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1 DEC 1993
THE DESIGN AND CONSTRUCTION OF AN AUTOMATIC CAPACITANCE DILATOMETER AND ITS USE AT LOW TEMPERATURES

by

ABDUR RASHID KHAN, MSc

A thesis submitted in partial fulfilment of the requirements for the award of
DOCTOR OF PHILOSOPHY
of the
Loughborough University of Technology

December 1982

Supervisor: Dr M A Brown
Director of Research: Professor J F Raffle

Department of Physics

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To my mother, may her soul be in peace in greatest heaven.

May Almighty God give her reward for her life long struggle and hard labour she put to build my career.
To my wife
To my sons: Habib-ur-Rehman Khan
Anis-ur-Rehman Khan
ACKNOWLEDGEMENTS

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particularly Dr Syed Ijaz Ahmad, Mr Rashid Ali, Mr M K B Baluch, Mr Yareb Nabhan and Mr M U Valhari for their help in many ways.

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SYNOPSIS

An apparatus to measure linear thermal expansion of various specimens using three terminal capacitance technique has been designed and constructed. The measurement is controlled by a DAI microcomputer through an industrial rack interface which monitors all aspects of the experimental control and measurement over a 3-4 days period required for each experiment. All interfaces were "in house" designed and built and all control software was custom designed. Early experiments using an adapted Michelson interferometer method confirmed that the three terminal capacitance dilatometer can be used with confidence under specific experimental conditions and suitable guidelines were produced for their use.

The apparatus has been used to measure the thermal expansion of several materials including Cr-doped GaAs and amorphous arsenic.
# CHAPTER I
## INTRODUCTION

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1.1 Thermal Expansion: A Spectroscopic Technique

Thermal expansion is one method of investigating the anharmonicity of forces in crystals. The volume expansion coefficient is defined by:

\[ \beta = \frac{1}{V} \left( \frac{\partial V}{\partial T} \right)_P \]  

where \( V \) is the volume, \( T \) the temperature and \( P \) is the pressure. The temperature dependence of \( \beta \) is given by (see Grüneisen 1912, 1926):

\[ \beta = A \frac{T^3}{V} \frac{d}{dP} \left( \frac{V}{V^3} \right) \quad T \ll \theta_D \]  

where \( \theta_D \) is the Debye temperature, \( \bar{V} \) is the velocity of sound and \( A \) is a constant, or

\[ \beta = \frac{C_v}{V \omega} \frac{d\omega}{dP} \quad T \gg \theta_D \]  

where \( C_v \) is the specific heat at constant volume and \( \omega \) is the average frequency of oscillation of atoms in crystals. For \( T < \theta_D \), the expansion coefficient will be proportional to \( T^3 \) whereas for \( T \gg \theta_D \), \( \beta \) approaches a limiting value that is independent of temperature. At absolute zero the expansion coefficient becomes zero in accordance with Nersat heat theorem. Grüneisen (1912, 1926) established a relation between \( \beta \) and other thermodynamic properties such as specific heat and compressibility which is given by

\[ \beta = \frac{\gamma C_v}{V} \lambda_T \]  

(1.4)
where $\chi_T = \frac{1}{V} \left( \frac{\partial V}{\partial P} \right)_T$ is isothermal compressibility, and

$$\gamma = -\left( \frac{\partial (\log \Theta)}{\partial (\log V)} \right)$$  \hspace{1cm} (1.5)

is the Grüneisen constant.

We see from equation (1.4) that the sign of $\beta$ will be determined by the sign of $\gamma$ because all other quantities are intrinsically positive. It is evident from equation (1.5) that $\gamma$ is related to the frequency spectrum of the solid through the Debye temperature. Thus a study of $\gamma$ can give an idea of how the frequency of vibration of solids depends upon the volume (or pressure). Consequently, the study of thermal expansion provides additional information on the dependence of the natural frequencies of vibration on volume which other thermodynamic properties such as specific heat fail to provide.

The Grüneisen parameter will be constant if the atoms in a solid vibrate independently with only one frequency—Einstein model or if the dependence of the frequency of vibration is the same for all vibrations—Debye model. Recent theoretical and experimental work has shown that $\gamma$ decreases slightly with decreasing temperature. This indicates that the various frequency spectra depend differently on volume (or on pressure). The quantity $\gamma$ thus describes the deviation of the spectrum from the harmonic approximation (harmonic approximation is explained in Chapter 2) and hence can give a measure of the anharmonicity of vibration of atoms in solids.

It has been revealed through intensive experimental work (e.g. Brown, M A and Brown I J (1981), and Brown I J (1982) and Sheard (1976)) that quite small concentrations
of impurities have a detectable effect on the thermal expansion of crystals. The defects having localised energy levels give rise to an anomalous contribution (a bump) known as "Schottky peak" to the thermal expansion and are of particular interest. Therefore a study of the contribution due to impurity ions is a useful method of obtaining information on the nature of energy level splittings, particularly in the range of 1 to 10cm\(^{-1}\). These "strongly coupled" ions are difficult to detect by conventional resonance techniques such as APR and EPR. This led to the use of thermal conductivity to detect the low lying levels of paramagnetic ions via resonant scattering of phonons (e.g. Brown, M A (1971, Challis et al (1968)). However uncertainties in the form of phonon relaxation times hamper the interpretation of these experiments. A more direct method is by far infra-red spectroscopy which lacks sensitivity below 5 cm\(^{-1}\). Sheard (1969, 1971) first suggested that the study of thermodynamic properties can play a useful role in this field. Specific heat gives information on energy level splittings, but it is very difficult to measure experimentally and also lacks the precision of a spectroscopic technique. Therefore the attention of various experimentalists has been focussed in recent years on using thermal expansion techniques for this purpose which not only provides information on energy level splittings, but also gives their volume (or pressure) dependences.

The standard Gruneisen theory (1912, 1926) may be generalised to include the effect of two level impurity ion with level splitting \(E_s\). The expansion coefficient is given by:

\[
\frac{\beta}{\chi_T} = \frac{\gamma_L C_L + \gamma_S C_S}{V}
\]  

(1.6)
where $C_L$ and $C_S$ are the specific heats at constant volume of the lattice and that of the impurity ion respectively. It will be shown later in Chapter 2, that lattice Grüneisen parameter $\gamma_L$ is given by

$$\gamma_L = -\left(\frac{\partial^2 n}{\partial \ln V} \frac{\bar{\omega}_D}{V}\right)_T \tag{1.7}$$

where $\bar{\omega}_D$ is the Debye frequency. Similarly the Grüneisen parameter for impurity is given by

$$\gamma_S = -\left(\frac{\partial^2 n}{\partial \ln V} \frac{E_S}{V}\right)_T \tag{1.8}$$

The effect of the impurity will be detectable if

$$\gamma_L C_L = \gamma_S C_S,$$

For $\frac{E_S}{K}$ (Boltzmann constant) = 50K (Kelvin degree), and a Debye temperature of 300K this only requires 0.05 atomic %. For such weak concentrations of impurities, the effect on compressibility will be negligible. We should therefore expect a peaked anomaly in the thermal expansion at a temperature similar to Schottky peak in specific heat provided all levels behave similarly.

1.1.1 Paramagnetic Ions: Static Crystal Field Model

The magnitude of $\gamma_L$ is often obtained from the pressure dependence of elastic constants. Similarly $\gamma_S$ can be calculated from the pressure dependence of the spectrum if EPR is possible between two levels with separation $E_S$. Consider an iron group transition metal ion in a cubic crystal (e.g. Cr in GaAs). The crystal field splitting of the orbital states of the free ion are of magnitude $\Delta \sim 10^4$ cm$^{-1}$. For cubic symmetry the lowest crystal field term is either a singlet (repre-
FIGURE 1.1: Example of energy levels in cubic crystal field \( \text{Cr}^{2+} \) (3d) in tetrahedral field.

(a) free ion  (b) crystal field  
(c) spin-orbit (first order)  (d) spin-orbit (second order)
sentation \( A_2 \) of cubic group) a doublet (\( E \) representation) or a triplet (\( T_1 \) or \( T_2 \)). If the orbital angular momentum is not quenched (only for \( T_1 \) and \( T_2 \)) further splitting occurs due to spin-orbit coupling. The splitting due to first order spin orbit coupling (first order perturbation theory) is of the order of \( \frac{\lambda}{\hbar} \sim 10^2 \text{ cm}^{-1} \). When the lowest level is more than four-fold generate, it will further split in second order perturbation theory (second order spin orbit coupling) giving small splitting of \( \frac{\lambda^2}{\Delta} \sim 1 \) to 10 \( \text{ cm}^{-1} \). This is shown in Figure 1.1).

On a point-charge model the crystal field splitting in a cubic field is \( \Delta \sim a^{-5} \) where \( a \) is distance between magnetic ion and its neighbour. Since \( V \propto a^3 \), for \( E_S \sim \frac{\lambda^2}{\Delta} \), we will have

\[
\gamma_S = -\frac{\frac{\lambda}{\hbar} n}{\frac{\lambda}{\hbar} a^3} = -\frac{5}{3}
\]

This corresponds to negative thermal expansion anomaly in the region of the Schottky peak. The negative sign arises because of the fact that crystal contracts, the crystal field strength is increased, the level splitting \( E_S \) is decreased and available free energy is reduced.

1.2 Experimental Technique

The spectroscopic applications of thermal expansion requires a resolution of \( 10^{-10} \) in the measurement of \( \frac{\Delta l}{l} \). Although there are a number of methods of measuring thermal expansion (a brief review describing only their merits and limitations will be given in Chapter 2), only three terminal capacitance techniques meet this requirement. The General Radio Co precision capacitance
bridge model 1616 accompanied by lock-in amplifier arrangement has made it possible to detect a capacitance change of 1/1000 attofarad (10^{-21} \text{ farad}). In other words this technique enables us to detect a length change of 0.01 \text{ Å} to 0.001 \text{ Å} in our samples. This technique therefore being extremely sensitive has been used in the present work.

1.3 Structure of the Thesis

Chapter 2 describes a theoretical background (concerning only the present work) and a very brief review of general experimental techniques describing only their merits and their limitations.

Chapter 3 describes the effect of epoxy resin as a guard ring spacer and the effect of non-parallelism on the linearity of three terminal capacitance transducers used. Some guidelines were produced for further experimental work on thermal expansion using three terminal capacitance dilatometry techniques.

Chapter 4 describes very briefly the design, construction and working of the thermal expansion cryostat. A brief description of the electronic detection system and the computer control of the cryostat is also given.

Chapter 5 describes in detail the automation of the dilatometer. It describes the operation of each interface device and the relevant software.

The last chapter describes the results obtained with the apparatus and briefly describes the results of measurement of thermal expansion of three samples: chromium doped GaAs, amorphous arsenic and vanadium silicate.
CHAPTER II

THERMAL EXPANSION - THEORETICAL
BACKGROUND AND EXPERIMENTAL TECHNIQUE

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2.1 Introduction

In crystals the atoms are arranged in a regular three dimensional array. At any temperature the atoms are vibrating about their mean positions. The potential energy of a crystal can be expressed as a function of the displacement of a typical particle from its equilibrium position which in turn may be expressed as a power series expansion. If we consider only the terms up to second power of the amplitude of displacement and the restoring force at the mean position to be zero, the potential energy will simply be proportional to the square of amplitude of the displacement. Such a motion would be simple harmonic in form. This theoretical approach is commonly known as the harmonic approximation. The harmonic approximation is frequently used in solid state theory and in many cases this simple approach produces results that give good description of the experimental measurements. However phenomena like thermal expansion, temperature and pressure dependence of elastic constants cannot be explained on the basis of the harmonic approximation. These phenomena are therefore classified as anharmonic phenomena. Actually the vibration of an atom of a crystal is never purely harmonic, there is always some anharmonic contribution. We, therefore, have to consider the higher terms beyond the second power of the amplitude of displacement in the expression for potential energy of a solid. These terms are known as anharmonic terms. As the temperature rises, the amplitude of oscillation will increase and anharmonic effects become more and more important.
The study of thermal expansion of a solid is one of the methods used in investigating anharmonicity in forces acting in a crystal. The thermal expansion of a solid can be considered as a variation with temperature of the dimensions and structure of a solid. The Grüneisen constant (this will be defined later) can be measured from the knowledge of experimentally measurable quantities i.e. the expansion coefficient, specific heat, volume and compressibility. The Grüneisen constant gives an idea of the dependence of natural frequencies of vibration of a solid upon volume (or pressure). Thus the study of thermal expansion of solids gives us information about those properties of solids which cannot be obtained by studying specific heat, thermal conductivity, neutron diffraction spectra and Mössbaur effect.

We start with widely used quasi-harmonic model of thermal expansion which treats the vibration as harmonic, but assumes that the frequency of vibration depends upon volume (or pressure). The general thermodynamic theory with derivations of important quantities, will be followed by the influence of paramagnetic impurities on the thermal expansion of solids and the experimental technique of measuring thermal expansion with emphasis on three terminal capacitance dilatometry.

2.2 Quasi-Harmonic Model

In a harmonic model the potential energy does not contain terms beyond second order in interatomic displacement. The vibrations are then a superposition of normal modes, whose symmetry indicates that there can be no thermal expansion. The second order coefficients and hence frequencies of the modes remain unchanged under the effect of any external force and are therefore independent of volume.
In practice no crystal is purely harmonic, in fact every crystal is anharmonic, no matter how small anharmonicity it possesses. Therefore we have to consider terms in potential energy beyond second order so as to make our system comparable to the real situation and thus make thermal expansion possible. In the presence of anharmonicity second order coefficients and hence frequencies of modes are volume dependent.

Leibfried and Ludwig (1961) have shown that to a first approximation (for weakly anharmonic vibration) the phenomenon of thermal expansion can be explained by the widely used quasi-harmonic approach which treats the vibrations as harmonic but assumes the frequencies of vibration to be volume dependent. In this approximation the lattice vibrational entropy $S_{l}$ is sum of the separate contributions.

$$
S_{l} = \sum_{J} S_{J} = \sum_{J} \frac{h \omega_{J}}{kT} = \sum_{J} S(x)
$$

(2.2.1)

where $x = \frac{KT}{\hbar \omega_{J}}$

where $S(x)$ is the entropy function for harmonic oscillator

$$
S(x) = k \left[ \frac{x}{e^{x}} - \ln (1 - e^{-x}) \right]
$$

(2.2.2)

From equation (2.2.1) it follows that

$$
\frac{\partial S_{J}}{\partial \ln V} \frac{1}{T} = \frac{\partial S(x)}{\partial \ln V} \frac{1}{T} \frac{d \ln (x)}{d \ln V} = \left( \frac{\partial S_{J}}{\partial \ln V} \right) \left( \frac{d \ln \omega_{J}}{d \ln T} \right) = \left( \frac{\partial S_{J}}{\partial \ln T} \right) \left( \frac{d \ln \omega_{J}}{d \ln V} \right)
$$

(2.2.3)
It will be shown in the next section that

\[
\frac{d \ln \omega_j}{d \ln V} = \gamma_j
\]  

(2.2.4)

where \( \gamma_j \) is the Grüneisen constant of an individual mode. and

\[
\left( \frac{\partial S_j}{\partial \ln V} \right) = C_J
\]  

(2.2.5)

where \( C_J \) is the contribution of the individual mode to specific heat \( C_V \). Therefore the equation (2.2.3) takes the form:

\[
\left( \frac{\partial S_j}{\partial \ln V} \right) = C_J \gamma_j
\]  

(2.2.6)

The Grüneisen function can be measured by experimentally measurable quantities i.e.

\[
\gamma(T,V) = \frac{\beta V}{x_T C_V}
\]  

(2.2.7)

where \( \beta \) = expansion coefficient

\( V \) = the volume

\( x_T \) = isothermal compressibility

and \( C_V \) is the specific heat

The Grüneisen function thus measured is an average of \( \gamma_j \) (of individual modes) weighted by respective heat capacities.
This equation gives \( \gamma(T,V) \) as an average of the mode parameters \( \gamma_j \) with temperature dependent weighting factor \( C_j \).

We thus obtain an expression which relates the macroscopic lattice vibrational Gruneisen function \( \gamma_\chi \) to the Gruneisen parameter \( \gamma_j \) for individual modes.

Each mode can be labelled by \( (q,j) \) where \( q \) is the wave vector and \( j \) now denotes the polarisation. The equations (2.2.4) and (2.2.9) can be written as:

\[
\gamma(q,j) = -\frac{d \ln \omega(q,j)}{d \ln V} \tag{2.2.10}
\]

\[
\gamma_\chi(V,T) = \frac{\int \{ \sum_j \gamma(q,j) C(q,j) \} \ dq}{C_V} \tag{2.2.11}
\]

where the integration is over the first Brillouin Zone and can be done by standard numerical methods (e.g. see Wallace 1972, p 453). The Gruneisen rule states that \( \gamma_\chi(V,T) \) should have no explicit temperature dependence because at constant pressures the volume changes very little with temperature. Therefore the necessary condition for the Gruneisen rule is that average \( \overline{\gamma}(\omega) \) of \( \gamma_j \) in each infinitesimal frequency interval should be constant over the whole range of frequencies. Blackman (1955) has
shown that this condition can be met if $\gamma_J$ in different branches of spectrum compensate for each other. However a majority of solids show a slight variation of $\gamma_J$ with temperature indicating a variation of $\tilde{\gamma}(\omega)$ with frequency.

At very low temperatures when only long acoustic waves are excited, the entropy is of the form

$$S_l = \frac{1}{3} BT^3 + \frac{1}{5} CT^5$$  \hspace{1cm} (2.2.12)$$

provided there is no other contribution to entropy.

Similarly the volume expansion coefficient can be expressed as

$$\beta = bT^3 + CT^5$$  \hspace{1cm} (2.2.13)$$

The lattice Grüneisen function can be expressed (this will be explained in detail in the next section)

$$\gamma_l(T,V) = \frac{\frac{3S}{3\ln V}}{CV}$$  \hspace{1cm} (2.2.14)$$

From equation (2.2.12) and (2.2.14) it follows that $\gamma_l$ can be expressed as a power series in $T^2$ i.e.

$$\gamma_l = \frac{1}{3} \frac{d \ln B}{d \ln V} + \frac{C}{B} \left\{ \frac{1}{5} \frac{d \ln C}{d \ln V} - \frac{1}{3} \frac{d \ln B}{d \ln V} \right\} T^2 + \cdots \cdots$$  \hspace{1cm} (2.2.15)$$

at $T + \Theta$, $\gamma_l$ can be denoted by $\gamma_0$ in the low temperature limit
\[ \gamma = \frac{1}{3} \frac{d \ln B}{d \ln V} = -\frac{d \ln \Theta_D}{d \ln V} \] (2.2.16)

where \( \Theta_D \) is the Debye equivalent temperature for vibrational heat capacity as \( T \to 0 \) which can be calculated from the knowledge of density and second order elastic constants \( C_{\lambda\mu} \) at zero temperature and \( \gamma_0 \) can be calculated if volume dependence of \( C_{\lambda\mu} \) is also known.

