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A Temperature Control System for the Canadian Pendulum Apparatus

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Abstract—**A temperature control system has been developed for use with the Canadian Pendulum Apparatus for relative gravity measurements. This system, which maintains the pendulums at a constant temperature of 40.00°C, consists of three major components: a vacuum enclosure in which to house the pendulums; an electronic thermometer to measure their temperature; and an electronic thermostat to maintain a constant temperature. Extensive testing of the system indicates that the temperature of the pendulums may be measured with an accuracy of ±0.01°C and that the electronic thermostat has a stability of about 0.002°C when the vacuum chamber is kept continuously closed. Under normal operating conditions, when the pendulum case is opened regularly to change pendulums, the observed temperature fluctuations amount to a maximum of ±0.025°C. As small corrections may be applied to the pendulum periods to compensate for these temperature fluctuations, the error in gravity due to temperature effects never exceeds 1/6 mGal.**

Introduction

THE Canadian Pendulum Apparatus for relative gravity measurements utilizes a set of six bronze pendulums that were constructed around the turn of the century. Since only differences in gravity between two or more locations are required for relative measurements, it is tacitly assumed that the lengths of the pendulums are invariable. Unfortunately, as bronze has a coefficient of linear expansion amounting to 17 ppm/°C, a change in pendulum temperature of only 0.06°C introduces an error in gravity of about 1.0 mGal. On the other hand, it is to be expected that the age of these pendulums may contribute significantly to their dimensional stability. As it was felt that the advantages of using the old pendulums outweigh the disadvantage of providing a constant temperature environment, these pendulums were returned to service, after about eight years of retirement, by Thompson[2] in 1956.

Gravity measurements were conducted using this equipment until 1960 when a large-scale development program was begun to improve its overall accuracy. One of the objectives of this program was to develop a system to maintain the pendulums at a constant temperature of approximately 40°C and to measure the pendulum temperature with an accuracy of 0.01°C.

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Temperature Control System

The Pendulum Case

In order to minimize the influence of ambient temperature, an insulated container was designed to house the pendulums while they operate. Fig. 1 is a simplified cross section of the pendulum case. The outermost shell is a vacuum chamber consisting of an aluminum base surmounted by a glass bell jar whose inner surface is gold-plated to reduce heat loss by radiation. The oven is located directly inside the vacuum chamber, is constructed from thin-sheet aluminum, and has a highly polished outer surface to further reduce heat loss. A heating element is attached to the oven's inner surface with silicone rubber and is arranged to supply an even distribution of heat over the surface of the oven. The radiation shield, which prevents radiant energy from being transferred directly from the oven to the pendulums, is located inside the oven and completely surrounds the pendulums. An additional function of this part is to shield the pendulums from any thermal gradients and short-term temperature fluctuations that may occur in the oven. This is accomplished by constructing the radiation shield from heavy ¾-inch (19-mm) aluminum plate so that it has a large heat capacity. The oven on the other hand reacts quickly to changes in environmental conditions because of its light construction.

Heat loss through conduction is minimized by supporting the oven on three ⅜-inch- (9.5 mm) diameter glass spheres. These spheres are held in position by three conoidal depressions located in the oven base plate and by a "slot-cone-plane" arrangement in the base of the vacuum chamber. The radiation shield is separated from the oven in a similar manner. Evacuating the entire assembly to below 10 microns of Hg virtually eliminates heat loss through conduction and convection. This arrangement is so effective that only 6.5 watts of electrical power are required to maintain a temperature of 40°C, despite the large size of the pendulum case which measures approximately 18 inches (457 mm) in diameter by 24 inches (610 mm) in height.

The operation of the pendulum case may be simply stated as follows. The pendulums are located inside the radiation shield, which functions as a black-body enclosure having a uniform wall temperature. Under these circumstances radiant energy flows between the pendulums and heat shield until any temperature differential is eliminated. The temperature of the pendulums, which cannot

