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AN ALTERNATE METHOD FOR ACHIEVING TEMPERATURE CONTROL IN THE -130°C to 75°C RANGE [1]

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ABSTRACT

Thermal vacuum testing often requires temperature control of chamber shrouds and heat exchangers within the -130°C to 75°C range. There are two conventional methods which are normally employed to achieve control through this intermediate temperature range: 1) single-pass flow where control is achieved by alternately pulsing hot gaseous nitrogen (GN2) and cold LN2 into the feed line to yield the setpoint temperature; and, 2) closed-loop circulation where control is achieved by either electrically heating or LN2 cooling the circulating GN2 to yield the setpoint temperature. A third method, using a mass flow ratio controller along with modulating control valves on GN2 and LN2 lines, provides excellent control but equipment for this method is expensive and cost-prohibitive for all but long-term continuous processes. The single-pass method provides marginal control and can result in unexpected overcooling of the test article from even a short pulse of LN2. The closed-loop circulation method provides excellent control but requires an expensive blower capable of operating at elevated pressures and cryogenic temperatures. Where precise control is needed (± 2°C), single-pass flow systems typically have not provided the precision required, primarily because of overcooling temperature excursions. Where several individual circuits are to be controlled at different temperatures, the use of expensive cryogenic blowers for each circuit is also cost-prohibitive, especially for short duration or one-of-a-kind tests.

At JPL, a variant of the single-pass method has been developed that has been shown to provide precise temperature control in the -130°C to 75°C range while exhibiting minimal setpoint overshoot during temperature transitions. This alternate method uses a commercially available temperature controller along with a GN2/LN2 mixer to dampen the amplitude of cold temperature spikes caused by LN2 pulsing. This paper describes the design of the GN2/LN2 mixer, the overall control system configuration, the operational procedure, and the prototype system test results .

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INTRODUCTION

Preparation for the thermal vacuum testing of the Wide Field/Planetary Camera II (WF/PC II) required the review of existing temperature control methods to determine which method could best accommodate the WF/PC II special test needs. Since the instrument will be inserted into the instrument bay of the Hubble Space Telescope (HST) body and, when in place, its curved surface will face cold space while all other surfaces will be enclosed within the warmer HST body, there was a need to create a test fixture that would simulate multiple temperature environments. At JPL, a test fixture consisting of eight individually controllable shroud circuits has been built which can simulate these multiple temperature environments.

Because the WF/PC II thermal vacuum test is of relatively short duration, closed-loop temperature control of each circuit was deemed cost-prohibitive. Also, since the single-pass temperature control method that had been used to test WF/PC I had not provided the desired precision, a different technique was requested. In response, an alternate temperature control method was developed to provide precision temperature control in the -130°C to 75°C range with minimal overshoot during temperature transitions. This method includes a custom designed in-line GN2/LN2 mixer used to dampen the amplitude of cold temperature spikes from LN2 pulsing. The flow schematic and instrumentation layout of this system is illustrated in Figure 1. Details of the GN2/LN2 mixer design are shown in Figure 2.

GN2/LN2 MIXER CONFIGURATION

The GN2/LN2 mixer consists of a high-conductivity mass acting as a thermal shock-absorber at the point of GN2 and LN2 mixing. The GN2/LN2 mixer design criteria were: 1) provide enough in-line mass to yield the desired thermal shock-absorber effect but not so much as to make the system temperature control feedback response sluggish; 2) configure the mass in a way that provides high heat transfer rates to the flowing GN2; 3) minimize the pressure drop in the mixer; and, 4) make the design as simple and low-cost as possible. Based on these criteria, the configuration described below was developed.