At high temperatures \( C_J \) in equation (2.2.9), all tend to the same limit and the resulting limiting value of \( \gamma_J \) is a simple average of \( \gamma_J \).

\[ \gamma_\alpha = \bar{\gamma}_J. \]

This limit is typically approached at \( \frac{\Theta_D}{25} \) where \( \Theta_D \) is the Debyetemperature and for higher temperatures the Grüneisen rule is a fair approximation. The experimental accuracies of 1% in expansion coefficient measurement are fairly easily attainable because of relatively large thermal expansion at these temperatures. However it is difficult to estimate the correct value of quasi-harmonic limit \( \gamma_\alpha \) because corrections have to be made for higher order anharmonic effects.

2.3 General Thermodynamic Theory

2.3.1 Debye Equation of State

Following his specific heat theory Debye in 1913 developed an equation of state of a solid taking into consideration the volume changes with temperature. Helmholtz free energy by definition is given by

\[ F = U - TS \] (2.3.1)
where $U$ is the internal energy of the system.

Partial differentiation gives

$$dF = dU - TdS - SdT$$

(2.3.2)

Also we know from the first law of thermodynamics that

$$dQ = dU + pdV$$

(2.3.3)

and from the law of increase of entropy we get

$$dS = \frac{dQ}{T}$$

where $dS$ is the change in entropy.

$$dQ = TdS$$

Therefore equation (2.3.3) becomes

$$TdS = dU + pdV$$

(2.3.4)

Using this in equation (2.3.2)

$$dF = -pdV - SdT$$

If temperature is kept constant, $dT = 0$

\[ \therefore dF = -pdV \]
or \[ P = - \left( \frac{\partial F}{\partial V} \right)_T \] (2.3.5)

The Helmholtz free energy \( F \) can be separated into two parts, one the internal energy at 0 K which can be termed as \( U_0 \) and the other arising from the contribution due to temperature dependent lattice vibration in Debye approximation which can be termed as \( F_D (T,V) \).

Therefore:

\[ F = U_0 + F_D (T,V) \] (2.3.6)

Differentiating with respect to \( V \) at constant temperature:

\[ \left( \frac{\partial F}{\partial V} \right)_T = \left( \frac{\partial U_0}{\partial V} \right) + \left( \frac{\partial F_D}{\partial V} \right)_T \]

using equation (2.3.5)

or

\[ -P = \left( \frac{\partial U_0}{\partial V} \right) + \left( \frac{\partial F_D}{\partial V} \right)_T \]

\[ -P = \left( \frac{\partial U_0}{\partial V} \right) + \left( \frac{\partial F_D}{\partial \theta_D} \right)_T \left( \frac{\partial \theta_D}{\partial V} \right)_T \] (2.3.7)

where \( \theta_D \) is known as Debye temperature.

The internal energy \( U \) in the Debye approximation is given by

\[ U_D = 9RT \left( \frac{T}{\theta_D} \right)^3 \int \frac{x^3}{(e^x - 1)} \, dx \]

\[ U_D = T \cdot f \left( \frac{\theta_D}{T} \right) \]
i.e. temperature dependent internal energy may be expressed as product of temperature and a function of $\frac{\theta_D}{T}$.

By definition $F_D$, the temperature dependent part of free energy must be of the same form as $U_D$

$$F_D = T \cdot f \left( \frac{\theta_D}{T} \right)$$

$$\frac{\partial F_D}{\partial \theta_D} = \frac{\partial}{\partial \theta_D} \left( T \cdot f \left( \frac{\theta_D}{T} \right) \right)$$

$$= T \cdot \frac{\partial \left( f \left( \frac{\theta_D}{T} \right) \right)}{\partial \theta_D} \frac{d \left( \frac{\theta_D}{T} \right)}{d \theta_D}$$

$$= \frac{\partial \left( f \left( \frac{\theta_D}{T} \right) \right)}{\partial \theta_D} \frac{\theta_D}{T}$$

Also:

$$\frac{\partial \left( f \frac{\theta_D}{T} \right)}{\partial \theta_D} = \frac{\partial f \left( \frac{\theta_D}{T} \right)}{\partial \left( \frac{\theta_D}{T} \right)} \cdot \frac{\partial \left( \frac{\theta_D}{T} \right)}{\partial \theta_D} = \frac{\partial f \left( \frac{\theta_D}{T} \right)}{\partial \theta_D} \frac{\theta_D}{T} \cdot \frac{1}{T}$$

Using equation (2.3.8) we get

$$\frac{\partial \left( \frac{F_D}{T} \right)}{\partial \left( \frac{\theta_D}{T} \right)} = \theta_D \frac{\partial F_D}{\partial \theta_D} \frac{1}{T}$$

But

$$\frac{\partial \left( \frac{F_D}{T} \right)}{\partial \left( \frac{1}{T} \right)} = U_D$$
Thus from (2.3.9) and (2.3.10) we get
\[
\frac{3F_D}{3\theta_D} = \frac{U_D}{\theta_D}
\]  
(2.3.11)

using this result in equation (2.3.7) we get
\[
-P = \frac{3U_0}{3V} + \frac{U_D}{\theta_D} (\frac{3\theta_D}{3V})_T
\]
\[
-P = \frac{3U_0}{3V} + \frac{U_D}{V} \{ \frac{V}{\theta_D} (\frac{3\theta_D}{3V})_T \}
\]  
(2.3.12)

or
\[
P = - \frac{3U_0}{3V} - \frac{U_D}{V} \{ \frac{V}{\theta_D} (\frac{3\theta_D}{3V})_T \}
\]  
(2.3.12)

This equation is known as Debye equation of state and is usually written as

\[
P = - \frac{3U_0}{3V} + \gamma \frac{U_D}{V}
\]

where \( \gamma = - \frac{V}{\theta_D} (\frac{3\theta_D}{3V})_T \)

or \( \gamma = - \frac{d (\ln \theta_D)}{d (\ln V)} \)  
(2.3.13)

where \( \gamma \) (gamma) is known as Grüneisen constant.
2.3.2 Volumetric Expansion

The coefficient of volumetric expansion with which we will be mainly concerned is defined mathematically as:

\[ \beta = \left( \frac{\partial \ln V}{\partial T} \right)_P \]  

(2.3.14)

where \( V \) is the volume of the sample.

For an isotropic and cubic solid it is obtained from the coefficient of linear expansion.

\[ \beta = 3a \]

\[ \beta = 3 \left( \frac{\partial \ln l}{\partial T} \right)_P \]  

(2.3.15)

where \( l \) is the length of the sample.

The changes in the dimensions of the lattice tend to minimise the free energy contribution to which can come from static lattice, lattice vibration, electric dipole magnetic ions, nuclear spin, electrons etc.

The coefficient of volumetric expansion can be very simply related to Gibbs free energy i.e. \( G(P, T) \).

We know that:

\[ dG = -SdT + VdP \]  

(2.3.16)

If temperature is kept constant

\[ \left( \frac{\partial G}{\partial P} \right)_T = V \]  

(2.3.17)
Differentiating again with respect to $T$

\[ \frac{\partial V}{\partial T} = \frac{\partial^2 G}{\partial P \partial T} \]  

or

\[ \frac{1}{V} \left( \frac{\partial V}{\partial T} \right) = \frac{1}{V} \frac{\partial^2 G}{\partial P \partial T} \]

or

\[ \frac{\partial \ln V}{\partial T} = \frac{1}{V} \left( \frac{\partial^2 G}{\partial P \partial T} \right) \]

Using equation (2.3.14) we have

\[ \beta = \frac{1}{V} \left( \frac{\partial^2 G}{\partial P \partial T} \right) \]  

(2.3.18a)

Using equation (2.3.17) we get:

\[ \beta = \frac{\frac{2}{2} \left( \frac{\partial G}{\partial P} \right) \left( \frac{\partial \ln V}{\partial T} \right)}{\frac{\partial G}{\partial P} \frac{\partial T}{\partial T}} \]  

(2.3.19)

Similarly $\beta$ can be related to Helmholtz free energy $F(V,T)$ which is more useful in many ways.

We know that:

\[ dF = -SdT - PdV \]  

(2.3.20)

If temperature is kept constant.

\[ \left( \frac{\partial F}{\partial V} \right) = -P \]  

(2.3.20a)
Differentiating with respect to $T$ we get:

$$- \frac{\partial P}{\partial T} = \left( \frac{\partial^2 F}{\partial V \partial T} \right)$$ \hspace{1cm} (2.3.21)

Rewriting equation (2.3.14) we get:

$$\beta = \left( \frac{\partial \ln V}{\partial T} \right)_P$$

which can be written as:

$$\beta = \left( \frac{\partial \ln V}{\partial P} \right)_T \left( \frac{\partial P}{\partial T} \right)_V$$ \hspace{1cm} (2.3.22)

Isothermal compressibility $\chi_T$ is defined as:

$$\chi_T = - \left( \frac{\partial \ln V}{\partial P} \right)_T$$

Therefore

$$\beta = - \chi_T \left( \frac{\partial P}{\partial T} \right)_V$$ \hspace{1cm} (2.3.23)

Making use of equation (2.3.21)

$$\beta = \chi_T \left( \frac{\partial^2 F}{\partial V \partial T} \right)$$ \hspace{1cm} (2.3.24)

It follows from (2.3.20) that

$$\frac{\partial F}{\partial T} = -S$$
Therefore

\[ \beta = \chi_T \left( \frac{\partial S}{\partial V} \right)_T \]  \hspace{1cm} (2.3.25)

Isothermal bulk modulus \( B_T \) is defined as:

\[ B_T = - \left( \frac{\partial P}{\partial \ln V} \right)_T \]  \hspace{1cm} (2.3.26)

we see that \( \chi_T \) is reciprocal of \( B_T \).

Rewriting the above equation

\[ B_T = -V \left( \frac{\partial P}{\partial V} \right)_T \]  \hspace{1cm} (2.3.27)

From equation (2.3.20a)

\[ \left( \frac{\partial F}{\partial V} \right) = -P \]

Differentiating with respect to \( V \) at constant temperature:

\[ \left( \frac{\partial^2 F}{\partial V^2} \right)_T = - \left( \frac{\partial P}{\partial V} \right)_T \]  \hspace{1cm} (2.3.28)

Using this in equation (2.3.27), we get

\[ B_T = V \left( \frac{\partial^2 F}{\partial V^2} \right)_T \]  \hspace{1cm} (2.3.29)

It follows from equation (2.3.24)

\[ \beta B_T = \left( \frac{\partial^2 F}{\partial V \partial T} \right) \]  \hspace{1cm} (2.3.30)

\[ \therefore B_T = \frac{1}{\chi_T} \]
It follows from equation (2.3.20)

\[(\frac{\partial^2 F}{\partial T^2})_V = -S\]  \hspace{1cm} (2.3.31)

Differentiating with respect to \(T\)

\[(\frac{\partial^2 P}{\partial T^2})_V = -\frac{\partial S}{\partial T}\]  \hspace{1cm} (2.3.32)

The law of increase of entropy

\[\frac{dS}{dV} = \frac{dQ}{dT}\]

Therefore

\[-(\frac{\partial^2 F}{\partial T^2})_V = \frac{1}{T} (\frac{\partial Q}{\partial T})_V\]

\[\therefore C_V = \frac{dQ}{dT}\]

Hence

\[C_V = -T \frac{\partial^2 F}{\partial T^2}_V\]  \hspace{1cm} (2.3.33)

The equations (2.3.22) and (2.3.24) each have their physical significance. The equation (2.3.22) reveals that thermal expansion comes about in two stages: first a change of pressure as the temperature is increased keeping the volume constant and then a change of volume as the body is allowed to relax elastically at a higher temperature to the external pressure \(P_o\). From (2.3.24) it follows that thermal expansion can be regarded as determined by minimization at each temperature of the constrained Gibb's function
FIGURE 2.3.1: The role of entropy in thermal expansion at external pressure $P_0$. 
(F + F_0 V), the position of minima changes only if entropy is volume dependent (see Figure 2.3.1). The change in volume will always be in the direction of increasing entropy. This equation further explains that substances having greater compressibility i.e. \( \chi_T \) will have larger thermal expansion. When temperature approaches zero, compressibility remains finite, the temperature dependence of thermal expansion depends mainly on that of \( \left( \frac{\partial S}{\partial V} \right)_T \).

The microscopic theory of thermal expansion originates from the work of Mie (1903) and Grüneisen. Grüneisen (1912) in a seminar paper adopted Einstein model which is characterised by a single vibrational frequency \( \omega \) derived from interatomic forces.

On a microscopic scale the energy content of vibration changes give rise to increased amplitude of vibration. Also the nature of vibration changes with temperature provided the temperature is not too high. The first sign of anharmonicity can be taken into account by allowing the crystal to expand, by assuming that frequency of vibration is volume dependent, but they remain harmonic in character. These assumptions form the basis of widely accepted quasi-harmonic approach and also help us in calculating the moments of frequency distribution of a solid and their volume dependence.

The contribution to Helmholtz free energy \( F \) of a solid comes from different sources, i.e. ionic lattice, conduction electron, spin and magnetic impurity. The algebraic sum of all these contributions gives the total free energy \( F \) of a solid. The separation of particular components from rest is possible provided the relaxation time for the component is sufficiently different for the energy state of the component to be calculated to a good accuracy by assuming that the energy states of all other components
to be frozen in some instantaneous or averaged configuration. In this way independent contributions to derivative of $F$ from entropy, heat capacity and bulk modulus (but not for thermal expansion which is ratio of derivatives), can be calculated. However it is not convenient to separate the contribution to the bulk modulus which at low temperatures is mainly dominated by the static lattice and varies little with the temperature, therefore:

$$
\beta = \sum \beta_r = x_T \sum \langle \frac{\delta S}{\delta V} \rangle_T 
$$

We conclude that magnitude of $\beta_r$ depends on sensitivity of free energy contribution $F_r$ to the changes of volume or more generally to strain.

The contribution to thermal expansion usually arises from lattice, conduction electron and paramagnetic impurities or Schottky defect. These different contributions can be easily identified due to their different temperature dependence. The coefficient of thermal expansion due to electron varies as $T$, that due to lattice at low temperature varies as $T^3$ and higher \textit{odd} powers of $T$ and Schottky defect introduces a "bump" with higher temperature tail varying as $T^{-2}$.

Any change in order, hence in entropy due to cooperative interaction between electrons, magnetic spin and electric dipoles during a thermodynamic transformation should be reflected at transition temperature in heat capacity and thermal expansion. These anomalies can also be identified by their characteristic temperature dependence at temperatures above and below the transition. The relative size of the anomalies in thermal expansion and heat capacity can be determined by their volume or strain sensitivity of the interaction or of the ordering of temperature.
2.3.3. Grüneisen Parameter

Thermodynamic Grüneisen functions play a very vital role in the analysis and interpretation of thermal expansion data. Rewriting the Debye equation of state, we have:

\[ p = - \frac{\partial U_0}{\partial V} - \left( \frac{\theta_D}{\theta_D} \right) \frac{\partial \theta_D}{\partial V} \frac{U_D}{V} \]

\[ = - \frac{\partial U_0}{\partial V} + \gamma \left( \frac{U_D}{V} \right) \]

where \( \gamma = \frac{V}{\theta_D} \left( \frac{\partial \theta_D}{\partial V} \right) \)

\[ \gamma = \frac{d \ln \theta_D}{d \ln V} \quad (2.3.35) \]

According to Debye theory \( \theta_D \) is independent of temperature so \( \gamma \), known as Grüneisen constant, should also be temperature independent. But we know the fact that a fairly wide range of frequency exists over which solids can vibrate, so we should think in terms of frequency distribution (\( \omega \)) defining number of normal modes of vibration per unit frequency range. To each frequency we can associate one \( \gamma \) denoted by \( \gamma_J \). According to quasi-harmonic approach, \( \gamma \) is weighted average of \( \gamma_J \) weight for each mode being equal to its contribution to \( C_V \). Therefore we should expect temperature variation of \( \gamma \) with low and high temperature limiting value given by:

\[ \gamma_0 = -\frac{d \ln \theta_D}{d \ln V} \quad (2.3.36) \]

\[ \gamma_\infty = \frac{3n}{\sum_{J=1}^{\infty} \gamma_J / 3n} \quad (2.3.37) \]
where \( \theta_D \) is the low temperature limiting value of Debye characteristic temperature and \( n \) is the number of vibrating particles in the assembly. The numerical value of \( \gamma_0 \) and \( \gamma_\infty \) and their temperature variation between two limits can be compared with experimental results because as will be shown later, \( \gamma \) can be expressed in terms of physically measurable quantities. However if all particles in the assembly are vibrating with the same frequency \( \omega \) (say) then \( \gamma \) gives volume variation of this frequency

\[
\gamma = - \frac{d \ln \omega}{d \ln V}
\]  

(2.3.38)

The differential change in entropy \( S(V,T) \) can be written as:

\[
ds = \left( \frac{\partial S}{\partial T} \right)_V dt + \left( \frac{\partial S}{\partial V} \right)_T dv
\]

(2.3.39)

We know that \( C_V = \frac{dQ}{dT} \)

Also \( ds = \frac{dQ}{T} \)

Therefore

\[
\left( \frac{\partial S}{\partial T} \right)_V dt = \frac{1}{T} \frac{dQ}{dt} dT
\]

\[
\left( \frac{\partial S}{\partial T} \right)_V dt = \frac{dQ}{dT} d(\ln T)
\]

\[
\left( \frac{\partial S}{\partial V} \right)_T dt = C_V d(\ln T)
\]

\[
\left( \frac{\partial S}{\partial T} \right)_V dt = C_V d(\ln T)
\]  

(2.3.40)
Similarly coefficient of volumetric expansion by definition is given by:

\[
\beta = \frac{1}{V} \left( \frac{\partial V}{\partial T} \right)_P \tag{2.3.41}
\]

and isothermal bulk modulus \( B_T \) is given by

\[
B_T = -V \left( \frac{\partial P}{\partial V} \right)_T \tag{2.3.42}
\]

Multiplying (2.3.41) and (2.3.42) we get:

\[
\beta B_T = -\left( \frac{\partial P}{\partial T} \right)_V \tag{2.3.43}
\]

We know that the first law of thermodynamics can be expressed mathematically as:

\[
dQ = dU + PdV
\]

If internal energy of the system is constant then \( dU = 0 \)

\[
dQ = PdV
\]

But

\[
dQ = TdS
\]

\[
TdS = PdV
\]

or

\[
\frac{\partial S}{\partial V} = \frac{\partial P}{\partial T} \tag{2.3.44}
\]

d\( V \) can be written as:

\[
dV = V d\ln V \tag{2.3.45}
\]
So the second part of equation (2.3.39) can be written by making use of equations (2.3.43) and (2.3.44) as

\[
\left( \frac{\partial S}{\partial V} \right)_T dV = \beta B_T V d \ln V \tag{2.3.46}
\]

So making use of equations (2.3.40) and (2.3.46) the equation (2.3.39) can be written as:

\[
dS = C_V d \ln T + \beta B_T V d \ln V \tag{2.3.47}
\]

If entropy of system is constant, then \( dS = 0 \)

\[
-C_V d \ln T = \beta B_T V d \ln V
\]

\[
-(\frac{\partial \ln T}{\partial \ln V})_S = \frac{\beta B_T V}{C_V} = \gamma(V,T) \tag{2.3.48}
\]

Thus the Grüneisen parameter relates to strongly temperature dependent quantities \( C_V \) and \( \beta \) but itself is weakly dependent on temperature. Similarly it can be easily proved that:

\[
\gamma = \frac{\beta B_S V}{C_P} \tag{2.3.49}
\]

where \( B_S \) is adiabatic bulk modulus.

