0.54606,130.0,
0.95327,090.0,1.00460,070.0,
1.04070,055.0,1.07460,040.0,
1.09020,034.0,1.09700,032.0,
1.10580,030.0,1.11160,029.0,
1.11900,028.0,1.13080,027.0,
1.14860,026.0,1.07200,025.0,
1.25070,023.0,1.35050,021.0,
1.63590,017.0,1.76100,015.0,
1.90660,013.0,2.11720,009.0,
2.53660,003.0,2.59840,001.4,
6.55360,000.0[term]
```

ECUR11

Edit or Add A Data Point In User Curve 11.

Input: `ECUR11,X.XXXXX,YYY.Y`

Returned: Nothing

Remarks: Fill in the point to be added or edited, where X.XXXXX is voltage and YYY.Y is the temperature in kelvin. If the Model 321 does not recognize either the units value or the temperature value, it will assume that you are entering a new point and place it in the proper ascending position.

Example: If the point to be edited was input as 0.19083,364.0 and should have been 0.19083,365.0, input the command as follows:

`ECUR 11,0.19083,365.0[term]`

The Model 321 will recognize the units field and replace that data point with the new temperature value.

KCUR11

Delete User Curve 11 Data Command.

Input: `KCUR11`

Returned: Nothing

Remarks: Will delete all data stored for the User Curve 11.

SCAL

SoftCal™ Voltage Entry.

Input: `SCAL 12,X.XXXXX,Y.YYYYY,Z.ZZZZZ`

Returned: Nothing

Remarks: Stores the SoftCal™ voltage values at 4.2 K, 77.32 K, and 300 K, where X.XXXX = 4.2 K voltage, Y.YYYYY = 77.32 K voltage, and Z.ZZZZZ = 300 K voltage.

Example: `SCAL 12,1.6260,1.0205,0.5189[term]`

4.2.4 Analog Output Commands

This paragraph provides a detailed description of each Analog Output Command. The commands allow the user to control the output of the analog output over the interface.

ANOD

Set Analog Output Default.

Input: **`ANOD 0`** or **`ANOD 1`**

Returned: Nothing

Remarks: Set default off with ANOD 0 and on with ANOD 1. Default on gives 10 mV/K (10 V analog output for 1000 K and 0 V for 0 K).

ANOD?

Analog Default Query.

Input: **`ANOD?`**

Returned: **`0`** or **`1`**

Remarks: 1 indicates the default analog output scaling is in effect. The default scaling is 10 mV/K (10 V analog output for 1000 K and 0 V for 0 K).

ANOH

Set Analog Output Maximum (High).

Input: **`ANOH XXX.X`**

Returned: Nothing

Remarks: Set the analog output maximum (high), where XXX.X is between 0 and 999.9.

Example: **`ANOH 500[term]`** instructs the Model 321 to make the 10 V output correspond to 500 K.

ANOH?

Analog Output Maximum (High) Query.

Input: **`ANOH?`**

Returned: **`XXX.X`**

Remarks: Returns the current value of the temperature in kelvin which gives 10 V output.

ANOL

Set Analog Output Minimum (Low).

Input: **`ANOL XXX.X`**

Returned: Nothing

Remarks: Set the analog output minimum (low), where XXX.X is between 0 and 999.9.

Example: **`ANOL 100[term]`** instructs the Model 321 to make the 0 V output correspond to 100 K.

ANOL?

Analog Output Minimum (Low) Query.

Input: **`ANOL?`**

Returned: **`XXX.X`**

Remarks: Returns the current value of the temperature in kelvin which gives 0 V output.

4.3 USER CURVE 11 LOADING PROGRAM

To simplify the loading of User Curve 11, the following curve loading program is provided. The program is written in QuickBASIC V4.0. The user should create an ASCII file with the curve data in the same format as used in the CURV11 command. Immediately following the program are two sample user curve files. Then launch the Curve Loading Program where you will be prompted for a file name. The program will then open the ASCII file and download the data.

```
'*********************************************************************
'*  321 CURVE LOADING PROGRAM. NOTE: SPACING OF THE DATA STRING IS    *
'*  VERY CRITICAL, SEE THE ATTACHED SAMPLE CURVE. The curve data      *
'*  must be in an ASCII file using the same format as the example.    *
'*********************************************************************

   CLS                                   'Clear Screen

   M$ = CHR$(13) + CHR$(10)              'Define M$ as <cr><lf> terminator
   CHECKER$ = SPACE$(3000)               'Preset variable lengths
   C$ = SPACE$(2000)
                                         'Get the file name to load
   INPUT "TYPE IN DRIVE NAME AND SERIAL NUMBER OF SENSOR AND PRESS ENTER";
   A$ B$ = A$

   OPEN B$ FOR INPUT AS #1               'Open ASCII disk file
   LINE INPUT #1, C$                     'Read disk file into string C$
   STRIP$ = MID$(C$, 9)                  'Strip off the DRC series file header
   LOADER$ = "CURV11," + STRIP$          'Add the 300 series curve header
   PRINT LOADER$                         'Screen prints to show what is sent
   PRINT
   PRINT "COMMANDS SENT TO 321"
   PRINT                                 'Close disk file
   CLOSE #1
   OPEN "COM1:300,O,7,1,RS" FOR RANDOM AS #2  'Open com port for I/O
   LOADTRIM$ = LEFT$(LOADER$, 50)        'Pick out first 50 chars for first cmd
   LOADTRIM$ = LOADTRIM$ + M$
   PRINT LOADTRIM$;                      'Show command string on screen
   PRINT #2, LOADTRIM$;                  'Send curve create cmd to 321
   FOR Z = 1 TO 2000: NEXT Z

'*********************************************************************
'***   BEGINNING OF THE EDIT LOOP, WHICH ADDS ONE DATA POINT TO     ***
'***   THE CURVE AT A TIME USING THE ECUR COMMAND                   ***
'*********************************************************************

EDITLOOP:

   PREEDIT$ = MID$(LOADER$, 51)          'String clean-up

EDITLOOP1:

   LENGTH = LEN(PREEDIT$)                'Check for end of string
   IF LENGTH < 14 THEN GOTO EDITEND

   EDITPIECE$ = LEFT$(PREEDIT$, 14)      'Pull data point from the
   PREEDIT$ = MID$(PREEDIT$, 15)         'string and send it to the 321
   EDITOUT$ = "ECUR11" + EDITPIECE$ + M$
```

```
   PRINT EDITOUT$;
   PRINT #2, EDITOUT$;
   FOR Z = 1 TO 5500: NEXT Z
   GOTO EDITLOOP1

EDITEND:                               'End of edit loop

'*********************************************************************
'***   This section reads back the curve in 256 byte chunks       ***
'***   and displays the results on screen.                        ***
'*********************************************************************

   PRINT
   PRINT "RESPONSE FROM INSTRUMENT, PLEASE WAIT"
   PRINT
   READCMD$ = "CURV?11" + M$
   PRINT READCMD$;
   PRINT #2, READCMD$;

READLOOP:

   LINE INPUT #2, CHECKCURVE$
   FCOUNT = LEN(CHECKCURVE$)
   PRINT CHECKCURVE$;
   IF FCOUNT = 256 THEN GOTO READLOOP

END
```

Sample ACSII File No. 1

```
XC06,S02TG120ACS2 8333,0.86045,325.0,0.90212,310.0,0.94350,295.0,0.98457,280.0,1
.02532,265.0,1.06566,250.0,1.09231,240.0,1.11874,230.0,1.14489,220.0,1.15784,215
.0,1.17072,210.0,1.18349,205.0,1.19616,200.0,1.20869,195.0,1.22109,190.0,1.23331
,185.0,1.24534,180.0,1.25717,175.0,1.26875,170.0,1.28009,165.0,1.29116,160.0,1.3
0194,155.0,1.31241,150.0,1.32258,145.0,1.33241,140.0,1.34192,135.0,1.35108,130.0
,1.35991,125.0,1.36840,120.0,1.37657,115.0,1.38440,110.0,1.39189,105.0,1.39908,1
00.0,1.40597,095.0,1.41258,090.0,1.41894,085.0,1.42509,080.0,1.43712,070.0,1.443
27,065.0,1.44993,060.0,1.45288,058.0,1.45611,056.0,1.45973,054.0,1.46394,052.0,1
.46904,050.0,1.47551,048.0,1.48412,046.0,1.49606,044.0,1.51300,042.0,1.53706,040
.0,1.55250,039.0,1.57064,038.0,1.59183,037.0,1.61638,036.0,1.64461,035.0,1.67679
,034.0,1.71316,033.0,1.75390,032.0,1.79917,031.0,1.84902,030.0,1.90348,029.0,1.9
6261,028.0,2.02646,027.0,2.09484,026.0,2.16753,025.0,2.24441,024.0,2.32537,023.0
,2.41034,022.0,2.49920,021.0,2.63876,019.5,2.83726,017.5,3.05000,015.5,3.27618,0
13.5,3.51800,011.5,3.71192,010.0,3.91739,008.5,4.13945,007.0,4.36487,005.6,4.577
72,004.4,4.82963,003.1,5.03503,002.1,5.12385,001.6,5.15376,001.4*
```

Sample ACSII File No. 2