The GN2 feed line to the GN2/LN2 mixer is a 3/4" copper tube located at the center of the mixer assembly. The LN2 feed line is a 1/2" copper tube which is plumbed concentrically inside the 3/4" GN2 feed line and extends downward about half the distance of the GN2 feed line. The 3/4" GN2 feed line passes through the center of and is attached to seven 1/4" thick copper discs. The copper discs have two configurations: the first has twelve evenly spaced 3/8" holes drilled near the outer diameter of the disc, and the second has eight evenly spaced 3/8" holes drilled near the inner diameter of the center hole in the disc. The copper discs are silver soldered to the GN2 feed line at 2.25" spacing, the two disc configurations mounted alternately. This internal structure, consisting of the GN2 feed line and copper discs, penetrates at and is silver soldered to the top center of a 150# brass blind flange. An off-center 3/4" exit port tube penetrates and is soldered to this flange. The internal structure is enclosed by a 3" copper pipe (Type K) which has a slip-joint pipe cap silver soldered at the bottom end and a 3" 150# brass flange silver soldered at the top end. The two flanges, sealed with a durabla gasket, bolt together to complete the assembly. The assembly is insulated with foam, about 3" thick, and is encased within a 10" diameter section of sonotube. A thermocouple is installed on the outside surface of the 3" copper pipe near the bottom to provide a means for monitoring the mix-point temperature. The thermal mass in the system is about 15-lbs.

OPERATIONAL PROCEDURE

A constant flow rate GN2 stream is fed into the control circuit at the GN2 manifold, first through a hand controlled shut-off valve, and then through an open/close solenoid valve (which opens when the master temperature controller is powered). Next, the GN2 passes through a flow element (a rotameter equipped with a small throttle valve to provide manual GN2 flow control adjustment) and then through an in-line electric heater (controlled by a triac power unit with zero crossover firing), installed just upstream of the mixer. A mixer by-pass line allows heated GN2 to flow directly to the shrouds for bakeout tests when cooling is not needed. Power to the heater is automatically shut off if the shroud overheats beyond the limit setpoint of the failsafe temperature controller. Heater power is also turned off whenever the setpoint temperature is below ambient (~20°C). The LN2 is fed into the control circuit at the LN2 manifold, first through a failsafe open/close solenoid valve, then through a master control open/ close solenoid valve (operated by a solid state relay) and a hand-controlled throttle valve. The failsafe solenoid is automatically de-energized (closed) if the shroud overcools beyond the limit set-points of the failsafe temperature controller. The master control solenoid cycles open and closed as the master controller calls for cooling. The throttle valve is manually adjusted to limit the amount of LN2 delivered per cycle or pulse. The pressure in the circuit is manually adjusted with a backpressure hand control valve located downstream of the shroud and just upstream of the vent manifold.

During cooling periods, GN2 is fed down the 3/4" copper tube at the mixer at constant temperature (unheated, ambient) and flow rate. When the master temperature controller calls for cooling, LN2 is pulsed into the mixer through the 1/2" copper tube. The pulsed slug of LN2 mixes with the continuous GN2 stream and the mixture impinges on a bed of copper wool to provide turbulent mixing. The flow then changes direction 180 degrees and is directed upward through the holes in the 1/4" thick copper discs in a weaving flow path (which prevents flow channeling and enhances heat transfer to the copper discs and the pipe wall). The tempered GN2 then leaves the mixer through the exit port and continues to the shroud.

Two types of master temperature controllers were used to test the prototype circuit, and are referred to here as type-one and type-two. These two types of controllers were chosen because each type was available and we wanted to determine if one provided better control than the other in this control system configuration. Type-one used average shroud temperature as the control variable (measured by connecting together two thermocouples: the shroud inlet (TE-2) and the shroud outlet (TE-3)). This type of control configuration is illustrated in Figure 1. Type-two used a cascade-like control technique where the test article temperature (measured by TE-4) is the primary control variable and the temperature at the top of the mixer is the secondary control variable. In both cases, the test article temperature (thermocouple TE-4) was used as the input to the failsafe temperature controller.

PROTOTYPE SYSTEM TEST RESULTS

Two sets of tests were run to study the response of the prototype control system. The temperature control variable for the first set of tests was a 30-lb copper plate heat exchanger, and, for the second set of tests, the control variable was a small (3 to 4-lb) stainless steel heat exchanger (used for cooling a thermoelectric quartz crystal microbalance (TQCM)). Both types of commercial temperature controllers were used in each set of tests to provide a functional comparison between the two types. The purpose of this comparison was to determine which type to install in the control circuits for the WF/PC II thermal vacuum tests.

