

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 ($\tau \propto C_p/\kappa$) 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 10–100 $\mu\text{V}/^\circ\text{C}$ 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.

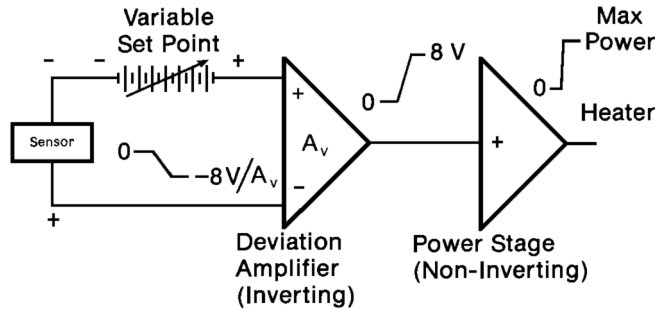


FIGURE 1. Block diagram of Cryogenic Temperature Controller. A_v is amplifier voltage gain.

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 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”.

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 $A_v = 1000$, 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.

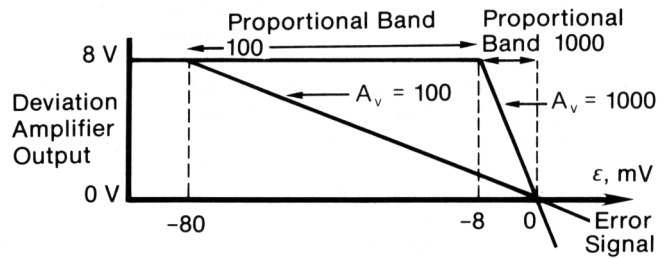


FIGURE 2. Output plot of the deviation amplifier showing Proportional Bands for gain settings of 100 and 1000. For the DRC-82C, the maximum available gain is 1000.

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.

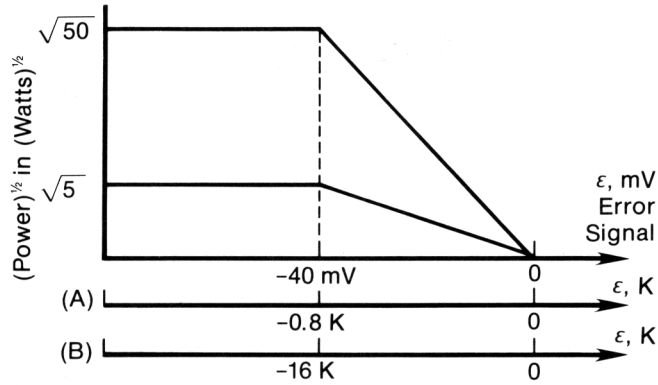


FIGURE 3. Output Power versus error signal in voltage or equivalent temperature of sensor for two different power settings: (A) corresponds to a sensor sensitivity of -50 mV/K; (B) corresponds to a sensor sensitivity of -2.5 mV/K. Note that the curves are linear in voltage, *not* power.

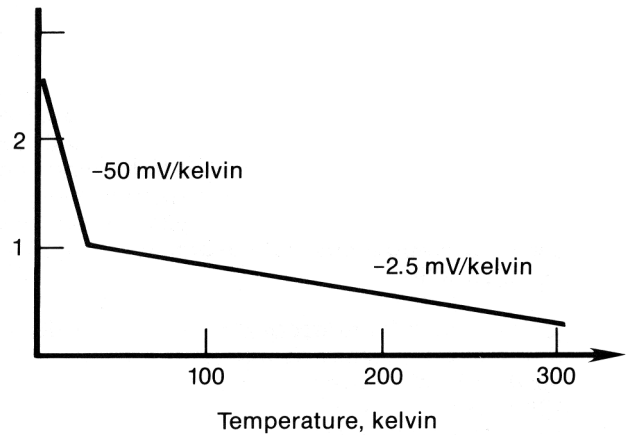


FIGURE 4. Idealized curve for Lake Shore Cryotronics, Inc. DT-500 Series silicon diode temperature sensors.

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.

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.

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.

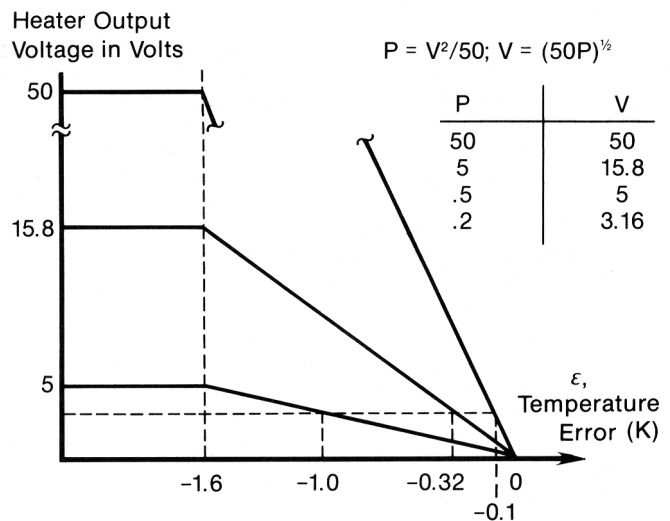


FIGURE 5. Effect of output power setting on offset for a proportional controller *only*.

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 closed loop signal of the controller. 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 $\frac{1}{2}$ 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.

Adding Derivative (Rate) to the Temperature Control Loop (Continued)

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.

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 sweep 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 (10 μ V/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.

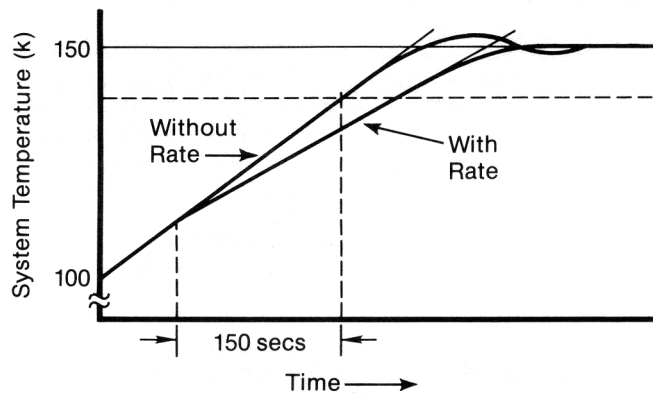


FIGURE 6. The effect of adding Rate to the control circuit to dynamically widen the proportional band and reduce the overshoot which would occur in its absence.

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 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 Gulston 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.