```
XC06,DT-500CU D46254,0.37198,300.0,0.44204,275.0,0.54863,235.0,0.61840,210.0,0.7
3229,170.0,0.84333,130.0,0.95137,090.0,1.00351,070.0,1.04031,055.0,1.07506,040.0
,1.08564,036.0,1.09194,034.0,1.09964,032.0,1.11028,030.0,1.11764,029.0,1.12731,0
28.0,1.14093,027.0,1.16147,026.0,1.19192,025.0,1.23370,024.0,1.28745,023.0,1.434
52,021.0,1.68003,018.0,1.91882,014.0,2.09621,010.0,2.32759,006.5,2.54962,003.6,2
.62794,002.0,2.64172,001.4*
```

CHAPTER 5

OPTIONS AND ACCESSORIES

5.0 GENERAL

This chapter provides lists of Model 321 Autotuning Temperature Controller options and accessories. Model number are listed in Paragraph 5.1. Options are detailed in Paragraph 5.2. Finally, accessories are detailed in Paragraph 5.3.

5.1 MODELS

A list of Model 321 Temperature Controllers is provided as follows.

MODEL NUMBER	DESCRIPTION OF 321 MODELS
321-01	**Model 321 designed for use with Silicon Diode Temperature Sensors.**
321-02	**Model 321 designed for use with 100 Ω Platinum RTD Temperature Sensors.**
321-04	**Model 321 designed for use with Thermocouples.**

5.2 OPTIONS

A list of Model 321 options is provided as follows.

MODEL NUMBER	DESCRIPTION OF MODEL 321 OPTIONS
8000	**Precision Option, Floppy Disk.** The Model 8000 Precision Option consists of breakpoint pairs from a Sensor Precision Calibration being loaded on a floppy disk in ASCII format for Customer downloading.
8001	**Precision Option, Factory Installed.** The Precision Option provides custom programming of specific sensor calibration curve at the factory. The Precision Option improves combined sensor/instrument accuracy to within ±0.1 K or better over the calibrated temperature range of the sensor. The Precision Option data is stored in a memory chip (NOVRAM). Requires the use of a calibrated sensor.
8002-05	**Precision Option, Field Installation.** For field installation of the precision option for users who already own a Model 321. When ordering, please specify your instrument serial number and calibrated sensor model and serial number. A new NOVRAM will be sent for Customer installation.

5.3 ACCESSORIES

Accessories are devices that perform a secondary duty as an aid or refinement to the primary unit. A list of accessories available for the Model 321 is as follows:

MODEL NUMBER	DESCRIPTION OF MODEL 321 ACCESSORIES
106-009 *	**Heater Output Connector.**
106-233 *	**Sensor Mating Connector.**
115-006 *	**Detachable 120 VAC Line Cord.**

* Accessories included with a new Model 321.

Accessories (Continued)

MODEL NUMBER	DESCRIPTION OF MODEL 321 ACCESSORY
2001	**RJ-11 Cable Assembly**. Four-Wire Cable Assembly with RJ-11 plugs on each end. Used with RS-232C Interface. Cable is 14 feet (4.6 meters) long. See Figure 5-1.
2002	**RJ-11 to DB-25 Adapter**. Adapts RJ-11 receptacle to female DB-25 connector. Used to connect Model 622/647 to RS-232C Serial Port on rear of Customer's computer. See Figure 5-2.
2003	**RJ-11 to DE-9 Adapter**. Adapts RJ-11 receptacle to female DE-9 connector. Used to connect Model 622/647 to RS-232C Serial Port on rear of Customer's computer. See Figure 5-3.
3003	**Heater Output Conditioner.** The heater output conditioner is a passive filter which further reduces the already low heater output noise of the Model 321. The typical insertion loss of for the Model 3003 is 20 dB (at 10 µV) at line frequency, and >40 dB from double the line frequency up. The Model 3003 is housed in a 144 mm wide by 72 mm high by 165 mm deep (5.67 x 2.84 x 6.5 inches) panel mount enclosure and weighs 1.6 kilograms (3.5 pounds).
3022	**Half-Rack Mounting Kit for One Model 321 Temperature Controller.** Half-length mounting panel and mounting ears to attach one Model 321 to a 482.6 mm (19-inch) rack mount space. See Figure 5-4.
3026	**Dual Mounting Shelf for Two Model 321 Temperature Controllers.** Mounting shelf to attach two Model 321 Temperature Controllers side-by-side on a 482.6 mm (19-inch) rack mount shelf. See Figure 5-5.
8271-20	**Sensor/Heater Cable Assembly.** This cable assembly is used for Silicon Diode and 100 Ω Platinum RTD Temperature Sensors.
9001-00X	**Lake Shore Cryogenic Wire**. Lake Shore sells the following types of cryogenic wire: DT = Duo-Twist™, MN = Single Strand, MW = Manganin, NC = Nichrome Heater, ND = Heavy Duty, QL = Quad-Lead™, and QT = Quad-Twist™. Please refer to the Lake Shore Accessories Catalog for details.
9004-020	**Apiezon® "N" Grease, 25 gram Tube**. General purpose grease well-suited for cryogenic use because of its low viscosity. It is often used as a means of thermally anchoring cryogenic sensors as well as lubricating joints and o-rings. Contains high molecular weight polymeric hydrocarbon additive which gives it a tenacious, rubbery consistency allowing the grease to form a cushion between mating surfaces.
9007-002	**Indium Foil (5 Pieces).** Indium is a semi-precious non-ferrous metal, softer than lead, and extremely malleable and ductile. It stays soft and workable down to cryogenic temperatures. May be used as a sealing gasket for covers, flanges, and windows in cryogenic applications.
HTR-25	**25 Ω Cartridge Heater.** The heater features precision-wound nickel-chromium resistance wire, magnesium oxide insulation, two solid pins, non-magnetic package, and has UL and CSA component recognition. The heater is 25 W, 6.35 mm (0.25 inch) diameter by 25.4 mm (1 inch) long. The 25 W rating is in dead air. In cryogenic applications, the cartridge heater can handle many times this dead air power rating.
HTR-50	**50 Ω Cartridge Heater.** The heater features precision-wound nickel-chromium resistance wire, magnesium oxide insulation, two solid pins, non-magnetic package, and has UL and CSA component recognition. The heater is 25 W, 6.35 mm (0.25 inch) diameter by 25.4 mm (1 inch) long. The 25 W rating is in dead air. In cryogenic applications, the cartridge heater can handle many times this dead air power rating.
MAN-321*	**Model 321 User's Manual.**

* Accessories included with a new Model 321.

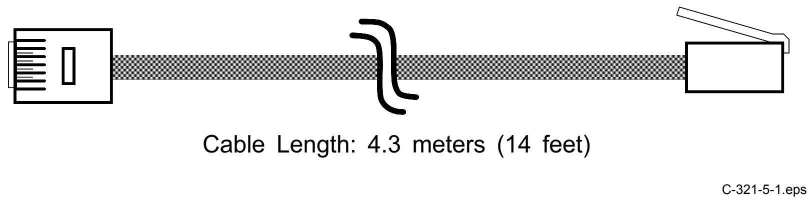


Figure 5-1. Model 2001 RJ-11 Cable Assembly

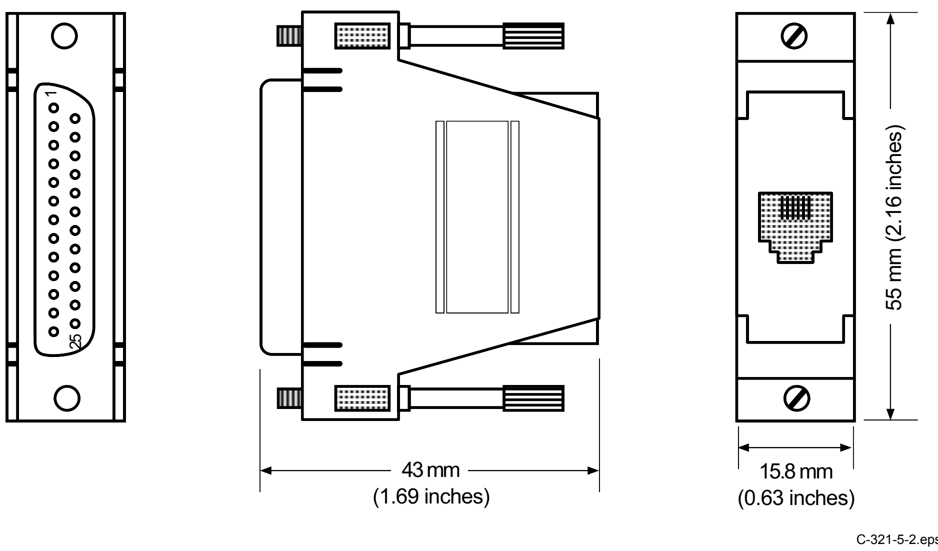


Figure 5-2. Model 2002 RJ-11 to DB-25 Adapter

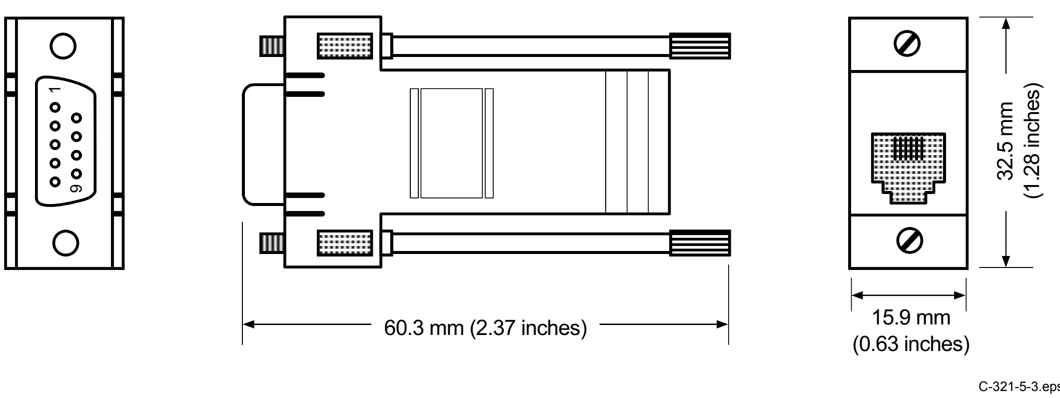
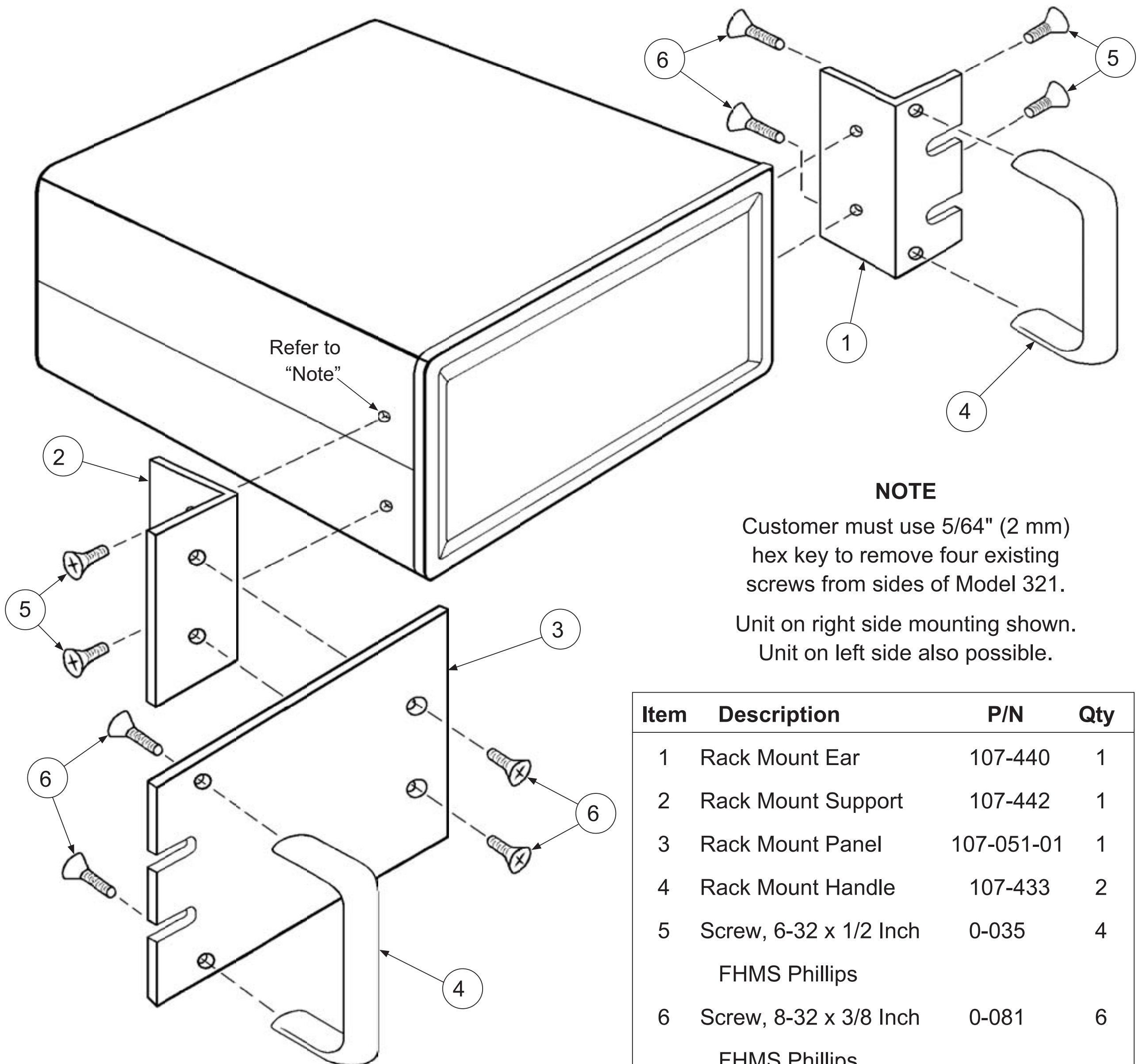


Figure 5-3. Model 2003 RJ-11 to DE-9 Adapter



NOTE

Customer must use 5/64" (2 mm) hex key to remove four existing screws from sides of Model 321.

Unit on right side mounting shown. Unit on left side also possible.

Item	Description	P/N	Qty
1	Rack Mount Ear	107-440	1
2	Rack Mount Support	107-442	1
3	Rack Mount Panel	107-051-01	1
4	Rack Mount Handle	107-433	2
5	Screw, 6-32 x 1/2 Inch FHMS Phillips	0-035	4
6	Screw, 8-32 x 3/8 Inch FHMS Phillips	0-081	6

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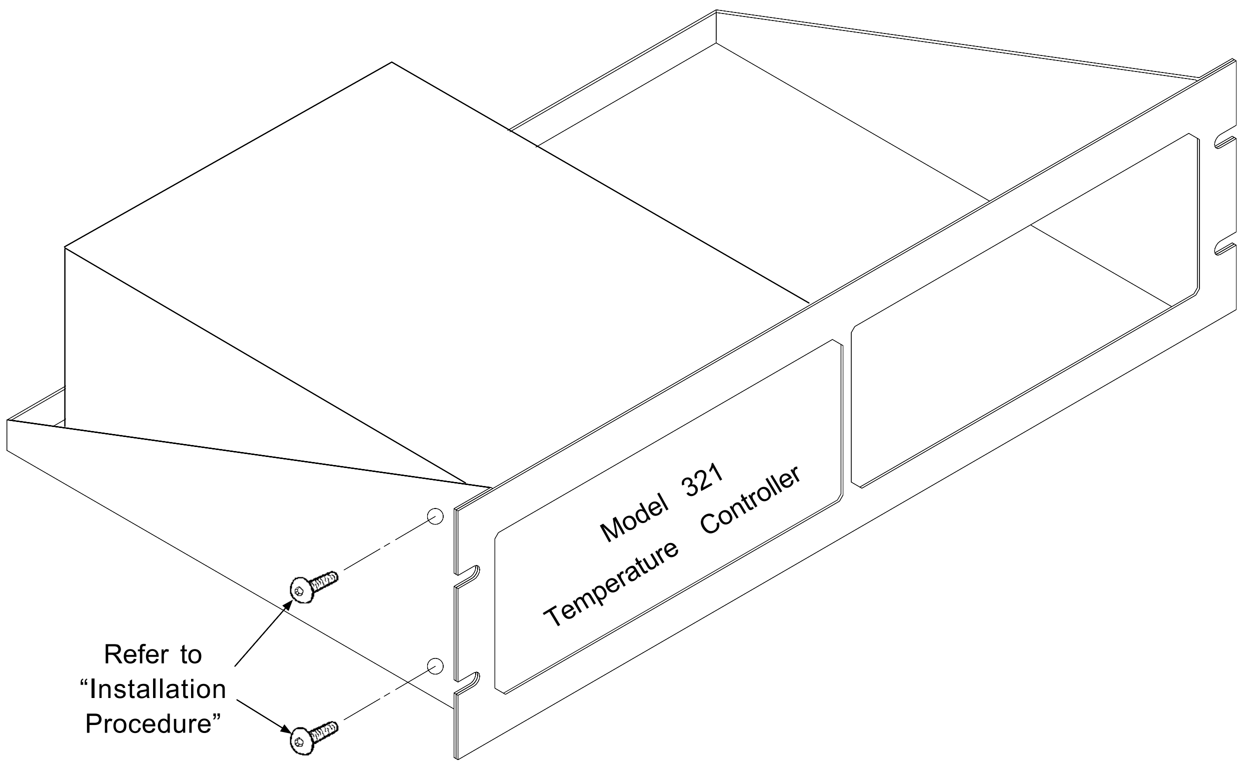
Figure 5-4. Model 3022 Rack-Mount Kit



Installation Procedure

1. Use 5/64 inch (2 mm) hex key to remove two 6-32 x 1/4 black button head screws from side of Instrument.
2. Place Instrument on shelf.
3. Use 5/64 inch (2 mm) hex key to reinstall two 6-32 x 1/4 black button head screws through side of rack into corresponding holes in the side of the Instrument.

C-321-5-5.eps

Figure 5-5. Model 3026 Dual Rack-Mount Shelf

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CHAPTER 6

SERVICE AND CALIBRATION

6.0 GENERAL

This chapter describes the service and calibration for the Model 321 Temperature Controller. Paragraph 6.1 provides general maintenance information. Changing power settings and fuse rating is described in Paragraph 6.2. Rear panel connector definitions are provided in Paragraph 6.3. Optional serial interface cable and adapters are described in Paragraph 6.4. The operating software EPROM replacement procedure is provided in Paragraph 6.5. Power up errors are described in Paragraph 6.6. Changing sensor input type is described in Paragraph 6.7. Paragraphs 6.8 thru 6.10 describe the calibration procedure for the Model 321-01, -02, and -04, respectively. Two calibrations for each model are provided: the first with the available precision equipment, the second without.

6.1 GENERAL MAINTENANCE

If the keyboard locks up, press the Escape key for ≈10 seconds. This will reset internal RAM to factory default values. The instrument would then require the various user setpoints be reentered.

If there is no power, ensure you are plugged into a live outlet and that both ends of the power cord are plugged in. Next check the fuse. Remove line cord then place a small slotted screwdriver in the slot of the small door at the rear of the unit to gain access to the fuse. See Figure 6-1. For 100/120 V operation, the fuse rating is 1.5 A and the fuse type is 3AG Slow Blow. For 220/240 V operation, the fuse rating is 0.75 A and the fuse type is 5×20 mm T. Test fuse with ohmmeter. Do not rely on visual inspection of fuse.

To clean the Model 321 periodically to remove dust, grease and other contaminants, perform the following:

1. Clean front/back panels and case with soft cloth dampened with mild detergent and water solution.

NOTE: Do not use aromatic hydrocarbons or chlorinated solvents to clean the Model 321. They may react with the silk screen printing on the back panel.

2. Clean surface of printed circuit boards (PCBs) using clean, dry air at low pressure.

6.2 CHANGING POWER SETTING AND FUSE RATING

There are two basic power configurations: domestic and foreign. Domestic has a single fuse on the hot. Foreign has a double fuse arrangement for the hot and neutral. Units with specific power requirements specified when purchased will be preconfigured at the factory for the proper power setting. If power settings are incorrect for your application, use the following procedure to change the power settings.

WARNING: To avoid potentially lethal shocks, turn off the instrument and disconnect it from the AC power line before performing this procedure. Only qualified personnel should perform this procedure.

1. Turn off unit.
2. Unplug line cord from rear of unit.
3. Use small screwdriver to open fuse drawer.
4. Pull out the fuse holder, rotate until the proper voltage setting is displayed through the window in the fuse drawer. Place fuse holder back in fuse drawer.
5. Remove existing fuse(s). Replace with proper fuse ratings as follows: 1.5 A for 100/120 VAC; or 0.75 A for 220/240 VAC.
6. Slide fuse drawer back into unit.
7. Plug line cord into rear of unit.
8. Perform initial setup and system checkout procedure in Paragraph 2.12.

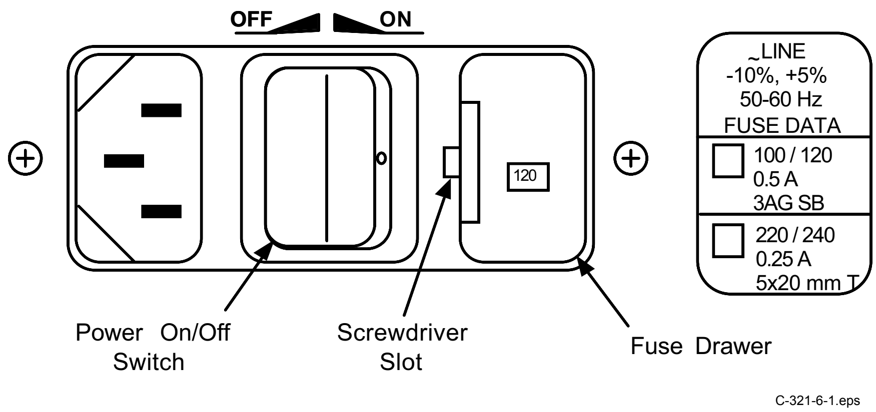
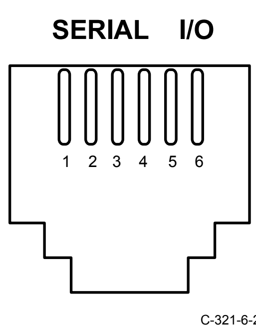


Figure 6-1. Power Fuse Access

6.3 REAR PANEL CONNECTOR DEFINITIONS

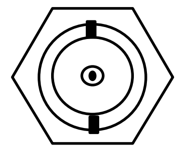
The Serial I/O, Analog Output, Sensor input, and Heater Output connectors are defined in Figures 6-2 thru 6-5.



PIN	DESCRIPTION
1	RS-232C In (RxD)
2	RS-232C In (RxD)
3	RS-232C Ground
4	RS-232C Ground
5	RS-232C Out (TxD)
6	RS-232C Out (TxD)

Figure 6-2. SERIAL I/O RJ-11 Connector Details

ANALOG OUTPUT



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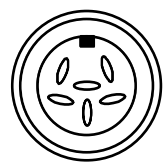
PIN	DESCRIPTION
1	Analog Output – Center Conductor
2	Ground – Connector Shell

Figure 6-3. ANALOG OUTPUT Connector Details

SENSOR



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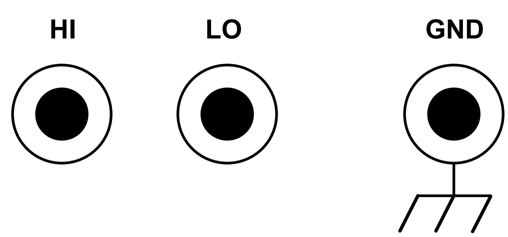
PIN	DESCRIPTION
1	– Current
2	– Voltage
3	+ Current 500 µA (Platinum)
4	+ Voltage
5	+ Current 10 µA (Diodes)
6	Shield

Figure 6-4. Diode and Platinum SENSOR Connector Details

HEATER OUTPUT



C-321-6-5.eps

PIN	DESCRIPTION
1	HI
2	LO
3	GROUND

Figure 6-5. HEATER Connector Details

6.4 OPTIONAL SERIAL INTERFACE CABLE AND ADAPTERS

To aid in Serial Interface troubleshooting, wiring information for the optional cable assembly and the two mating adapters are provided in Figures 6-6 through 6-8.

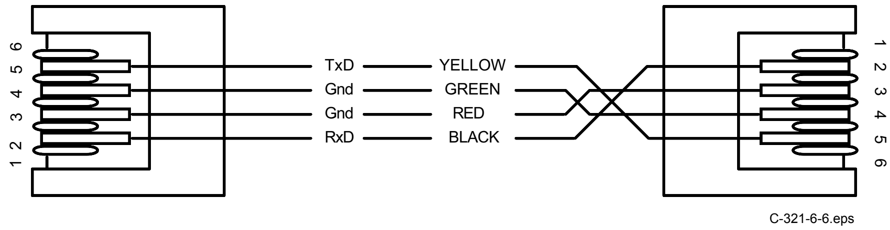


Figure 6-6. Model 2001 RJ-11 Cable Assembly Wiring Details

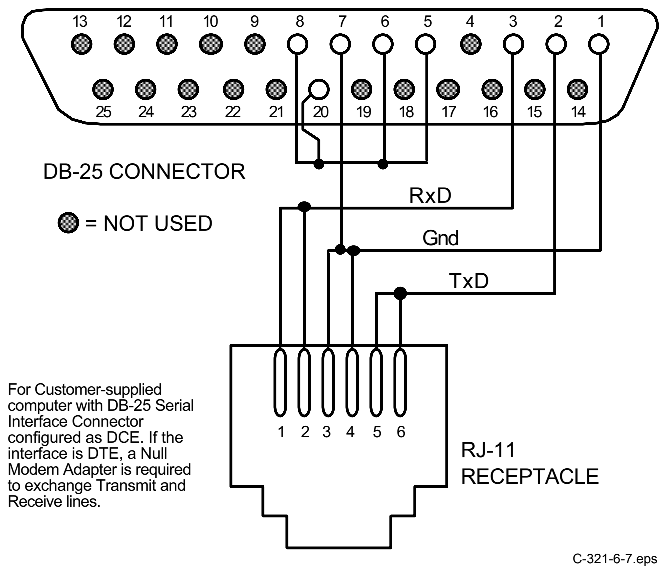


Figure 6-7. Model 2002 RJ-11 to DB-25 Adapter Wiring Details

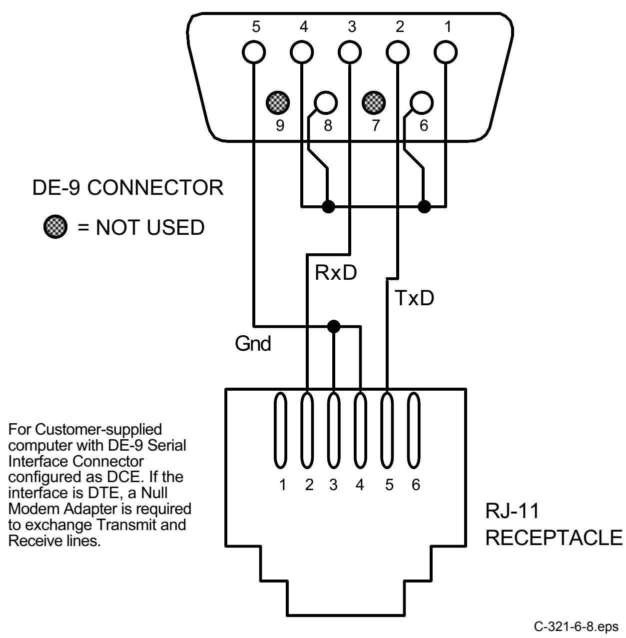


Figure 6-8. Model 2003 RJ-11 to DE-9 Adapter Wiring Details

6.5 OPERATING SOFTWARE EPROM REPLACEMENT

The operating software for the Model 321 is contained on two Erasable Programmable Read Only Memory (EPROM) Integrated Circuits (ICs). The EPROM are numbered U22 (Master) and U19 (Slave). The EPROMs will also have a label on top identifying the software version and date. See Figure 6-10. Please use the following procedure to replace either one or both the operating software EPROMs.

WARNING: To avoid potentially lethal shocks, turn off the instrument and disconnect it from the AC power line before performing this procedure. Only qualified personnel should perform this procedure.

1. Set power switch to off and disconnect power cord from rear of unit.
2. Use 5/64 hex key to remove four screws attaching top panel to unit.
3. Use 5/64 hex key to loosen two screws attaching bottom panel to unit.
4. Carefully remove back bezel.
5. Slide top panel back and remove from unit.
6. Locate software EPROM U22 (Master) or U19 (Slave) on main circuit board. Note orientation of existing EPROMs (circular notch on front of IC). See Figure 6-10.
7. Use IC puller to remove existing EPROM(s) from socket.
8. Noting orientation of new EPROM(s), use IC insertion tool to place new EPROM(s) into socket.
9. Replace top of enclosure and secure with four screws.
10. Replace back bezel and use 5/64 hex key to tighten two screws attaching bottom panel to unit.
11. Reconnect power cord to rear of unit and set power switch to on.
12. Proceed to Paragraph 2.12 and perform the initial setup and system checkout. When replacing the operating software EPROM(s), all operating parameters will be returned to the factory default settings.

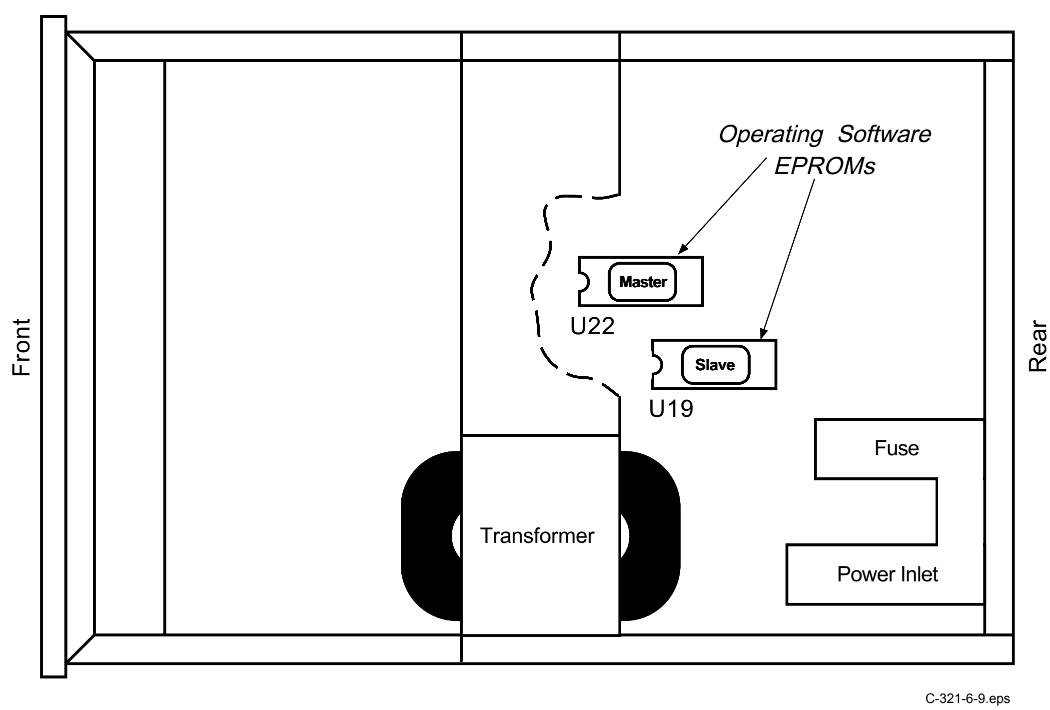


Figure 6-9. Location Of Operating Software EPROMs

6.6 ERROR MESSAGES

On power up, the Model 321 does a check of the internal memory. There are two potential error messages. The first is usually recoverable, the second is not. The first error display is shown below.