The type-two controller was tested first. At the beginning of testing, the prototype mixer was filled with about 10-lbs of small steel balls (BBs) to provide mass. The BBs filled the spaces between the copper discs. Very sluggish feedback response from the first test revealed that there was too much mass in the mixer. The BBs were removed and the test was started again with copper wool at the bottom of the mixer and nothing between the discs. This arrangement yielded a more rapid feedback response, but showed that temperature control was quite sensitive to the GN2 and LN2 throttle valve settings. Several trials were required to establish optimum settings for the valves and the temperature controller (programmable settings for proportional, integral, and differential control). However, within three test days, optimum settings had been determined and stable temperature control had been established. Figures 3 through 8 illustrate the results of subsequent temperature control testing.

Figure 3 illustrates results from a test using a type-one controller to provide temperature control of the 30-lb copper plate heat exchanger. The test begins with the copper plate at ambient temperature, then the plate is cooled in steps to setpoints at -25°C, -50°C, -75°C, -100°C, and -130°C,. After holding at -130°C, the plate is reheated in steps to setpoints at -25°C and 20°C. At each step, the temperature was held at setpoint for only ten minutes so that several setpoint levels could be demonstrated within a short time period. It is evident in Figure 3 that no overshooting occurred at the setpoint temperatures. Figure 4 shows results from a test using a type-one controller to provide temperature control of the TQCM heat exchanger. This test was conducted to demonstrate the ability of the control system to hold precise setpoint temperatures (in this case -80°C and -110°C) for long durations.

Figure 5 illustrates results from a test using a type-two controller to provide temperature control of the TQCM heat exchanger. This was a comparison test at the same conditions as the test shown in Figure 4, and, as can be seen in Figure 5, similarly favorable control precision results were demonstrated. Figure 6 shows detail of the control precision in the -110°C region (± 2°C) demonstrated by this test.

Figure 7 illustrates results from a test using a type-two controller to provide temperature control of the TQCM heat exchanger during a rapid temperature transition from 75°C to -80°C which occurred within 20 minutes. Even here, when the temperature of the TQCM heat exchanger was changing at over 7°C per minute, there was no significant overshoot of the setpoint temperature as evidenced by the detail shown in Figure 8. Even in this case the control precision at setpoint was ± 1°C.

CONCLUSIONS

An alternate method for providing economical and precise temperature control in the -130°C to 75°C range has been developed and demonstrated. There are no apparent reasons why this method cannot be used effectively for controlling test articles below -130°C but temperature control below this level has not yet been demonstrated. Use of this method requires close attention to the establishment of optimum valve and temperature controller settings prior to testing. Also, it is important to understand that, during test periods when the control setpoint is below ambient temperature, the GN2 flow rate and temperature must remain constant and the LN2 feed pressure must remain stable so that the LN2 delivery rate is the only variable affecting the outcome of the controlled temperature. Therefore, the heater should not be powered during periods when the control setpoint is below ambient temperature.

Based on the favorable results presented here, ten separate temperature control circuits containing GN2/LN2 mixers of the design detailed in Figure 2, and having the configuration as illustrated by Figure 1, were installed at JPL's 10-FT Space Simulator facility in preparation for WF/PC II thermal vacuum testing. The type-one controller was chosen for installation because it had demonstated its ability to deliver precise temperature control and we already had enough of these controllers onhand to provide ten master controllers and ten failsafe controllers. Test results using these installed circuits were not yet available at the time of this writing.