Because compressibility is reciprocal of bulk modulus therefore \( \gamma \) can be expressed in terms of compressibility as:

\[
\gamma = \frac{\beta V}{\chi_T C_V} = \frac{\beta V}{\chi_s C_P} \tag{2.3.50}
\]
where \( \chi_T \) is the isothermal compressibility and \( \chi_S \) the adiabatic compressibility.

At the time of development of these equations \( B_T \) was assumed to be temperature independent, this therefore led directly to the conclusion that \( \beta \propto C_V \) to a good approximation. This is known as the Grüneisen law. The experimental data has shown that Grüneisen law is only true at intermediate and higher temperatures. So this can be regarded as a first approximation.

In many theoretical calculations, the Grünneisen constant \( \gamma \) is usually expressed in terms of derivative of Helmholtz free energy \( F \). We know that:

\[
\gamma(T,V) = \left( \frac{\partial S}{\partial \ln V} \right)_{C_V} \tag{2.3.51}
\]

We know from equation (2.3.33)

\[
C_V = -T \left( \frac{\partial^2 F}{\partial T^2} \right)_V \tag{2.3.52}
\]

We know from equation (2.3.31)

\[
-S = \left( \frac{\partial F}{\partial T} \right)_V
\]

\[
- \left( \frac{\partial S}{\partial V} \right) = \left( \frac{\partial^2 F}{\partial T \partial V} \right)_V
\]

\[
- \frac{V}{V} \left( \frac{\partial S}{\partial V} \right) = \left( \frac{\partial^2 F}{\partial T \partial V} \right)_V
\]

\[
- V \left( \frac{\partial S}{\partial V} \right) = V \left( \frac{\partial^2 F}{\partial T \partial V} \right)_V
\]

\[
\left( \frac{\partial S}{\partial \ln V} \right) = -V \left( \frac{\partial^2 F}{\partial T \partial V} \right)_V \tag{2.3.53}
\]
Using equations (2.3.52) and (2.3.53) in equation (2.3.51) we get:

\[ \gamma(T,V) = \frac{V \left( \frac{\partial^2 F}{\partial V \partial T} \right)}{T \left( \frac{\partial^2 F}{\partial T^2} \right)} \]  

(2.3.54)

The statistical derivation of the Grüneisen constant will be given in the next section.

It becomes evident from this section that a study of Grüneisen constants gives us the idea of dependence of natural frequencies of a solid on the volume. Thus thermal expansion is phenomenon which can provide us information about those properties of a solid which cannot be obtained by studying specific heat, the neutron diffraction spectra or Mössbauer effect. Generally the Grüneisen constant is evaluated from the knowledge of experimentally measured quantities \( \beta, C_V, \chi_T \) and \( V \). At temperatures close to Debye temperature \( \gamma \) is constant, whose value depends on the nature of the forces present in the crystal and range from 1 to 3. If atoms in a solid vibrate independently of each other with a single frequency (Einstein model), or if dependence of frequency \( \omega \) on volume is the same for all vibrations (Debye model) \( \gamma \) would be a constant. Recent experimental data have indicated that \( \gamma \) decreases with a decrease in temperature which means that various frequency spectra have different volume dependence (or on pressure). Therefore the Grüneisen parameter describes the deviation of spectrum from harmonic approximation. Hence it is quite justifiable to say that \( \gamma \) gives us a direct measure of anharmonicity of vibration of atom in a solid.
2.4 Influence of Paramagnetic Impurity on Thermal Expansion

When a paramagnetic impurity from transition metal is introduced into an otherwise perfect crystal e.g. vanadium or chromium in ruby and chromium in GaAS, it has some discrete energy levels capable of thermal excitation dynamically independent from those of the lattice. Thus the paramagnetic impurity depending on its concentration has capability of drastically changing the properties of the crystal e.g. chromium when introduced into crystal of GaAS changes it from semiconductor to semiconductor.

Various spectroscopic techniques EPR, ESR, TDEPR, Mössbauer and infrared spectroscopy, have widely been used in recent years for the purpose of studying such systems. Sheard (1969, 1972) for the first time discussed the possibility of using thermal expansion as a tool for studying volume dependence of energy level splitting of a paramagnetic ion in a crystal. A study of thermal expansion can provide useful information about spacing of energy levels and their dependence on volume. Grüneisen parameters have been widely used for the study of volume dependence of phonon and electron spectra (Collins and White (1964) and to a lesser extent as a measure of volume dependence magnetic ordering energy (White and Sheard 1974).

At low temperatures where perfect crystal contribution to specific heat and thermal expansion are very small, the paramagnetic impurity can have anomalously large contribution. This effect can usually be described to a good approximation by an additional independent contribution to the Helmholtz free energy and consequently entropy. Griffith (1960) has derived an expression for contribution to heat capacity known as Schottky anomaly from a finite number of discrete energy levels $E_0, E_1, \ldots$.
\( E_2 \ldots E_n \) with degeneracies \( f_0, f_2, f_3 \ldots f_n \) which is given by:

\[
C_S = \frac{1}{KT^2} (\langle E^2 \rangle - \langle E \rangle^2) \tag{2.4.1}
\]

where angular brackets denote averages of the form:

\[
\langle X \rangle = \frac{\sum f_n X_n \exp (-E_n/KT)}{\sum f_n \exp (-E_n/KT)} \tag{2.4.2}
\]

Implicit assumptions in this derivation that energy level \( E_n \) may be regarded as dynamically independent from energy state of total systems is equivalent in the case of crystals with atomic systems having discrete energy levels to writing an independent contribution to Heltholtz free energy, i.e. \( F = F_L + F_S \) where \( F_L \) is the contribution to free energy from the lattice and \( F_S \) is the contribution to free energy from discrete energy levels. Using the standard expression (2.3.33) for specific heat we can write an equivalent expression for Schottky contribution due to discrete levels as

\[
C_S = -T \frac{\partial^2 F_S}{\partial T^2} \tag{2.4.3}
\]

Using the expression (2.3.24) for coefficient of volume expansion, we can write an equivalent expression for \( \beta \) as contribution due to discrete levels

\[
\beta_S = \chi_T \frac{\partial^2 F_S}{\partial V \partial T} \tag{2.4.4}
\]

where \( \chi_T \) is isothermal compressibility.
It follows that paramagnetic impurities give rise to anomalies in the thermal expansion of Schottky type in specific heat which arises from dependence of atomic levels $E_n$ on the crystal volume. Using the relation (2.3.50) we can write an expression for $\beta$ as:

$$\beta_S = \frac{\gamma x_T C_S}{V} \quad (2.4.5)$$

Putting the value of $C_S$ from (2.4.1) we get:

$$\beta_S = \frac{x_T}{V KT^2} \left( <E^2> \gamma - <E><E\gamma> \right) \quad (2.4.6)$$

We should note that in calculation of thermal properties, the energy of the ground state may be taken to be zero so that $E_n$ gives the energy level separation between the ground state and the excited state. Continuing in the same spirit, the Grüneisen parameter associated with discrete energy levels is given by:

$$\gamma_n = - \left( \frac{\partial \ln E_n}{\partial \ln V} \right)_T \quad (2.4.7)$$

which is quite analogous to Grüneisen parameter for the lattice oscillator vibrating with frequency $\omega$

$$\gamma_L = - \left( \frac{\partial \ln \omega}{\partial \ln V} \right)_T \quad (2.4.8)$$

Combining equations (2.4.1) and (2.4.5) we get an expression for average Grüneisen parameter:

$$\gamma_S = \frac{V \beta_S}{x_T C_S} \quad (2.4.9)$$
FIGURE 2.4.1: Theoretical curve of Schottky heat capacity anomaly $C_S$ for two level system of energy splitting $E_o$ and equal degeneracy.
Putting the value of $\beta_S$ and $C_S$ from (2.4.1) and (2.4.5) we get:

$$\gamma_S = \frac{\langle E^2 \gamma \rangle - \langle E \rangle \langle E \gamma \rangle}{\langle E^2 \rangle - \langle E \rangle^2}$$ \hspace{1cm} (2.4.10)

We see that $\gamma_S$ will be temperature independent only if all the excited states $n$ have the same Grüneisen parameter. Taking the particular case of two level systems where there is only one Grüneisen parameter corresponding to the excited state $n = 1$, so if $\gamma_S$ is constant, it follows from equation (2.4.9) that $\beta \propto C_S$ provided $\chi_T$ is not substantially affected by thermal excitation of the lattice or of the discrete energy levels. This will be valid only for a crystal at low temperature containing a dilute concentration of impurity atoms.

For a two level system the energy splitting $E_0 \propto KT/E$ has been plotted in Figure (2.4.1). The Schottky specific heat rises exponentially for $KT \ll E_0$ and falls as $T^{-2}$ for $KT > E_0$ (e.g. Rosenberg, 1963, p 25). The Grüneisen parameter for such a system will be given by

$$\gamma_S = -\frac{d \ln (E_0)}{d \ln V}$$ \hspace{1cm} (2.4.11)

At low temperatures i.e. $T \ll \theta_D$ very small amounts of paramagnetic impurity may give rise to Schottky "bump" in thermal expansion which are usually large as compared to the contribution of the lattice. Brown I J and Brown M A (1981) have observed such an anomaly in thermal expansion of chromium doped Al$_2$O$_3$. Sheard (1969, 1972) has pointed out that values of $\gamma_S$ obtained from thermal expansion measurement can determine the nature of energy level
splitting and that $\gamma_S$ should distinguish between splitting produced by a static crystal field and that produced by J T effects.

2.5 Experimental Techniques

The coefficient of linear expansion $\alpha$ is measured by measuring length changes over finite temperature changes and average value over a temperature change $\Delta T$ is given by

$$\alpha = \frac{1}{L} \frac{\Delta L}{\Delta T}$$

At room temperature the $\alpha$ for most of the solids is about $10^{-5}$ K$^{-1}$ so that $\alpha$ can be measured to within 1% if resolution in measurement of $\frac{\Delta L}{L}$ is $\sim 10^{-7}$, a range of sensitivity given by interferometry. However at low temperatures $\alpha$ is much smaller necessitating a much better resolution in measurement of $\frac{\Delta L}{L}$. For example at $\frac{\theta_D}{20}$ $\alpha$ is approximately $10^{-7}$ and a resolution in $\frac{\Delta L}{L}$ of $10^{-9}$ is required to measure $\alpha$ within 1% which means that the measuring technique must be able to detect length changes of the order of 0.1 Å (e.g. for a sample of 10 mm length).

Similarly at $\frac{\theta_D}{40}$, $\alpha$ is $10^{-8}$ K$^{-1}$ thus a resolution of $10^{-10}$ is required or length changes of the order of 0.01 Å e.g. for a sample of 10 mm length, should be measurable. The sensitivity can be improved by increasing the length of the sample, but very often design of cryostat and that of dilatometer impose limits on using very long samples.

The detection levels of 0.1 Å to 0.01 Å are smaller than the average interatomic distances and very much smaller than the scale of roughness on a solid surface in that even the best lapping technique leaves the surface roughness of
some nanometres. At low temperatures the limitation on measuring $a$ are imposed by difficulties in measuring very small length changes (0.1 $\text{Å}$ to 0.01 $\text{Å}$) while at normal temperatures, thermometry may impose limits. Using calibrated thermometers of germinium and platinum, the temperature should be measurable with an uncertainty of $<0.2\%$ at $\sim 1\text{K}$. The detection and measurement of the energy level splitting of a paramagnetic impurity in dielectric crystals required a resolution of $10^{-9}$ to $10^{-10}$ in measurements of $\Delta E$. This requirement is met by three terminal capacitance techniques. The recent version of General Radio Co. capacitance bridge model GR1616 accompanied by lock in amplifier arrangement, has made it possible to detect a capacitance change of $1/1000$ of an attofarad ($10^{-21}$ Farad). Because the present work is concerned with detection of paramagnetic impurities in semiconductors by their energy level splitting, e.g. Cr in GaAs, and tunnel splitting e.g. amorphous arsenic which required above mentioned range of sensitivity, we have used a three terminal capacitance technique, the details of which will be given later. There are a number of other techniques of measuring thermal expansion depending on the sensitivity level required by a particular measurement. These are X-ray methods, optical interferometry and optical levers etc. For details of these techniques the reader is referred to Yates (1975). However a brief description is given here just to outline the merits and limitations of these techniques.

2.5.1 X-Ray Method

The thermal expansion of a crystal can be easily measured by measuring a lattice parameter at two different temperatures. The X-ray method has two merits in that firstly absolute thermal expansion can be measured directly and secondly it gives expansion coefficients uncomplicated by dimensional changes resulting from vacancy formation,
from the presence of impurities or from other causes. These merits are offset by the disadvantage that this method is not so sensitive as compared to other methods so that it cannot be applied to measure thermal expansion at low temperatures. The usual resolution in the measurement of lattice parameter \( \frac{\Delta a}{a} \) is \( \sim 10^{-5} \). Although Batchelder and Simmon (1965) have achieved a resolution of \( 5 \times 10^{-6} \) by using oscillating back reflection technique.

2.5.2 Optical Method

2.5.2.1 Optical Interferometer:

An early well known method of measuring thermal expansion with considerable precision was due to Fizeau (1864, 1866). This method consisted in preparing a block from crystal under investigation with one face being polished. The crystal under investigation was stood on a table, above which was supported a glass plate. A beam of monochromatic light was made to incident on the system. This beam of light suffers reflection from the lower surface of the glass plate and upper face of the sample. By slightly adjusting the angle between the two surfaces, the two reflected beams were made to interfere, thus resulting in an interference pattern. The movement of the fringe pattern as a result of temperature changes of the samples made the measurement of expansion coefficient possible, relative to the supports. Repeating the experiment without the sample facilitates allowance for the expansion of supports. Since then the method has been gradually improved by many experimentalists. The recent users include Rubin (1954), Miencke and Graham (1963), Waterhouse and Yaes (1968). The sample is usually a hollow cylinder or three rods of equal length so that separation of two etalon plates is changed as the specimen expands or contracts. The resolution in the measurement of \( \frac{\Delta l}{l} \) by this method is approximately in the range \( 10^{-7} \) to \( 10^{-8} \). The disadvantage of the technique, apart from lower sensitivity (measurement of thermal expansion of crystal at very
low temperature demands a resolution of $\sim 10^{-10}$, is that there is every likelihood that some error may arise from mechanical junction between specimen and optical plates.

The sensitivity has been further improved by Fabry Perot multiple beam using a stabilised laser (e.g. Jacob et al (1970)), provided the end plates of cylindrical cell are matched in expansion coefficient to the specimen. The deformation of the end plates can cause serious errors if not well matched. The sensitivity in measurement of $\frac{\Delta l}{l} \sim 10^{-9}$ is limited by laser stability.

For measuring a regularly alternating displacement as in the piezoelectric effect, the sensitivity of the spherical Fabry Perot interferometer can be used by using a tuned lock in amplifier to improve signal to noise ratio.

The polarising interferometers are another class of instrument capable of greater sensitivity. Robert (1975), using Dyson's (1968) idea, which avoids the effect of tilt and includes a stabilised laser, was able to detect less than $5 \times 10^{-4}$ of a fringe.

The author has used interferometry technique (Michelson Interferometer) to study the effect of non-parallelism and behaviour of capacitance transducer using epoxy resin as a guard ring spacer. The details of the experiment will be given in Chapter 3.

2.5.2.2 Optical Amplifier

A review of the optical amplifier and optical lever has been given by Jones (1961) which he, with collaborators, developed for detecting an angular displacement of $10^{-10}$ rad and a linear displacement of $<1$ ppm. Andres (1961,1964) has used an optical grid amplifier for measuring the coefficient of linear expansion for a number of
metals with a resolution of 0.1 nm (< 1 Å) which corresponds to a sensitivity of $10^{-9}$ in $\frac{\Delta L}{L}$ at liquid helium temperatures. The disadvantage of the technique lies in the amount of drift and hysteresis on thermal cycling due most probably to the mechanical linkage in coupling the sample to one of the grids.

Bunton and Weintroub (1968) used another optical lever plus grid system with detection limit of 0.1 nm.

Shapiro et al (1964) and Pirera (1970) developed an optical lever based on double twisted Ayrton strip with a sensitivity of 1 ppm. Their value of $\alpha$ for copper has a scatter of $\sim 10^{-9}$ K$^{-1}$ at low temperatures, but differs much more than that between the samples which reflects either genuine differences in copper or problems of mechanical linkage.

2.5.3 Electrical Method

As mentioned in the introduction to this section that the measurement of thermal expansion of dielectrics and semiconductors, especially of those doped with a paramagnetic impurity, required a resolution of $10^{-10}$ in the measurement of $\frac{\Delta L}{L}$, which none of the techniques reviewed earlier are able to provide at low temperatures.

Although the three terminal capacitance technique has been used for measurement of thermal expansion of solids for the last twenty years or so, the technique has reached a sensitivity of $10^{-10}$ only in recent years. The technique is now being successfully used for detection of paramagnetic impurities in crystals (Brown, M A and Brown I J (1981)).

The basic idea of the three terminal capacitance technique is that a small movement of one of the plates of capacitor results in change in capacity which may be
FIGURE 2.5.1: Three terminal capacitor and its equivalent circuit
measured electronically and this change may be related to the corresponding linear displacement. Bijl and Pullman (1955) incorporating a capacitor in the tank circuit of radio frequency Colpitt oscillator, applied this technique to the measurement of thermal expansion at low temperature. A more recent adaptation of the capacitance dilatometer to the work of this type is due to White (1961a), a modified version of the instrument is due to Carr (1964) et al and later workers have designed systems similar in principle to improve sensitivity. These are all based on comparison of a three terminal capacitance bridge with a transfer ratio arm. The credit for developing this technique goes to the original work of A.M. Thompson and his group in CSIRO. Thompson (1958) has discussed the sensitivity that could be obtained with a capacitance probe for measuring mechanical displacement. He discussed the probe to be a small disc with a guard. For example a small disc of diameter 4 mm spaced 0.1 mm from the reference surface would easily support 100 volts giving a sensitivity of 10^-7 pF.

2.5.3.1 Capacitance Measurement

A three terminal capacitor along with its equivalent circuit is shown in Figure 2.5.1. The electrode G should completely surround the other two electrodes. In the equivalent circuit is shown three capacitances $C_{HL}$, the direct capacitance between the terminal H and L, $C_{HG}$ and $C_{LG}$ capacitance of conductors H and L with respect to ground. The terminal capacitances $C_{HG}$ and $C_{LG}$ are affected by the changes in the environment. The direct capacitance $C_{HL}$, usually referred to as capacity of three terminal capacitor is determined only by its internal geometry. This direct capacitance can be calibrated by three terminal measurement methods, utilising guard
FIGURE 2.5.2: Basic ratio bridge
circuits or transformer ratio arm bridge which include the terminal capacitance.