```
RAMnotRecog.Er#2
Escape to Init.
```

This indicates than an attempt to read the internal non-volatile RAM for the Model ID was unsuccessful. In some situations, this error can be corrected by the user by initializing the Model 321 memory. There are three methods that can be used to reinitialize the instrument: (1) Press the Escape key when the error message is being displayed, (2) hold the Escape key down when the instrument is off and then turning the instrument on, or (3) holding the Escape key down for more than 5 seconds. Wait until a message is given before releasing the key.

The second error display is shown below.

```
RAM Rd/Wr   Er#1
Escape to Retry.
```

This error message indicates that an attempt to write and then read the internal non-volatile RAM was unsuccessful. This error is not correctable by the user. Please consult the factory.

There are two additional error messages associated with the sensor input. If an input signal from the sensor exceeding full scale is applied to the input leads, an overload condition is present and is indicated by "OL" on the display, as shown below.

```
   OL
```

If no signal or a signal of the wrong polarity is present at the input leads, a Zero Error is indicated by "Er27" on the display, as shown below.

```
  Er27
```

6.7 CHANGING SENSOR INPUT TYPE

Sensor input type (and hence the model number) are established at the factory before shipping. Sensor input type is set by setting two DIP switches on the main PCB inside the unit. If you wish to check the DIP switch settings, open the unit using the procedure in Paragraph 6.5, Steps 1 thru 5. Use Figure 6-10 to locate DIP Switches **S1** and **S2**. The sensor input settings are switched identically to change input type. The settings are as follows.

DIP Switch S1 *

	Silicon Diode (Model 321-01)	Platinum (Model 321-02)	Thermocouple (Model 321-04)
S1-1	Closed	Open	Open
S1-2	Open	Closed	Open
S1-3	Open	Open	Closed
S1-4	Open	Open	Closed

DIP Switch S2 *

	Silicon Diode (Model 321-01)	Platinum (Model 321-02)	Thermocouple (Model 321-04)
S2-1	Closed	Open	Open
S2-2	Open	Closed	Open
S2-3	Open	Open	Closed
S2-4	Open	Open	Closed

**To change sensor input type, DIP switches on S1 and S2 must be switched identically.*

The Model 321 must be recalibrated when switched between sensor input types.

6.8 MODEL 321-01 (SILICON DIODE) CALIBRATION

There are two Model 321-01 (Silicon Diode) calibrations provided. If you have a 100 kΩ, 0.01% 25 ppm precision resistor available, use the procedure in Paragraph 6.8.1. If no precision resistor is available, use the optional procedure in Paragraph 6.8.2.

6.8.1 Model 321-01 Calibration (With Precision Resistor)

The Model 321-01 calibration with precision resistor is presented in four parts. First is list of test equipment in Paragraph 6.8.1.1. Second is the test setup in Paragraph 6.8.1.2. Third is the input calibration in Paragraph 6.8.1.3. Finally, analog output calibration is provided in Paragraph 6.8.1.4. These procedures will be performed with power supplied to the unit. Due to the presence of lethal currents, only personnel experienced in working with live circuits should perform this procedure.

6.8.1.1 Test Equipment

This procedure requires the following test equipment:

- Digital Multimeter (DMM) with a 4½-digit display, capable of 4-lead resistive measurements.
- Precision Resistor, 100 kΩ, 0.01%, 25 ppm/°C.

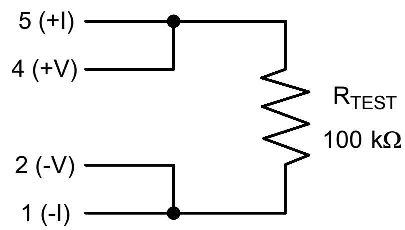
6.8.1.2 Test Setup

Calibration test setup is as follows:

WARNING: Lethal line voltage is present inside the box. Only qualified personnel should attempt to perform this procedure.

1. Set power switch to off and disconnect power cord from rear of unit.
2. Use 5/64 hex key to remove four screws attaching top panel to unit.
3. Use 5/64 hex key to loosen two screws attaching bottom panel to unit.
4. Carefully remove back bezel.
5. Slide top panel back and remove from unit.

6. Attach 100 kΩ precision resistor as shown below:



6.8.1.3 Input Calibration

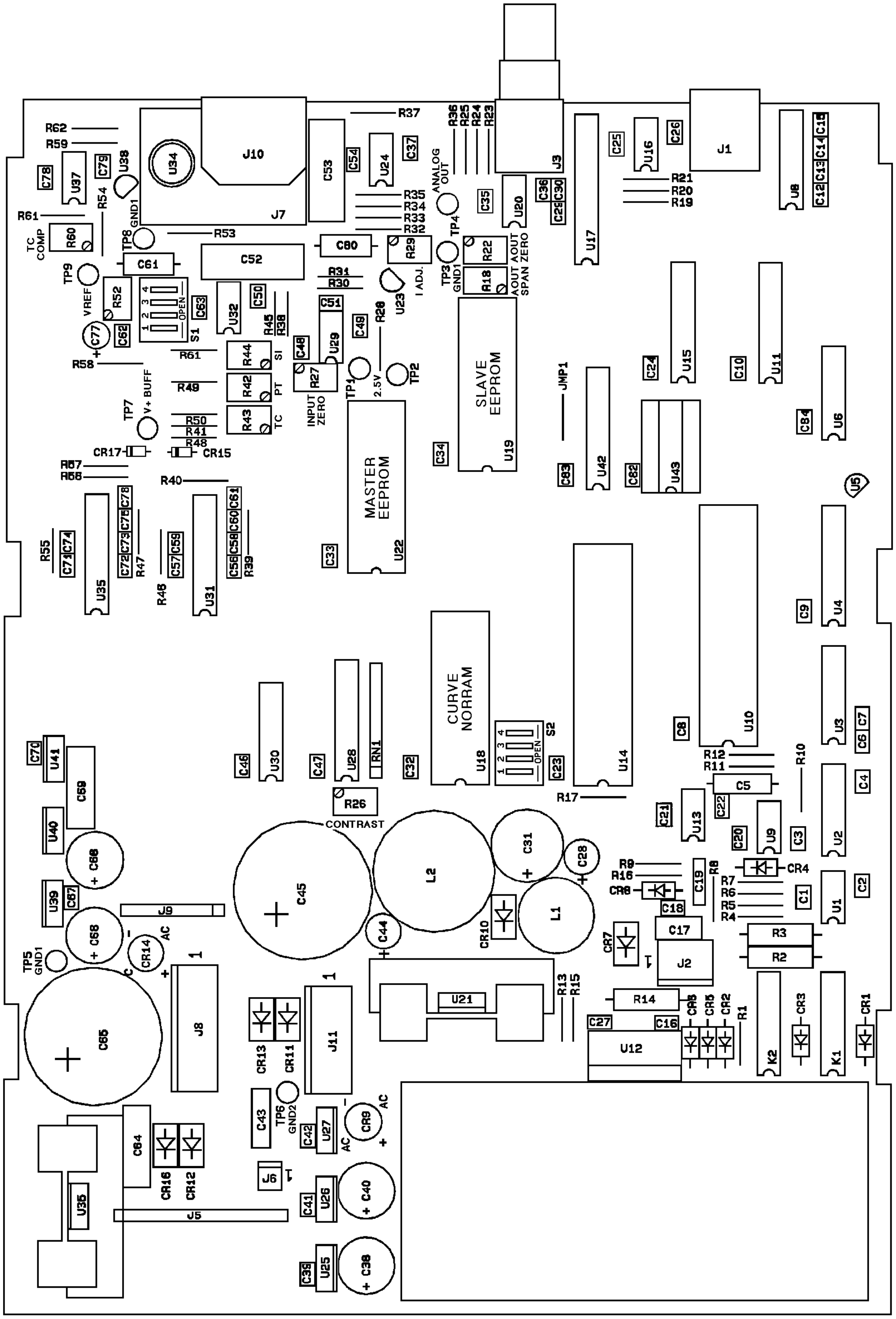
Use the following procedure to perform the input calibration.

1. Place a short across the 100 kΩ resistor.
2. Power on (**I**) instrument.
3. Allow instrument to warm up for at least one hour.
4. With DMM in DC voltage mode, attach test leads between TP2 (–) and TP1 (+).
5. Adjust R29 until DMM voltage reads 2.5000 ±0.0005 VDC.
5. Attach test leads to TP8 (GND1) and TP9 (Vref adj.).
7. Adjust R52 until DMM voltage reads 2.5000 ±0.0001 VDC.
8. Place positive test lead on TP7 (V+Buff).
9. Adjust R27 until DMM voltage reads 0.0000 ±0.0001 VDC.
10. Remove the short from the 100 kΩ resistor.
11. Configure the Model 321 to display units in voltage.
12. Adjust R44 until the display reads exactly 1.0000 VDC.

6.8.1.4 Analog Output Calibration

Use the following procedure to perform the analog output calibration.

1. Attach test leads to TP3 (gnd1) and TP4 (Analog out).
2. Press and hold the Analog Out key until the Model 321 enters the Analog output calibration mode.
3. Press the Up arrow key until Zero is selected.
4. With the DMM in DC voltage mode, adjust R22 until the voltage is 0.000 ±0.001 VDC.
5. Press the Up arrow key until Span is selected.
6. Adjust R18 until the voltage is 10.000 ±0.001 VDC.
7. Press Escape on the Model 321 to exit the Analog output calibration mode.
8. Set power switch to off (**O**). Disconnect power cord and test resistor.
9. Replace top of enclosure and secure with four screws.
10. Replace back bezel and use 5/64 hex key to tighten two screws attaching bottom panel to unit.



P-321-5-10.bmp

Figure 6-10. Typical Model 321 PCB Layout

6.8.2 Optional Model 321-01 Calibration (Without Precision Resistor)

The optional Model 321-01 (Silicon Diode) calibration without precision resistor is presented in four parts. First is list of test equipment in Paragraph 6.8.2.1. Second is the test setup in Paragraph 6.8.2.2. Third is the input calibration in Paragraph 6.8.2.3. Finally, analog output calibration is provided in Paragraph 6.8.2.4. These procedures will be performed with power supplied to the unit. Due to the presence of lethal currents, only personnel experienced in working with live circuits should perform this procedure.

6.8.2.1 Test Equipment

This procedure requires the following test equipment:

- Digital Multimeter (DMM) with a 4½-digit display, capable of 4-lead resistive measurements.
- Resistor, 100 kΩ, as temperature stable as possible (20 – 50 ppm/°C), metal film preferred.

6.8.2.2 Test Setup

Calibration test setup is as follows:

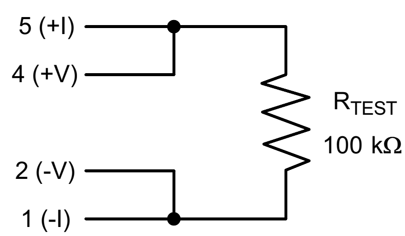
WARNING: Lethal line voltage is present inside the box. Only qualified personnel should attempt to perform this procedure.

1. Set power switch to off and disconnect power cord from rear of unit.
2. Use 5/64 hex key to remove four screws attaching top panel to unit.
3. Use 5/64 hex key to loosen two screws attaching bottom panel to unit.
4. Carefully remove back bezel.
5. Slide top panel back and remove from unit.

6.8.2.3 Input Calibration

Use the following procedure to perform the input calibration.

1. Measure the resistance of the 100 kΩ resistor to the nearest 10 Ω and write it down.
2. Place a short across the 100 kΩ resistor and attach to sensor input.



3. Power on (**I**) instrument.
4. Allow instrument to warm up for at least one hour.
5. With DMM in DC voltage mode, attach test leads between TP2 (–) and TP1 (+).
6. Adjust R29 until DMM voltage reads 2.5000 ±0.0005 VDC.
7. Attach test leads to TP8 (GND1) and TP9 (Vref adj.).
8. Adjust R52 until DMM voltage reads 2.5000 ±0.0001 VDC.
9. Place positive test lead on TP7 (V+Buff).
10. Adjust R27 until DMM voltage reads 0.0000 ±0.0001 VDC.
11. Remove the short from the 100 kΩ resistor.
12. Configure the Model 321 to display units in voltage.
13. The current through the 100 kΩ resistor is 10 µA. Multiply 0.00001 times the resistance measured is Step 1. Adjust R44 until the display reads the result of the current times the resistance. For example, if the 100 kΩ resistor measured 100.25 kΩ, multiply 0.00001 times 100,250.00. The result would be 1.0025. R44 would be adjusted until the Model 321 displays 1.0025 VDC.

6.8.2.4 Analog Output Calibration

Use the following procedure to perform the analog output calibration.

1. Attach test leads to TP3 (gnd1) and TP4 (Analog out).
2. Press and hold the Analog Out key until the Model 321 enters the Analog output calibration mode.
3. Press the Up arrow key until Zero is selected.
4. With the DMM in DC voltage mode, adjust R22 until the voltage is 0.000 ±0.001 VDC.
5. Press the Up arrow key until Span is selected.
6. Adjust R18 until the voltage is 10.000 ±0.001 VDC.
7. Press Escape on the Model 321 to exit the Analog output calibration mode.
8. Set power switch to off (**O**). Disconnect power cord and test resistor.
9. Replace top of enclosure and secure with four screws.
10. Replace back bezel and use 5/64 hex key to tighten two screws attaching bottom panel to unit.

6.9 MODEL 321-02 (PLATINUM RESISTOR) CALIBRATION

There are two Model 321-02 (Platinum Resistor) calibrations provided. If you have a 100 Ω, 0.01% 25 ppm precision resistor available, use the procedure in Paragraph 6.9.1. If no precision resistor is available, use the optional procedure in Paragraph 6.9.2.

6.9.1 Model 321-02 Calibration (With Precision Resistor)

The Model 321-02 calibration with precision resistor is presented in four parts. First is list of test equipment in Paragraph 6.9.1.1. Second is the test setup in Paragraph 6.9.1.2. Third is the input calibration in Paragraph 6.9.1.3. Finally, analog output calibration is provided in Paragraph 6.9.1.4. These procedures will be performed with power supplied to the unit. Due to the presence of lethal currents, only personnel experienced in working with live circuits should perform this procedure.

6.9.1.1 Test Equipment

This procedure requires the following test equipment:

- Digital Multimeter (DMM) with a 4½-digit display, capable of 4-lead resistive measurements.
- Precision Resistor, 100 Ω, 0.01%, 25 ppm/°C.

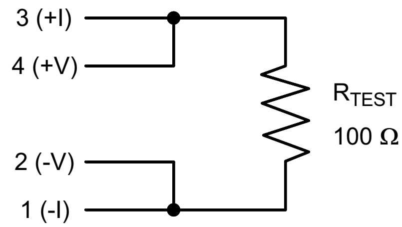
6.9.1.2 Test Setup

Calibration test setup is as follows:

WARNING: Lethal line voltage is present inside the box. Only qualified personnel should attempt to perform this procedure.

1. Set power switch to off and disconnect power cord from rear of unit.
2. Use 5/64 hex key to remove four screws attaching top panel to unit.
3. Use 5/64 hex key to loosen two screws attaching bottom panel to unit.
4. Carefully remove back bezel.
5. Slide top panel back and remove from unit.

6. Attach 100 Ω precision resistor as shown below:



6.9.1.3 Input Calibration

Use the following procedure to perform the input calibration.

1. Place a short across the 100 Ω resistor.
2. Power on (**I**) instrument.
3. Allow instrument to warm up for at least one hour.
4. With DMM in DC voltage mode, attach test leads between TP2 (–) and TP1 (+).
5. Adjust R29 until DMM voltage reads 2.5000 ±0.0005 VDC.
6. Attach test leads to TP8 (GND1) and TP9 (Vref adj.).
7. Adjust R52 until DMM voltage reads 2.5000 ±0.0001 VDC.
8. Place positive test lead on TP7 (V+Buff).
9. Adjust R27 until DMM voltage reads 0.0000 ±0.0001 VDC.
10. Remove the short from the 100 Ω resistor.
11. Configure the Model 321 to display units in ohms.
12. Adjust R42 until the display reads exactly 100.00 Ω.

6.9.1.4 Analog Output Calibration

Use the following procedure to perform the analog output calibration.

1. Attach test leads to TP3 (gnd1) and TP4 (Analog out).
2. Press and hold the Analog Out key until the Model 321 enters the Analog output calibration mode.
3. Press the Up arrow key until Zero is selected.
4. With the DMM in DC voltage mode, adjust R22 until the voltage is 0.000 ±0.001 VDC.
5. Press the Up arrow key until Span is selected.
6. Adjust R18 until the voltage is 10.000 ±0.001 VDC.
7. Press Escape on the Model 321 to exit the Analog output calibration mode.
8. Set power switch to off (**O**). Disconnect power cord and test resistor.
9. Replace top of enclosure and secure with four screws.
10. Replace back bezel and use 5/64 hex key to tighten two screws attaching bottom panel to unit.

6.9.2 Optional Model 321-02 Calibration (Without Precision Resistor)

The optional Model 321-02 (Platinum Diode) calibration without precision resistor is presented in four parts. First is list of test equipment in Paragraph 6.9.2.1. Second is the test setup in Paragraph 6.9.2.2. Third is the input calibration in Paragraph 6.9.2.3. Finally, analog output calibration is provided in Paragraph 6.9.2.4. These procedures will be performed with power supplied to the unit. Due to the presence of lethal currents, only personnel experienced in working with live circuits should perform this procedure.

6.9.2.1 Test Equipment

This procedure requires the following test equipment:

- Digital Multimeter (DMM) with a 4½-digit display, capable of 4-lead resistive measurements.
- Resistor, 100 Ω, as temperature stable as possible (20 – 50 ppm/°C), metal film preferred.

6.9.2.2 Test Setup

Calibration test setup is as follows:

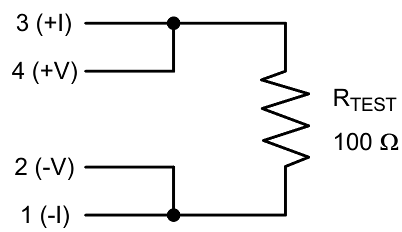
WARNING: Lethal line voltage is present inside the box. Only qualified personnel should attempt to perform this procedure.

1. Set power switch to off and disconnect power cord from rear of unit.
2. Use 5/64 hex key to remove four screws attaching top panel to unit.
3. Use 5/64 hex key to loosen two screws attaching bottom panel to unit.
4. Carefully remove back bezel.
5. Slide top panel back and remove from unit.

6.9.2.3 Input Calibration

Use the following procedure to perform the input calibration.

1. Measure the resistance of the 100 Ω resistor to the nearest 0.01 Ω and write it down.
2. Place a short across the 100 Ω resistor and attach to sensor input.



3. Power on (**I**) instrument.
4. Allow instrument to warm up for at least one hour.
5. With DMM in DC voltage mode, attach test leads between TP2 (–) and TP1 (+).
6. Adjust R29 until DMM voltage reads 2.5000 ±0.0005 VDC.
7. Attach test leads to TP8 (GND1) and TP9 (Vref adj.).
8. Adjust R52 until DMM voltage reads 2.5000 ±0.0001 VDC.
9. Place positive test lead on TP7 (V+Buff).
10. Adjust R27 until DMM voltage reads 0.0000 ±0.0001 VDC.
11. Remove the short from the 100 Ω resistor.
12. Configure the Model 321 to display units in ohms.
13. Adjust R42 until the display reads the value of the 100 Ω resistor measured in Step 1. For example, if the resistance measured 100.28 Ω, R42 should be adjusted until the Model 321 displays 100.28 Ω.

6.9.2.4 Analog Output Calibration

Use the following procedure to perform the analog output calibration.

1. Attach test leads to TP3 (gnd1) and TP4 (Analog out).
2. Press and hold the Analog Out key until the Model 321 enters the Analog output calibration mode.
3. Press the Up arrow key until Zero is selected.
4. With the DMM in DC voltage mode, adjust R22 until the voltage is 0.000 ±0.001 VDC.
5. Press the Up arrow key until Span is selected.
6. Adjust R18 until the voltage is 10.000 ±0.001 VDC.
7. Press Escape on the Model 321 to exit the Analog output calibration mode
8. Set power switch to off (**O**). Disconnect power cord and test resistor.
9. Replace top of enclosure and secure with four screws.
10. Replace back bezel and use 5/64 hex key to tighten two screws attaching bottom panel to unit.

6.10 MODEL 321-04 (THERMOCOUPLE) CALIBRATION

There are two Model 321-04 (Thermocouple) calibrations provided. If you have a Millivolt Voltage Standard (with microvolt resolution) available, use the procedure in Paragraph 6.10.1. If no precision voltage source is available, use the optional procedure in Paragraph 6.10.2.

6.10.1 Model 321-04 Calibration (With Millivolt Voltage Standard)

The Model 321-04 calibration with Millivolt Voltage Standard is presented in six parts. First is list of test equipment in Paragraph 6.10.1.1. Second is the test setup in Paragraph 6.10.1.2. Third is the input calibration in Paragraph 6.10.1.3. Fourth is the analog output calibration is provided in Paragraph 6.10.1.4. Fifth is the thermocouple offset adjustment in Paragraph 6.10.1.5. Finally, the internal thermocouple compensation calibration is provided in Paragraph 6.10.1.6. These procedures will be performed with power supplied to the unit. Due to the presence of lethal currents, only personnel experienced in working with live circuits should perform this procedure.

6.10.1.1 Test Equipment

This procedure requires the following test equipment:

- Digital Multimeter (DMM) with a 4½-digit display, capable of 4-lead resistive measurements.
- Millivolt Voltage Standard (with microvolt resolution range).

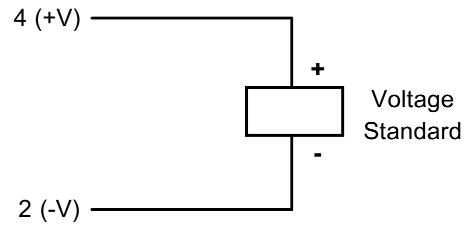
6.10.1.2 Test Setup

Calibration test setup is as follows:

WARNING: Lethal line voltage is present inside the box. Only qualified personnel should attempt to perform this procedure.

1. Set power switch to off and disconnect power cord from rear of unit.
2. Use 5/64 hex key to remove four screws attaching top panel to unit.
3. Use 5/64 hex key to loosen two screws attaching bottom panel to unit.
4. Carefully remove back bezel.
5. Slide top panel back and remove from unit.

6. Configure the Millivolt Voltage Standard as shown below:



6.10.1.3 Input Calibration

Use the following procedure to perform the input calibration.

1. Power on (**I**) instrument.
2. Allow instrument to warm up for at least one hour.
3. Set Voltage Standard to zero volts.
4. Attach test leads to TP8 (GND1) and TP9 (Vref adj.).
5. Adjust R52 until DMM voltage reads 2.5000 ±0.0001 VDC.
6. Configure the Model 321 to display units in millivolts.
7. Turn off temperature compensation.
8. Adjust R27 until Model 321 display reads exactly 0.000 mV DC.
9. Change Voltage Standard to +44.000 mV.
10. Adjust R43 until Model 321 display reads exactly 44.000 mV DC.
11. Switch Voltage Standard to -44.000 mV DC. The Model 321 display should read -44.000 ±0.002 mV DC. If not, set Voltage Standard to zero volts and repeat steps 8 through 11.

6.10.1.4 Analog Output Calibration

Use the following procedure to perform the analog output calibration.

1. Attach test leads to TP3 (gnd1) and TP4 (Analog out).
2. Press and hold the Analog Out key until the Model 321 enters the Analog output calibration mode.
3. Press the Up arrow key until Zero is selected.
4. With the DMM in DC voltage mode, adjust R22 until the voltage is 0.000 ±0.001 VDC.
5. Press the Up arrow key until Span is selected.
6. Adjust R18 until the voltage is 10.000 ±0.001 VDC.
7. Press Escape on the Model 321 to exit the Analog output calibration mode.
8. Set power switch to off (**O**). Disconnect power cord and test resistor.
9. Replace top of enclosure and secure with four screws.
10. Replace back bezel and use 5/64 hex key to tighten two screws attaching bottom panel to unit.

6.10.1.5 Thermocouple Offset Adjustment

When a new or different thermocouple is attached to the instrument, and external thermocouple compensation is being used, it may be necessary to adjust the offset to compensate for discrepancies in thermocouple material, leads and connections. Use the following procedure to perform the thermocouple offset adjustment.

1. Open the Model 321 enclosure. Refer to Paragraph 6.10.1.2, Steps 1 – 5.
2. Place the thermocouple in a reference bath of known temperature (liquid nitrogen, ice, etc.) and install external compensation. Allow the system to stabilize to the reference temperature.
3. On the front panel of the Model 321, select the desired temperature units.