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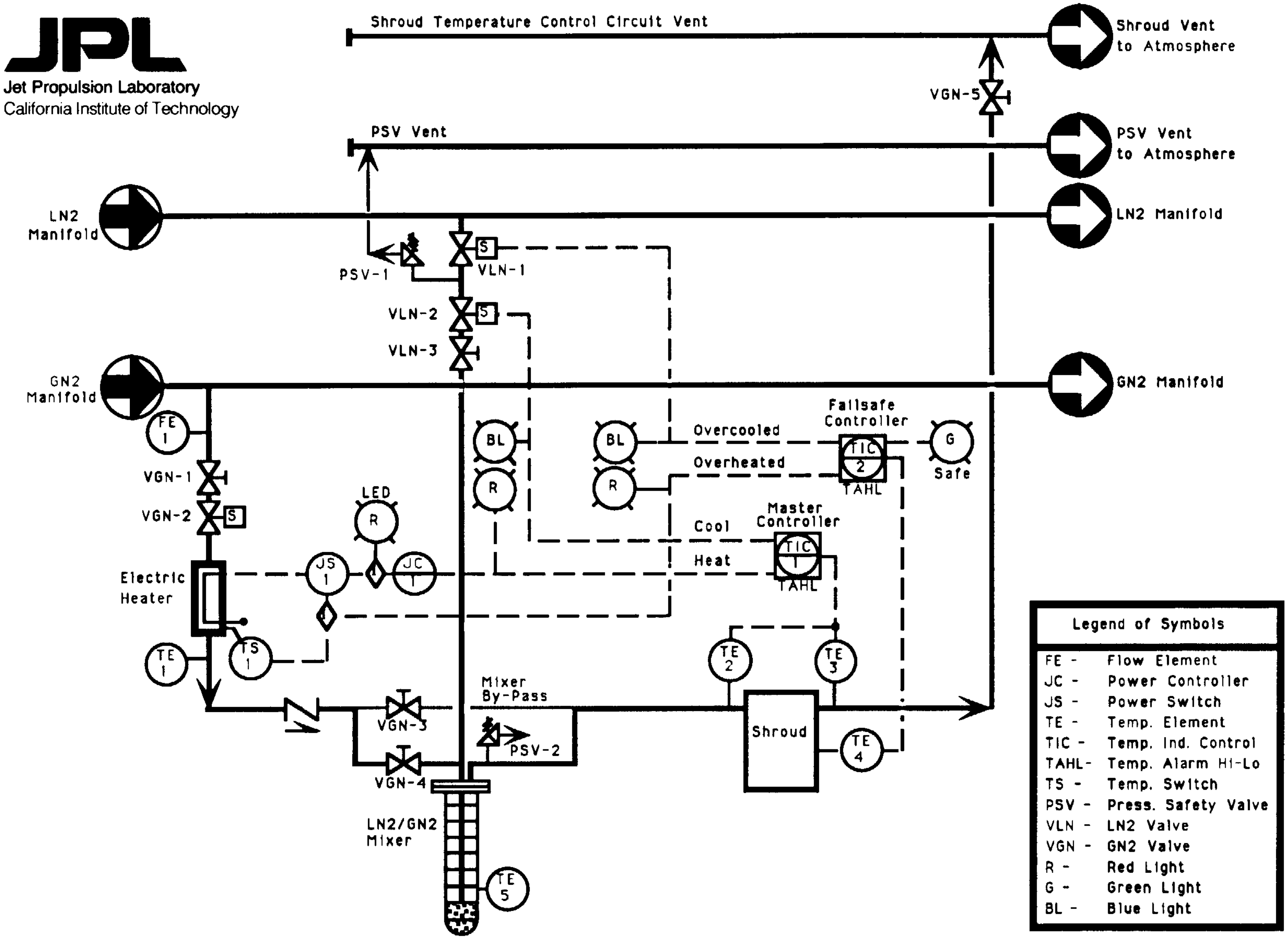
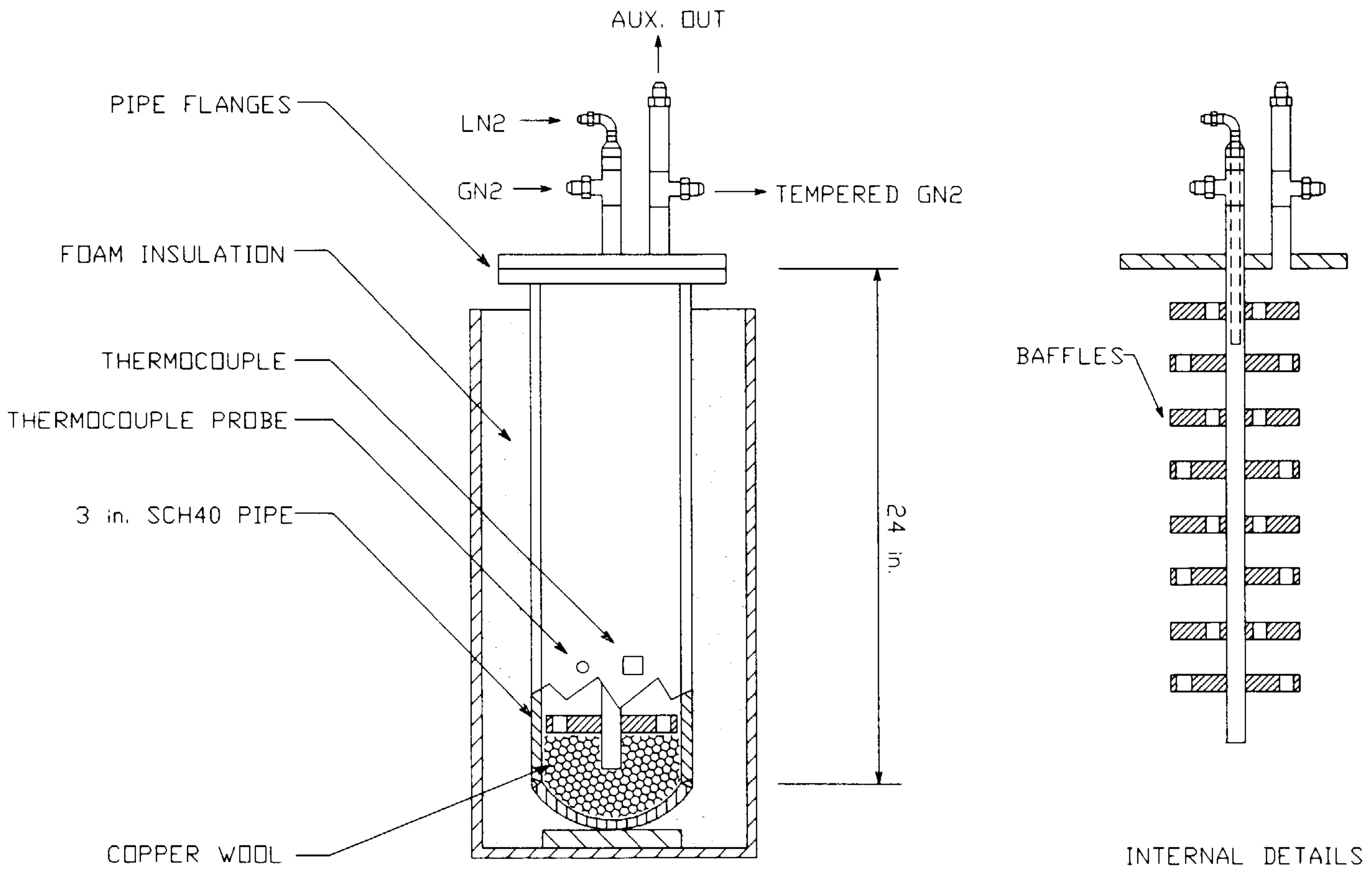