The capacitances, particularly those of high accuracy are measured by the null method which uses some form of conventional ratio bridge shown in Figure 2.5.2. The unknown capacitance $C_x$ is balanced by a calibrated, variable standard capacitor $C_S$ or by a fixed standard capacitor and variable ratio arm such as $R_1$. Such bridges with resistive ratio arms and calibrated variable capacitors or resistors can be used over a wide range of both capacitance and frequency. A much higher accuracy, better resolution and stability in capacitance measurement has been obtained with the help of inductively coupled or transformer ratio arms bridges.

2.5.3.2 Transformer Ratio Arms

To illustrate some of the salient features of the capacitance bridge, a simple capacitance bridge with transformer ratio arm is shown in Figure 2.5.3. A primary coil is wound symmetrically on a high permeability torodial core. The number of turns of the primary, used to excite the core, determine the load on the generator and do not affect the bridge network. The magnetic flux in a symmetrically wound high permeability toroid is confined to the core. Under such conditions the ratio of the open circuit voltage induced in the secondaries must be equal to the ratio of number of turns of the two secondaries. This ratio can be changed by the use of taps along the two secondaries, but when the number of turns between the taps is fixed, the voltage is highly invariant. The permeability of the core changes with time and temperature and this modifies to a small amount the leakage flux which is not confined to the core in a practical transformer. Thus the ratio is unaffected by permeability changes and hence is highly reliable, accurate and stable.
FIG. 2.5.3

AN ELEMENTARY CAPACITANCE BRIDGE WITH TRANSFORMER RATIO ARMS.
Figure 2.5.1: Geometry of different dilatometers (After Kroeger and Swenson 1977)

(a) Differential cell (normal)
(b) Differential cell (inverted)
(c) Absolute cell

Central electrode (low)
Gap between central electrode and its guard
Guard ring electrode
Sample
Expansion cell
High
Moveable plate
Sample
Expansion cell
Guard ring electrode
Low
Guard ring electrode
Low
Expansion cell
Sample
Low
Insulating space
Guard ring electrode
High
In the figure shown two transformer secondary windings are used as ratio arms of the capacitance bridge with standard capacitor $C_S$ and unknown capacitor $C_X$ as the other two arms in a four arm conventional bridge network. The condition for balance or zero detector current is given by

$$V_S C_S = V_X C_X$$

$$C_S / C_X = V_X / V_S = N_S / N_X$$

$$C_S / C_X = N_S / N_X \quad (2.5.1)$$

The junction of the two secondaries is known as guard point which is at ground potential. Both the standard and unknown capacitor are shown as three terminal capacitors. The capacity from the H terminal of these capacitors to the guard point is shown to be placed across the bridge secondaries. Under the ideal condition of no resistance of the secondaries and no flux that does not link equally, both the secondaries, the current drawn by H-G capacitance does not affect the induced voltages $V_S$ and $V_X$ and hence the balance condition. The capacities of L terminal of the capacitor $C_S$ and $C_X$ with respect to guard point are shown to shunt the detector, so that they only affect the bridge sensitivity. All capacitances from H or L corners of the bridge to the guard point G are excluded from the measurement. Therefore the bridge measures only the direct capacitance $C_X$ of the unknown in terms of direct capacitance $C_S$ of the standard without additional guard circuits or balances. The stability of the capacitance transform ratio arm bridge is mainly
determined by the temperature stability of the standard capacitors which are used for comparison with unknown capacity of the dilatometers. According to the instruction of the manufacturer, the bridge has been calibrated at $23 \pm 1^\circ C$ (where it can give best results - see manual of GR 1616 for details). This temperature was maintained and controlled electronically and the bridge calibrated quite often with the help of 10 pF standard capacitor type 1404C.

2.5.3.3 Dilatometers

General Radio high precision capacitance bridge GR 1616, capable of measuring capacity directly with a resolution of $10^{-6}$ pF was used to measure thermal expansion of various samples under investigation. With the help of a lock in amplifier, comprising of low noise amplifier, coherent filters and phase sensitive detectors, the sensitivity was improved to $10^{-7}$ pF. Thus with this arrangement length changes of 0.1 Å to 0.01 Å were easily detectable. The block diagram of the electronic detection system and computer control will be given in Chapter 4.

The most modern capacitance dilatometer uses three terminal capacitors and measures the capacity with associated ratio-transformer bridge using a technology originally developed by Thompson (1958). The balance conditions are not affected by lead capacitance. In the literature have been used various types of dilatometers (see Figure 2.5.4), after their first use by White (1961a) (also see Carr (1964) et al, White and Collins (1972)), but we have found differential dilatometer most suitable for the sample under investigation in this work, because of the small size of the samples used in our study, e.g. GaAS:Cr was 17.046 mm long, a-arsenic was 9.12 mm and vanadium silicate was 0.909 mm long.
The general design of differential dilatometer used in this work is shown in the Figure 2.5.4a, while for every particular sample it had to be modified according to the dimension of the sample. The central electrode (conical shape) is isolated from the ground by Stycast (Stycast 2850 and Catalyst 24LV). The various dilatometer are all non-linear devices in which sensitivity varies as the square of the gap which means that high sensitivity can be obtained by using a very small gap subject to the limitations described in Chapter 3.
CHAPTER III
AN INVESTIGATION INTO THE EFFECT OF NON-PARALLELISM AND BEHAVIOUR OF CAPACITANCE TRANSDUCER USING EPOXY RESIN AS AN ELECTRODE-GUARD RING SPACER

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CHAPTER 3
AN INVESTIGATION INTO THE EFFECT OF NON-PARALLELISM AND BEHAVIOUR OF CAPACITANCE TRANSUDER USING EPOXY RESIN AS AN ELECTRODE-GUARD RING SPACER

3.1 Introduction

The three terminal capacitance dilatometry has recently become a well established technique for measuring the thermal expansion of solids and is particularly suited to the measurement of length changes of the order of $0.01\mu m$ at very low temperatures where high sensitivity and stability are required. The foundation stone of the technique was laid largely by A M Thomson (1958) and his group. The pioneer work on this technique was done by White (1961a) and Collins and White (1964). Lancaster and Donaldson (1968) have used the technique to investigate magnetic critical phenomenon. Heerens and Vermeulen (1975) have done some work on the theoretical behaviour of guard ring capacitor. The experimental measurement of a linearity of capacitance transducer was carried out by Gladwin and Wolf (1975) under ideal conditions.

It was for the first time that M A Brown and C E Bulleid (1978) carried out experimental work in this area under non-ideal practical situations where electrodes may not be exactly parallel and surface states are often unknown. The gap between the central electrode and guard ring was filled with epoxy resin (Stycast 2850 + catalyst 24LV) as opposed to the original guard capacitor where Maxwell (1904) assumed a free space in deriving an equation for capacity of parallel plate capacitor. Consequently Brown and Bulleid suggested a slight modification to the Maxwell equation, hereafter referred to as 'Brown's equation'.
Their study of non-linearity was incomplete in the sense that its main plate could only be tilted along the horizontal axis with respect to the guard ring plate. They also studied the effect of non-linearity at larger angles i.e. 5.5' and 11.0' and hence at larger distances of separation. Unfortunately the data obtained by Brown et al could not very clearly discriminate between the two equations i.e. Maxwell's equation and its modified form. This was thought mainly due to two reasons, partly because it was extremely difficult to set up the apparatus to achieve and maintain the best parallel position of the plate, and partly because simple lapping of the plates might have left some curvature. These were some of the factors which inspired us to reinvestigate the matter to prove, or otherwise, the suggested modification to the Maxwell equation and also to extend the study of non-linearity to much smaller angles and distances of separation between the plates.

3.2 Theory of Guard Ring Capacitor Transducer

The simple expression for capacitance of an ideal parallel plate capacitor i.e. a capacitor consisting of two infinite, parallel and opposing charged plates, assuming no fringes of the field at the edges of the plate, is given by:

$$C = \frac{A \epsilon}{g}$$  \hspace{1cm} 3.1

where \( A \) is area of one of the plates, \( \epsilon \) is the absolute permittivity of the medium between the plates and \( g \) is the separation between the plates. Under the ideal condition the electric field between the plates to a first approximation can be assumed to be uniform and directed in a direction perpendicular to the plate surface. This fact
allows us to calculate directly the surface charge
density from the potential difference between the plates
and consequently the capacitance per unit area is given
by $\frac{\varepsilon}{d}$.

Since a practical capacitor does not have infinite
plates even under the best conditions, the field between
the plates will not be uniform. We should take account of
what happens to the lines of force at the edges of the
plates.

There is always some extra flux which arises because
of increased charge density at the edges of the plates and
charge on the sides and outer faces of the plates. This
is called fringing effect and is equivalent to lengthening
of the field at its edges. This fringing effect is shown
in Figures 3.2 and 3.3. The fringing effect can be effec-
tively reduced by use of a guard ring capacitor that
is the electrode at lower potential is surrounded by a
coplanar guard ring. The fringing effect can be reduced
to minimum provided gap between central electrode and its
guard ring is very small and deep and that $(r_1 - r_2) > g$
where $r_1$ is the radius of the guard ring and $r$ is the radius
of the central electrode. But the condition of no fringing
cannot be met completely, therefore fringing effect can be
reduced but cannot be eliminated altogether. That is why
in spite of a guard ring there is still some fringing
effect near the edge of the electrode, therefore a correc-
tion had to be made to the equation (3.1). This correction
roughly approximates to increasing the effective area of
the electrode from $A$ to $A + \Delta A$ where $\Delta A$ is the area of
additional strip extending over half of the width $\omega$ of
the gap between the central electrode and the guard ring.
The correction derived by Maxwell (1904) to the equation 3.1
is given by:
Attraction

Longitudinal tension in the lines of force

(a)

Repulsion

Lateral repulsion between the lines of force

(b)

FIGURE 3.1

Lines of Force between two Plates

FIGURE 3.2
The guard-ring capacitor: (a) the distorted field, (b) plan view, (c) side view (different scale).

FIGURE 3.3

GUARD RING GAP ELECTRODE

PLAIN PLATE

FIGURE 3.4
\[ C = \frac{A \varepsilon}{g} (1 + n) \]

where \( n \) is given by:

\[ n = \frac{\omega}{r} \left( 1 + \frac{\omega}{2r} \right) \left( 1 + \frac{0.22 \omega}{\varepsilon_s g} \right) \]

where \( r \) is the radius of the central electrode.

In order to achieve maximum mechanical stability, the gap between central electrode and guard ring was filled with Stycast 2850 + Catalyst 24LV by Brown et al. While Maxwell (1904) in the above derivation assumes that space between the guard and central electrode is a narrow deep gap without a dielectric filling it. The epoxy resin used by Brown et al had the effect of increasing the capacitance of space between the guard ring and the central electrode. Consequently to take account of this effect, Brown et al suggested a first order correction to Maxwell's equation.

\[ C = \frac{A \varepsilon}{g} \left( 1 + \frac{\omega}{r} \left( 1 + \frac{\omega}{2r} \right) \left( 1 + \frac{0.22 \omega}{\varepsilon_s g} \right) \right) \]

where \( \varepsilon_s \) is relative permittivity of Stycast.

3.3 Design Description

3.3.1 General

The existing apparatus was found to be very unstable and reproducibility, especially of the position of parallelism of the two capacitor plates, was very poor. The main plate could only be tilted with respect to the guard ring plate along
only one axis. It was thought that in order to study the effect of non-linearity properly, the main plate should be capable of being tilted along mutually perpendicular axes i.e. horizontal as well as vertical. The method of counting the fringes was not poor at all. Actually a binary counter was used to count the number of fringes. It was observed that a slight noise in the laboratory could produce hundreds of fringes more than were actually caused by the movement of the guard ring plate. The micrometer at the back of the guard ring plate used to move the guard ring plate towards or away from the main plate, was manually operated. We observed that a simple touch of two fingers (in order to rotate the micrometer) could produce tens of fringes which were counted by the binary counter. These were some of the considerations which made us completely redesign the whole apparatus. A schematic diagram of the apparatus is shown in Figure 3.5.

3.3.2 Mechanical

A cylindrical support (for the main plate) capable of rotating along the horizontal axis was designed and made out of brass. It consisted of a brass cylinder of 1.5 inch diameter, with a hole of about 1 cm diameter at its centre. An axle of suitable diameter with ball bearings, was fitted inside the cylinder with nuts on both sides. The cylindrical support contained a brass rod six inches long of diameter about 1 cm screwed on one side. The other side of this brass cylindrical support was made flat for mounting the capacitance plate. The main capacitance plate was mounted on this support which was screwed onto its base plate of dimensions 8" x 4" x 0.5" made out of steel. This base plate contained a micrometer screw at its other end with the help of which the plate could be tilted along the vertical axis. At a distance of about six inches from the cylindrical support, a steel
KEY TO THE DIAGRAM
1. Synchronous motor clock
2. Micrometer
3. Guard ring plate
4. Mirror
5. Plain plate
6. Beam splitter
7. Mirror
8. He-neon laser
9. Micrometer
10. Micrometer
11. Photo-diode
12. Leaf springs

FIG. 3.5. DIAGRAM OF APPARATUS
block of dimensions 3" x 1" x 1" was bolted on to this base plate. At a suitable height this block contained a long micrometer screw in the horizontal position. A groove was made at a suitable position in the horizontal brass rod, coming from the cylindrical support. A ball bearing of suitable size was placed in this groove. The horizontal micrometer screw from the steel block was made to touch the brass rod at the ball bearing point. The horizontal rod was fastened to the steel block with the help of a spring and a nail. This long micrometer screw and the horizontal brass rod stood perpendicular to each other. This arrangement of lever and screw mechanism made us capable of tilting the main plate with respect to the guard ring plate along two mutually perpendicular axes. This base plate was placed on to another base plate beneath it of similar dimensions with grooves and ball bearings of suitable size at the front two corners. The two base plates were capable of adjustment exactly parallel to each other with the help of vertical micrometer screws on the top plate. To achieve maximum mechanical stability the two base plates were fastened to each other with the small springs. The lower base plate was in turn bolted to a very big steel plate of thickness 6 mm reinforced with angle iron.

The adjustable assembly to which the guard ring plate was fixed consisted of two identical springs which together with two blocks of mild steel, moved as a part of the parallelogram. One of the blocks was fixed to the base plate, whilst screwed centrally in the other, was a post which was pushed via a rod and 10:1 reduction lever system by a two turn to a micrometer. The push rod acts on the post in the centre of the parallelogram in that applied force is symmetric. The post was held against the push rod by two coil springs which acted via pivotting bar so that their tensions were equal. Fixed to this was a mounting plate of the guard ring capacitor plate which could be tilted by means of
three adjustable screws at its back. Exactly similar mechanism was used to mount the moving mirror of the Michelson interferometer.

3.3.3 Capacitor plates

The capacitor plates were made from stainless steel to resist corrosion. Each plate was precision turned on a lathe. The guard ring plate was made in two parts. The cross-section of the two plates are shown in Figure 3.6. The diameter of the main plate is 60 mm and 10 mm thick. The central electrode was made of conical shape of diameter 25 mm. The conical hole of diameter 25.1 mm at angle of 30° was made in the guard ring. Two pieces of guard ring plates were bonded together with epoxy resin (Stycast 2850 + Catalyst 24LV). The central electrode was positioned as centrally as possible. The simple lapping of the plates might have left some curvature, therefore the plates were optically polished by Rank, Taylor Hobson Ltd to a curvature of less than a quarter of wavelength of sodium light over the entire width (60 mm), thus ensuring the optical flatness of the plates. The polished plates were bonded onto the mounting plates using the same epoxy resin, provision having been made for electrical connection to the three electrodes.

3.3.4 Optical system

This consisted of a 5 mW HeNe laser, a beam divider, two plane mirrors, a photodiode and an oscilloscope. The beam divider is a piece of glass coated on both sides to be 50% transmitting and 50% reflecting and is mounted on its stand at an appropriate place such that it makes an angle of 45° to the two plane mirrors i.e. stationary and moving ones, and to the beam coming from the HeNe laser. An exact 50-50 beam divider is not critically essential
FIGURE 3.6: Electrode Geometry
since both beams are reflected and transmitted again before reaching the photodiodes. The detector, in that a beam which is transmitted first is reflected a second time and the one which is reflected first is transmitted the second time. The moving mirror hereafter referred to as $M_m$, is pasted on an extension provided for the purpose on the mounting for the guard ring plate. The stationary mirror, hereafter referred to as $M_s$, is pasted on a metal plate of a suitable size and is held with the help of a spring and three screws, on the side of a mounting specially designed and made for the purpose which is bolted on to the main base plate. Initially both the mirrors $M_m$ and $M_s$ are set at equal distances from the beam divider. A beam coming from the HeNe laser placed on a stand bolted to the main base plate, is made to fall on the beam divider where from half is reflected and goes towards the stationary mirror $M_s$. The other half, which is transmitted, goes towards the moving mirror $M_m$. The stationary mirror $M_s$ has three screws at its back so that it can be adjusted exactly perpendicular to the incident beam. The $M_m$ is always perpendicular to the incident beam. These two beams incident perpendicularly on $M_s$ and $M_m$ get reflected and fall on the beam divider. The beam from $M_m$ is reflected at the beam divider towards the photodiode. The beam from $M_s$ is transmitted towards the photodiode. These two beams are coherent in that they are derived from the same source. The two beams therefore interfere constructively or destructively producing a bright or dark fringe according to their path difference being $0$, integral multiple of $\lambda$, the wavelength of HeNe laser $\lambda$ and $\lambda/2$, $3\lambda/2$, $(2n - 1)\lambda/2$ respectively. The distance through which the guard ring plate moves can be measured by counting the number of bright fringes which its motion causes. The simple relation used for calculating the separation between plates is:
\[ g = \frac{n\lambda}{4} \]

where \( n \) is the number of bright fringes.

3.4 **Fringe Counting**

The original electronic binary fringe counter constructed by Brown et al could not be used because of the reasons already described in that slight noise was found to be able to trigger the counter. Therefore this binary counter was bypassed and instead output from the photodiode was displayed on an ordinary oscilloscope through an amplifier. The output from the photodiode appeared as a slowly varying DC level on which noise was superimposed. Although some times the noise level was still quite high, it was found quite easy to detect changing DC levels as a fringe passed through the photodiode. The fringes which result as a movement of the guard ring plate were counted manually with the help of a hand counter. The fringes were counted at the single maxima (i.e. centre of bright fringes) by observing the output from the photodiode on the oscilloscope. This method of counting the fringes was found to be much more accurate than the binary counter. The advantage of this method was that it allowed the observer to detect any errors (bumps in DC level) as a result of some slight noise, although not heard by the observer in the laboratory, but might have penetrated the laboratory through the wall and consequently to the apparatus, while the binary counter would have counted the number of fringes as a result of slight noise without being detected by the observer.
3.5 Vibration Damping

The experiment was reckoned to be extremely vibration sensitive. Therefore every effort was made to make it as vibration free as possible. The main base plate with angle iron reinforcement at its bottom carrying the whole apparatus was placed on a really heavy steel plate of thickness 15 mm and of dimensions 1.5m x 1m which was capable of being floated on four partially inflated children's bicycle tubes. The entire apparatus was placed on a vibration free zone of the laboratory, i.e. a region of floor isolated from the rest of the building with foundations going as far down as the bed rock below the laboratory. This prevented most of the low frequency vibration generated within the building entering the experimental space. Unfortunately the experiment was found to be sensitive to sound vibration, in particular the low frequency sound. For example, normal speech caused only small ripples in the signal while a cough (predominantly low frequency composition), caused a very large noise signal to appear. Likewise the scraping of the chair and pipe noise generated by turning water taps on and off in various parts of the building also produced intolerably high noise levels.