4. Turn off thermocouple compensation.
5. Adjust R27 until the display reads the reference temperature.
6. Close the Model 321 enclosure. Refer to Paragraph 6.10.1.4, Steps 8 – 10.

6.10.1.6 Internal Thermocouple Compensation Calibration

When a new or different thermocouple is attached to the instrument, and internal thermocouple compensation is being used, it may be necessary to adjust the offset to compensate for discrepancies in thermocouple material, leads and connections. Use the following procedure to perform the internal thermocouple compensation calibration.

1. Open the Model 321 enclosure. Refer to Paragraph 6.10.1.2, Steps 1 – 5.
2. Short across the input with as short as lead as possible.
3. Configure the Model 321 to display units in °C.
4. Turn on thermocouple compensation.
5. Adjust R60 until display reads room temperature (25 °C nominal).
6. Close the Model 321 enclosure. Refer to Paragraph 6.10.1.4, Steps 8 – 10.

6.10.2 Optional Model 321-04 Calibration (Without Millivolt Voltage Standard)

The optional Model 321-04 (Thermocouple) calibration without a millivolt voltage standard is presented in six parts. First is list of test equipment in Paragraph 6.10.2.1. Second is the test setup in Paragraph 6.10.2.2. Third is the input calibration in Paragraph 6.10.2.3. Fourth is the analog output calibration is provided in Paragraph 6.10.2.4. Fifth is the thermocouple offset adjustment in Paragraph 6.10.2.5. Finally, the internal thermocouple compensation calibration is provided in Paragraph 6.10.2.6. These procedures will be performed with power supplied to the unit. Due to the presence of lethal currents, only personnel experienced in working with live circuits should perform this procedure.

6.10.2.1 Test Equipment

This procedure requires the following test equipment

- Digital Multimeter (DMM) with a 4½-digit display, capable of 4-lead resistive measurements.
- Voltage source capable of providing a stable, nominal ±44.0 mV DC.

6.10.2.2 Test Setup

Calibration test setup is as follows:

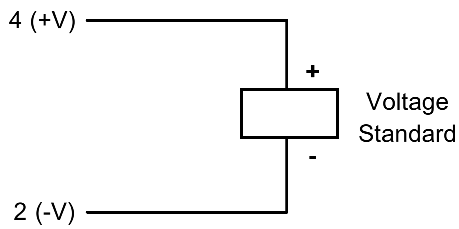
WARNING: Lethal line voltage is present inside the box. Only qualified personnel should attempt to perform this procedure.

1. Set power switch to off and disconnect power cord from rear of unit.
2. Use 5/64 hex key to remove four screws attaching top panel to unit.
3. Use 5/64 hex key to loosen two screws attaching bottom panel to unit.
4. Carefully remove back bezel.
5. Slide top panel back and remove from unit.

6.10.2.3 Input Calibration

Use the following procedure to perform the input calibration.

1. Power on (**I**) instrument.
2. Allow instrument to warm up for at least one hour.
3. Short across the input with as short a lead as possible.
4. Attach test leads to TP8 (gnd1) and TP9 (Vref adj.).
5. Adjust R52 until DMM voltage reads 2.5000 ±0.0001 VDC.
6. Configure the Model 321 to display units in millivolts.
7. Turn off temperature compensation.
8. Adjust R27 until the Model 321 display reads exactly 0.0000 mV DC.
9. Remove short from input and attach voltage source.



10. Adjust voltage source to a nominal +44.0 mV DC.
11. Attach the DMM to the input. DMM should be in the DC millivolt mode.
12. Adjust R43 until Model 321 display exactly matches the DMM reading.
13. Reverse voltage source to -44.0 mV DC. The Model 321 display should match the DMM reading within ±0.002 mV DC. If not, set voltage source to zero volts and repeat steps 8 through 13.

6.10.2.4 Analog Output Calibration

Use the following procedure to perform the analog output calibration.

1. Attach test leads to TP3 (GND1) and TP4 (Analog out).
2. Press and hold the Analog Out key until the Model 321 enters the Analog output calibration mode.
3. Press the Up arrow key until Zero is selected.
4. With the DMM in DC voltage mode, adjust R22 until the voltage is 0.000 ±0.001 VDC.
5. Press the Up arrow key until Span is selected.
6. Adjust R18 until the voltage is 10.000 ±0.001 VDC.
7. Press Escape on the Model 321 to exit the Analog output calibration mode.
8. Set power switch to off (**O**). Disconnect power cord and test resistor.
9. Replace top of enclosure and secure with four screws.
10. Replace back bezel and use 5/64 hex key to tighten two screws attaching bottom panel to unit.

6.10.2.5 Thermocouple Offset Adjustment

When a new or different thermocouple is attached to the instrument, and external thermocouple compensation is being used, it may be necessary to adjust the offset to compensate for discrepancies in thermocouple material, leads and connections. Use the following procedure to perform the thermocouple offset adjustment.

1. Open the Model 321 enclosure. Refer to Paragraph 6.10.1.2, Steps 1 – 5.
2. Place the thermocouple in a reference bath of known temperature (liquid nitrogen, ice, etc.) and install external compensation. Allow the system to stabilize to the reference temperature.
3. On the front panel of the Model 321, select the desired temperature units.
4. Turn off thermocouple compensation.
5. Adjust R27 until the display reads the reference temperature.
6. Close the Model 321 enclosure. Refer to Paragraph 6.10.1.4, Steps 8 – 10.

6.10.2.6 Internal Thermocouple Compensation Calibration

When a new or different thermocouple is attached to the instrument, and internal thermocouple compensation is being used, it may be necessary to adjust the offset to compensate for discrepancies in thermocouple material, leads and connections. Use the following procedure to perform the internal thermocouple compensation calibration.

1. Open the Model 321 enclosure. Refer to Paragraph 6.10.1.2, Steps 1 – 5.
2. Short across the input with as short as lead as possible.
3. Configure the Model 321 to display units in °C.
4. Turn on thermocouple compensation.
5. Adjust R60 until display reads room temperature (25 °C nominal).
6. Close the Model 321 enclosure. Refer to Paragraph 6.10.1.4, Steps 8 – 10.

APPENDIX A

GLOSSARY OF TERMINOLOGY

absolute zero. The temperature of –273.15 °C, or –459.67 °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.

Alumel™. An aluminum-nickel alloy which comprises the negative lead of a Type K thermocouple.

American Standard Code for Information Exchange (ACSII). 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				b7 b6 b5 →	0 0 0	0 0 1	0 1 0	0 1 1	1 0 0	1 0 1	1 1 0	1 1 1
b4 1	b3 1	b2 1	b1 1	Row ↓ / Col. →	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.

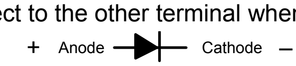
ampere/meter (A/m). The SI unit for the magnetic field strength (H). 1 ampere/meter = $4\pi/1000$ oersted ≈ 0.01257 oersted.

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 so it will have 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]



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 (**P**roportional), Reset (**I**ntegral), and Rate (**D**erivative) 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 (B). 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]

bifilar windings. A winding consisting of two insulated wires, side by side, with currents traveling through them in opposite directions.[1]

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

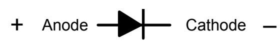
BNC. Bayonet Nut Connector.

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 EEPROM or installed in a Lake Shore instrument. Previously called a 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]



Carbon-Glass™. A temperature sensing material fabricated from a carbon-impregnated glass matrix used to make the Lake Shore CGR family of sensors.

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.

Cernox™. A Lake Shore resistance temperature detector based on a ceramic-oxy-nitride resistance material.

CGR. Carbon Glass Resistor.

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

Chromel™. A chromium-nickel alloy which comprises the positive lead of Type E and K thermocouples.

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.

Constantan. A copper-nickel alloy which comprises the negative lead of Type E, J, and T thermocouples.

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]

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 sensor's signal to temperature.

Curve 10. The voltage versus temperature characteristic followed by all DT-400 Series Silicon Diode Temperature Sensors.

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]

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 $S_d = d \ln R / d \ln T$. Note that the 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]

dynamic data exchange (DDE). A method of interprocess communication which passes data between processes and synchronized events. DDE uses shared memory to exchange data between applications and a protocol to synchronize the passing of data.

dynamic link library (DLL). A module that contains code, data, and Windows resources that multiple Windows programs can access.

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.

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.

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.

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.

GaAlAs. Gallium-aluminum-arsenide semiconducting material used to make the special Lake Shore TG family of diode temperature sensors.

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. 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.

germanium (Ge). A common temperature sensing material fabricated from doped germanium to make the Lake Shore GR family of resistance temperature sensor elements.

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	Α	Iota	ι	Ι	Rho	ρ	Ρ
Beta	β	Β	Kappa	κ	Κ	Sigma	σ	Σ
Gamma	γ	Γ	Lambda	λ	Λ	Tau	τ	Τ
Delta	δ	Δ	Mu	μ	Μ	Upsilon	υ	Υ
Epsilon	ε	Ε	Nu	ν	Ν	Phi	φ	Φ
Zeta	ζ	Ζ	Xi	ξ	Ξ	Chi	χ	Χ
Eta	η	Η	Omicron	ο	Ο	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 relatively 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), an American physicist.

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.

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

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.

I.D. Inner diameter.

IEC. International Electrotechnical Commission.

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.

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

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

infrared (IR). For practical purposes any radiant energy within the wavelength range 770 to 10^6 nanometers is considered infrared energy.[2] The full range is usually divided into three sub-ranges: near IR, far IR, and sub-millimeter.

input card. Electronics on a printed circuit board (card) that plug into an instrument main frame. Used by configurable instruments to allow for different sensor types or interface options.

interchangeability. Ability to exchange one sensor or device with another of the same type without a significant change in output or response.

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).

$B_i = B - \mu_0 H$ (SI) $B_i = B - H$ (cgs)

IPTS-68. International Practical Temperature Scale of 1968. Also abbreviated as T_{68}.

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 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 Label: Nonflammable Gas
	DOT Class: Nonflammable Gas
DOT Name: Helium, Refrigerated Liquid	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 Label: Nonflammable Gas
	DOT Class: Nonflammable Gas
DOT Name: Nitrogen, Refrigerated Liquid	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.

LSCI. Lake Shore Cryotronics, Inc.

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: $B = \mu_0(H + M)$ for SI, and $B = H + 4\pi M$ for cgs, where H = magnetic field strength, M = magnetization, and μ_0 = 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 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.

material safety data sheet (MSDS). OSHA Form 20 contains descriptive information on hazardous chemicals under OSHA's 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.

microcontroller. A microcomputer, microprocessor, or other equipment used for precise process control in data handling, communication, and manufacturing.[1]

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.

NbTi. Niobium-titanium. A superconductive alloy with a transition temperature typically near 9 K in zero magnetic field.

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

National Institute of Standards and Technology (NIST). Government agency located in Gaithersburg, Maryland and Boulder, Colorado, that defines measurement standards in the United States.

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 temp. 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.

O.D. Outer diameter.

oersted (Oe). The cgs unit for the magnetic field strength (H). 1 oersted = 10¾ π 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]

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): μ = 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.

pop-off. Another term for relief valve.

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 Helium is boiled off, and the Magnet Power Supply will 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 will allow it to be securely mounted in a 19-inch instrument rack. A full rack instrument requires the entire width of the rack. Two half rack instruments will fit horizontally in a 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 an instrument's physical display. 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.

RhFe. Rhodium-iron. Rhodium alloyed with less than one atomic percent iron is used to make the Lake Shore RF family of sensors. Rhodium-iron is a spin fluctuation alloy which has a significant temperature coefficient of resistance below 20 K where most metals rapidly lose sensitivity.

RJ-11. A modular connector with 6 conductors commonly used with telephones.

Roman numerals. Letters employed in the ancient Roman system of numeration as follows:

I	1	VI	6	L	50
II	2	VII	7	C	100
III	3	VIII	8	D	500
IV	4	IX	9	M	1000
V	5	X	10		

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]

room temperature compensation. Thermocouples are a differential measurement device. Their signal represents the difference in temperature between their ends. An ice bath is often used to reference the measurement end to 0 degrees Celsius so most curves are normalized to that temperature. Room temperature compensation replaces an ice bath by monitoring the temperature of the thermocouple's terminals and normalizing the reading mathematically.

RS-232C. Bi-directional computer serial interface standard defined by the Electronic Industries Association (EIA). The interface is single-ended and non-addressable.

Seebeck effect. The development of a voltage due to differences in temperature between two junctions of dissimilar metals in the same circuit.[1]

self-heating. Heating of a device due to dissipation of power resulting from the excitation applied to the device. The output signal from a sensor increases with excitation level, but so does the self-heating and the associated temperature measurement error.

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]

serial interface. A computer interface where information is transferred one bit at a time rather than one byte (character) at a time as in a parallel interface. RS-232C is the most common serial interface.

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

silicon diode. Temperature sensor based on the forward voltage drop at constant current through a pn semiconductor junction formed in crystalline silicon.

SoftCal™. In Lake Shore instruments, SoftCal™ is used to improve the accuracy of a DT-400 Series Silicon Temperature Diode Sensor. This reduces the error between the sensor and the Standard Curve 10 used by the instrument to convert input voltage from the diode to a corresponding temperature.

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

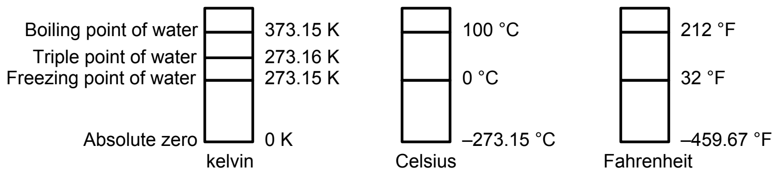
strain relief. A predetermined amount of slack to relieve tension in component or lead wires. Also called stress relief.

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). $\chi = M/H$. 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 x °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]

thermocouple. A pair of dissimilar conductors so joined at two points that an electromotive force is developed by the thermoelectric effects when the junctions are at different temperatures.[2]

thixotropy. Property of certain gels which liquefy when subjected to vibratory forces, such as ultrasonic waves or even simple shaking, and then solidify again when left standing.[1]

tolerance. The range between allowable maximum and minimum values.

torr. Unit of pressure. 1 torr ≈ 1 mm of mercury. 1 atmosphere = 760 torr.

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 it is placed 1 cm away from a like pole, the force between the two is 1 dyne.

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]

VSM. Vibrating Sample Magnetometer.

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]

References:

1 Sybil P. Parker, Editor. *Dictionary of Scientific and Technical Terms: Third Edition*. New York: McGraw Hill, 1969 (IBSN 0-395-20360-0)

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 B

HANDLING OF LIQUID HELIUM AND NITROGEN

B1.0 GENERAL

Liquid Helium (LHe) and liquid nitrogen (LN_2) may be used in conjunction with the Model 321. Although not explosive, the following are safety considerations in the handling of LHe and LN_2.

B2.0 PROPERTIES

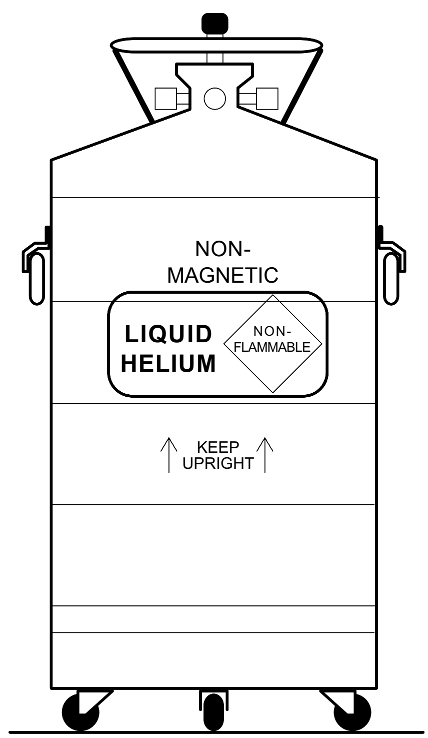
LHe and LN_2 are colorless, odorless, and tasteless gases. Gaseous nitrogen makes up about 78 percent of the Earth's atmosphere, while helium comprises only about 5 ppm (Reference 1). Most helium is recovered from natural gas deposits. Once collected and isolated, the gases will liquefy when properly cooled. A quick comparison between LHe and LN_2 is provided in Table B-1.

Table B-1. Comparison of Liquid Helium to 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

B3.0 HANDLING CRYOGENIC STORAGE DEWARS

All 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 B-1.



C-321-B-1.eps

Figure B-1. Typical Cryogenic Storage Dewar

B4.0 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, transfers accomplished, and systems 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.

B5.0 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.

References:

1. Linde Union Carbide Document No. L-3499H, Dated December 1988, Safety Precautions for Oxygen, Nitrogen, Argon, Helium, Carbon Dioxide, Hydrogen, and Fuel Gases

APPENDIX C

CURVE TABLES

C1.0 GENERAL

The following are curve tables applicable to the Model 321 Autotuning Temperature Controller.

Table C-1. Standard Diode and Platinum Curves

Breakpoint	D CURVE		E1 CURVE		DT-470 CURVE 10		Platinum 100 Ω	
Number	Temp.(K)	V	Temp.(K)	V	Temp.(K)	V	Temp.(K)	Ω
1	499.9	0.00000	499.9	0.00000	499.9	0.00000	000.0	0.00000
2	365.0	0.19083	330.0	0.28930	475.0	0.09032	030.0	0.03820
3	345.0	0.24739	305.0	0.36220	460.0	0.12536	032.0	0.04235
4	305.0	0.36397	285.0	0.41860	435.0	0.18696	036.0	0.05146
5	285.0	0.42019	265.0	0.47220	390.0	0.29958	038.0	0.05650
6	265.0	0.47403	240.0	0.53770	340.0	0.42238	040.0	0.06170
7	240.0	0.53960	220.0	0.59260	280.0	0.56707	042.0	0.06726
8	220.0	0.59455	170.0	0.73440	230.0	0.68580	046.0	0.07909
9	170.0	0.73582	130.0	0.84490	195.0	0.76717	052.0	0.09924
10	130.0	0.84606	100.0	0.92570	165.0	0.83541	058.0	0.12180
11	090.0	0.95327	075.0	0.99110	140.0	0.89082	065.0	0.15015
12	070.0	1.00460	060.0	1.02840	115.0	0.94455	075.0	0.19223