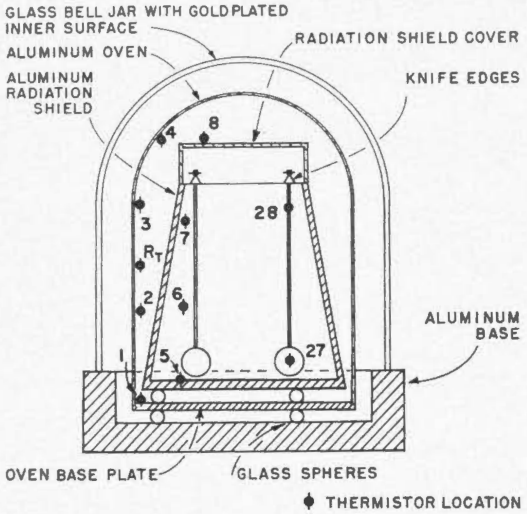


Fig. 1. Schematic diagram of pendulum case showing approximate location of thermistors. To minimize heat loss, the major components are separated by glass spheres arranged in a kinematic mounting system.

be measured directly, may be obtained after equilibrium is established by measuring the radiation shield temperature.

The Electronic Thermometer

Eight thermistors of the glass bead variety, mounted on both the oven and radiation shield as shown in Fig. 1, are employed to monitor the temperature of these components. A fixed resistor, having a resistance that is nearly equal to the thermistor resistances, is located inside the pendulum case as well and is used to calibrate and test the operation of the thermometer. A pair of leads, short-circuited inside the pendulum case, is also provided for zero reference. The eight thermistors, the standard resistor, and the short-circuited pair may be individually selected from the operator's console.

The thermistor resistances are measured with a Schering Bridge[1] circuit using a substitution technique. The difference in resistance between the short circuit and each of the eight thermistors, as well as the fixed resistor, is obtained. An ac bridge technique was selected to measure the thermistor resistances in order to eliminate the effect of contact potentials generated within the thermistors and their leads. This method also simplifies the problem of amplifying the bridge output to a suitable level for null detection. The null detector consists of a conventional two-stage transformer-coupled plate-tuned amplifier providing a voltage gain of about 80 dB. The amplifier output is visually displayed using a commercial ac vacuum-tube voltmeter.

The accuracy and stability of the bridge circuit may be obtained from measurements of the fixed resistor. A sample of the measured values of the fixed resistance is included in Table I. The standard deviation of these measurements is less than 0.1 ohm and the mean differs from the true resistance (998.76 ± 0.05 ohm) by about 0.5 ohm. Since the thermistor temperature coefficient is approximately 50 ohm/°C, these values are equivalent to errors in temperature of about 0.002 and 0.01°C, respectively. Thus, it can be seen that changes in radiation shield and oven temperatures of 0.01°C can be easily detected and measured. The accuracy of the thermometer also depends on the stability of the thermistors and the accuracy of their calibration. The thermistors have been calibrated over a small range between 39.8 and 40.2°C by the National Research Council of Canada with a certified accuracy of ± 0.01°C. Two of the thermistors (nos. 27 and 28) were initially calibrated in 1956, while the rest were placed into service in 1960. Calibrations performed in 1956, 1960, and 1964 have disclosed no observable change in the thermistor resistances at 40.0°C.

The Electronic Thermostat

This circuit consists of an amplifier, with an open-loop gain A, operating in conjunction with a bridge-type feedback network as shown in Fig. 2. The temperature-sensing thermistor (R_T), located as shown in Fig. 1, forms one arm of the bridge. Another arm consists of a fixed resistor (R_s) whose resistance is chosen to nearly equal the thermistor resistance at the desired temperature. If R_s is vari able, the set point may be adjusted as required. The feedback ratio β is given by

$$\beta = \frac{R_T - R_s}{2n\ (R_T + R_s)},$$

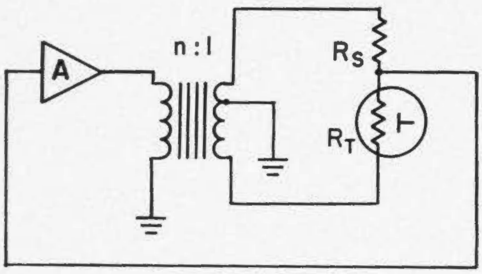
where n = transformer turns ratio.

When the controlled object is too hot, R_T is smaller than R_s so that feedback is degenerative and the circuit is quiescent. As the object cools, a point is reached where the product $A\beta$ equals unity and the circuit oscillates to provide a usable output. If the value of A is large, R_T approximately equals R_s at the set point. Clearly, if the output of the circuit is used to control a switching device such as a relay or SCR, an ON–OFF type of thermostatic action is obtained. A small amount of hysteresis whose magnitude depends on the value of A is observed, and it limits the sensitivity of the circuit to about 0.01°C.