The electrical noise generated by mains arcs when switches were turned on/off was also found to be a problem. This was minimised by encasing the entire apparatus in a metal shield connecting along with metal base plate to the mains earth. The double screened cables were used throughout to connect the capacitor electrode to the bridge. The outer screen was connected to the mains earth and inner screen to the bridge earth (a separate earth, i.e. copper pipe drilled into the bed rock below the laboratory), see Figure 3.7. Brown et al directed the micrometer manually, but in our case, due to unknown reasons, this was found
to be a source of noise. It was noticed that when the micrometer was touched with only two fingers (in a try to move it forward or backward) the binary counter recorded some fringes even though the micrometer was not moved at all. Therefore it was decided to use a synchronised electric clock motor (which completes one cycle in 15 minutes) to drive the micrometer to eliminate any noise generated when the micrometer is touched by hand. A heavy metal ring was mounted on the ends of the micrometer. On this ring were screwed two thin metal rods which engaged at right angles with two bars attached to the motor drive wheel. The results obtained with the electric clock motor were far more accurate than without it, in spite of the fact that the motor itself did induce 50 Hz mains vibration into the system. It was also noted that even switching on and off of this motor created slight noise which was considered negligible. Another probable source of some noise, if not impossible but very difficult to eliminate, was the mechanical noise generated as the guard ring plate and moving mirror were moved. The small bursts of noise are believed to be generated by leaf springs cracking or by the push rod making contact with the side of one of the springs as it moves through a small hole cut in that spring. The magnitude of this noise was not noticeable and therefore was considered negligible.

Using this arrangement, a number of efforts were made to take a vibration and noise free data, but unfortunately every time we tried we were met with partial success. This was thought due to the fact that the Physics building was not quiet, in that our laboratory itself had a number of rotary pumps working 24 hours and also elsewhere in the building very large numbers of equipment were working 24 hours producing a lot of electrical and mechanical noise. It was noticed that anybody walking upstairs in the corridor produced enough noise to disrupt our observation.
It was therefore decided to make a final effort during the Christmas holiday and nearby laboratories were requested to shut down their equipment. During this time the building was found to be quiet in every respect. Accordingly the experiment was performed at midnight till early morning from the 24 to 30 December. This time we were fortunate enough to get a vibration and noise free data set.

3.6 Preliminary Adjustments

There are two types of preliminary adjustments which are essential to be correctly made before starting the experiment:

1. Plate parallelism.
2. Alignment of Michelson interferometer.

3.6.1 Plate parallelism

Gladwin et al (1975) have used a very sophisticated technique of setting plate parallel. This technique consists of dividing the capacitor plates into three identical segments. The tilt of the plates is then adjusted till the capacitance of three segments becomes equal. This technique ensures the position of parallelism. The technique carries the disadvantage in that the edges or boundaries of the different segments would give additional fringing effects. This technique was therefore found highly unsuitable for the purpose of the present investigation.

Brown et al adopted a different technique in that they used a sheet of paper as a feeler gauge between the plate to judge the gap. The sheet of paper was lightly clamped between the plate, the sheet of paper was rotated to find
the point where the gap was narrowest. By judging the
gap between the plate, the guard ring plate was
accordingly adjusted with the help of tilt screws at
its back provided for the purpose, such that rotation
of the feeler gauge gave an idea of the gap between the
plates. This process was repeated several times until
it was realised that the rotation of the feeler gauge
made them feel that the gap between the plates was
uniform. This is an approximation and it was noticed
that reproducibility of this position of parallelism
was very poor.

We modified slightly the technique in that on the
sheet of paper to be used as a feeler gauge, was drawn a
circle of the same diameter as that of the plates and
this sheet was then positioned concentrically between
the capacitor plates and clamped lightly. Then by
rotating the sheet of paper, it was possible to estimate
the position of the point (conical point) on the sheet
about which the sheet rotates. If the sheet of paper is
rotating at a point other than the centre of the circle,
then definitely the plate is not parallel. Accordingly
the adjustment of the tilt screw at the back of the guard
ring plate was made and the centre of rotation of the
sheet examined again. This process had to be repeated
several times before we managed to get a position of the
plates where the sheet of paper between the plates rotated
around the centre of the circle on it. This technique
was found to be reasonably good and sensitive to small
adjustments of the adjusting screws. The calibrated
screw and lever tilt mechanism on the base plate carrying
the plain capacitor plate was used to estimate the accuracy
attained by this method. The calculation showed that one
turn of the calibrated micrometer screw was equivalent to
produce a tilt of the plain plate with respect to the guard
plate through 89 minutes. The head of the screw was divided into 16 equal segments by drawing lines on it. A reference point was chosen on the steel block (on the base plate). The rotation of the micrometer screw through 1/16 of a turn means an angle of 30 seconds, approximately.

It was noticed that when the plates were set parallel, a rotation of head of screw through the 1/16 of turn, or even less than this, i.e. angle of 30 seconds between the plates was easily detectable. Because the tilt of one of the plates with respect to the other through 30 seconds or even less made a quite substantial difference in the capacitance, i.e. the capacitance between the plates reduced drastically when the plates were not parallel, it must be stressed that this method is a crude approximation.

It is quite difficult to say with full confidence that the position we say is parallel, was absolutely parallel. The position of parallelism actually depends on the skill of the person performing the experiment. By following this method carefully one could easily manage to get a position of parallelism which is not very far off from the exact parallelism. The reproducibility was found to be a bit better than Brown et al.

We continued doing experiments following this technique of setting the plates parallel for some time, but we failed to produce any presentable results. For modification purpose, we had to dismantle the whole apparatus. We observed that rotation of the sheet of paper while clamped lightly between the plates had left the plates scratched very badly. Brown et al had shown that surface roughness affects the results in that surface roughness at very small separation and at very small angles between the plates extends the region of non-linearity. Therefore the plates were repolished optically again by Rabk, Hoffman and Taylor Ltd and the previously used technique of setting the plates parallel had to be abandoned altogether.
The method then adopted was similar in principle, the only difference being that no sheet of paper was used as a feeler gauge. The plates were moved as far apart as possible by moving the micrometer backward. One of the plates, preferably the plain plate, was set exactly parallel with reference to a source held between the plates. Then extreme care was taken so that none of the capacitor plates touched the source to avoid any scratches on the plates. The plain plate was set parallel with respect to the source in two phases. At first the plate was set parallel (vertical) with the help of the vertical micrometer screw at the end of the base plate and using a spirit level on the base plate.

The horizontal micrometer screw on the base plate was used to set the plain plate parallel horizontally. Thus a nearly perfect parallelism of one of the plates was ensured. The guard ring plate was brought as near to the plain plate as possible, i.e. very near to the touch point. At a small distance of separation i.e. \(< 50 \mu\text{m}\) capacitance between the plate is very sensitive to the non-parallelism. This fact was used as a basis for this method. Now the angle of guard ring plate was adjusted with the help of the tilt screw provided for the purpose at the back of this plate. If the value of the capacitance had increased, the adjustment is in the right direction. This procedure of moving the guard ring plate backward and forward and adjusting the angle with the help of screws at its back continued till maximum possible capacity was achieved. As is shown in the results, the position of parallelism thus obtained was 100% reproducible. Thus with the modified apparatus we were able to achieve a position of perfect parallelism. This proved beyond any doubt that the apparatus was quite stable and results obtained could be reliable.
3.6.2 **Alignment of Michelson Interferometer**

A simple and slightly different method as compared to Brown et al., was followed for the alignment of the Michelson interferometer. First of all the HeNe laser was adjusted so that the laser beam was incident on the beam divider. By placing a small piece of paper in front of the plain mirrors $M_m$ and $M_s$ it was ensured that the split parts of the laser beam were incident on the plain mirrors. A large sheet of white paper was used as a screen and placed at a distance of about 2 metres from the apparatus in the path of the two final beams coming from the beam divider, usually two small spots of light corresponding to two beams were seen on the screen. At the start these spots were well apart from each other. The tilt screws at the back of the mirror $M_s$ provided for the purpose, were slightly adjusted so that two spots coincide with each other and are seen as a single spot. A magnifying glass was then placed in the path of these beams, and a very clear view of the fringes was seen. The magnifying glass was then removed and instead a photodiode was placed at a suitable distance (< metre so that the photodiode should locate inside the aluminium box placed on the apparatus in order to screen the apparatus), such that the spot on the screen disappeared meaning thereby that two beams fall on the photodiode. The output from the photodiode was displayed on the oscilloscope. The real test of alignment is that the slightest tapping by pen, pencil or finger on the main base plate will produce hundreds of fringes on both the binary counter and oscilloscope. The synchronised motor was then switched on and the guard ring plate allowed to move. This produced fringes on the oscilloscope and binary counter, thus ensuring the complete alignment of the interferometer.
3.7 Capacitance Measurement

The diagram of connection of the capacitor electrodes to the capacitance bridge is shown in Figure 3.7. The central electrode is connected to the terminal L of the bridge, the guard ring being connected to earth (separate from the bridge earth (L)). It is stressed that both the guard ring and central electrode should be at the same potential but well isolated from each other. The plain electrode was connected to the H terminal of the bridge. The double screened cables were used throughout. The capacitance measurement was made with a General Radio high precision capacitance bridge GR 1615A accompanied by a General Radio frequency tuned amplifier and a null detector. This bridge had a capability of capacitance measurement with a resolution of 1 in $10^{-5}$.

The bridge is exactly the same in principle as the Wheatstone resistance bridge, only difference being that two halves of a centre tapped secondary of the transformer replaced the two resistance arm while the other two resistance arms were replaced by two capacitors, one known and calibrated and the other unknown, hence the name capacitance bridge. For the details the reader is referred to the previous chapter. The bridge sensitivity was further increased by working at an oscillator frequency of 7.2 kHz which enabled us to increase the working voltage up to 40 Volts. Furthermore, the measurements were made in constant temperature conditions, the temperature at which the bridge had originally been calibrated by the manufacturer. The equivalent circuit of three terminal capacitor is shown in Figure 3.8.

3.8 Analysis of the Data

After making preliminary adjustment of the position of parallelism at an angle of the capacitor plates and alignment of the Michelson interferometer, the guard ring
FIGURE 3.7: WIRING DIAGRAM FOR PLATES TO BRIDGE
FIGURE 3.8: Equivalent Circuit of Three Terminal Capacitor
plate was moved forward such that the two plates touched each other i.e. the DC resistance between the plates became zero ohms. The guard plate was then moved out slightly so that the DC resistance was more than 1 MΩ. This process was repeated two or three times in order to ensure that the plates were as close as possible without touching and that the capacity was maximum for that particular run.

The experiment gave us only relative separation between the plates. The separation between the plates when they were as close as possible and the capacitance was maximum, should be considered as a reference for calculating the absolute separation. Theoretically the separation between the plates when the capacitance was maximum, could be calculated most easily from the equation for an ideal parallel plate capacitor, but practically under the non-ideal condition, this may not be true especially when the plates are at an angle. Therefore it was very carefully estimated by counting the number of fringes between maximum capacity position and the touch point, that the condition when the DC resistance fell to zero at the touch point when the guard ring plate was moved in and that the DC resistance became greater than 1 MΩ when the guard ring plate was slightly moved out, was reproducible to \( \approx 2 \mu m \), when the plates were set exactly parallel to each other. This condition would definitely be true at a distance \( >2 \mu m \) in the case when the plates were set at an angle. Therefore in order to be systematic and uniform, we assumed this initial separation to be 10 \( \mu m \) as the reference point. This would in no way affect our experimental results because this distance of 10 \( \mu m \) used as reference was added to the separation of every data point of a set. In the most sensitive region \( <50 \mu m \), a region of particular interest in the present investigation, capacitance was measured when
the guard ring plate had moved a distance equivalent to a couple of fringes i.e. 1, 2, 3. It was noticed that in this region change of capacitance was of the order of ~30 pF for a single fringe.

Theoretically for an ideal capacitor, a plot of reciprocal capacitance vs plate separation must be a straight line passing through the origin, but practically under non-ideal conditions, the expression $C = \frac{A\epsilon_0}{g}$ for an ideal capacitor becomes a gross approximation especially when the plates are at an angle relative to each other. Thus when reciprocal capacitance vs plate separation was plotted for practical capacitor, it was seen that a straight line instead of passing through the origin bends towards the X axis in a region <100 µm and cuts the X axis before reaching the origin, see Figure 3.9. This region from the point where the curve starts bending towards the X axis to the origin, is known as the non-linear region in that the device does not behave as expected. The region beyond that i.e. a complete straight line which shows the linear region as in the case of an ideal capacitor. However when the straight line portion of the linear region is extrapolated, it cuts the X-axis on the negative side. Therefore a correction had to be made for non-linearity of the device. Thus the last few points of every data set beyond 150 µm were plotted as reciprocal capacitance vs plate separation. This resulting straight line was then extrapolated to join the X-axis. It was noticed in the case of parallel plates that the straight line joined on the negative side of the X-axis, but not very far off from the origin. As the angle between the plates was increased, i.e. the device became more and more non-linear, the straight line extrapolated joined the negative side of the X-axis at a further and further point. This distance on -ve X-axis was calculated in every case and was added to the separation of every data
$G_0 =$ GRADIENT PREDICTED BY MAXWELL'S EQUATION

$G =$ EXPERIMENTAL GRADIENT

FIG. 3.9: RECIPROCAL CAPACITANCE Vs PLATE SEPARATION
FIG. 3.10: RECIPROCAL CAPACITANCE VS PLATE SEPARATION FOR CALCULATING CORRECTION TO BE APPLIED IN THE INITIAL SEPARATION.
point for the particular data set. This is shown in Figure 3.10.

The data thus calculated were further processed by the computer. A computer program in Basic/Fortran was written by Brown I J. The computer program comprised two parts: The first part in Basic language was written for weighted 3rd order polynomial fit to the data of reciprocal capacitance and separation between the plates. The computer output was in the form of corresponding series of values of separation, reciprocal capacitance, fitted reciprocal capacitance, residuals and gradient. The second part of the computer program was written in Fortran language calling built in subroutines Grafit, Grafic and Axiplot for Plotting Capacitance vs separation, reciprocal capacitance vs separation and gradients vs separation.

A completely separate program was written in Basic to analyse theoretically Maxwell's and Brown's equations and comparing our results with those of Brown et al for changing values of $\varepsilon_s$, the relative permittivity of Stycast, the epoxy resin.

3.9 Results

By the technique outlined in the previous articles, measurement of the plate separation, $g$, and the corresponding capacitance $C$, were obtained with various relative orientation of the plates. Firstly the plates were aligned as near and parallel as possible by fine adjustment to maximise the value of capacitance obtainable. The separation of plates was then systematically increased whilst monitoring the capacitance and results are shown in Figure 3.11, plotted as reciprocal capacitance vs separation. The data obtained for $g$ gives relative changes in the
plate separation, but as described in detail in previous sections, the data can be corrected to produce 'absolute' plate separation and these values are the ones used throughout.

As can be seen from the Figure (3.11), a linear relationship is obtained between $1/C$ and $g$, but a small departure from linearity occurs at small values of $g$. As is shown in Figure 3.10 and explained earlier, this becomes clear when results are displayed in a different form i.e. point to point gradients are calculated and plotted as a function of plate separation $g$. The measurements were also taken after one of the plates had been rotated (a) clockwise by 1', (b) clockwise by 2' (c) clockwise by 5', (d) reset to perfect parallelism and (e) anticlockwise by 4'. The results are displayed in Figure 3.12. All the different orientations produced results that tend to the same gradient $(1/Cg)$ of $161.8 \times 10^{-6}$ (pf. $\mu m^{-1}$) at large plate separation. From equation 3.1 the gradient $G = \frac{1}{Cg} = \frac{1}{\varepsilon \sigma A}$ and thus one can calculate the effective area of the central electrode of the guard ring plate. The value obtained is $698.3 \pm 0.2 \text{ mm}^2$. The physical area of the electrode measured using a travelling microscope was $674.3 \pm 0.3 \text{ mm}^2$ giving a ratio between effective and physical areas of $1.036 \pm 0.003$.

The resetting of the parallel position was extremely difficult, the value of capacitance obtained being highly sensitive to the rotation of the order of seconds of arc. The two sets of data for parallel setting, obtained after much fine adjustment, agree very well. Also the curve obtained for anticlockwise rotation falls into the family of curves.
FIGURE 3.11: Reciprocal capacitance plotted against plate separation for parallel position of the electrodes.
FIGURE 3.12: Point to point gradients plotted against plate separation for the positions indicated below between the electrodes.
FIGURE 3.13: Point to point gradients plotted against peak separation. Fit obtained for different values of dielectric constant of Stycast used to fill in gap between central electrode and its guard.
3.10 Discussion

In order to compare the experimental data obtained with prediction of two models, Maxwell and Brown's equations i.e. equations 3.2 and 3.3, we have reported the data for small values of $g$ on a larger scale in Figure 3.13. Both models agree at limits of $g \to 0$ and $g \to \infty$, the difference lies in the intermediate range. Also both models can be interpreted to mean that the effective area of inner electrode of the guard ring system is:

$$A^* = A (1 + \eta)$$

where $A = \pi r^2$ is the physical area of the electrode and $\eta$ is the correction factor. Of course the values of $\eta$ are different in two different models, although they agree at a large plate separation where

$$\eta = \frac{\omega}{r} (1 + \frac{\omega}{2\pi})$$

giving a value of $\eta = 0.038 \pm 0.002$ if one substitutes the measured values of $\omega$ and $r$. Thus a ratio of $1.038 \pm 0.002$ between the effective and physical areas of large values of $g$ is predicted compared with the experimental value of $1.036 \pm 0.002$.

At small values of $g$ ($g \to 0$) both models predict the gradient should tend to a value of $(\pi \epsilon r^2)^{-1} = 167.9 \times 10^{-6}$ (pf. $\mu$m$^{-1}$). Such a value is not obtained experimentally and it is thought that this must be caused by residual non-parallelism of the order of seconds, the extreme sensitivity of the parallel setting giving some justification for the conclusion.
The only fixed point that we have to begin a comparison between the experimental and two theoretical models is at the $g \rightarrow \infty$ gradient value where both theories give common prediction. The experimental gradient of $161.8 \times 10^{-6}$ (pf. $\mu$m$^{-1}$) can be fitted with the values of $r = 14.635$ mm and $w = 0.54$ mm (compared with directly measured of $r = 14.65 \pm 0.005$ mm and $w = 0.55 \pm 0.022$ mm), the fit being very sensitive to the value of $r$, the radius of the inner electrode.