13	055.0	1.04070	040.0	1.07460	095.0	0.98574	085.0	0.23525
14	040.0	1.07460	036.0	1.08480	077.4	1.02044	105.0	0.32081
15	034.0	1.09020	034.0	1.09090	060.0	1.05277	140.0	0.46648
16	032.0	1.09700	032.0	1.09810	044.0	1.08105	180.0	0.62980
17	030.0	1.10580	030.0	1.10800	036.0	1.09477	210.0	0.75044
18	029.0	1.11160	029.0	1.11500	031.0	1.10465	270.0	0.98784
19	028.0	1.11900	028.0	1.12390	028.0	1.11202	315.0	1.16270
20	027.0	1.13080	027.0	1.13650	027.0	1.11517	355.0	1.31616
21	026.0	1.14860	026.0	1.15590	026.0	1.11896	400.0	1.48652
22	025.0	1.17200	025.0	1.18770	025.0	1.12463	445.0	1.65466
23	023.0	1.25070	024.0	1.23570	024.0	1.13598	490.0	1.82035
24	021.0	1.35050	022.0	1.33170	020.0	1.21555	535.0	1.98386
25	017.0	1.63590	018.0	1.65270	015.5	1.29340	585.0	2.16256
26	015.0	1.76100	013.0	1.96320	012.0	1.36687	630.0	2.32106
27	013.0	1.90660	009.0	2.17840	009.0	1.44850	675.0	2.47712
28	009.0	2.11720	004.0	2.53640	003.8	1.64112	715.0	2.61391
29	003.0	2.53660	003.0	2.59940	002.0	1.68912	760.0	2.76566
30	001.4	2.59840	001.4	2.65910	001.4	1.69808	800.0	2.89830
31	000.0	6.55360	000.0	6.55360	000.0	6.55360	999.9	6.55360

Table C-2. Thermocouple Curves – Chromel versus Gold/Iron

Breakpoint Number	Chromel–AuFe(0.03%)		Chromel–AuFe(0.07%)	
	Temp (K)	V_{TC}(mV)	Temp (K)	V_{TC}(mV)
1	3.5	– 4.6676	1.4	– 5.2982
2	8.0	– 4.6067	3.0	– 5.2815
3	13.5	– 4.5259	4.8	– 5.2594
4	18.0	– 4.4571	7.0	– 5.2285
5	24.0	– 4.3703	10.5	– 5.1742
6	30.0	– 4.2869	19.0	– 5.0315
7	52.0	– 3.9928	26.0	– 4.9126
8	60.0	– 3.8830	48.0	– 4.5494
9	65.0	– 3.8126	58.0	– 4.3810
10	70.0	– 3.7411	70.0	– 4.1733
11	80.0	– 3.5948	80.0	– 3.9952
12	90.0	– 3.4436	90.0	– 3.8132
13	105.0	– 3.2026	100.0	– 3.6270
14	115.0	– 3.0374	110.0	– 3.4370
15	125.0	– 2.8689	120.0	– 3.2435
16	135.0	– 2.6957	135.0	– 2.9477
17	145.0	– 2.5184	150.0	– 2.6452
18	160.0	– 2.2468	165.0	– 2.3372
19	170.0	– 2.0615	180.0	– 2.0242
20	180.0	– 1.8725	200.0	– 1.6004
21	195.0	– 1.5839	220.0	– 1.1693
22	210.0	– 1.2905	245.0	– 0.6232
23	225.0	– 0.9912	270.0	– 0.0705
24	240.0	– 0.6847	300.0	+ 0.5986
25	265.0	– 0.1670	305.0	+ 0.7158
26	275.0	+ 0.0378	310.0	+ 0.8431
27	285.0	+ 0.2387	315.0	+ 0.9944
28	305.0	+ 0.6350	320.0	+ 1.1940
29	325.0	+ 1.0387	325.0	+ 1.4841

Table C-3. Thermocouple Curves – Chromel versus Copper

Breakpoint	Chromel vs. Constantan		Chromel vs. Alumel		Copper vs. Constantan	
Number	Temp (K)	E V_{TC}(mV)	Temp (K)	K V_{TC}(mV)	Temp (K)	T V_{TC}(mV)
1	3.0	– 9.8355	3.0	– 6.4582	3.0	– 6.2584
2	5.6	– 9.8298	6.0	– 6.4551	6.5	– 6.2523
3	9.0	– 9.8182	10.0	– 6.4486	11.0	– 6.2401
4	13.5	– 9.7956	14.5	– 6.4376	16.5	– 6.2184
5	19.0	– 9.7570	19.5	– 6.4205	22.0	– 6.1888
6	25.0	– 9.7013	25.0	– 6.3951	29.0	– 6.1404
7	32.0	– 9.6204	32.0	– 6.3529	38.0	– 6.0615
8	40.0	– 9.5071	40.0	– 6.2913	48.0	– 5.9535
9	50.0	– 9.3366	48.0	– 6.2149	60.0	– 5.7995
10	60.0	– 9.1345	58.0	– 6.1022	75.0	– 5.5753
11	70.0	– 8.9030	65.0	– 6.0099	90.0	– 5.3204
12	80.0	– 8.6475	75.0	– 5.8634	105.0	– 5.0337
13	90.0	– 8.3673	85.0	– 5.6989	120.0	– 4.7194
14	105.0	– 7.9064	95.0	– 5.5156	135.0	– 4.3767
15	120.0	– 7.3943	105.0	– 5.3166	155.0	– 3.8781
16	135.0	– 6.8386	120.0	– 4.9881	175.0	– 3.3278
17	150.0	– 6.2400	135.0	– 4.6240	195.0	– 2.7342
18	170.0	– 5.3831	150.0	– 4.2267	220.0	– 1.9295
19	190.0	– 4.4564	165.0	– 3.7994	245.0	– 1.0586
20	210.0	– 3.4702	185.0	– 3.1866	270.0	– 0.1254
21	235.0	– 2.1605	205.0	– 2.5259	300.0	+ 1.0616
22	260.0	– 0.7666	230.0	– 1.6463	330.0	+ 2.3247
23	290.0	+ 0.9948	260.0	– 0.5186	360.0	+ 3.6639
24	320.0	+ 2.8428	295.0	+ 0.8688	395.0	+ 5.3095
25	350.0	+ 4.7704	350.0	+ 3.1298	430.0	+ 7.0419
26	385.0	+ 7.1149	395.0	+ 4.9999	470.0	+ 9.1113
27	420.0	+ 9.5570	460.0	+ 7.6164	510.0	+11.2758
28	460.0	+12.4425	510.0	+ 9.6125	555.0	+13.8053
29	475.0	+13.5573	575.0	+12.2790	575.0	+14.9685

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APPENDIX D

APPLICATION NOTES

D1.0 GENERAL

This appendix includes these Lake Shore Applications Notes:

FUNDAMENTALS FOR USAGE OF CRYOGENIC TEMPERATURE CONTROLLERS

by

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I INTRODUCTION

Cryogenic temperature controllers have been available for years, but users often have an incomplete understanding of their operating principles and of the closed-loop interactions between the controller and the controlled low temperature environment. The object of this primer is to address this problem by presenting some fundamental and practical concepts of control at low temperatures. The so-called "three-mode" or "PID" controller, utilizing Proportional (gain), Integral (reset), and Derivative (rate) functions, will be discussed and examples given of its operation and adjustment. While the emphasis will be placed on analog control systems, the advantages and disadvantages of digital versus analog control will also be presented.

II CHARACTERISTICS OF CRYOGENIC TEMPERATURE CONTROL SYSTEMS

The adjective "cryogenic" as applied to temperature control systems defines a set of conditions that distinguishes such systems from those for which the great majority of applications exist, i.e., industrial processes in which temperatures are above—and often well above—room temperature. There are at least five factors which crucially affect temperature control performance when one compares a cryogenic system with that existing inside a furnace, for example:

1. The values of heat capacity (lower, C_p, and thermal conductivity (often higher, κ, are such that much shorter thermal time constants ($\tau \alpha C_p/\kappa$) are the rule at low temperatures.
2. The temperature sensor used in a furnace is almost always one of a variety of thermocouples with sensitivities in the 10-100uV/°C range. In the cryogenic regime, resistance thermometers (both metallic and semi-conductive), diode, and capacitance thermometers provide from one to three order-of-magnitude higher sensitivity.
3. The heat input for furnaces is almost always derived from a line frequency source, and is controlled by relays, variable transformers, saturable reactors, or SCRs. Experiments performed in a cryostat usually involve low level signals, and hence require a low noise background. For that reason, ripple-free direct current, usually controlled by a series transistor bank, should be used to power the heater.
4. As one traverses the cryogenic regime from the liquid helium range up towards room temperature, there can be quite large *variations* in both the thermal time constants and thermometer sensitivities.
5. In the case of the furnace in which the load does not experience large endo- or exothermic reactions, the heat input required to maintain a set point temperature is approximately constant. This is because the heat loss through a fixed thermal conductance to the room temperature environment outside the furnace is also constant. However, there are cryogenic systems where the low temperature environment provided by, e.g., a surrounding cryogen such as a liquid helium or liquid nitrogen bath, may vary drastically as the level of the cryogen changes. In addition, the thermal conductance to the outside world is highly dependent on the gas pressure (vacuum) maintained in the cryostat. The resulting variations in "cooling power" will cause the heat input requirements to be anything *but* constant. A few cryogenic systems employ a controller cooling loop, but this type of system will not be discussed.

Most of the difficulties in cryogenic control applications are associated with factors 4 and 5, where changes in parameters are involved.

III PROPORTIONAL CONTROL

The block diagram in Figure 1 shows a systems in which only proportional control is being used. In this system, the desired control temperature setting (set point) is being compared to the sensor signal and the difference, or error signal (including polarity), is amplified within the controller. When the sensor temperature corresponds to the set point temperature (in voltage for a diode or resistance for a resistor), the sensor signal will be equal to, but opposite in polarity to the set point signal and the error signal will be zero. In older instruments, the set point is normally calibrated in millivolts or volts or resistance, corresponding to the sensor output signal. Most modern controllers have stored within them the appropriate voltage-temperature or resistance-temperature sensor characteristic so that the set point can be calibrated directly in temperature. However, as discussed in Section VII, this convenience feature can compromise the resolution and accuracy of the controller.

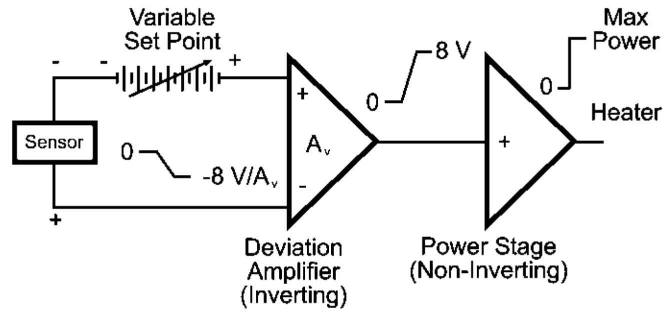


FIGURE 1. Block diagram of Cryogenic Temperature Controller. A_v is amplifier voltage gain.

The output of the controller is dc power to a resistive heater, the output magnitude of which depends on the size and sign of the error signal, as well as on the gain of the deviation amplifier and the output power supply. Since the controller's power output state tracks the deviation amplifier output, it is evident that the power output is proportional to the magnitude of the error signal. In process control nomenclature, this response is described in terms of "proportional control".

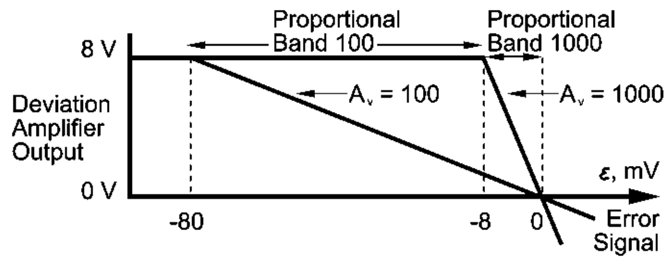


FIGURE 2. Output plot of the deviation amplifier showing Proportional Bands for gain settings of 100 and 1000. For the DRC-82C, the maximum available gain is 1000.

Let us examine the behavior of the sensor signal—set point—deviation circuit in a modern cryogenic controller, the Lake Shore Cryotronics Model DRC-82C. In figure 2, the amplifier output (deviation gain times error) is plotted against the error signal for two amplifier gains: A_v = 100 and A_v = 1000. "Gain" in this closed loop system refers not to the power gain, as in an audio amplifier, but is related to the maximum amount of error signal allowed before the controller is directed to produce full output power. The DRC-82C requires a 0 to 8 volt signal from the deviation amplifier to drive the power output stage from zero-to-maximum. In Figure 2, For Av = 1000, there is a narrow band of error signals (0 to -8 mV) within which the proportional action occurs. This "proportional band" expands tenfold for A_v = 100, and so on for lower gains; obviously, gain and proportional band are inversely related. Proportional band is expressed as a percentage of full scale range.

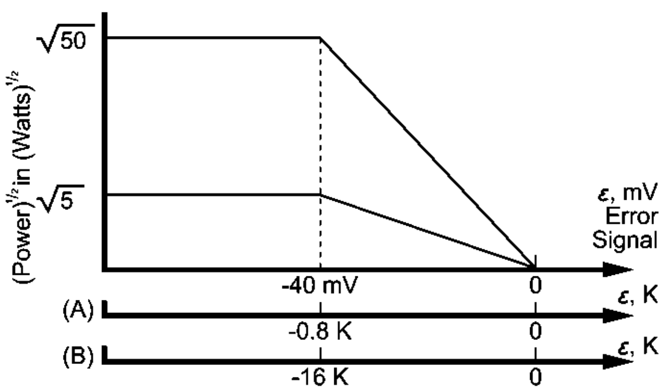


FIGURE 3. Output Power versus error signal in voltage or equivalent temperature of sensor for two different power settings: (A) corresponds to a sensor sensitivity of -50 mV/K; (B) corresponds to a sensor sensitivity of -2.5 mV/K. Note that the curves are linear in voltage, *not* power.

Note that the proportional band in mV can be converted to temperature in kelvins if the sensitivity of the sensor in mV/K is known. As an example, suppose the sensor producing the error signal in Figure 2 had a sensitivity of 1 mV/K and the set point full scale range was 100 mV = 100 K. The proportional band would then be 8% (or 8 K) and 80% (or 80 K) for A_v = 1000 and 100, respectively. In cryogenic applications, this terminology is less significant; gain, which is multiplicative, is usually more useful, since it is more easily understood by the user.

The power output stage of a cryogenic controller may or may not have variable gain associated with it. If the controller has several output power stage ranged for example, 5, covering 5 orders of magnitude in power) as does the DRC-82C, then the controller output into a 50 ohm load and with a gain of 200 for 5 watts and 50 watts would have the response shown in figure 3. Note that the *overall* voltage and power gain of the controller is modified by changing the output power settings.

To illustrate the effect of the sensor, in more detail, consider the idealized curve (Figure 4) for a Lake Shore silicon diode which has a nominal sensitivity of -50 mV/K below 30 kelvin and -2.5 mV/K above 30 kelvin. Figure 3 illustrates the effect of converting the voltage error signal (horizontal axis) to its equivalent temperature error for the two sensitivity regions of the silicon diode sensor. These curves introduce the concept of loop gain dP/dT (watts/kelvin), which includes the gain of the sensor as well as that of the deviation amplifier and power output stage. As the transition in temperature from above 30 kelvin to below 30 kelvin is made, the loop gain is increased by a factor of 20 because of the increased sensitivity of the silicon diode thermometer. Because of noise and thermal phase lag, the deviation amplifier gain will normally have to be reduced by the same factor so that the loop gain remains relatively constant.

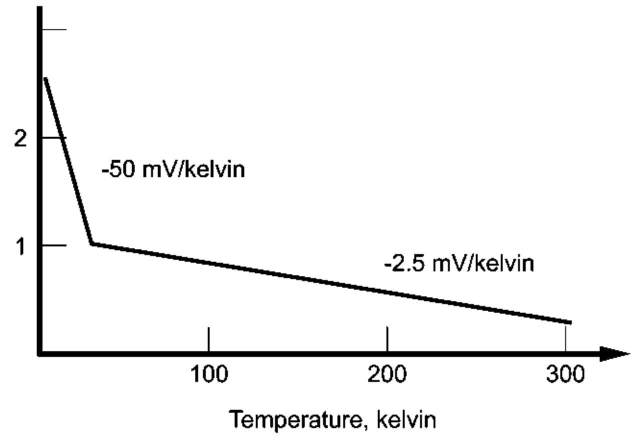


FIGURE 4. Idealized curve for Lake Shore Cryotronics, Inc. DT-500 Series silicon diode temperature sensors.

In order to maintain any desired temperature above that of the cryogen in a cryogenic system, of course some level of heater power must be supplied by the controller. We have seen in Figures 2 and 3 that a non-zero temperature error signal is necessary to produce an output, and that the magnitude of the error—or temperature *offset*— is a function of the power output level and the loop gain. Let us demonstrate the nature of the offset, also called droop, with an example.

Assume that a system sample block (the mass whose temperature is to be controlled) has a finite heat capacity, but that its thermal conductivity is infinite, as is the thermal conductance between the block and the sensor and heater. The result will be that the temperature within the block will be isothermal, no matter at what rate the block is heated or cooled. For the following discussion, ignore any noise associated with the system and assume that to control at 20 kelvin, the heating power required is 0.2 watts. Assume also that 50 watts of heater power is available, reducible in five steps of one decade each. Figure 5 shows the control offset for an amplifier gain of 100 and three output power settings which will deliver enough power to the system to balance the cooling power.

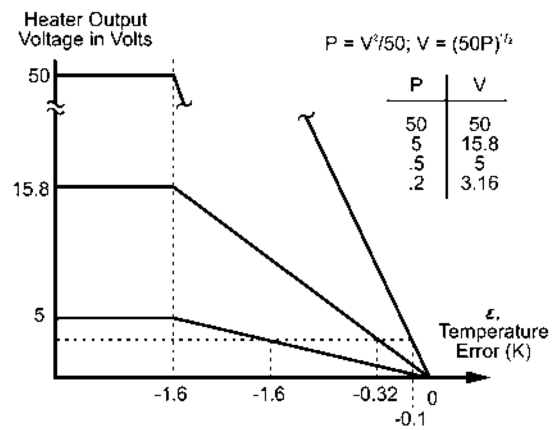


FIGURE 5. Effect of output power setting on offset for a proportional controller *only*.

The temperature offsets for a power level of 0.2 watts at 20 kelvin are easily calculated from Figures 2 and 4 for the three maximum power settings: 0.1 K for a 50 watt setting, 0.32 for a 5 watt setting, and 1.0 for the 0.5 watt setting. As expected, the temperature offsets become smaller as the loop gain increases. However, there are limits to this approach as we move from the idealized example to a real system.

The Real World

Unfortunately, the thermal conductivity within a system is not infinite, and both it and the heat capacity may vary by several orders of magnitude between 1 K and 300 K. Also, the controller, the sensor, the sensor leads, and the block may all have electrical noise. This noise is amplified by the controller; for a high enough amplifier gain setting, the output of the controller will become unstable and oscillate. In addition, the placement of the sensor with respect to the heater and the sensor construction and mounting itself introduce thermal lags. This is due to the finite thermal conductivity of the block and the thermal resistances between the heater, sensor and the block. These thermal lags introduce a phase shift between the controller output and the sensor, which will reduce even further the gain at which the system will be stable.

Therefore, the thermal block design is extremely important in the proper performance of any cryogenic system. No controller can make up for poor thermal design of the system, nor can good design overcome the inherent limiting properties of the materials and sensor packages which are currently available.

Since the thermal conductivity of cryogenic materials is finite, good practice dictates that the controller power output be the same order of magnitude as the cooling power. If, for example, the cooling power is 0.2 watt, and 50 watts is available, a change in set point to a higher temperature outside the proportional band of the controller will dump 50 watts into the system block. Due to the thermal lag of the block, etc., a large temperature overshoot may occur, with the system stabilizing only after several oscillations. This thermal lag can easily be observed since the sensor temperature will continue to rise long after the output from the controller has been reduced to zero. The obvious way to reduce this effect is to limit the heater power to the system to, for example, 0.5 watts. This can readily be done with a controller such as the DRC-82C which has multiple maximum output power settings. The overshoot will therefore be smaller when the set point is changed and the system will stabilize much faster although the rate of temperature rise will be less. Because changing the power output setting affects the loop gain (dP/dT), it may be necessary to readjust the deviation amplifier gain (controller gain setting) for optimum control. It is normally good practice to determine the power requirements for one's system prior to or during the first experimental run. Some system manufacturers may have that information available and may possibly supply a power load curve with the system.

Two other aspects of temperature control should be mentioned. First, ON-Off controllers are frequently encountered at room temperature and above. As the name implies, such systems have only two states: power on when the temperature is below the set point, and off when it is above. The proportional controller with excessive loop gain approximates this mode. Although ON-OFF controllers perform adequately with large furnaces, for example, they are generally unsatisfactory for cryogenic applications, because of the relatively short thermal time constants encountered at low temperatures.

Secondly, some controllers, such as the DRC-82C, have a manually adjustable power output control. This control can be used in either of two modes: (1) open loop, with a manual adjust of heater power *in place of* the signal from the deviation amplifier and (2) automatic, where the adjustment is *in addition to* the controller's closed loop signal. Mode 1 is extremely helpful in set up procedures and in subsequently determining the power levels associated with the desired temperatures. In Mode 2, one can reduce and sometimes eliminate temperature offset by providing the required power without the need for a large error signal to drive the output stage. This latter method has a name—manual reset—and serves as an introduction to the next section on reset control.

IV PROPORTIONAL (GAIN) PLUS INTEGRAL (RESET) TEMPERATURE CONTROL

The manual reset adjustment described above varies markedly with the temperature set point and with the often changing heater power demands of the system. Thus, it is normally neither convenient nor desirable to have to resort to such a means of eliminating temperature droop (offset). Instead, suppose a circuit could be added to the loop that would: (1) sense that there is a steady state offset signal within the proportional band; (2) make a bit-by-bit addition to the power output, proportional to the magnitude of the offset; and (3) continue the corrective action until the offset is reset to zero. The practical realization of this circuit is an integrator inserted between the deviation amplifier and the power stage. The origin of the interchangeable terms "integral" control and (automatic) "reset" is evident.