Figure 1. Prototype Control System Flow Schematic and Instrumentation Diagram



LN2/GN2 MIXER ASSEMBLY

Figure 2. GN2/LN2 Mixer Detail

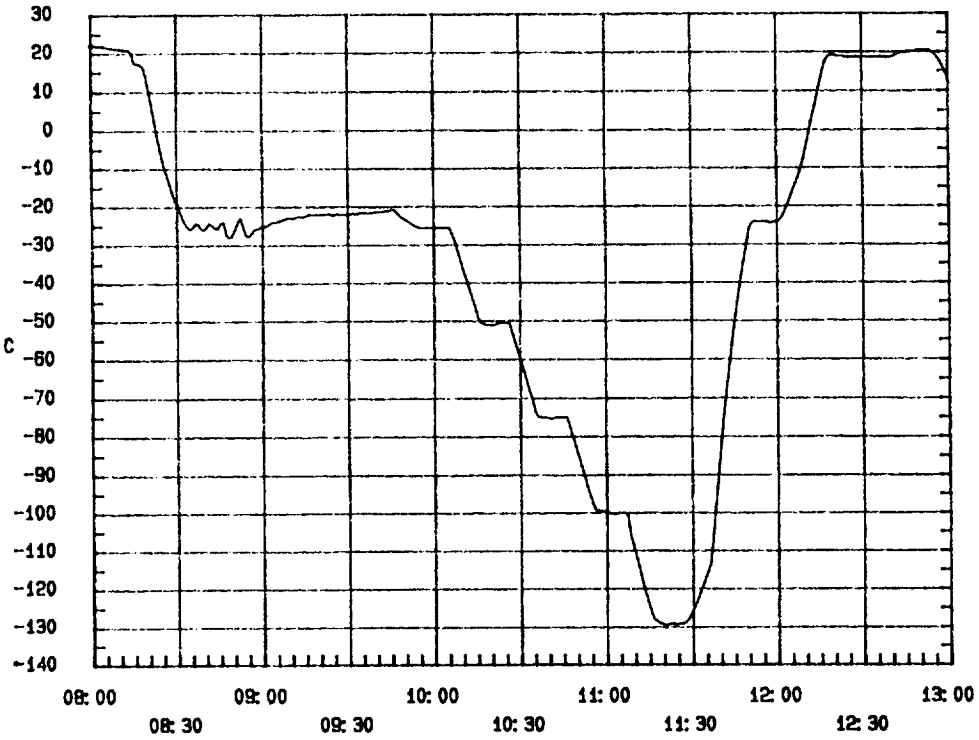


Figure 3. Copper Plate Heat Exchanger Temperature Control Profile Using Type-One Controller

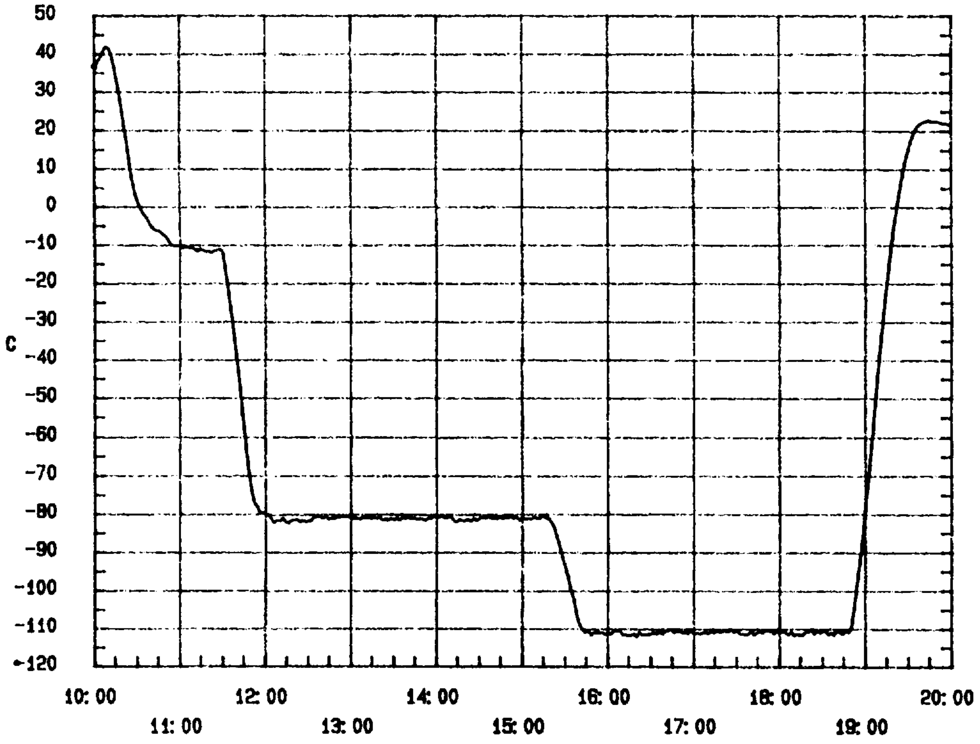


Figure 4. TQCM Heat Exchanger Temperature Control Profile Using Type-One Controller