Taking this $g \rightarrow \infty$ fit, the theoretical curve can be computed using value of $\varepsilon_s$ and these curves are presented, together with experimental data in Figure 3.13. Of course a value of $\varepsilon_s = 1$ corresponds to the simple Maxwell's model (equation 3.2). Looking at the parallel plate data in Figure 3.13 to which the theoretical curve corresponds, it is clear that $\varepsilon_s = 1$ curve is unable to explain the experimental data. As one increases the value of $\varepsilon_s$ the theoretical curve falls lower and lower in the region $50 < g < 120 \ \mu$m and a reasonable fit to the experimental data is obtained for $\varepsilon_s > 10$, except for very small values of plate separation ($g < 40 \ \mu$m) where residual non-parallelism affects are thought to be important.

Using a standard capacitance technique, we measured the relative permittivity of Stycast 2850 with Catalyst 24LV, mixed and formed in our customary manner in this laboratory, from 500 Hz to 13 KHz. The value fell by only $\sim 12\%$ over the entire frequency range with increasing frequency and had the absolute value of $10 \pm 1$ at 7.2 KHz. This compared with a value of 6.3 at 1 KHz quoted by the manufacturer.

Finally, it is noted that including a dielectric filler between the central electrode and guard ring of the capacitance transducer, not only increases the mecha-
nical stability of the device, but should also produce a transducer that is linear down to smaller electrode separation. Indeed, the larger relative permittivity of the filler, the smaller the non-linear region should be. The Stycast is the most suitable material for such a dielectric filler having a relative permittivity of \( \sim 10 \) and being an extremely hard material, readily bonding to a wide variety of materials.

3.11 Conclusions

When separation between parallel electrodes of a capacitance transducer, i.e. \( g \) is greater than \( \sim 200 \) \( \mu \text{m} \), any effect of non-parallelism is small and any difference between theoretical models tested are unlikely to be important. With small plate separation, the effect of non-parallelism (\( \sim \) a few minutes) can be appreciable.

The simple Maxwell's model often used to describe the behaviour of parallel plate capacitance transducers, cannot describe our experimental results precisely. This is not unexpected since Maxwell's model assumed that the space between the inner electrode and guard ring was narrow, deep and under vacuum - not the practical situation. A simple modification of the Maxwell's equation including effects of using Stycast as a filler can satisfactorily fit our data down to \( g < 50 \) \( \mu \text{m} \) - when it is thought that residual non-parallelism effects become important. The value of relative permittivity of Stycast required to obtain an acceptable fit to the experimental data is consistent with the value obtained in a separate experimental determination.

It is concluded that, for very detailed experimental work, the modified Maxwell model is a more satisfactory
description of the behaviour of "perfectly parallel" plate capacitance transducers using dielectric as inter-electrode filler. Further the use of suitable fillers not only increases the mechanical stability of the system, but in principle could increase the linearity of the device for small electrode separation.
## CHAPTER IV
APPARATUS DESIGN, CONSTRUCTION 
AND WORKING

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CHAPTER 4

APPARATUS DESIGN CONSTRUCTION AND WORKING

4.1 The Design Criteria

The proposed area of investigation required a means of measuring thermal expansion of solids over a wide range of temperatures i.e. from 1.2°K to room temperature. The liquid helium temperature of 4.2°K can be obtained by directly immersing the system in it. Temperatures lower than 4.2°K can only be obtained by reducing vapour pressure over liquid helium surface. This required an additional can in the cryostat with some system of filling it with liquid helium controlled on the top of the cryostat i.e. at atmospheric pressure and temperature. We needed to have a high vacuum system to the can and a means of measuring the vapour pressure over the liquid surface inside the can. The dimension of the cryostat should be such that a considerable working space is available and should easily fit in the helium glass dewar already available in the laboratory. The large dimension of the apparatus obviously places a limit on the speedy cooling of the system, but once cooled can maintain that temperature for a considerable time due to its large thermal capacity.

The method of cooling should not involve any inefficient method of transfer of liquid helium so that running costs of the experiment can be kept as low as possible.

One of the major problems in any such design, apart from the obvious ones of availability of material, workshop facilities and necessary life time, is that of heat transfer.

In any apparatus designed to operate at temperatures considerably different from its surrounding and to measure
the properties of the sample which are strongly
temperature dependent, this factor is of vital impor­
tance. As a result a major part of the success or
failure of an apparatus to give accurate results can
often be traced back to the care taken to reduce heat
leak due to (i) conduction through low pressure gas
when vacuum is not sufficiently good, (ii) radiation,
(iii) conduction of heat flow along the tubes and
electrical leads (iv) Joule's heating or eddy current
heating effect. Therefore very careful calculation of
possible heat flows were made at an early stage.

4.2 General Construction

The outline given above resulted in the following
overall design being adopted. The schematic diagram is
shown in Figure 4.1. The apparatus which was placed in
the inner helium glass dewar simply consisted of a stain­
less steel can which formed the vacuum jacket. The sealing
arrangement of the can with its top plate (an indium seal
is used in the groove on the can under the top plate) is
self evident from the diagram and should need no further
explanation. The small stainless steel can is used for
lowering the temperature of the cryostat below 4.20K
by reducing vapour pressure over the liquid in it. As
is seen from the diagram, three stainless steel tubes,
one of diameter 10 mm at the centre and the other two of
diameter 5mm at a diameter of about 1 inch from the centre
of the can are soldered on its top plate. The central
tube is used for evacuating the can or pumping over the
liquid surface as required. The second stainless steel
tube of diameter 5 mm is used to measure the vapour pres­
sure over the liquid helium inside the can. The third
stainless steel tube of diameter 5 mm is used to fill
the can with liquid helium with a needle valve. In
KEY TO THE CRYOSTAT DIAGRAM

1 & 2 BNC Sockets (carrying capacitance leads) stycasted to CU piece making vacuum joint with the bush on SS tube

3 Needle valve

4 & 5 Ten pin sockets making vacuum joint with T piece on the SS Tube

6 Cu tube for pumping the vacuum jacket

7 A hole for liquid helium transfer tube

8 A hole for connecting the helium gas from the system to storage system

9 Top place of the cryostat

10 A stainless steel tube for pumping the small can

11 A stainless steel tube for measuring vapour pressure on the surface of liquid helium in the can

12 Vacuum jacket threaded male sealing ring

13 Top plate for making vacuum seal to the large can

14 Female threaded sealing ring

15 Large stainless steel can

16 Small stainless steel can.

17 Germinium thermometer CCG 731.

18 Thermal anchoring posts.

19 Cu tube of dia 3/4".

20 Stainless steel tube carrying the capacitance leads to the dilatometer

21 Brass piece for separating the capacitance leads.

22 Capacitance lead (low)

23 Stainless steel tube carrying the capacitance lead (high)

24 Holes for connecting the guard ring electrode to the expansion cell.

25 Plain electrode (HIGH)

26 Expansion cell.

27 Specimen

28 Platinum thermometer CCP

29 Capacitance lead (HIGH)

30 Germinium thermometer CCG 520.
addition to three stainless steel tubes from the small can, another two stainless steel tubes, one of diameter 7 mm and the other of diameter 3 mm, are soldered on the top plate of the vacuum jacket. The stainless steel of diameter 7 mm is used for dual purposes, i.e. for pumping the large can and also for carrying the experimental electrical wires from the top of the cryostat to the dilatometer. The stainless tube of diameter 3 mm is used for capacitance leads. The stainless steel tubes of diameter 10 mm and 7 mm used for pumping the small and large cans respectively, contain specially designed radiation shields at appropriate distance from the vacuum jacket so as to avoid any heat leak coming through these tubes. Some copper turning were also fed in, in order to minimise further any chances of heat leak.

Thus the top plate of the large can contained five stainless steel tubes. The length of these stainless steel tubes was estimated to be 70 cm from the top plate of the large can so that it can sit on polystyrene blocks at the bottom of the dewar without any strain on the tubes. These tubes were soldered in the top plate of the cryostat.

The needle valve for the inlet of liquid from the dewar into the small can is a stainless steel tapered needle seated in brass shoulder and is operated by turning the knurled head above the main plate.

At the top of the 3 mm stainless steel tube going to the vacuum jacket, is soldered a brass T piece at the ends of which is stycasted two BNC sockets carrying the capacitance leads to the dilatometer. Similarly at the top of the 7 mm diameter stainless steel tube is soldered a double T piece of copper, the two ends of which are used for 10 pin socket carrying the experimental electrical wires to the dilatometer and the third end is used for pumping the can.
At the bottom of the small stainless steel can is seen a brass plate of thickness about 1 cm and diameter 60 mm which carries a Cu tube of ¼" diameter and about 3" long. This Cu tube carries at its bottom another brass plate of similar dimension which is connected to the guard ring electrode of the dilatometer. The expansion cell may be connected to the guard ring plate by nuts and bolts. To the brass plate at the bottom of the small can are screwed two Cu rods of diameter 5 mm and about 70 mm long for thermally anchoring the experimental wires coming to the dilatometer to remove any heat they are carrying from the top of the cryostat.

4.3 High Vacuum System

One of the most important requirements in any low temperature apparatus is that of maintaining a high vacuum. Whether this vacuum lies in space around the refrigerant liquid (i.e. glass dewar), or in an enclosure in the liquid (i.e. large stainless steel can), a pressure of $10^{-5}$ torr or less must be maintained in order to ensure good thermal isolation and thermal equilibrium. Many authors, including Dushman (1962), Yarwood (1967), Roth (1976) and Barrington (1963) have discussed the technique of producing a high vacuum. The heat losses from the specimen by conduction and convection can be effectively minimised by producing a pressure of $10^{-4}$ torr or less in the experimental chamber. A schematic diagram of the high vacuum system for the cryostat is shown in Figure 4.2. The system requires four vacuums to be maintained, one for each of the following:

1. Larger stainless steel can
2. Small stainless steel can
3. Helium glass dewar
4. Manometers.

To economise we used three systems, one independent system was used for glass dewar, the vacuum system used for evacuating the larger stainless steel can was also used for evacuating the manometer. The diffusion pump on this system included a nitrogen vapour trap. The small stainless steel can was connected to a high speed helium sealed rotary pump.

4.4 Specimen Mounting

For cylindrical samples, the specimen mounting simply consisted of making a base plate to be screwed at the base of the dilatometer and a top plate (holding the top of the sample) forming the electrodes at higher potential which faces the guard ring electrode. For cylindrical samples, it is very easy to keep the electrode at higher potential perfectly parallel with respect to the guard ring electrode. However the samples under investigation were not cylindrical. We shall describe the sample mounting of the following of our samples:

1. Chromium doped gallium arsenide.
2. Amorphous arsenic.
3. Vanadium silicate.

The chromium doped gallium arsenide sample was rectangular in shape of length about 17.5 mm. For this a special base plate (shown in Figure 4.4) with a projection on it and similar top electrode, were made so that the sample may be clamped with the help of small metallic springs and screws. The sample was slightly clamped (sample was very brittle so a little unnecessary force could smash the sample) and G E Varnish was used to hold the electrodes firmly in
FIGURE (4.4): Top and Bottom Plates for Clamping the Non-Cylindrical Samples

Not to scale
FIGURE 4.5: Semi-Absolute Expansion Cell for Vanadium Silicate Sample
place. Extreme care was taken to ensure that there should not be any varnish between the sample and the electrode. The varnish was used only on the sides; Because the top and bottom faces of the sample were not perfectly flat, therefore, we could not stick the top electrode perfectly parallel to the guard ring electrode. Although non-parallelism does not effect the capacitance changes within limits, it does affect the absolute capacitance and moreover it extends the non-linear region to greater distance of separation between electrodes which can affect the sensitivity of the device. For the details of the effect of non-parallelism of the electrodes of capacitance transducer, the reader is referred to Chapter 3.

Almost the same technique was used to hold the amorphous arsenic sample at the base of the dilatometer and to stick the electrode at the top of the sample. In this case it was rather more difficult to stick the top electrode parallel to the guard ring electrode because of non-regular shape of the sample. However the top and bottom faces of the sample were ground to make them as flat as possible to get the best results.

The vanadium silicate sample was extremely short, i.e. about 0.9 mm long. A semi-absolute expansion cell was used. In this case a special second electrode plate of brass was made (see Figure 4.5). The three pieces of the sample were stuck with the help of G E varnish onto the guard plate. Extreme care was taken not to use the varnish between the electrodes and the sample. Extremely small quantities of varnish were used on the sides of the samples only. This plate carrying the sample was connected to the guard ring electrode with the help of nuts and bolts accompanying the elastic spring on the top of the guard ring electrode. The expansion cell was wrapped completely with aluminium foil to ensure electrical continuity.
4.5 Vibrations - A Problem

The thermal expansion measurements by a capacitance method is a technique where length changes of the order of 1/1000 of an angstrom are detectable. Therefore vibration can be a source of very serious disturbance. The problem of vibration in the study of capacitance transducers has been discussed in detail in Chapter 3 and needs no further explanation here. In order to minimise the chances of any vibration affecting the dilatometer, the cryostat was installed on a vibration free area of the laboratory completely isolated from the rest of the building with foundations going as far down as the bed rock below the laboratory. This prevented most of the low frequency vibration entering the experimental space. In order to further minimise the chances of vibration of any frequency disturbing the dilatometer, a concrete block of about 1½ tons housed in a wooden box supported by angle iron resting on wooden bars on the floor, was made. The concrete block was capable of being floated on tyres under the block between the wooden bars. The main rigid frame carrying the cryostat was bolted on to this block. This arrangement successfully prevented most of the vibration likely to disturb the experimental cell as could be seen by observing the noise spectrum of the capacitance signal.

4.6 Electronic Detection System

The electrical noise was also a problem in our experiments. The off balance signal from the capacitance bridge is of the order of microvolts which is difficult to recover at the original frequency of the oscillator used to energise the primary of the transformer. The unwanted frequencies may disturb the system. A block diagram of the detection system along with computer control of the cryostat is shown in
FIG. 4.3. Detection System and Computer Control of Cryostat
Figure 4.3. In order to minimise the noise pick up, double screened cables were used throughout. Furthermore a separate earth (a cu pipe drilled into the bed rock below the laboratory, soaked with water from a nearby water tap before every experiment) was used to connect the main frame carrying the cryostat, the outer case of the capacitance bridge and the outer shields of all the screened cables of the detection circuitry to one point. A separate "Servomex" AC stabilised power supply was used to supply power to the low noise amplifier, coherent filters, phase sensitive detectors and reference unit. The General Radio Co. oscillator model 1310B was used to energise the primary of the transformer of the capacitance bridge. The working frequency of the oscillator was set to 1 KHz. The original signal was amplified by a voltage amplifier before reaching the primary of the transformer. The original signal from the oscillator without being amplified, was also supplied to the reference unit through a buffer amplifier. The idea of using the buffer amplifier was to break the earth loop between the reference signal and the off balance signal from the capacitance bridge amplified by low noise amplifier. Two signals from a reference unit with a phase difference of $\frac{\pi}{2}$ were provided as reference signals to the coherent filters.

The off balance signal from the capacitance bridge is amplified by the low noise amplifier. The output from the low noise amplifier is fed to the coherent filters, one of which is used to recover the capacitance off balance signal while the other is used to recover the conductance off balance signal. The off balance signals and reference signals from the coherent filters are supplied to the phase sensitive detectors where off balance signals are detected. The capacitance off balance signal from the phase sensitive detector is measured digitally by connecting it to a Keithley nanovoltmeter and can also be monitored by connecting the
output to the chart recorder. This circuitry successfully reduced the electrical noise to an acceptable limit.

4.8 Computer Control of the Cryostat

Although a full chapter has been devoted to this subject, it seems worthwhile to give a brief outline here to act as a preparation for the detailed description in the next chapter. The block diagram of the computer control of the cryostat is shown in Figure 4.3 which also contains the detection circuitry.

The experiment involves the measurement of the capacitance of the dilatometer as a function of the temperature of the sample. In order to monitor the temperature of the sample over a wide temperature range i.e. from liquid helium temperature to room temperature, two thermometers on the sample cell, one germanium thermometer which can be used up to 700 K and a platinum thermometer which can be used from 700 K upwards to room temperature, were used. There is another germanium thermometer on the bath (small stainless steel can) which can monitor the thermal link between the bath and the dilatometer. A current source is required to supply current to these thermometers so that their potentiometric resistance and hence temperature can be calculated. There needs to be some sort of device to switch different currents (1 mA, 100 μA, 10 μA, 1 μA) at different temperatures, as given in the instructions in the manual of the manufacturer of the Ge thermometer, in order to avoid any excess Joule's heating effect. For this purpose a very sensitive Keithley nanovoltmeter was used to measure voltage across the thermometer and also to measure the off balance signal from the capacitance bridge.

A real world interface card was wired to enable the computer to read data from the Keithley DVM. Because the
Keithley DVM, as already explained, has to make a number of measurements (at least five in this case: voltage drop across three thermometers, current source and off balance signal), we needed to have some device for multiplexing the DVM. For this purpose a relay circuit containing 16 relays (mercury wetted reed type Form A of Radiospares £9) for eight different measurements was wired on an RS strip board card. On the same strip board card were wired 4 relays of the same type for switching different currents at different temperatures. This strip board relay card was controlled by computer using another real world interface card.

The third and most difficult aspect of the experiment was to manually balance the capacitance bridge against the large changes in capacitance of the dilatometer as a result of the temperature changes.

At liquid helium temperatures we need to have a resolution of $10^{-10}$ in the measurement of $\Delta l/l$, therefore the amplifier gain must be very high i.e. 90 dB. As the temperature rises, the capacitance of the dilatometer starts changing rapidly, therefore at this stage the low noise amplifier can work at lower gain positions i.e. 70, 50, 30 dB etc. This means that we had to have some means of switching different gain positions on the amplifier from lower to higher and vice versa. For this purpose a relay circuit containing equivalent output resistance of low noise amplifier was wired on an ordinary matrix board inside a well screened box. This relay circuit was controlled by another real world interface card. Because changes in the gain position of the amplifier were related to the time spent by the bridge at a certain gain position, a real time clock was wired onto a strip board RS card which was controlled by the same real world interface card.
At the time of change of balance on the bridge, we had to change to a short time constant for the phase sensitive detector so that it could respond to the changes immediately. Therefore a computer controlled relay circuit for switching time constants was built.

For changing the bridge balance, a relay circuit using conventional relays which were used to drive motors on the arms of the bridge were built. This relay circuit was controlled by another real world card.

The software controlling all these aspects of the experiment will be explained in detail later.

4.8 Data Analysis Technique

4.8.1 Calculation of the gap between electrodes of the dilatometer

The dilatometer produces a series of values of capacitance as a function of temperature. In order to convert the capacitance changes to the length changes, it is vital that separation of the electrode (i.e. gap) is calculated correctly at every point of the data set. From the knowledge of the original length of the sample and the gap thus calculated, it is fairly easy to convert capacitance changes to length changes. For this purpose a computer program in "Fortran" was developed by Brown I J (1982) to calculate the gap using well known expressions (explained in some detail in Chapter 3) for Kelvin guard ring capacitor i.e.

\[
C = \frac{\pi r^2 \varepsilon \varepsilon_0}{g} \left(1 + \frac{w}{r} \left(1 + \frac{w}{2r}\right) \left(1 + \frac{0.22w}{\varepsilon_s g} \right)\right)
\]

where \(g\) is the gap between the dilatometer electrode, \(r\) is the radius of central electrode, \(w\) is gap between central
electrode and its guard which was filled with Stycast, as explained earlier, and \( \varepsilon \) is the permittivity of Stycast. Knowing \( C, \omega, r \) the gap \( g \) between the electrodes can be calculated.