How does a proportional-plus-integral controller behave in a cryogenic system?

First, in the idealized case, let us again assume an infinite thermal conductivity, which results in zero thermal resistance between the sensor and the heater. The reset integrator continues to integrate until the error signal reaches zero, which stops the integral action, but keeps its output at the level corresponding to that needed by the power stage to overcome the droop. This output is now the only drive to the power stage since the proportional error signal has been forced to zero. No overshoot will occur since zero thermal resistance eliminates the thermal lag which is the cause of overshoot. The zero thermal time constant also means that *any* amount of reset will eventually force the system to zero error.

Before we switch the discussion back to real systems, let us deal with the nomenclature and units involved in integral control. Automatic reset action can be expressed in terms of a time constant (minutes) or its inverse, reset rate (repeats per minute). The reset time constant is the time required—measured in minutes—for the reset circuit to integrate to full output with an input signal which is *constant* and equal to the proportional band error signal. The amount of reset action can also be measured in "repeats per minute", or the number of times which the integrator can integrate between zero and full output in a time period of one minute for the constant proportional band error signal. Thus, if the time constant were, say, two minutes, this is the same as saying that the reset circuitry repeats the proportional action in two minutes, or ½ repeats per minute.

The term "reset windup" refers to a condition occurring in reset controller when an offset persists for a sufficiently long time. The integration of the error, with time, will cause the integrator to saturate or "windup" at maximum output and remain so until the control point is traversed. By the time this has happened, a large overshoot may have occurred. This problem can be prevented by disabling the reset action when controller response goes outside the proportional band. A controller such as the DRC-82C accomplishes this with an anti-reset windup (or reset inhibit) circuit.

The Real World Revisited

Since a real cryogenic system has non-zero thermal resistance, the value of the reset is important in setup of the controller. The amount of reset desired is dependent on: (1) the time required for the control sensor to reach equilibrium once it enters the proportional band; and (2) the amount of output signal required from the reset action to overcome the cooling power of the cryogenic system. For example, assume that 50% output is required and the time to reach equilibrium is 3 seconds (.05 minutes). Therefore the repeats per minute is 10 and the time constant is 0.1 minutes. In actuality, this is not easy to determine without a few tries. Almost always, however, the time constant increases with increasing temperature so that if one is operating over a broad temperature range, finding the appropriate time constants for the two extremes will bracket the appropriate time constants within that temperature range. Once the correct time constant has been selected, the system should settle to its control set point within two or three time constants. If significant overshoot is still occurring, the system design should be carefully reviewed.

V ADDING DERIVATIVE (RATE) TO THE TEMPERATURE CONTROL LOOP

If there is still an overshoot of the control temperature during transient changes of the set point within one's system, it can be significantly reduced by the addition of a third control function to the controller, called rate or derivative control.

Normally, overshoot can be attributed to one of two causes: (1) the application of much more power than is required to maintain the system at its desired set point; or (2) the result of the thermal response relationships between the cooling power, the heating power, and the control sensor. The best solution to the first possibility is to reduce the available power as discussed previously. The second problem normally occurs with a large thermal mass, where response is slow and overshoot due to the thermal inertia of the system can be quite large. This overshoot is caused by the time lag between a change in output power and the control sensor sensing this change. In very large non-cryogenic systems this time lag can be 10-30 minutes. In cryogenic systems, it is usually less than a minute, even near room temperature. Consequently, placement of the control sensor with respect to the heater is extremely important in the design of a cryogenic system, as is the placement of both the heater and sensor with respect to the cooling power.

Rate action can be achieved by means of a differentiator circuit which provides a signal proportional to the *rate* of temperature change, and which is subtracted from the proportional output signal. This reduces the effective overall amplifier gain driving the output power stage. The reduced gain effectively increases the proportional band of the controller. This slows down the rate of temperature rise and therefore allows more time for the block to stabilize. Consequently, the overshoot is substantially reduced or eliminated, depending on the magnitude of the thermal problem, as is indicated in Figure 6.

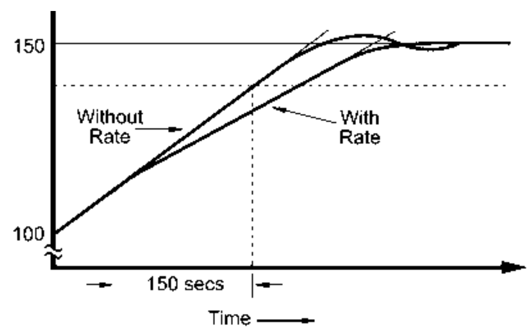


FIGURE 6. The effect of adding Rate to the control circuit to dynamically widen the proportional band and reduce the overshoot which would occur in its absence.

The addition of rate is necessary only because of inherent thermal problems which cannot be substantially eliminated by improvements in thermal design. Also note that rate is effective only during the transition from one set point to another. Near or at the set point, rate has a destabilizing influence. It should therefore be normal practice to turn off the rate control when near the control point.

The differentiator circuit should precede the reset integrator in the circuit so that the deviation and derivative signals acting on the integrator input will be just sufficient to create the proper reset value by the time the temperature reaches set point. In some cases, it is important for the rate circuit to precede the deviation amplifier as well, i.e., immediately following the sensor input. This would then prevent the rate circuit from operating on *changes* in the set point, such as in temperature seep applications. Fortunately, most sweeping is done slowly enough so as to be unaffected by typical rate time constants.

To determine the rate control setting (in seconds) for a system, an abrupt increase in power is applied to the system while in equilibrium. The time delay is then observed to the start of the resulting temperature increase as indicated by the control sensor. This delay corresponds to the value to be set on the rate control.

VI SENSOR CONSIDERATIONS

Sensor Gain Revisited: Since a controller will amplify input noise as well as sensor signal, it becomes important to consider sensor performance when designing a complete system. The Lake Shore DT-500 Series Sensors have a voltage-temperature characteristic which lend themselves to cryogenic temperature control use because of their high sensitivity at low temperatures (Figure 3). Coupled with this sensitivity is an extremely low noise-level which results, in part, from assembly techniques used for all DT-500 Sensors which comply with the relevant portions of MIL STD 750C. It is therefore possible to obtain short-term control at low temperatures which can approach 0.1 mK in specially designed systems such as the Lake Shore calibration facility. Even above 30 K, where the sensitivity is reduced by a factor of 20, short-term controllability is better than 2 mK.

With diodes, there is no need for a sensor pre-amplifier, which would precede the set point control and deviation amplifier. However, in the case of resistance thermometers, including both semiconductor and metal types, a pre-amplifier becomes necessary. In a dc measurement system, such as is used in the DRC-82C, it is sometimes possible to obtain temperature control stability with resistance thermometers superior to that obtainable with diodes. This requires a highly stable and adjustable constant current source in addition to a pre-amplifier designed for very low noise and drift. The choice of sensor is not at all obvious; it depends on many factors besides sensitivity, including sensor size, time response, power dissipation, magnetic field dependence and temperature range. In the less common case of cryogenic thermocouples, the very low sensitivity (10uV/K) requires quite large pre-amplifier gains and a stable reference junction arrangement. Thermocouples are sometimes used when sensor size or time response are more important than temperature stability and accuracy. At cryogenic temperatures, thermocouple accuracy does not approach that of a semiconductor diode or resistance thermometer when either are properly installed.

VII ANALOG VERSUS DIGITAL CONTROL

In this day of computers, designing digital instrumentation with a microprocessor is definitely in vogue. In a digital control system, the sensor voltage is digitized by an analog-to-digital (AD) converter. The digitized temperature is then compared to the digital set point within the microprocessor and by means of an appropriate algorithm, the average power to the heater is adjusted.

A converter with a 14 bit resolution (1 part in 16,384) enables the microprocessor to determine the temperature to approximately 4 mK at 4.2 kelvin using the diode sensor of Figure 2. In a system which is inherently stable, the control temperature stability can be no better than the temperature resolution of the AD converter (4 mK for this example). Cost-effective AD converters with such resolution have sampling times in the half-second range. In the world of ovens, furnaces, and other large industrial processes which operate above room temperature, stable control can be maintained by digital systems updating temperature only once or twice a second. This is for the same reason that ON-OFF controllers are successful in these cases: the large thermal time constants of the controlled environments.

However, as discussed in Section II, the time constants are much shorter in cryogenic systems, so much so that temperature can, and frequently does, change at a rate which exceeds the sampling frequency of a typical digital cryogenic controller (approximately 2 Hz). A good example is a mechanical refrigerator based on the Gifford-McMahon cycle. At 10 kelvin and below, these refrigerators, unloaded, often have a peak-to-peak variation in temperature which exceeds 1 kelvin at a nominal 3 Hz frequency. That variation represents an inherent disadvantage which is difficult for the all-digital system to overcome since the sampling rate is lower than the frequency of the temperature variation. The Sampling Theorem of Electrical Engineering implies that no sampled data control system can be stable unless it is sampled at a rate which exceeds at least twice the highest frequency variation within the system.

Some designers of all-digital controllers for cryogenic temperatures appear to have overlooked this sampling rate problem. There are also examples of digital controller which fail to achieve optimum performance because of the design of their output stage: heater power is varied on a cyclical time-proportioning ON-OFF basis. This often introduces noise within the system which may interfere with the cryogenic experiment.

An advantage that the microprocessor and its read-only memory provides for users of digital controllers is that of a direct reading (in temperature) set point and sensor readout. However, as noted in Section III, this feature may exact a price. In the real world, there is always an error due to lack of perfect conformity between the *true* sensor voltage- (or resistance-) temperature characteristic and the value actually stored in memory. This error will depend on the degree of non-linearity of the characteristic and on the amount of storage available. It is seldom cost-effective to keep the conformity error as small as the useful resolution of the controller system. Thus, in the 14-bit system referred to earlier in this section, its 4 mK resolution would be swamped by, e.g., a conformity-limited 100 mK. Fortunately, in a controller such as the DRC-82C, the user can select either a temperature *or* voltage (resistance) set point and readout.

The choice between analog and digital controllers turns out to be not a choice at all but an optimum combination of the best features of each. True analog control provides a heater output that is a continuous function of the sensor signal, and so eliminates the sampled data problem. This analog control may be combined with digital circuitry for readout of sensors and power output, for setting the PID control parameters and for deriving the set point signal. This approach is used in most of the Lake Shore Cryotronics, Inc. controllers.

For Further Reading

1. E. M. Forgan, "On the Use of Temperature Controllers in Cryogenics". Cryogenics 14 (1974), pp. 207-214. This is a cogent discussion of the interaction between the electrical and thermal response times in a typical *cryogenic* control system. The mathematical analyses are straightforward and relatively easy to follow.
2. A series on "process Control" published in the journal, Measurement & Control, Part 3, "On/Off and Proportional Control", September 1984, pp. 165-170; Part 4, "Reset and Rate Control", October 1984, pp. 133-145; Part 5, "Selecting the Mode of Control", December 1984, pp. 132-136. Some of this material has appeared in "Principles of Temperature Control", available from Gulton Industries, West Division. Unlike reference 1, the discussion is not related to cryogenics but temperature control system principles are briefly and clearly explained.
3. C. L. Pomernacki, "Micro Computer-Based Controller for Temperature Programming the Direct Inlet Probe of a High Resolution Mass Spectrometer", Review of Scientific Instruments, *48* (1977), pp. 1420-1427.
4. W. M. Cash, E. E. Stansbury, C. F. Moore, and C. R. Brooks, "Application of a Digital Computer to Data Acquisition and Shield Temperature Control of a High-Temperature Adiabatic Calorimeter", Review of Scientific Instruments, *52* (1981), pp. 895-901.
5. R. B. Strem. B. K. Das, and S. C. Greer, "Digital Temperature Control and Measurement System", Review of Scientific Instruments, 52 (1981), pp. 1705-1708.

STANDARD CURVE 10

Standard Curve 10: Measurement Current = 10 µA ±0.05%

T (K)	Voltage	dV/dT (mV/K)	T (K)	Voltage	dV/dT (mV/K)	T (K)	Voltage	dV/dT (mV/K)
1.40	1.69812	-13.1	16.0	1.28527	-18.6	95.0	0.98564	-2.02
1.60	1.69521	-15.9	16.5	1.27607	-18.2	100.0	0.97550	-2.04
1.80	1.69177	-18.4	17.0	1.26702	-18.0	110.0	0.95487	-2.08
2.00	1.68786	-20.7	17.5	1.25810	-17.7	120.0	0.93383	-2.12
2.20	1.68352	-22.7	18.0	1.24928	-17.6	130.0	0.91243	-2.16
2.40	1.67880	-24.4	18.5	1.24053	-17.4	140.0	0.89072	-2.19
2.60	1.67376	-25.9	19.0	1.23184	-17.4	150.0	0.86873	-2.21
2.80	1.66845	-27.1	19.5	1.22314	-17.4	160.0	0.84650	-2.24
3.00	1.66292	-28.1	20.0	1.21440	-17.6	170.0	0.82404	-2.26
3.20	1.65721	-29.0	21.0	1.19645	-18.5	180.0	0.80138	-2.28
3.40	1.65134	-29.8	22.0	1.17705	-20.6	190.0	0.77855	-2.29
3.60	1.64529	-30.7	23.0	1.15558	-21.7	200.0	0.75554	-2.31
3.80	1.63905	-31.6	24.0	1.13598	-15.9	210.0	0.73238	-2.32
4.00	1.63263	-32.7	25.0	1.12463	-7.72	220.0	0.70908	-2.34
4.20	1.62602	-33.6	26.0	1.11896	-4.34	230.0	0.68564	-2.35
4.40	1.61920	-34.6	27.0	1.11517	-3.34	240.0	0.66208	-2.36
4.60	1.61220	-35.4	28.0	1.11212	-2.82	250.0	0.63841	-2.37
4.80	1.60506	-36.0	29.0	1.10945	-2.53	260.0	0.61465	-2.38
5.00	1.59782	-36.5	30.0	1.10702	-2.34	270.0	0.59080	-2.39
5.50	1.57928	-37.6	32.0	1.10263	-2.08	280.0	0.56690	-2.39
6.00	1.56027	-38.4	34.0	1.09864	-1.92	290.0	0.54294	-2.40
6.50	1.54097	-38.7	36.0	1.09490	-1.83	300.0	0.51892	-2.40
7.00	1.52166	-38.4	38.0	1.09131	-1.77	310.0	0.49484	-2.41
7.50	1.50272	-37.3	40.0	1.08781	-1.74	320.0	0.47069	-2.42
8.00	1.48443	-35.8	42.0	1.08436	-1.72	330.0	0.44647	-2.42
8.50	1.46700	-34.0	44.0	1.08093	-1.72	340.0	0.42221	-2.43
9.00	1.45048	-32.1	46.0	1.07748	-1.73	350.0	0.39783	-2.44
9.50	1.43488	-30.3	48.0	1.07402	-1.74	360.0	0.37337	-2.45
10.0	1.42013	-28.7	50.0	1.07053	-1.75	370.0	0.34881	-2.46
10.5	1.40615	-27.2	52.0	1.06700	-1.77	380.0	0.32416	-2.47
11.0	1.39287	-25.9	54.0	1.06346	-1.78	390.0	0.29941	-2.48
11.5	1.38021	-24.8	56.0	1.05988	-1.79	400.0	0.27456	-2.49
12.0	1.36809	-23.7	58.0	1.05629	-1.80	410.0	0.24963	-2.50
12.5	1.35647	-22.8	60.0	1.05267	-1.81	420.0	0.22463	-2.50
13.0	1.34530	-21.9	65.0	1.04353	-1.84	430.0	0.19961	-2.50
13.5	1.33453	-21.2	70.0	1.03425	-1.87	440.0	0.17464	-2.49
14.0	1.32412	-20.5	75.0	1.02482	-1.91	450.0	0.14985	-2.46
14.5	1.31403	-19.9	80.0	1.01525	-1.93	460.0	0.12547	-2.41
15.0	1.30422	-19.4	85.0	1.00552	-1.96	470.0	0.10191	-2.30
15.5	1.29464	-18.9	90.0	0.99565	-1.99	475.0	0.09062	-2.22

Lighter numbers indicate truncated portion of Standard Curve 10 corresponding to the reduced temperature range of DT-471 diode sensors. The 1.4 – 325 K portion of Curve 10 is applicable to the DT-450 miniature silicon diode sensor.

POLYNOMIAL REPRESENTATION

Curve 10 can be expressed by a polynomial equation based on the Chebychev polynomials. Four separate ranges are required to accurately describe the curve. Table 1 lists the parameters for these ranges. The polynomials represent Curve 10 on the preceding page with RMS deviations of 10 mK. The Chebychev equation is:

$$T(x) = \sum_{i=0}^{n} a_i t_i(x) \qquad (1)$$

where T(x) = temperature in kelvin, $t_i(x)$ = a Chebychev polynomial, and a_i = the Chebychev coefficient. The parameter x is a normalized variable given by:

$$x = \frac{(V - VL) - (VU - V)}{(VU - VL)} \qquad (2)$$

where V = voltage and VL and VU = lower and upper limit of the voltage over the fit range. The Chebychev polynomials can be generated from the recursion relation:

$$t_{i+1}(x) = 2xt_i(x) - t_{i-1}(x) \qquad (3)$$
$$t_0(x) = 1,\ t_1(x) = x$$

Alternately, these polynomials are given by: $t_i(x) = \cos[i \times \arccos(x)]$ (4)

The use of Chebychev polynomials is no more complicated than the use of the regular power series and they offer significant advantages in the actual fitting process. The first step is to transform the measured voltage into the normalized variable using Equation 2. Equation 1 is then used in combination with equations 3 and 4 to calculate the temperature. Programs 1 and 2 provide sample BASIC subroutines which will take the voltage and return the temperature T calculated from Chebychev fits. The subroutines assume the values VL and V"U have been input along with the degree of the fit. The Chebychev coefficients are also assumed to be in any array A(0), A(1),..., A(i_{degree}).

An interesting property of the Chebychev fits is evident in the form of the Chebychev polynomial given in Equation 4. No term in Equation 1 will be greater than the absolute value of the coefficient. This property makes it easy to determine the contribution of each term to the temperature calculation and where to truncate the series if full accuracy is not required.

Program 1. BASIC Subroutine to evaluate temperature T from the Chebychev series using Equations 1 and 3. An array Tc (Ndegree) should be dimensioned.