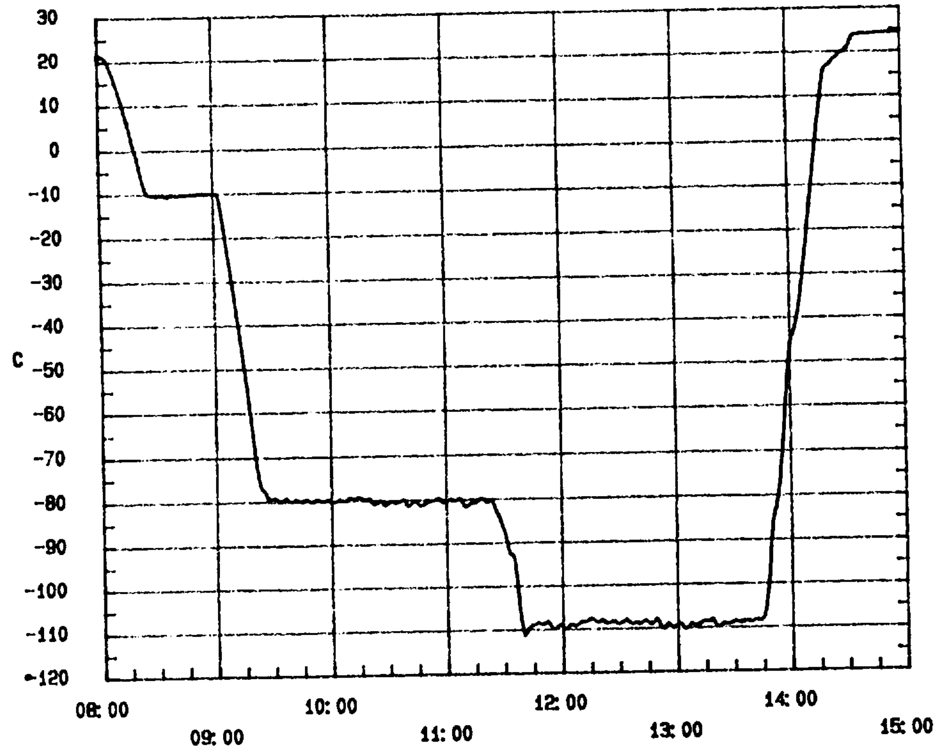


Figure 5. TQCM Heat Exchanger Temperature Control Precision Profile Using Type-Two Controller

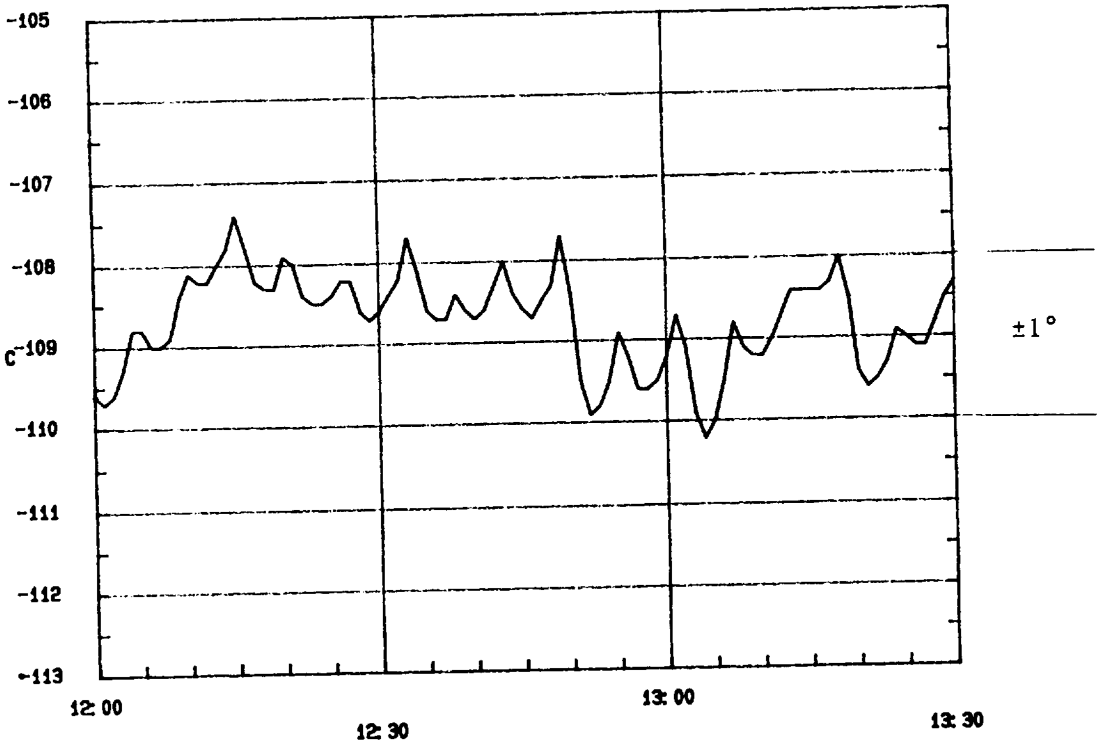


Figure 6. TQCM Heat Exchanger Temperature Control Precision Profile at -110 °C Using Type-Two Controller