It is also understood that variable \( r \), the radius of the central electrode is a function of thermal expansion of Cu, the material used for its preparation. Its value at any temperature \( T_2 \) may be calculated from its measured value at a certain temperature \( T_1 \) by using the following relation:

\[
\frac{r_{T_2}}{r_{T_1}} = 1 + \int_{T_1}^{T_2} \alpha_{Cu} \, dt
\]

where \( \alpha \) is expansion coefficient of copper.

4.8.2 Calculation of expansion coefficient of copper

As already mentioned, we have used in most cases the differential dilatometer for measuring the thermal expansion of our samples. Therefore in order to enable us to calculate the absolute expansion coefficient of our samples it was vital to calculate the expansion coefficient of copper, the material from which the expansion cell was made. For this a computer program in 'Fortran' was developed by Brown I J (1982) which carried out the numerical integration of the power series expansion for Cu (Kroeger and Swenson (1977)) (which is widely accepted as standard expansion data for Cu) by the Guassian integration method.

4.8.3 Data fitting procedure

After converting the capacitance changes to the length changes as a function of temperature, the values of the expansion coefficient \( \alpha \) appropriate to successive pairs of
values of a data set could be calculated by using standard expression:

\[ \alpha = \frac{1}{\ell} \frac{\Delta \ell}{\Delta T} \]

\( \Delta T \) must be kept as small as possible otherwise a correction for finiteness of temperature interval may be required.

This method carries the disadvantage in that values of \( \alpha \) thus determined are susceptible to a great extent to random errors in \( \Delta \ell \) from point to point calculation.

The second more common approach for analysing thermal expansion data is to fit weighted polynomials to the data and to carry out numerical differentiation of the fit.

We have however, in this work followed a slightly different technique which consisted of fitting cubic spline functions to the data and to carry out numerical differentiation of the fit. The only reason for using cubic spline functions to our data being that it was available as a library subroutine in the University Computer Centre which, in addition to calculating polynomial fit also gave three derivatives of the fitted polynomial. For the detail of the technique the reader is referred to Brown I J (1982). The availability of library subroutine of interactive graphics systems was utilised and was incorporated in the computer program. The curve fitting of every experimental data set was carried out on the interactive graphic Sigma terminal S5600.
PLATE NO. 4.2.1: A Close-up of the Semi-Absolute Expansion Cell (Dilatometer) for Vanadium Silicate Sample. Also shows wiring from the thermal anchoring posts to the dilatometer.
PLATE NO 4.2.2: Top View of the Cryostat. Copper pipes shown go to different vacuum systems.
PLATE 4.2.3: Shows Cryostat and 1½ Ton Concrete Block on a Vibration Free Area. Also shows the vacuum system.
PLATE 4.6: Shows Necessary Electronics and DAI Computer
CHAPTER V
AUTOMATION OF THERMAL EXPANSION CRYOSTAT

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CHAPTER 5
AUTOMATION OF THERMAL EXPANSION CRYOSTAT

5.1 Introduction

As it has already been explained, anomalies in thermal expansion of most of the semiconductors and dielectrics of interest due to energy level splittings of impurity from transition metal ions e.g. chromium in GaAs or due to tunnel splitting occur at a very low temperature, i.e. around liquid temperature. However it is necessary to study the behaviour of some samples over a wide temperature range i.e. from 1.30K to room temperature. The low temperature range i.e. from 1.30K to 200K or so can be monitored easily, but to monitor the whole temperature range continuously from 1.30K to room temperature, is extremely difficult and tiresome because it takes at least 72 hours for the system, i.e. cryostat, to come to room temperature. Moreover manual observations are susceptible to errors. These were some of the factors which inspired us to completely automate the cryostat by making use of very recent DCE (Digital Control Element) technology of DAI microcomputer. The reason for selecting DAI microcomputer for this job, compared to other microcomputers on the market, was its capability of independently driving an industrial rack which can have 15 Real World interface cards, each having three I/O ports.

The automation was achieved by connecting crucial measuring equipment to the computer. In particular, a General Radio precision capacitance bridge model 1616 was bought for £10,000 which has a BCD connector at its rear panel for digital output. We already had a high precision Keithley nanovoltmeter which has the capability of giving a digital output (there is a 50 pin amphenol socket
at its rear panel for digital output). The Keithley DVM was multiplexed for making various voltage measurements. The most difficult part of the dilatometer automation was manually balancing the capacitance bridge. This was achieved by moving the bridge balance levers using threaded rods and worm drives powered by small DC motors (normally used by model making enthusiasts). The position of the levers was sensed by the computer monitoring the BCD output from the rear of the General Radio capacitance bridge.

Finally the gain of the amplifier and the time constant of the phase sensitive detector were changed as required by the computer.

5.2 The Structure of an 8-Bit Typical Microcomputer

The diagram (5.2) shows the internal organisation of a typical 8-bit microcomputer. The structure of most of the microcomputers are essentially the same in principle, although they vary in size of data and address bus, the type of control signal they use and finally in the technology behind the manufacture of memory devices such as ROM, RAM, PROM etc. The block diagram of a typical 8-bit microcomputer shows only the essential elements for the only reason of simplicity and not all technical details so as to make the things easier to understand.

5.2.1 The Microprocessor

A microprocessor is physically a very large scale integrated circuit containing equivalent to several thousand discrete electronic components (i.e. transistors, resistors and capacitors, etc) on a single semiconductor (e.g. silicon) chip about ½ cm square encapsulated with dual in line package with typically 40 pins. A microprocessor
contains a very large number of sequential circuits i.e. a circuit which will change its internal state and hence its output signal in phase with clock pulses which are usually generated externally. Each change of internal state is determined by microprocessor current internal state with a set of input signals. A microprocessor contains a number of registers (storage areas) and master control systems often called central processing unit (CPU), which forms the core of any computing system. The most important register is ALU (Arithmetic Logic Unit) which performs various logical operations such as addition, subtraction of the input words and determines such things as equality between them. This register also holds the results of various operations performed on the data. The other important registers are (i) program counter (PC) which at any time contains the address of the next instruction to be executed (ii) condition or flag register which consists of various flag conditions such as arithmetic overflow, a carry and a result 0 etc.

The sequence of instruction required to cause the microprocessor to complete a certain task - called a program which are held in a store or memory which can be understood to be a large array of bistable elements (flip flops). An address (a binary number defining the location of the memory) for each instruction is generated by the processor and presented to the memory. A copy of the instruction is then input to the microprocessor keeping the contents of the memory undisturbed.

5.2.2 The Bus System

The bus in a microcomputer is a group of wires which carry the information to and from the microprocessor and therefore form an essential element of any computing system. The buses can be unidirectional as well as bidirectional. In general there are three buses in a microcomputer
which carry all the information and signals involved in the operation of the system. The buses connect the microprocessor to each of the memories and the input/output element so that data information can flow between the microprocessor and any of these elements. In other words, a microprocessor is continuously involved in sending or receiving information to and from a location in a memory, an input or output device. The operation of a microprocessor when it is receiving data from another element is known as "READ" operation and the process of sending information is known as "WRITE" operation.

There are three kinds of buses in a microcomputer.

5.2.2.1 Address bus
This is a unidirectional bus because information can flow over it in only one direction i.e. from the microprocessor to the memory or input/output element.

5.2.2.2 Data bus
This is a bidirectional bus because information over it can flow to and from the microprocessor.

5.2.2.3 Control bus
This bus carries a set of signals that are used to synchronise the activities of separate microcomputer elements. Some of these control signals such as READ/WRITE, are the signals, the CPU sends to the other elements to tell them what type of operation is currently in progress. The I/O element can send control signals to the CPU.

5.2.2.4 I/O ports
During the execution of a program the microprocessor is constantly READING or WRITING into the memory. The program may also call on the processor to read from one
of the input devices or write into one of the output devices. Although the diagram of an 8 bit microcomputer shows only one input and one output device, there can be any number of each tied to the bus system. Each I/O device is normally connected to the bus system through some type of interface circuit. The function of the interface is to make the microcomputer and the device compatible so that data can easily pass between them. The interface is needed when the I/O device uses different signal levels, signal timing or signal format than the microcomputer. Although the I/O devices are treated like memory locations, they are significantly different from the memory in certain respects. One large difference is that the I/O device can have capability to interrupt the microcomputer while it is executing a program. That is the I/O device can send a signal to the microprocessor chip interrupt (INT) to tell the processor that it wishes to communicate with it. The processor will then suspend the execution of the program it is currently working on and will perform the appropriate operation with the interrupting I/O device.

5.3 Memory

The memory of any computing system can be classified into two main classes:

i) ROM (Read only memory)

ii) RAM (Random access memory)

5.3.1 ROM

This is a type of memory which can be called the 'brain' of a computer. It is permanent in nature. It can never be altered. This is built in and designed at an early stage of manufacture. It cannot be used for
storing (or writing to) programs or associated results.

ROM can be further classified into three main groups:

i) **Mask Programmed**: The bit pattern in this type of memory is determined in a final metalisation process for which special masks are prepared. The bit pattern cannot subsequently be changed.

ii) **Programmable Read Only Memory (PROM)**. This is also known as field programmable memory because it is programmed according to the user's requirements after the manufacturing stage. A microscopic nickel chromium connecting link within each memory cell is fused which is used to store logic 0. When logic 1 is required, the link is maintained.

iii) **(Erasable PROM) or (EPROM)**. This type of memory can be programmed electrically and can be erased when required by passing ultraviolet light through the quartz window on the top memory package. After erasure a fresh program can be entered.

5.3.2 **RAM**

This type of memory is used for storing programs and associated data and for holding results. The user can address any location at any time. This type of memory is volatile and is completely lost when the power is switched off.

RAM can be classified into main classes:

i) **Static RAM**

The storage element in this memory is bistable flip flop which can maintain its status quo. It can be read any number of times until a reset pulse is applied.
ii) **Dynamic RAM:**

In this type of memory use is made of the inherent capacitance of a semiconductor usually at the gate of MOS transistor. For example when this capacitance is charged, the logic '1' can be considered to be stored and logic '0' otherwise. Since charge decays it has to be refreshed periodically, that is data is rewritten again after every 2 ms or so which is known as refresh cycle.

The static RAM can be bipolar as well as n or P channel MOS. The dynamic RAMs are generally n channel MOS. For a single IC package the capacity commonly ranges from 256 bits to 1 kilobits, the higher capacities can be obtained by using several packages in parallel.

Research has always been aimed at expanding the package density. The recent development in the field of memory is the "bubble" memory. In this type of memory the storage element is a magnetic "bubble", a mere 2-3 thousandths of a millimetre can have a memory capacity 1 megabit per unit.

When a RAM is addressed, the control has to switch into either a read or write (R/W) condition. If a 'read' signal is received, the byte in the addressed memory location is read out in the data bus. Alternatively if a 'write' signal is received, then byte waiting on the data bus is loaded into the addressed location, any data already there being erased.

5.3.3 **Direct Memory Access**

A useful feature of this type of memory is that a control signal sent to the microprocessor can cause an external device to suspend processing via the I/O unit, while both the data and address buses are held free.
Data is then transferred directly from the I/O unit into the external memory or equally read from it without any action by the processor.

5.4 Read and Write Operations

We know that a microprocessor contains all the control and arithmetic circuitry which is required to execute a program of instruction stored in the memory. During the execution of a program microprocessor continuously performs read and write operations. It fetches an instruction from the memory with a read operation. The instruction thus received is interpreted, and it might again have to perform a read operation to obtain an operand from memory or it may have to write data to the memory.

5.4.1 Read Operation

The whole read operation can be split into the following four steps for diagrammatic illustration.

i) The microprocessor generates a proper logic level on R/W line (normally R/W = 1 for read) for initialisation of read operation. The R/W line is a part of the control bus and goes to the memory or I/O element.

ii) At the same time the microprocessor places 16 bit address code on the address bus to select a particular memory location or I/O device from which the microprocessor wants to receive data.

iii) The selected memory or I/O element places an eight bit word on data bus. All nonselected memory or I/O elements will not affect the data bus because their tristate output will be in the high impedance state i.e. disabled.
FIGURE (5.4.1): Typical Microcomputer Timing for Read Operation
iv) The microprocessor receives 8 bit data word from the data bus on its data pins $D_0 - D_7$. These data pins will act as input for $R/W = 1$. The eight bit data word is thus latched into one of the microprocessor internal registers i.e. accumulator.

We can illustrate these steps diagrammatically with the help of timing diagrams showing the inter-relationship between signals on various buses. Everything is referred to the clock signals $Q_1$ and $Q_2$. The complete operation occurs in one clock cycle which is typically 1 $\mu$sec for a MOS microprocessor. The leading edge of $Q_1$ initiates the microprocessor to generate the proper $R/W$ and address signals. After a short delay, typically 100 nsec for a MOS microprocessor, the $R/W$ goes high and the address bus holds the new address code (point A on the timing diagram). It is worth noting that the address bus waveform shows both possible transition (low to high and high to low) because some of the 16 address lines will be changing in one direction while the other changes in the opposite direction.

During $Q_2$ pulse the selected memory or I/O element device is enabled (point B) and proceeds to put its data word on the data bus. Prior to this, the data bus is in high impedance state since no device connected to it has been enabled. At some point during the $Q_2$ pulse, the data of the data bus becomes stable (point C). Again both possible data line transitions are shown in the diagram. The delay between the start of the $Q_2$ pulse and the data bus stabilising depends on the speed of the memory and the I/O element. For the memory this delay would be its access time. On the falling edge of $Q_2$ the data on the data bus are latched into the microprocessor (point D). Clearly, then, memory or I/O devices must be capable of putting data on the bus prior to the falling edge of $Q_2$ or proper transfer to the microprocessor will not occur.
Thus it is necessary to ensure that these devices have a speed compatible with the microcomputer clock frequency. This full sequence of operation has been shown in the diagram (5.4.1).

5.4.2 Write Operation

The whole write operation can be split into the following steps for diagrammatic illustration.

i) The microprocessor will generate proper logic levels ON R/W (R/W=0 for write) for initialisation of the write operation.

ii) At the same time the microprocessor places 16 bit address code on the address bus.

iii) The microprocessor then sends an 8 bit data word via its data pins D0-D7 which will now act as output. This eight bit data word comes typically from an internal register i.e. accumulator of the microprocessor. All other devices connected to the data bus have their output disabled.

iv) The data is taken by the selected memory or I/O element from the data bus. All nonselected memory or I/O elements have their inputs disabled.

The timing diagram (5.4.2) shows the full sequence of the write operation. The leading edge of Q1 initialise the R/W and address signals (point A). During the Q2 pulse the selected memory or I/O device is enabled (point B) and the microprocessor places its data on the data bus. After a short delay (typically 100 ns) the data bus levels become stabilised (point C). These data are then written into the selected memory location while Q2 is high. If an I/O device has been selected it usually latches the data from the data bus on the falling edge of Q2 (point D).
FIGURE (5.4.2): Typical Microcomputer Timing for Write Operation
5.5 Computer Program Description

5.5.1 Initialisation Phase

The program starts with the initialisation of various real world interface cards and the setting up of various control matrices. It initially applies a current of 1 mA to the thermometers, a 30 dB gain to the low noise amplifier and a long time constant to the phase sensitive detector. It then asks the user what gain of amplifier he would like to work at (the gain of the amplifier is associated with a mechanical arm on the bridge, each arm controlling a decade digit, the higher the arm value, the lower the gain e.g. arm 2 controlling the 0nF digit is associated with a 90 dB (maximum gain), while the arm 6 controlling 100,000 nF digit is associated with a 30 dB (minimum gain).

The program then sets the clock to the date and time supplied by the user through the computer keyboard and proceeds either to calibrate the capacitance bridge or to use the internal calibration data already supplied in the initialisation. Finally it asks for the "number of bridge off balance voltage" readings that should be taken (to obtain an average) per measurement cycle.

5.5.2 Reading Cycle

It measures the voltage across the standard resistance of 1 kΩ to calculate the exact value of the current flowing through the thermometers. It then measures the voltage drop across two thermometers. It reads the off balance signal coming from the bridge through the detection circuit to the Keithley nanovoltmeter. It then reads the capacitance from the bridge through a BCD interface at its rear panel.
5.5.3 Thermometers and Bridge Parameters' Print Out Phase

The computer has to make a number of calculations before it can print out thermometer and bridge parameters. It calculates the value of the current flowing through and the voltage drop across the thermometers. It calculates the resistance and hence the temperature of the dilatometer by using the respective thermometer calibration data. It calculates the capacitance in attofarads equivalent to the off balance signal measured using the bridge calibration data already supplied in the initialisation. Finally it calculates the actual capacitance of the dilatometer by adding to or subtracting from the capacitance of the dilatometer directly read from the capacitance bridge, the capacitance equivalent to the off balance signal. All the relevant parameters are shown on an example print out in photograph 5.5.1.

5.5.4 Checks and Adjustments Carried Out by the Computer in Each Measurement Cycle

The constant current source is controlled by the computer through a series of selectable relays. After each measurement cycle the computer checks that the correct current is selected for the temperature range currently being monitored (as advised by the thermometer's manufacturers).

There is provision in the program that, if due to some reason (most probably relay faults), the Keithley DVM goes 'blank' (without actually the off balance exceeding 2V, the maximum voltage which the Keithley DVM is designed to measure), a condition of overload or flag faults, then after completing five cycles of overload, the computer should abort that reading and take a fresh start from the beginning of the cycle.
There is also provision in the program (to cover a division by zero error) that if due to some reason (most probably a sticky relay), the computer reads a zero current, then the computer should print out "current fault, current < $10^{-7}$ amp" and should assume a current of 1 mA in the calculation and should start a fresh cycle. This avoids a catastrophic failure mid-experiment.

If the off balance voltage from the phase sensitive detector monitoring the capacitance bridge exceeds ±0.7 Volts (a safe working limit set by the program) the computer will set about 'manually' rebalancing the bridge until this off balance voltage is reduced to below ±0.3 Volts. It does this adjustment through a series of threaded arms driven through worms by electrical motors. Full details will be given later, but briefly the computer activates the relevant motors (in the correct direction) and senses a change in bridge balance through the BCD interface built into the General Radio capacitance bridge. It repeats this process until a reasonable balance is achieved.