```
100     REM Evaluation of Chebychev series
110     X = ((V-VL) -(VU-V)) / (VU-VL)
120     Tc(0) = 1
130     Tc(1) = x
140     T = A(0) + A(1) * X
150     FOR I = 2 to Ndegree
160     Tc(I) = 2 * X * Tc(I-1) - Tc(I-2)
170     T = T + A(I) * Tc(I)
180     NEXT I
190     RETURN
```

Program 2. BASIC Subroutine to evaluate temperature T from the Chebychev series using Equations 1 and 4. ACS is used to represent the arccosine function.

```
100     REM Evaluation of Chebychev series
110     X = ((V-VL) -(VU-V)) / (VU-VL)
120     T = 0
130     FOR I = 0 to Ndegree
140     T = T + A(I) * COS(I * ACS(X))
150     NEXT I
160     RETURN
```

Table 1. Chebychev Fit Coefficients

2.0 K to 12.0 K	
VL	1.32412
VU	1.69812
A(0)	7.556358
A(1)	-5.917261
A(2)	0.237238
A(3)	-0.334636
A(4)	-0.058642
A(5)	-0.019929
A(6)	-0.020715
A(7)	-0.014814
A(8)	-0.008789
A(9)	-0.008554

12.0 K to 24.5 K	
VL	1.32412
VU	1.69812
A(0)	17.304227
A(1)	-7.894688
A(2)	0.453442
A(3)	0.002243
A(4)	0.158036
A(5)	-0.193093
A(6)	0.155717
A(7)	-0.085185
A(8)	0.078550
A(9)	-0.018312
A(10)	0.039255

24.5 K to 100.0 K	
VL	1.32412
VU	1.69812
A(0)	71.818025
A(1)	-53.799888
A(2)	1.669931
A(3)	2.314228
A(4)	1.566635
A(5)	0.723026
A(6)	-0.149503
A(7)	0.046876
A(8)	-0.388555
A(9)	0.056889
A(10)	-0.116823
A(11)	0.058580

100 K to 475 K	
VL	1.32412
VU	1.69812
A(0)	287.756797
A(1)	-194.144823
A(2)	-3.837903
A(3)	-1.318325
A(4)	-0.109120
A(5)	-0.393265
A(6)	0.146911
A(7)	-0.111192
A(8)	0.028877
A(9)	-0.029286
A(10)	0.015619

DT-470 SERIES TEMPERATURE SENSORS INSTALLATION AND OPERATION

There are three aspects of using a temperature sensor which are critical to its optimum performance. The first involves the proper electrical and thermal installation of the connecting leads which run to the sensor, while the second aspect is the actual mounting of the sensor to the sample assembly. The final concern is the measurement electronics used for reading and recording temperature data from the sensor.

CONNECTING LEADS

Although the majority of the DT-470 series sensors are two lead devices, measurements should preferably be made using a four wire configuration to avoid all uncertainties associated with the lead resistance. This is done by using four connecting leads to the device and connecting the V+ and I+ leads to the anode and the V- and I- leads to the cathode as shown in Figure 1. The exact point at which the connecting leads are soldered to the device leads results in negligible temperature measurement uncertainties.

In a two wire measurement configuration, the voltage connections (point A in Figure 1) are made near or at the current source so only two leads are actually connected to the device. Some loss in accuracy can be expected since the voltage measured at the voltmeter is the sum of the diode voltage and the voltage drop across the connecting leads. The exact temperature uncertainty will depend on the temperature range and lead resistance. For a 10 ohm lead resistance, the diode voltage will be offset by 0.1 mV which gives a negligible temperature error at liquid helium temperature but a 50mK error near liquid nitrogen temperature. Note the DI and CY adapter can be used only in a two wire configuration.

An excessive heat flow through the connecting leads to any temperature sensor can create a situation where the active sensing element (for the DT-470 this is the diode chip) is at a different temperature than the sample to which the sensor is mounted. This is then reflected as a real temperature offset between what is measured and the true sample temperature. Such temperature errors can be eliminated by proper selection and installation of the connecting leads.

In order to minimize any heat flow through the leads, the leads should be of small diameter and low thermal conductivity. Phosphor-bronze or manganin wire is commonly used in sizes 32 or 36 AWG. These wires have a fairly poor thermal conductivity yet the resistivities are not so large as to create any problems in four wire measurements.

Lead wires should also be thermally anchored at several temperatures between room temperature and cryogenic temperatures to guarantee that heat is not being conducted through the leads to the sensor. A final thermal anchor at the sample itself is a good practice to assure thermal equilibrium between the sample and temperature sensor. Note that the CU, CY, BO, and DI mounting adapters serve as their own sample thermal anchor.

If the connecting leads have only a thin insulation such as Formvar or other varnish type coating, a simple thermal anchor cn be made by winding the wires around a copper post or other thermal mass and bonding them in place with a thin layer of GE 7031 varnish. There are a variety of other ways in which thermal anchors can be fabricated and a number of guidelines which may be found in detail in the references given below.

SENSOR MOUNTING

General Comments

Before installing the DT-470 sensor, identify which lead is the anode and which lead is the cathode by referring to the accompanying device drawings. Be sure that the lead identification remains clear even after installation of the sensor, and record the serial number and location.

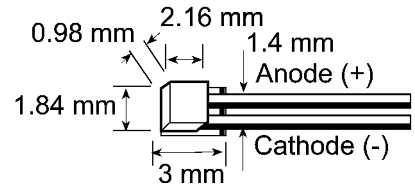
The procedure used to solder the connecting leads to the sensor leads is not very critical and there is very little danger in overheating the sensor, If for some reason the leads have to be cut short, they should be heat sunk with a copper clip or needle-nose pliers before soldering. Standard rosin core electronic solder (m.p. - 180 C) is suitable for most applications. Applications involving the use of the SD package up to 200° C will require a higher melting point solder. A 90% Pb 10% Sn solder has been used quite successfully with a rosin flux.

For all adapters except the CY, CU, and DI, the leads are a gold-plated Kovar. Prolonged soldering times may cause the solder to creep up the gold plated leads as the solder and gold alloy. This is not detrimental to the device performance.

When installing the sensor, make sure there are no shorts or leakage resistance between the leads or between the leads and ground. GE-7031 varnish or epoxy may soften varnish-type insulations so that high resistance shunts appear between wires if sufficient time for curing is not allowed. Teflon spaghetti tubing is useful for sliding over bare leads when the possibility of shorting exists. Also, avoid putting stress on the device leads and allow for the contractions that occur during cooling which could fracture a solder joint or lead if installed under tension at room temperature.

The DT-470 sensor is designed for easy removal for recalibration checks or replacement and the following discussions for each of the adapters are geared in this direction. If semi-permanent mountings are desired, the use of Stycast epoxy can replace the use of Apieson N Grease. In all cases, the mounting of the sensor should be periodically inspected to verify that good thermal contact to the mounting surface is maintained.

DT-470-SD



The SD version is the basic package for the DT-470 sensor line from which all other configurations are made using the appropriate adapter. The base of the device has a gold metallized surface and is the largest flat surface on the sensor. The base is electrically isolated from the sensing element and leads, and all thermal contact to the sensor must be made through the base. A thin braze joint around the sides of the SD package is electrically connected to the sensing element. Contact to the sides with any electrically conductive material must be avoided. When viewed with the base down and with leads towards the observer, the positive lead (anode) is on the right.

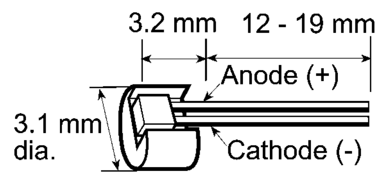
For a removable mount, the Sd sensor can be3 held against the mounting surface with the CO adapter (see below) or similar clamping mechanism. Any method of clamping the sensor must avoid excessive pressure and should be designed so that thermal contractions or expansions do not loosen contact with the sensor. For uses restricted to below 325 K, a thin layer of Apiezon N Grease should be used between the sensor and sample to enhance the thermal contact.

The SD package can also be bonded with an epoxy such as Stycast. The sensor should be pressed firmly against the surface during curing to assure a thin epoxy layer and good thermal contact. The device may be removed in the future by using the appropriate epoxy stripper.

The SD adpater can be soldered using a rosin flux (non-corrosive) if extreme care is exercised. First, tin the base of the sensor using a low wattage, temperature controlled soldering iron which will not exceed 200° C. Use only a minimal amount of solder. Tin the surface to which the sensor is to bonded and again avoid an excessive thickness of solder. Clean both the sensor and mounting surface of any residual flux. Next, re-heat the mounting surface to the melting point of the solder, press the device into position and allow the sensor to warm to the melting point of the solder. After both tinned surfaces have flowed together, remove the heat source and let the sample and sensor cool. Under no circumstance should the sensor be heated above 200° C and the solder must be limited to only the base of the sensor. Excess solder running up the sides of the SD package can create shorts. Repeated mounting and demounting of a soldered sensor may eventually cause wetting deterioration and ruin the thermal contact to the sensing element, although the nickel buffer layer should minimize these problems.

CAUTION: The preferred method for mounting the SD sensor is either the CO adapter or bonding with epoxy. Lake Shore Cryotronics, Inc. will not warranty replace any device damaged by a user-designed clamp or damaged through solder mounting.

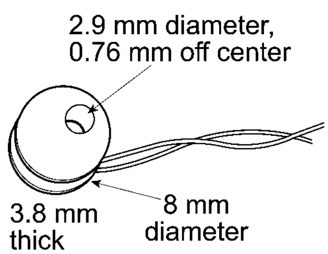
DT-470-LR



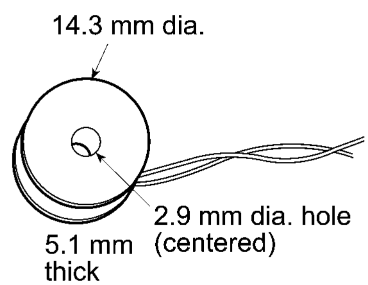
The gold-plated copper LR adapter is designed for insertion into a 1/8 inch diameter hole. A thin layer of Apiezon N Grease should be applied to the copper adapter before insertion. This eases installation at room temperature and enhances the thermal contact.

DT-470-CU / DT-470-DI / DT-470-CY

The gold-plated copper CU, DI, and CY adapters serve as both sensor and thermal anchor assembly. These adapters mount to a flat surface with a 4-40 brass screw. Avoid over-tightening the screw; use only enough force to firmly hold the sensor in place. A brass screw is recommended as the differential thermal contraction between the adapter and the screw causes the mounting assembly to tighten as opposed to loosen when the system cools. Apply a thin layer of Apiezon N Grease to enhance thermal contact between the adapter and mounting surface.



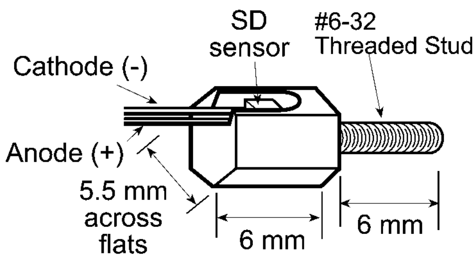
DT-470-CU / DT-470-DI



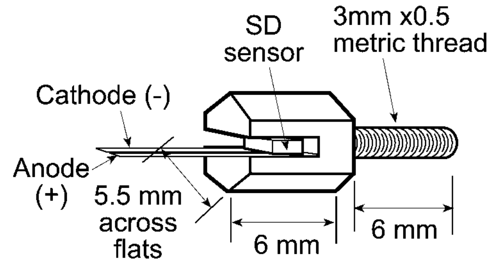
DT-470-CY

The CU adapter has four color-coded leads: Red (I-), Green (V-), Clear (V+), and Blue)I+). The CY adapter has two color-coded leads: Yellow (+) and Green (-). The green lead on the DI adapter is the cathode.

DT-470-ET / DT-470-MT



DT-470-ET

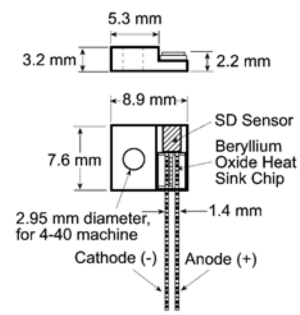


DT-470-MT

Both adapters are gold-plated copper hex head bolts with the SD package mounted in a slot on the adapter head. The ET adapter screws into a ¼ inch deep, 6-32 threaded hole while the MT adapter screws into a 6 mm deep, 3x0.5 mm threaded hole. Before assembly the threads should be lightly greased with Apiezon N Grease Do not over-tighten since the threads are copper and can be easily sheared. Finger tight should be sufficient.

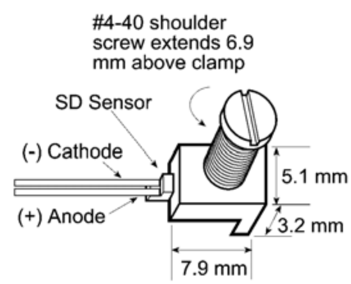
DT-470-BO

The BO adapter should be mounted in the same manner as the CU. The BO adapter contains its own thermal anchor and is an epoxy free assembly.



DT-470-CO

The CO adapter is a spring-loaded clamp to attach the DT-470-SD package to a flat surface. It maintains pressure on the SD package as the temperature varies. First, remove the hold down cap which holds the three piece CO assembly together. The CO assembly should appear as shown in the accompanying drawings. Bolt the assembly into a 4-40 threaded hole. The stop on the brass screw should rest against the mounting surface and it also prevents over-compressing the spring. Lift the edge of the clip using a small pliers or screw driver. Slide the SD package into place underneath the clip and gently lower the clip onto the lid of the SD package. Note that a slot is cut underneath the clip to accept the SD package. Refer to the drawing for details. If the device is to be used only below 325 K, apply a layer of Apiezon N Grease between the SD package and mounting surface to enhance thermal contact.



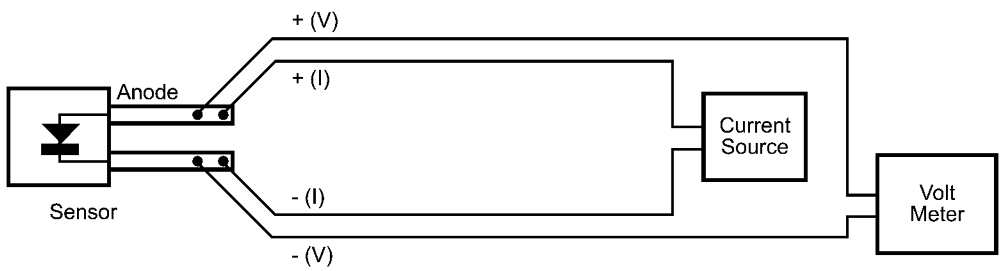


FIGURE 1. Four-Wire Configuration for DT-470 Installation

SENSOR OPERATION

Temperature controllers and thermometer instrumentation manufactured by Lake Shore Cryotronics are designed to be directly compatible with the DT-470 sensor to give optimum performance and accuracy together with direct temperature readouts. Simply follow the instructions provided with the instrument concerning sensor connection and instrument operation. If a user-supplied current source, voltmeter, or other instrumentation are going to used with the DT-470 sensor, special attention should be given to the following details.

The DT-470 is designed to operate at a constant current of 10 microamperes while the voltage variation with temperature is monitored. Therefore, the accuracy of the temperature measurement depends directly onf the specifications of the current source and the voltmeter. A current source operating at the level of 10 ±0.01 microamperes (±0.1%) gives a nominal temperature uncertainty of 10 millikelvin (0.01 K) which is probably suitable for most applications The voltmeter resolution required can be estimated from the sensitivity (dV/Dt) of the DT-470:

Temperature (K)	**Sensitivity (mV/K)**
305	2.4
77	1.9
4.2	33

Multiplying the above sensitivity by the desired temperature resolution in kelvin will give the required voltage resolution in millivolts.

The static impedance of the DT-470 sensor operating at a 10 microampere current is on the order of 100,000ohms. Therefore, the input impedance of the voltmeter must be significantly larger than this to avoid measurement errors. Voltmeters with input impedances of greater than 109 or 1010 ohms should be used.

Good quality instrumentation must be used and all instrumentation and wiring should be properly grounded and shielded. Temperature measurement errors will result if there is excessive AC noise or ripple in the circuitry. Further details can be found in the article by Krause and Dodrill given in the references.

NOTE: All materials mentioned which are used in sensor installation are available from Lake Shore Cryotronics, Inc.

References

Krause, J. K. and Swinehart, P. R. (1985). Demystifying Cryogenic Temperature Sensors. *Photonics Spectra*. August, 61-68. (Available on request from Lake Shore Cryotronics, Inc.

Krause, J. K. and Dodrill, B. C. (1986). Measurement System Induced Errors in Diode Thermometry. Review of Scientific Instruments 57 (4), 661-665. (Available on request from Lake Shore Cryotronics, Inc.)

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MEASUREMENT SYSTEM INDUCED ERRORS IN DIODE THERMOMETRY

by John K. Krause and Brad C. Dodrill

Diode temperature sensors are capable of being used at the accuracy level of a few hundredths of a kelvin. However, in order to achieve this performance, proper measurement techniques must be used. Poorly shielded or improperly grounded measurement systems can introduce ac noise which will create an apparent shift in the dc voltage reading across a diode sensor. This results in a temperature measurement error which may approach several tenths of a kelvin. The presence of the ac noise in question is not obvious during normal usage and several quick tests are outlined to verify whether or not a noise problem exists. Experimental data and derivations from theoretical *p-n* junction characteristics are given which correlate the ac noise level with possible voltage/temperature measurement errors. These results can be used in estimating the accuracy and performance of a temperature measurement system. Several of the more common problems which introduce noise into diode circuitry are described.

INTRODUCTION

Current technological uses of temperature sensors require better calibration accuracies and better device performance than ever before. However, the assurance of an accurate temperature measurement does not stop with simply the sensor specifications. Just as critical is the instrumentation used with the sensor and the manner in which the instrumentation is used. This paper concentrates on identifying, verifying, and eliminating an often overlooked instrumentation or system-induced error in the use of diode temperature sensors.

I. PROBLEM DEFINITION

Semiconductor diode temperature sensors have been in use for over 20 years and, with the advantages they offer over resistance sensors or thermocouples for many applications, their popularity continues to increase. Diodes are operated at a constant current, typically 1, 10, or 100 µA, while the voltage variation with temperature (V[T]) is monitored. The diode sensor has a useful temperature range from above room temperature to as low as 1 K, with reproducibilities to better than ±50 mK. Figure 1 shows the voltage variation with temperature for a typical silicon diode temperature sensor.