TABLE I

ANALYSIS OF 21 SHIELD AND PENDULUM TEMPERATURE MEASUREMENTS

Date	Time	T (5)	T (6)	T (7)	T (8)	T (27)	T (28)	Standard	Mean Shield Temperature	S.D.
19/3/65	0900	40.067	40.068	40.062	40.060	40.054	40.050	999.310	40.064	0.004
	1100	40.061	40.063	40.057	40.058	40.047	40.047	999.410	40.060	0.003
	1230	40.061	40.064	40.059	40.055	40.047	40.047	999.470	40.060	0.004
	1800	40.059	40.064	40.059	40.059	40.047	40.051	999.307	40.060	0.003
20/3/65	1145	40.061	40.064	40.057	40.057	40.051	40.050	999.377	40.060	0.003
	1900	40.062	40.063	40.059	40.058	40.046	40.049	999.280	40.061	0.002
	2130	40.061	40.062	40.057	40.058	40.050	40.048	999.357	40.059	0.002
21/3/65	1740	40.060	40.060	40.058	40.057	40.048	40.048	999.360	40.059	0.001
	1900	40.064	40.066	40.062	40.060	40.074	40.050	999.303	40.063	0.002
22/3/65	0900	40.062	40.064	40.061	40.058	40.054	40.052	999.230	40.061	0.002
	1000	40.064	40.065	40.060	40.060	40.051	40.051	999.287	40.062	0.003
	1100	40.062	40.064	40.061	40.061	40.052	40.053	999.327	40.062	0.001
	1205	40.064	40.064	40.061	40.060	40.054	40.051	999.297	40.062	0.002
	1320	40.063	40.060	40.060	40.060	40.049	40.052	999.323	40.061	0.001
	1545	40.063	40.066	40.061	40.062	40.050	40.050	999.273	40.063	0.002
	1630	40.061	40.062	40.060	40.059	40.052	40.049	999.247	40.060	0.001
23/3/65	0850	40.064	40.067	40.063	40.062	40.055	40.053	999.280	40.064	0.002
	0955	40.066	40.069	40.064	40.065	40.057	40.055	999.303	40.066	0.002
	1115	40.065	40.064	40.064	40.065	40.055	40.053	999.297	40.065	0.001
	1330	40.063	40.067	40.062	40.065	40.052	40.051	999.367	40.064	0.002
	1445	40.067	40.064	40.064	40.063	40.050	40.050	999.423	40.064	0.002
	Mean	40.063	40.064	40.061	40.060	40.052	40.050	999.325	40.062	0.002
	S.D.	0.002	0.002	0.002	0.003	0.006	0.002	0.060	0.002	0.001



$$\beta = \frac{R_T - R_S}{2n\,(R_T + R_S)}$$

Fig. 2. Block diagram of electronic thermostat.

As the amplifier output increases gradually from zero to maximum it may be further amplified and rectified to power the heaters directly. Proportional temperature control is, therefore, obtained in a narrow band whose width is determined by the hysteresis. In the proportional mode of operation, which is employed in the Canadian Pendulum Apparatus, the heating current falls from a maximum of 2.5 amperes to a steady value of about 1.1 amperes after thermal equilibrium has been established.

The circuit may be discussed in further detail with the aid of the complete schematic shown in Fig. 3. The main amplifier ($V_{3\text{-}a}$ and $V_{4\text{-}a}$) is a two-stage RC-coupled circuit providing a voltage gain of 86 dB. The second stage is tuned to a frequency of 500 Hz. The feedback circuit, as before, consists of T-1, R_s, and R_T. The output is transferred to a transistor power amplifier ($Q1$ and $Q2$) by a buffer amplifier ($V_{4\text{-}b}$). As the heaters form the load resistor for $Q2$, the power supplied to the pendulum case is controlled by this stage. A mechanical thermostat (TH-1) is included in the heater circuit to guard against accidental overheating. As the main heater resistance is quite low (5 ohms), a $\frac{1}{2}$ ampere fuse is connected across the oven thermostat to prevent variations in the contact resistance of the thermostat from affecting the set point. If TH-1 opens, the fuse burns out, placing the signal lamp in series with the heater. A set of auxiliary heaters, attached to the radiation shield and controlled by a second mechanical thermostat TH-2 is included for rapid warm-up. The auxiliary heaters raise the temperature of the radiation shield to about 39.5°C but do not operate after thermal equilibrium has been established.