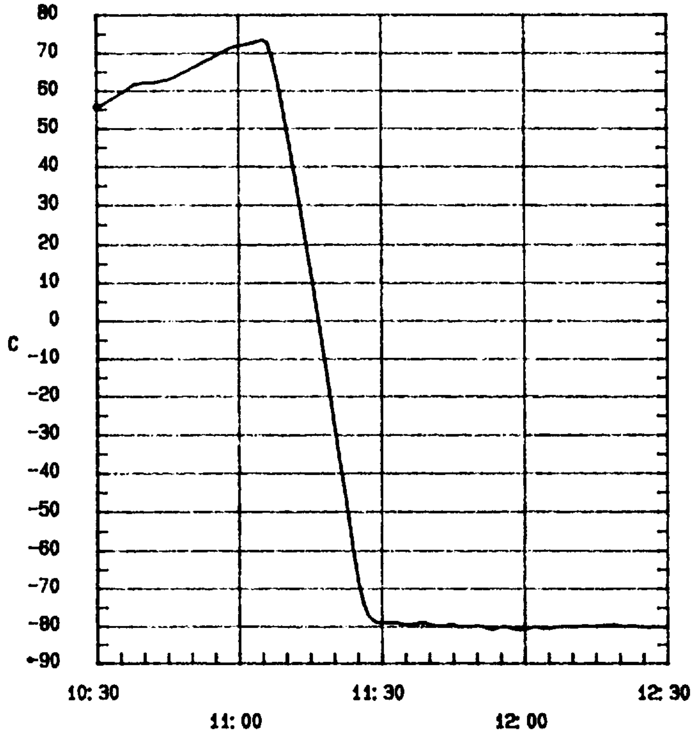


Figure 7. TQCM Heat Exchanger Temperature Control Precision Profile for Rapid Cooling Test Using Type-Two Controller

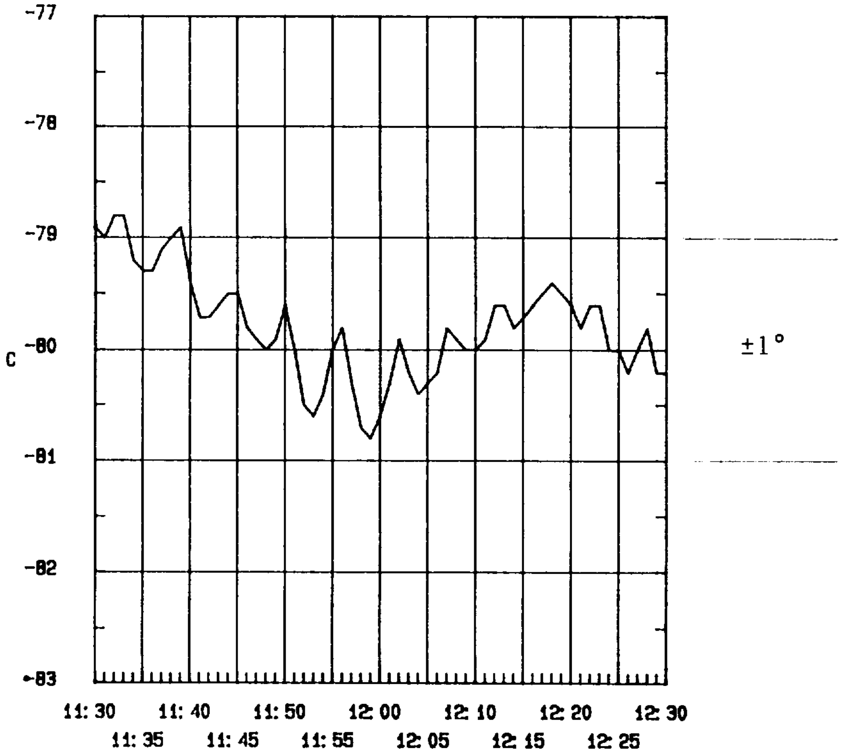


Figure 8. TQCM Heat Exchanger Temperature Control Precision Profile at -80 °C Following Rapid Cooling Test Using Type-Two Controller