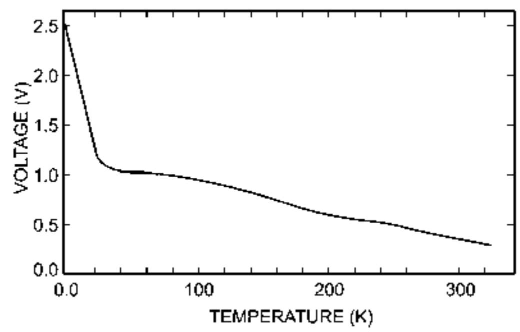

FIGURE 1. Voltage-temperature curve for a typical silicon diode temperature sensor at a constant current of 10 µA.

An error arises in diode thermometry if the excitation current is not a true dc current but has an ac component superimposed on the dc. Although the ac component can be due to a poorly designed current supply, a more common source of the ac is noise induced in the measurement circuit. This noise can be introduced through improper shielding, improper electrical grounds, or ground loops. Currently available voltmeters have sufficient normal-mode rejection capabilities in their dc measurement modes that these noise effects can go completely unnoticed if they are not explicitly checked. The equivalent temperature error which may be caused by this problem is typically a few tenths of a kelvin, although an extreme case with a 4 K error has been observed.

The effect of the ac noise appears as a shift in the dc voltage measurement due to the nonlinear current/voltage characteristics of the diode. An illustration of this effect is shown in Fig. 2 where an exaggerated IV curve is given. An induced ac noise current superimposed on the dc operating current (I_{dc}) is shown along the current axis. The resulting voltage seen by the voltmeter is shown along the voltage axis. The nonlinear IV characteristics of the diode have caused a distortion in the ac voltage signal making it asymmetrical with respect to the voltage reading corresponding to I_{dc}. When a voltmeter operating in a dc voltage mode reads this signal, the signal is processed (by integrating, filtering, etc.) to give an average dc voltage reading which will be lower than expected. The apparent temperature measurement will then be too high. Note that this voltage offset is due to induced currents in the total measuring system and is not simply a voltage pickup by the diode itself. An ac voltage superimposed symmetrically about the dc operating voltage of the diode would not cause a dc voltage offset.

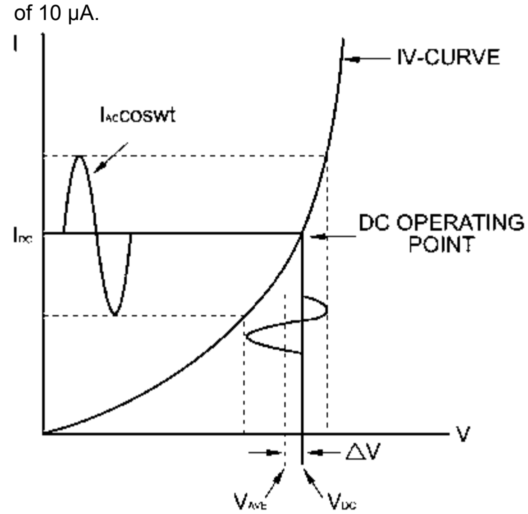

FIGURE 2. IV curve for a silicon diode sensor showing effect of an induced ac current superimposed on the dc operating current I_{dc}. The expected dc operating voltage is V_{dc}, which is shifted from the average voltage V_{ave} indicated by the voltmeter in a dc measurement mode.

There are two simple techniques which can be used to test whether these errors might be present in a measuring system. The first is to connect a capacitor (about 10 µF) in parallel with the diode to act as a shunt for any ac noise currents. The capacitor must have low leakage current so as not to alter the dc current through the diode. The capacitor may also alter the time response of the measurement system, so allow sufficient time for the capacitor to charge and for the system to equilibrate. If the dc voltage reading across the diode increases with the addition of the capacitor, there are probably ac noise currents present. The second method simply involves measuring the ac voltage signal across the diode. Although an oscilloscope is often the logical choice for looking at ac signals, many do not have the sensitivity required and they often introduce unwanted grounds into the system and compound the problem. Most testing can be performed with the same digital voltmeter used to measure the dc voltage by simply selecting the ac voltage function. There should be no ac voltage across the diode. If there is, the data presented in the following sections can be used to estimate the potential error in the temperature measurement.

II. EXPERIMENTAL

In order to quantify the effects of induced currents on silicon diode temperature sensors, the circuit of Fig. 3 was used to superimpose an ac current on the dc operating current. The dc current source was battery powered with currents selectable from < 1 µA to > 1 mA.. The signal generator could be varied in both amplitude and frequency. All voltage measurements were made with a Hewlett-Packard 3456A voltmeter in either the dc voltage mode or the ac (rms) voltage mode. The dc measurements were taken with an integration time of 10 power line cycles without using the filtering options available on the voltmeter. The average of several readings was taken to reduce the measurement uncertainty. An oscilloscope was also used to double-check and monitor signal frequency, shape, and distortion, but the oscilloscope was removed from the circuit when actual data were recorded.

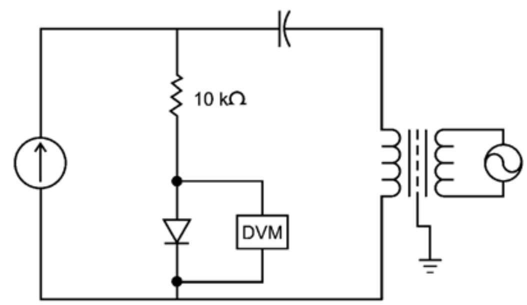

FIGURE 3. Measurement circuit schematic diagram.

Data were recorded at the three dc current values of 1, 10, and 100 µA with the temperature stabilized at 305, 77, or 4.2 K. At each temperature and dc current value, the dc voltage and the ac voltage across the diode were recorded as the amplitude and frequency of the signal generator were varied. The dc voltage reading across the 10 kΩ standard resistor was also monitored to verify that the dc component of the current remained constant to within 0.05%. In addition, the IV characteristic of the diode was measured at each temperature from 0.1 to 150 µA.

Although detailed measurements were taken on only one diode, other diodes were randomly selected and spot checked at all three temperatures and frequencies to verify consistency with the measured data. The diodes tested were of the DT-500 series of Lake Shore Cryotronics, Inc. and have been in production long enough to have a substantial reliability and calibration history.

III. RESULTS AND DISCUSSION

The data were analyzed by calculating a voltage offset ΔV. This offset is defined as the difference between the dc voltage reading across the diode when operated with an ac + dc current and the dc voltage reading when operated with a pure dc current (see Fig. 2). At first glance, the logical choice seems to be to examine the variation of this offset as a function of the ac current amplitude. However, the ac (rms) voltage across the diode was chosen instead for two reasons, the first of which is purely practical. In many circumstances, the ac voltage measurement can be made without any modifications to existing measurement systems, so laboratory checks can be quickly taken and compared directly to the data presented here to give an estimate of potential temperature errors. Second, in the calculations using the model presented below, one unknown parameter could be eliminated from the calculations by using the voltage across the diode instead of the current.

Figures 4 and 5 give the offset voltage as a function of the ac (rms) voltage across the diode for dc currents of 1, 10, and 100 µA with the ac current modulation at 60 Hz. The equivalent temperature error corresponding to the dc offset voltage is indicated along the right edge of the figure. Figures 6 and 7 give similar plots but at a fixed 10 µA dc current with the ac current modulation at 60, 1000, and 20,000 Hz. The magnitude of the dc offset voltages is consistent with what has been observed in measurement systems when corrective action has been taken to eliminate noise problems. Special note should be taken of the dc current independence in Fig. 4 and the frequency independence in Figs. 6 and 7. The data taken at 305 K have not been shown as the results are qualitatively very similar to the 77 K measurements and can be adequately described by the mathematical model which is presented below.

One surprising aspect of the data acquisition was how well the signal processing in the voltmeter could hide even high ac levels in the dc measurement modes. For example, operating at 10 µA dc and 77 K with a rms noise level of 6 mV gives a dc voltage offset of about 1.5 mV, which is about a 0.6 K temperature error. When reading the voltage signal using the filtering and integrating capabilities of the HP 3456A, the dc voltage reading is stable to better than ±0.02 mV (8 mK).

This stability gives a deceptive view of exactly how accurate the temperature measurement really is and emphasizes the importance of checking all aspects of a measuring system.

The measured offset voltages shown in Figs. 4 and 6 can be understood by using the well-known result from *p-n* junction theory:

$I = I_s\,[\exp(eV / nkT) - 1]$ (1)

where **I** = the forward current through the junction, $\mathbf{I_s}$ = the reverse saturation current, **e** = the electron charge, **V** = the voltage across the junction, **k** = Boltzmann's constant, and **T** = the absolute temperature. **n** is a parameter depending on the location of the generation and recombination of the electrons and holes and typically has a value between 1 and 2. This expression for the IV characteristics of a *p-n* junction is valid from approximately 40 K to above 300 K for the silicon diodes discussed here. Below 40 K, a new conduction mechanism becomes dominant, suggesting the influence of impurity conduction, carrier freezeout, increased ohmic behavior of the bulk material, and *p-i-n* diode type behavior.[1-6]

The only adjustable parameter in Eq. 1 which is necessary for the present analysis is the parameter **n**. This parameter can be determined quite easily from the IV characteristics of the silicon diode temperature sensor. The parameter $\mathbf{I_s}$ is eliminated by normalizing the IV curve to an arbitrarily chosen point on the curve. The value of n = 1.8 was found to give a relatively good fit to the IV data for both 305 and 77 K and has been assumed in the present discussion.7 Equation (1) can now be solved for V(I):

$V(I) = (nkT / e)\ln(I / I_s + 1)$ (2)

Substituting a dc current with an ac modulation, $I_{dc} + I_{ac}\cos\omega t$, the average voltage read by the voltmeter in the dc voltage mode can be calculated from:

$$\overline{V} = \frac{1}{T}\int_0^T V(I_{dc} + I_{ac}\cos\omega t)\,dt \qquad (3)$$

where T = the period of integration of the voltmeter or approximately $2\pi/\omega$. Implied in this derivation is the assumption that ω is sufficiently small so that effects from diode capacitance (on the order of picofarads) can be ignored.

On carrying out the integration of Eq. (3) and subtracting $V(I_{dc})$, the dc offset voltage is:

$$\Delta V = \overline{V} - V(I_{dc}) = \frac{nkT}{e}\ln\left[\frac{1}{2}\left(1+\sqrt{1-2\left(\frac{eV_{rms}}{nkT}\right)^2}\right)\right] \qquad (4)$$

where $I_{ac} \le I_{dc} + I_s$. If a small signal (linear) model is used, the rms voltage across the diode can be easily related to I_{ac}:

$$V_{rms} = \frac{I_{ac}}{\sqrt{2}}\left(\frac{dV}{dI}\right)\bigg|_{I=I_{dc}} = \frac{1}{\sqrt{2}}\left(\frac{nkT}{e}\right)\left(\frac{I_{ac}}{I_{dc}+I_s}\right) \qquad (5)$$

Evaluation of Eq. (5) and substitution back into (4) yields:

$$\Delta V = \frac{nkT}{e}\ln\left[\frac{1}{2}\left(1+\sqrt{1-2\left(\frac{eV_{rms}}{nkT}\right)^2}\right)\right] \qquad (6)$$

where $2(eV_{rms} / nkT)^2 \le 1$ for a physical solution. Equation (6) predicts an offset voltage which is independent of both frequency and dc operating current and is shown plotted in Fig. 4 by the solid line. The agreement with the experimental measurements is quite good, verifying the overall picture as to the effect of induced currents on diode temperature sensors. The results recorded at 305 K are described equally well by Eq. (6).

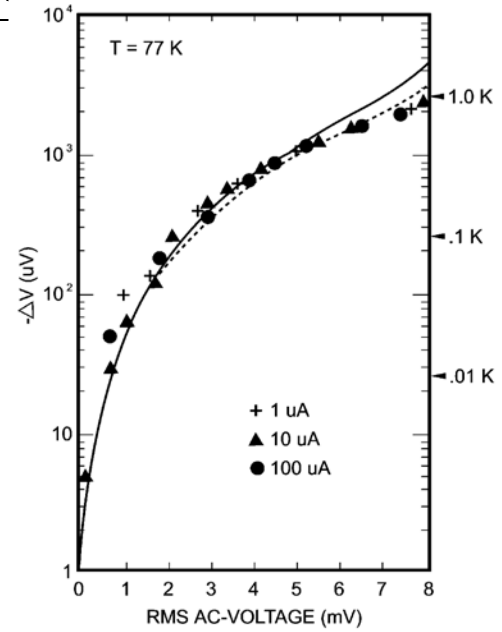

FIGURE 4. DC offset voltage as a function of rms ac voltage across a silicon diode temperature sensor operating at 77 K. The symbols represent data recorded at three different dc operating currents with a 60 Hz signal superimposed. The solid curve gives small signal model results while the dashed curve represents the extended calculations. Equivalent temperature errors are indicated along the right edge.

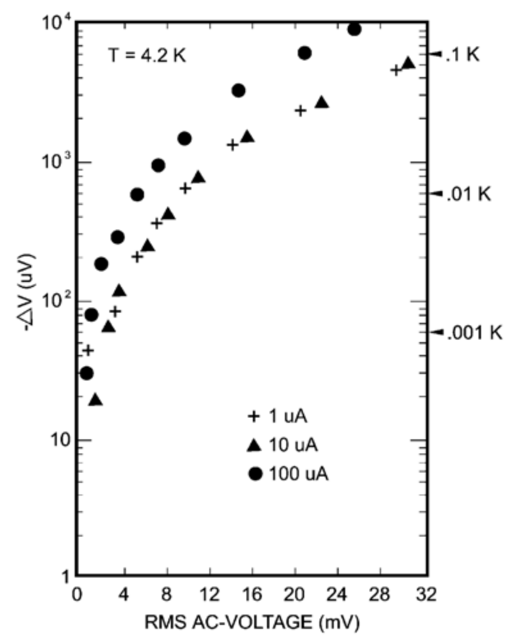

FIGURE 5. DC offset voltage as a function of rms ac voltage across a silicon diode temperature sensor operating at 4.2 K. The symbols represent data recorded at three different dc operating currents with a 60 Hz signal superimposed. Equivalent temperature errors are indicated along the right edge.

The utilization of the small signal model has the advantage of being analytically simple. However, the model does not contain the nonlinearity inherent in the forward biased IV characteristics of a *p-n* junction. In an attempt to retain the non linear characteristics, $V(I_{dc} + I_{ac}\cos\omega t)$ was expanded in a Fourier series. The first term (constant term) is just the average dc voltage in Eq. (3) and is not seen by the voltmeter operating in an ac measurement mode. The remaining terms in the Fourier series can then be used to calculate the rms voltage which will be read by the voltmeter:

$$V_{rms}^2 = \frac{1}{T}\int_0^T \left[\sum_{n=1}^{\infty} a_n \cos n\omega t + \sum_{m=1}^{\infty} b_m \sin m\omega t\right]^2 dt \qquad (7)$$

where $\mathbf{a_n}$ and $\mathbf{b_m}$ are the Fourier coefficients. In order to evaluate the Fourier coefficients, V(I) was expanded in a power series around I_{dc}. Sufficient terms were maintained in both the power series expansion and in Eq. (7) to give a second-order correction to Eq. (5):

$$V_{rms} = \frac{1}{\sqrt{2}}\left(\frac{nkT}{e}\right)\left(\frac{I_{ac}}{I_{dc}+I_s}\right)\left(1+\frac{5}{16}\frac{I_{ac}^2}{(I_{dc}+I_s)^2}\right)^{1/2} \qquad (8)$$

Substitution of this result into Eq. (4) gives the 77 K offset voltages shown in Fig. 4 by the dashed line. Slightly better agreement with the experimental data is seen at the higher rms voltages. At 305 K, the two calculation methods are in even better agreement and a plot similar to Fig. 4 would show no difference. The details of the extended calculation have not been given as the mathematics is somewhat tedious, and the slight discrepancies between the small signal model and the extended model do not justify the added complexity. For all practical purposes, Eq. (6) can be reliably used above 40 K.

The physics of a p-n junction at 4.2 K is not clearly understood and attempts to correlate the present data by modeling low-temperature IV characteristic of a diode failed. If the diode does take on a p-i-n type behavior, the different curves shown in Fig. 5 for 1, 10, and 100 μA can possibly be understood in terms of the additional current-dependent terms in the IV curve.6 Another explanation for the significant offset voltage at 100 μA could be self-heating in the diode. If the diode is operated at too high a power level, the diode has a tendency to warm slightly above the surrounding environment. This will have the effect of distorting the IV curve in the direction of lower voltages at higher currents. This distortion will then increase the offset voltage. At 4.2 K, self-Heating usually becomes a problem as the current approaches 100 μA.

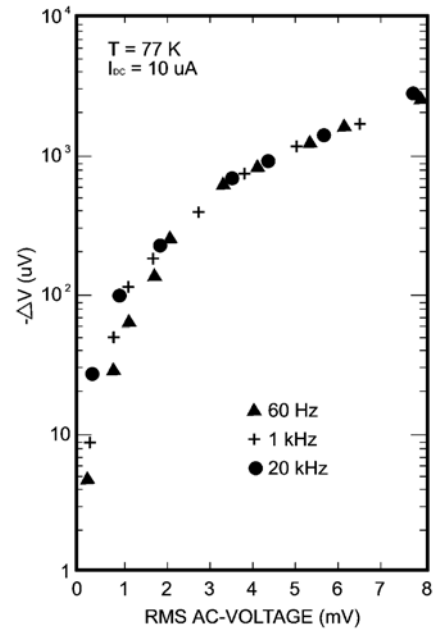

FIGURE 6. DC offset voltage as a function of rms ac voltage across a silicon diode temperature sensor operating at 77 K. The symbols represent data recorded at a 10 μA dc current with the ac current modulation at 60, 1000, and 20,000 Hz.

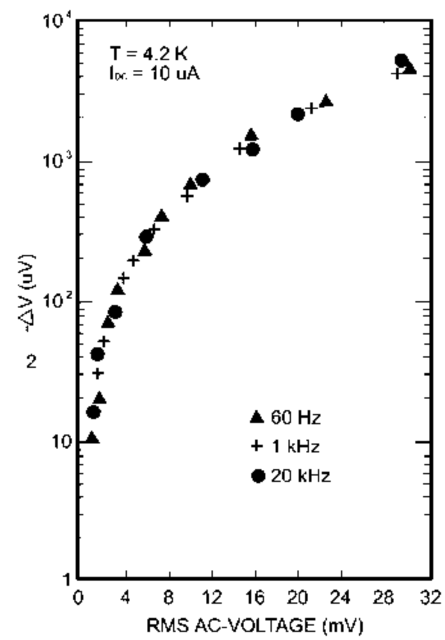

FIGURE 7. DC offset voltage as a function of rms ac voltage across a silicon diode temperature sensor operating at 77 K. The symbols represent data recorded at a 10 μA dc current with the ac current modulation at 60, 1000, and 20,000 Hz.

IV. CONCLUDING REMARKS

Noise in any measurement circuit is undesirable and should be eliminated to as great an extent as possible. The first step is to electrically shield all instrumentation and wiring and use proper grounding techniques.[8] Secondly, the diode measurement circuit should have a single circuit ground which is generally made at the voltmeter and which then requires a floating current source. The installation of the diode and its connecting leads should be done carefully to avoid introducing any unwanted circuit ground connections such as an electrical short to a cryostat.

As a last resort, a "quick fix" can be used to eliminate much of the dc offset voltage with some degradation in the diode circuit performance. A good quality capacitor (low leakage) can be placed across the diode to shunt the induced ac currents similar to the test procedure used for identifying a noise problem. This is most easily done by connecting the capacitor across the input to the voltmeter. The size of the capacitor needed will depend on the frequency of the noise (generally related to the power line frequency of 60 Hz) and the dynamic impedance of the diode (on the order of a few thousand ohms at a 10 μA operating current). A capacitor in the range of 10 to 20 μF should reduce most noise effects to an acceptable level. However, because the capacitor increases the time constant in the circuit, a sluggish response should be expected. In switching operations, 30 seconds or more may be required for the circuit to stabilize. This "quick fix" is not meant as a substitute for proper measurement techniques, but in certain circumstances it may be useful.

Note added in proof. The capacitance values given above are for the elimination of the effects of low-frequency noise such as 60 Hz. If high-frequency noise is a problem, an additional capacitor of lower capacitance value may be needed. The reason for this is because larger capacitors often have an associated inductance which limits their usefulness as a high-frequency shunt.

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