The tube-type (12FR8) that was chosen for its compatibility with the rest of the transistorized circuitry[3],[4] in the pendulum apparatus, has rapidly become obsolete. However, the stages using these tubes may be easily replaced with commercially available solid-state operational amplifiers. A circuit to simulate the control network using a solid-state operational amplifier has been constructed[5] and has been found to have a sensitivity similar to the tube version. Although the stability of this circuit was not tested, no difficulty is anticipated since the gain of the operational amplifier is primarily determined by externally applied resistors. As the present circuit is quite adequate, it is not intended to replace it with the solid-state version until the present stock of vacuum tubes has been depleted.

SYSTEM PERFORMANCE

Several tests were conducted before the circuit was put into service to check its performance. To carry out these tests a "dummy" pendulum, which is identical to the real

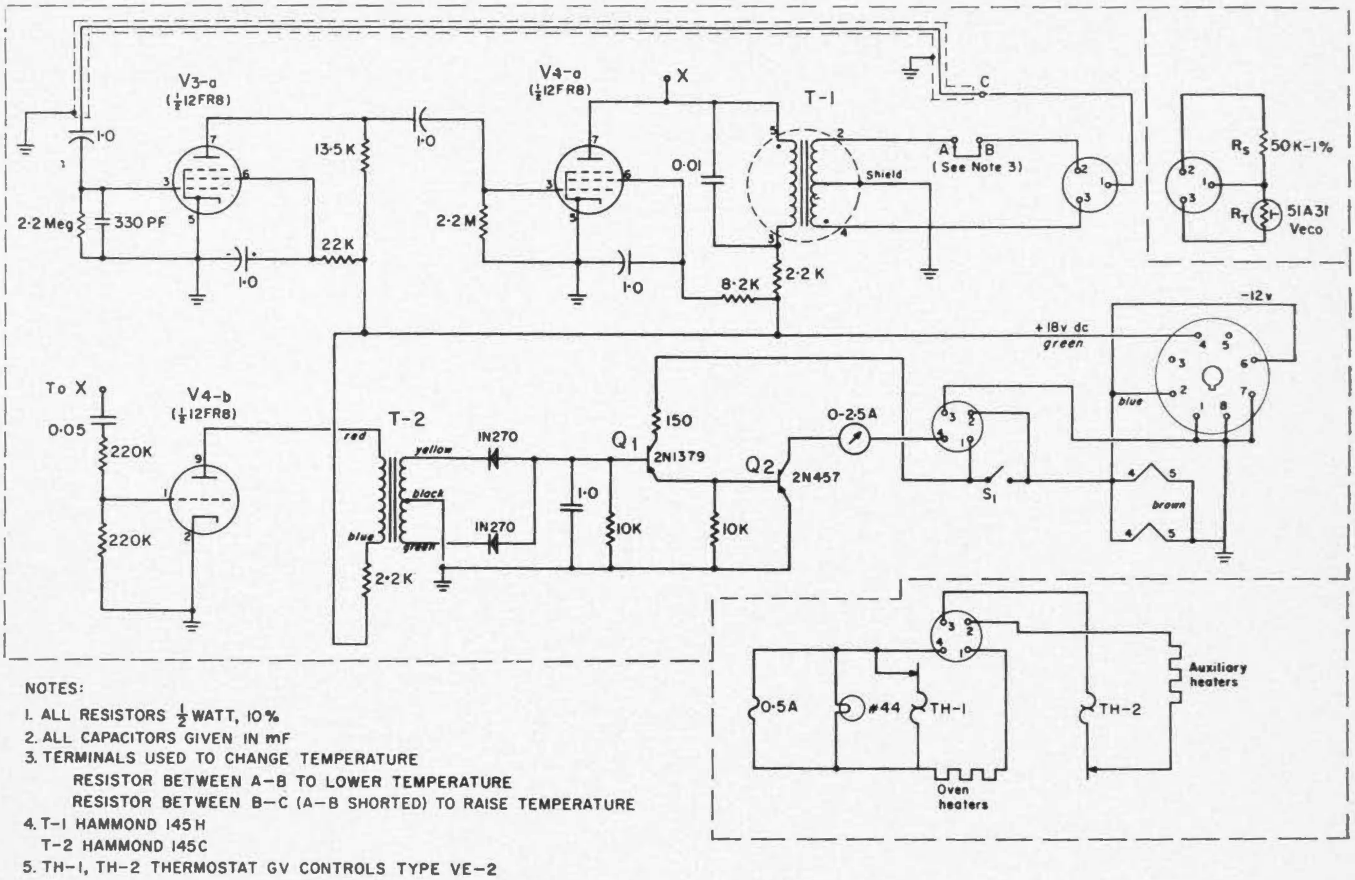


Fig. 3. Complete schematic of electronic thermostat.

pendulums in all respects except for two thermistors embedded inside the dummy (Fig. 1), was inserted into the pendulum case. One of the first tests was to monitor the temperature of the oven, radiation shield, and dummy pendulum for a period of four days. No attempt was made to control the ambient temperature, which had a mean value of 22.5°C and a standard deviation of 1.0°C. The result of this test is shown in Table II where it may be noted that the temperature of the oven extremities varies considerably more than the central portion although its mean temperature remains nearly constant. The temperature of the radiation shield (Table I) is much more stable, having a mean value of 40.062°C and a standard deviation of 0.002°C. The difference in the temperatures at the top and bottom of the dummy pendulum is about 0.002°C and the mean temperatures of the radiation shield and dummy pendulum differ by about 0.01°C.

The thermostatic coefficient (ratio of change in pendulum temperature to change in ambient temperature) was also determined. In this test the temperature of the dummy pendulum was measured while the room temperature was maintained constant. The room temperature was then altered a fixed amount and the pendulum temperature was again measured after thermal equilibrium had been established. These measurements were made with three different pressures inside the vacuum case. Fig. 4 shows that the thermostatic coefficient T_c tends to asymptotically approach a value of 22×10^{-4} as the pressure is reduced. The normal operating pressure range, which is from 3 to 6 microns of Hg, assures that the thermostatic coefficient does not exceed 25×10^{-4}.

Finally, the performance of the temperature control system under actual operating conditions should be discussed since the normal procedure is to open the pendulum case after each day's operation in order to change pendulums. The operating temperature depends upon the length of time the case has been closed continuously, the duration of the previous opening, and the terminal pressure. The terminal pressure, which depends on the cleanliness of the system, pumping speed, and pumping time, varies between 3 and 6 microns of Hg. The fluctuation in the radiation shield temperature is somewhat higher under these conditions than when the case is closed continuously. In order to indicate its magnitude as well as show the long-term stability of the circuit, all temperature measurements that were made under normal operating conditions between March and December, 1966, are plotted in Fig. 5. No measurements for which the warm-up time was less than 35 hours are included. In field operations, 48 hours are normally allowed to establish equilibrium conditions. These measurements were found to be distributed about a mean value of 39.986°C, with a standard deviation of

TABLE II

ANALYSIS OF 21 OVEN TEMPERATURE MEASUREMENTS

Date	Time	T (1)	T (2)	T (3)	T (4)	Mean Oven Temperature	S.D.
19/3/65	0900	40.029	39.990	40.025	39.954	39.999	0.035
	1100	40.015	39.984	40.034	39.997	40.008	0.022
	1200	40.002	39.982	40.033	39.994	40.003	0.022
	1800	40.024	39.987	40.025	39.957	39.998	0.032
20/3/65	1130	40.005	39.975	40.027	39.968	39.994	0.027
	1910	40.024	39.982	40.029	39.962	39.999	0.032
	2115	40.010	39.976	40.030	39.976	39.998	0.027
21/3/65	1250	49.012	39.975	40.026	39.969	39.995	0.028
	1900	40.029	39.983	40.028	39.959	40.000	0.035
22/3/65	0905	40.028	39.980	40.029	39.964	40.000	0.033
	0950	40.017	39.976	40.029	39.966	39.997	0.031
	1125	40.015	39.977	40.029	39.967	39.997	0.030
	1200	40.013	39.974	40.029	39.968	39.996	0.030
	1350	40.008	39.976	40.031	39.972	39.997	0.028
	1535	40.010	39.977	40.031	39.975	39.998	0.027
	1640	40.003	39.977	40.034	39.988	40.001	0.025
23/3/65	0845	40.028	39.988	40.036	39.964	40.004	0.034
	1000	40.014	39.984	40.039	39.985	40.006	0.026
	1105	40.008	39.984	40.043	39.995	40.008	0.026
	1340	39.995	39.980	40.043	40.004	40.006	0.027
	1440	40.000	39.987	40.044	40.005	40.009	0.024
	Mean	40.014	39.981	40.032	39.976	40.001	0.029
	S.D.	0.010	0.005	0.006	0.016	0.004	0.004

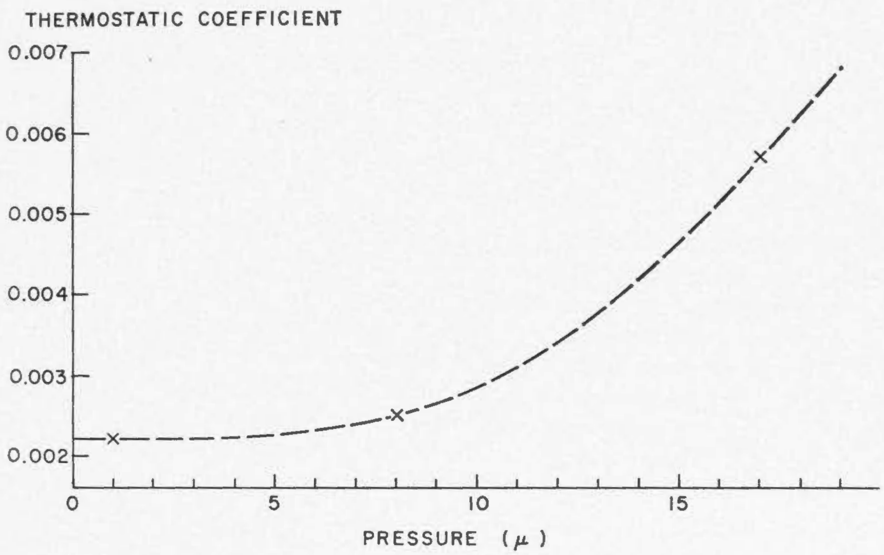


Fig. 4. The variation in thermostatic coefficient with pressure.

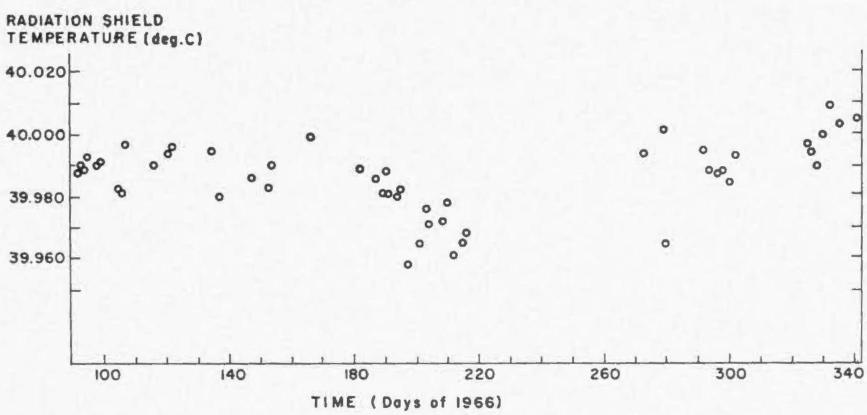


Fig. 5. Distribution of temperature measurements for 1966. The large gap between day 220 and day 270 represents a period when the temperature control was interrupted for the purpose of testing ancillary equipment.

0.012°C. As the laboratory temperature was maintained at 24.0 ± 0.3°C for all these measurements, the increased scatter reflects the influence of opening and closing the pendulum case as well as long-term variations in the set point.

Summary

A system to control and measure the temperature of the Canadian bronze pendulums with a precision of 0.01°C has been described. Although the circuit is capable of providing a temperature stability of 0.002°C, larger temperature fluctuations, amounting to a maximum of ± 0.025°C, are observed when the case is opened on a regular basis to change pendulums. As the pendulum temperature is measured for each set of gravity measurements, a small correction to the pendulum periods may be calculated. Thus errors in gravity measurements, due to temperature effects, should not exceed ±1/6 mGal.

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