If the time spent on a certain gain position exceeds 90 minutes from the last bridge balance and the balance has not changed, it would mean that this gain position is not sensitive enough to work. Therefore the computer should balance the bridge bringing the off balance signal down to 0.16 Volts and should then switch on to the next lower arm (i.e. the next more sensitive gain position if possible). On the other hand if the balance changes within half an hour from the last bridge balance, it would mean that this gain position of the amplifier is too sensitive to work at, and that the computer should balance the bridge bringing the off balance signal down to 0.3 Volt and should switch on to less sensitive gain position. This process of sensing the bridge arm, balancing the bridge, switching on more sensitive gain position from the less sensitive ones
PLATE NO 5.5.1: An Example Print Out of Bridge and Thermometer Parameter

**THERMOMETERS**

<table>
<thead>
<tr>
<th></th>
<th>NO. 1</th>
<th>NO. 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOLTAGE (V)</td>
<td>2.7226E-2</td>
<td>4.826E-3</td>
</tr>
<tr>
<td>CURRENT (A)</td>
<td>9.9755E-4</td>
<td>9.9755E-4</td>
</tr>
<tr>
<td>RESISTANCE (Ohm)</td>
<td>27.2919</td>
<td>4.83705</td>
</tr>
<tr>
<td>TEMPERATURE (°C)</td>
<td>291.315</td>
<td>102.35</td>
</tr>
</tbody>
</table>

**BRIDGE PARAMETERS**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BRIDGE VOLTAGE (V)</td>
<td>0.1603V</td>
</tr>
<tr>
<td>DELTA C</td>
<td>1565.98 aF</td>
</tr>
<tr>
<td>BRIDGE DISPLAY</td>
<td>025473131</td>
</tr>
<tr>
<td>BRIDGE READING</td>
<td>02547313.1 aF</td>
</tr>
<tr>
<td>ACTUAL CAPACITANCE VALUE</td>
<td>2545757.12</td>
</tr>
<tr>
<td>AT TEMPERATURE</td>
<td>291.315X</td>
</tr>
<tr>
<td>TIME ELAPSED FROM LAST BRIDGE BALANCE</td>
<td>33.0 MIN.</td>
</tr>
<tr>
<td>READING RELAY</td>
<td>0</td>
</tr>
<tr>
<td>BREAK IN LINE</td>
<td>2110</td>
</tr>
</tbody>
</table>
PLATE 5.5: (a) Shows the ribbon cable wiring for different interfaces from DAI microcomputer to the relevant equipment.
and vice versa, switching on short time constants to the PSD during the balancing operation and the long time constants afterwards, finally completing the measurement cycle and printing out of the relevant parameter continues until room temperature is reached.

It can be seen in the computer program given in the appendix that it is really a very long program (approximately 37 Kilobytes long) and therefore contains a number of major subroutines. We will give here a flow diagram of the main program to enable an overview of the automation of various aspects of the experiment to be obtained. The flow diagrams of some of the important subroutines will be given at the end of this chapter.

5.6 Interfacing

An interface is a connection between the digital world of a microcomputer and the Real World of analogue/digital voltage etc. An interface can be seen as hardware support for the software to enable the computer to control the peripheral device. Before discussing the necessary interfacing required to automate our cryostat it seems worthwhile to explain very briefly the General interface control, GIC, and Real World interface control RIC.

5.6.1 General Interface Control GIC

The DCE-bus of DAI Personal Computer provides a means of transfer of data and controls the information between the DCE bus compatible process and interface module. It is driven by GIC which provides 24 parallel input/output lines i.e. three 8 bit general purpose ports 0, 1 and 2. These ports can be software programmed independently to act as input, output, bidirectional or handshake control signals. Through selected bits or group of bits these
FLOW DIAGRAM OF MAIN PROGRAM

Block = 0

Set up Various dimensional arrays

Initialisation phase starts

Initialise DVM interface card 1 i.e. Out#13,130

Initialise RW' Card 3 to multiplex the data input from the capacitance bridge i.e. OUT#33,#90

Initialise RW Card 4 for multiplexing DVM i.e. Out#43,#80

Initialise the clock and amplifier gain control RW' card 5 i.e. Out#53,#88

FOR J%= 2 to 6

Read GAIN % (J%)

NEXTJ%

A

FIGURE 5.5.2
Initialise RW Card 6 for motors control i.e. Out#63,#90

Out#61,0 i.e. all motors off

GOSUB 6500 i.e. set the clock to the date and time supplied by the user

Start the clock by AC% (address) = 14 and DC% (data) = 1. GOSUB 6900 (write to the clock)

Set the initial time in STORET GOSUB 6700 i.e. (Reads the clock)

\[ \text{STORET} = \text{clock} \% (7) \times 10 + \text{clock} \% (6) \times 60 + \text{clock} \% (5) \times 10 + \text{clock} \% (4) \]

\[ \text{STORET} = \text{STORET} - 31.0 \]

Set up the bridge direction matrix

\[ \text{FOR } I\% = 0 \text{ to } 1 \]

\[ \text{FOR } J = 0 \text{ to } 8 \]

Read DIGIT\% (J\%, I\%)

\[ \text{NEXT } J\% \]

\[ \text{NEXT } I\% \]

FIGURE 5.5.2 ... continued
Set up the strobe array for DVM

FOR I% = 1 to 7

L% = 2\times L%

Strobe I lines IS% (I%) = 254 - L%

NEXT I%

Read Calibration data of germanium thermometer 1 or platinum thermometer on the expansion cell

Read calibration data of germanium thermometer 2 on the bath

Input ARM%

Print "New calibration" YES/NO

Gosub 9500 i.e. generate a bleep

Input Y$

\text{GOSUB, 9500 i.e. generate a bleep}
GOSUB 9000 i.e. temporary subroutine to calibrate the bridge

Print: 'Is this a real calibration?'

Y/N

Input Y$

GOSUB 9900 i.e. temporary subroutine to calibrate the bridge

GOSUB 9200 read the internal calibration data supplied already

Print the internal calibration data

When calibration finished print 'calibration complete - reset the bridge, press (space bar) when ready to continue''

GETC=A,(A=32 for space bar)

Input A

Is A=32?

Yes,

Print "How many capacitance reading"

Input U

FIGURE 5.5.2 ... continued
Reading phase starts

Print "reading relays"

Switch on relay pair φ, GOSUB 2000 i.e. DVM measures voltage across the standard resistance of 1 kΩ
DVM reading A = D

Wait

Switch on relay pair 1, GOSUB 2000 i.e. DVM measures voltage drop across thermometer 1
DVM reading C₁ = D

Wait

Switch on relay pair 2, GOSUB 2000 i.e. DVM measures voltage drop across thermometer 2
DVM reading C₂ = D

Wait

Switch on relay pair 3

Print relay pair i.e. Relay %

For S = 1 to U

FIGURE 5.5.2. contd
Print character A,B i.e. CHR$(64+S)$

Gosub 9500 i.e. generate a bleep.

Gosub 2000 i.e. DVM reads the bridge voltage
Bridge reading CO=D

NEXT S

Thermometers and bridge parameter calculation phase

Calculate the average bridge voltage CO=CO/U

Thermometer current
A = A/1000 i.e. STD Res. = 1000Ω

IERROR = ∅

Is the value of current >1E-7

No

Print "current reading fault i.e. A<1E-7"

A=ISTORE

Print "put current" =;A

IERROR=1.∅

Yes

FIGURE 5.5.2... continued
Germinium thermometer 1 resistance
\[ R = \frac{C}{A} \]
GOSUB 2300 i.e. calculate the temperature of thermometer 1 from its calibration data

Germinium thermometer 2 resistance
\[ R_2 = \frac{C_2}{A} \]
GOSUB 2500 i.e. calculate the temperature of the thermometer 2 from calibration data

GOSUB 2700 i.e. calculate delta \( C \), from bridge calibration data

Read the capacitance from the bridge directly and calculate the actual capacitance of dilatometer

Poke#31,0 i.e. switch on printer

Print output parameters

Switch off printer i.e. Poke#131,1

Decision making phase

If temp 1 < 2.9

No

Yes

FIGURE 5.5.2... continued
FIGURE 5.5.2. contd

Switch on 1 μamp current i.e. Out#42,130

If
   temp1 > 3.1K
   temp1 < 9.9

Yes
Switch on 10 μamp current i.e. Out#42,66

No

If
   temp1 > 10.2K
   & temp1 < 39K

Yes
Switch on 100μamp current i.e. Out#43,34

REM
temp1 > 40K

Yes
Switch on 1 mA current i.e. Out#42,18

Bridge balance check

Is the bridge working on arm = 2

Yes

Is the absolute value of the off balance signal i.e. CO < 0.7 volt

Yes

Is the bridge voltage CO < 0.7

Yes

No

No

No

No

No
Is the time spent on the arm is < 90 min i.e. (TIME-STORE < 90 min)

Decrease the arm
ARM% = ARM% - 1

Switch short time constant to P.S.D.

Switch relay pair 3
GOSUB 2000 i.e. read the bridge voltage
CO = D

Is bridge voltage
CO > 0.7

Switch on short time constant to P.S.D.

DIR$ = "D"
GOSUB 8500 i.e. Decrease the bridge capacitance by 1

Wait

Switch on relay pair 3
GOSUB 2000 i.e. Measure bridge voltage CO

Print CO = D, the bridge voltage

Is bridge voltage
CO < 0.3?

Is bridge voltage
D < 0.0?

Yes

Yes

No

FIGURE 5.5.2 ... continued
FIGURE 5.5.2... continued
Wait

Switch long time constant to P.S.D.

Poke#131,0
Switch on the printer

Print change of bridge ARM% to₂ARM%

Switch off the printer
i.e. Poke#131,1

STORET=CTIME
Go on monitoring the time and completing the measurement cycle

STOP
ports can be programmed to input/output data to or from the microprocessor. The DCE-bus is wired to provide 8 bit input/output data transfer, read/write control signal, two external interrupt request and 8 address control lines for selective access of module on the bus. Each interface module is plugged into the DCE-bus through the system connection and given a unique address via a hexadecimal switch on the module.

The GIC can operate in three I/O modes.

i) Simple input-output:
This mode requires no handshaking and data is simply read from or written to a specified post. Only outputs in this mode are latched.

ii) Handshaking input-output:
In this mode GIC automatically generates and processes the following handshake signals, i.e.

a) Input/output buffer full
b) Data strobe
c) Data acknowledge
d) Interrupt request

In this mode Ports 0 and 1 are devoted to input/output data, selected bits of Port 2 pass the handshake control signals.

iii) Bi-directional input-output:
In this mode Port 0 can be used for receiving data from a peripheral device and transmitting data from the microprocessor through a single 8 bit bus, i.e. it can be used both for inputting and outputting the data simultaneously. The handshaking signal maintains the proper bus discipline. The inputs and outputs are both latched independently from each other.
We have used the first mode i.e. parallel input-output, therefore it seems worthwhile to elaborate this further. The Figure (5.6.1) shows the pin arrangement of a 31 pin system connector. The 24 pins of these are reserved for parallel data communication through three 8 bit General interface (GIC) ports 0, 1 and 2. These ports are General purpose data channels configured under the direction of GIC. The Table (5.6.2) lists software controlled possibilities of different modes in the groups A and B. The group A lists the alternate modes that can be used to input/output data through the Port 0 and upper four bits of Port 2. Similarly the group B details the alternative modes that can be used to input/output data through the Port 1 and lower four bits of Port 2. A specific configuration from both the groups can be selected with the instruction of "GICC, A mode, B mode". For example "GICC, 2, 1" will select all the 8 bits of Port 0 in the input mode and all the 8 bits of Port 1 in the output, upper four bits (4-7) of Port 2 in the input mode and lower four bits (0-3) in the output mode. It can be seen from the Table (attached from the DAI manual), that the operations are fairly simple in the modes 0-3 in both the groups. In these modes data is simply written to and read from a specified port without requiring any hand-shaking control signals. Data written to the output port is latched and may be read back as if it were stored in the RAM memory. It is worth noting that Port 2 in these modes is used to transfer data to or from the peripheral device just like the Ports 0 and 1. We have written our program in high level language "BASIC". Therefore it was quite essential to make a command in "BASIC" language equivalent to that of the machine language "GICC, A mode, B mode", which can control the function of the ports. We have used different commands in different cases according to our requirement. The method of making an initialisation command for a Real World interface card will be explained in Section 5.6.2.1.
5.6.2 RWC-F Card

A Real World module is a connection between digital world of the microcomputer and Real World of analogue/digital voltage, noisy currents etc and enables the user to interface the custom designed circuitry to the DCE-bus. The user has simply to insert these cards up to a maximum of 15 cards in any combination with a unique address setting from 0-F provided by a hexadecimal switch on the board with parallel wired DCE Eurorack for realisation of his hardware requirements. This card is provided by the manufacturer of the DAI personal computer and carries a 31 pin system connector to be directly plugged into the DCE-bus, a comparator hexadecimal switch and Real World interface control RIC. The RIC is exactly the same type of device as the GIC on the DCE processor module. The functional block diagram of Figure 5.6.3 shows the hardware configuration of the RWC-F module. The RIC provides 8 bit three input/output data ports 0, 1, 2 (i.e. 24 I/O lines), two interrupt request lines, reset signal and power supplies. The wiring of the hardware component is brought to the edge of 100 x 100 mm predrilled free card are, as shown in the figure. The RIC on RWC-F has 3 data ports and a command register. The RIC may be configured in all specified modes specified for the GIC. Through a selection of bits or group of bits, the RIC ports may be programmed independently to act as input, output, bidirectional or handshaking control signals. The handshake control signal in a specified mode will be automatically generated by the RIC.

The four lines out of 8 lines of the DCE-bus reserved for card and device addressing are used for specific card address. The hexadecimal switch has a shaft with 16 positions from 0 to F. The different switch settings are selected by turning the shaft with a small screwdriver. The switch has 4 rockers each corresponding to a binary digit.
The 16 possible settings of the 4 rockers defines hexadecimal address in the range from 0-F. Every card plugged in the bus should have a unique address selected by the user. One side of each rocker is marked open or off and the other side marked with a number in the range 1 to 4. The end 1 corresponds to the least significant bit and end 4 corresponds to the most significant bit. Each rocker is pushed down towards the side marked open or off, and represents a binary 1 in 4 bit module address. All RWC modules present a standard hardware and software interface to the DCE bus. We have used the predrilled free area of the card for buffering the three input/output data ports with octal line tristate TTL drivers and thus 24 I/O lines are brought to the end of the card to be connected to the peripheral devices.

The RIC on RWC-F module must first be configured in any one of the above mentioned operational combinations by writing a control word to its command register. The bit definition for the control word is as follows:

```

B_7  B_6  B_5  B_4  B_3  B_2  B_1  B_0

=1' always

B mode in binary

A mode in binary
```

The RIC configuration sequence must always be followed by a compatible I/O command to RWC via the machine language subroutine or its equivalent. It must be ensured that the device connected to the I/O lines corresponds to the selected I/O operation. A photograph shows one of the Real World interface cards (RWC-F).
PLATE 5.6.1: Real World Interface Card (RWC-F)
(Component side)
PLATE 5.6.1(a): Real World Interface Card (RWC-F)  
(Track Side)
Figure 5.6.1 Positioning of Available Signals on RWC-F
RIC Configurations

Below is a summary of the different possible modes that can be used to input and output data through the three RIC ports:

<table>
<thead>
<tr>
<th>GROUP A MODE</th>
<th>PORT 0</th>
<th>PORT 2 (Bits affected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Output</td>
<td>Output (4-7)</td>
</tr>
<tr>
<td>1</td>
<td>Output</td>
<td>Input (4-7)</td>
</tr>
<tr>
<td>2</td>
<td>Input</td>
<td>Output (4-7)</td>
</tr>
<tr>
<td>3</td>
<td>Input</td>
<td>Input (4-7)</td>
</tr>
<tr>
<td>4</td>
<td>H.S. Output</td>
<td>H.S. C. (3, 6, 7) Output (4, 5)</td>
</tr>
<tr>
<td>5</td>
<td>H.S. Output</td>
<td>H.S. C. (3, 6, 7) Input (4, 5)</td>
</tr>
<tr>
<td>6</td>
<td>H.S. Input</td>
<td>H.S. C. (3, 4, 5) Output (6, 7)</td>
</tr>
<tr>
<td>7</td>
<td>H.S. Input</td>
<td>H.S. C. (3, 4, 5) Input (6, 7)</td>
</tr>
<tr>
<td>8</td>
<td>Bi-directional</td>
<td>H.S. C. (3, 4, 5, 6, 7)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>GROUP B MODE</th>
<th>PORT 1</th>
<th>PORT 2 (Bits affected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Output</td>
<td>Output (0-3) +</td>
</tr>
<tr>
<td>1</td>
<td>Output</td>
<td>Input (0-3) +</td>
</tr>
<tr>
<td>2</td>
<td>Input</td>
<td>Output (0-3) +</td>
</tr>
<tr>
<td>3</td>
<td>Input</td>
<td>Input (0-3) +</td>
</tr>
<tr>
<td>4</td>
<td>H.S. Output</td>
<td>H.S. C. (0, 1, 2)</td>
</tr>
<tr>
<td>6</td>
<td>H.S. Input</td>
<td>H.S. C. (0, 1, 2)</td>
</tr>
</tbody>
</table>

**Notes:**

+ Bit 3 not affected if Group A in modes 4 through 8

In the above H.S = Handshake

H.S. C = Handshake Control

.. **TABLE 5.6.2**
5.6.2.1 Method of Making Initialisation Command to a Real World Interface Card

It has already been explained in the previous sections, that this card could be addressed by any one of the available addresses i.e. 0-F. The card therefore needs to have an initialisation command which is sent to the command register either in machine language or its equivalent. Because we planned to write our program in the high level language "BASIC," it was therefore essential to make a means of initialising this card in BASIC equivalent to that in machine language. For this purpose we consider an 8 bit port split into two subports of 4 bits each, which can show all the different modes in groups A and B.

<table>
<thead>
<tr>
<th>Hexadecimal Equivalent</th>
<th>Mode No</th>
<th>Group A modes</th>
<th>Group B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Always=1</td>
<td>Group A</td>
<td>Group B</td>
<td></td>
</tr>
<tr>
<td>00</td>
<td>0</td>
<td>0 0 0 0</td>
<td>0 0 0</td>
</tr>
<tr>
<td>09</td>
<td>1</td>
<td>0 0 0 1</td>
<td>0 0 1</td>
</tr>
<tr>
<td>92</td>
<td>2</td>
<td>0 0 1 0</td>
<td>0 1 0</td>
</tr>
<tr>
<td>A3</td>
<td>3</td>
<td>0 1 0 0</td>
<td>0 1 1</td>
</tr>
<tr>
<td>B4</td>
<td>4</td>
<td>0 1 1 1</td>
<td>1 0 0</td>
</tr>
</tbody>
</table>

We see that three bits $2^0$, $2^1$, $2^2$ of port I have been reserved for all the modes in group B. The bit $2^3$ of Port 1 and bits $2^0$, $2^1$, $2^2$ of Port 2 have been reserved for all the modes in Group A. the bit $2^3$ of Port II is always =1. For card initialisation we adopted a general formula which is:

$$\text{Out} \#IJ, \#AB$$

where I is card address which can be any number from 0 to F, J is the number of ports which is usually 3, A is the mode number in Group A, and B is the mode number in Group B.
For example we want to set ports 1 and 2 as output ports and port 0 as input port of card 6. If we look at the Real World interface (RIC) card configuration of different possible modes (see Table 5.6.2), we see that mode 2 in Group A and mode 0 in Group B meets our requirements. The binary equivalent of mode 2 in Group A is 9 (see last page). Therefore initialisation command for this card would be:

\[
\text{Out#63,#90}
\]

Similarly, Out#43,#80 will set all the three ports 0, 1 and 2 of the card 4 as output ports. Likewise any card can be initialised by selecting different modes according to the specific requirements of the user.

The same command could be used with slight modification for sending logic "0" or "1" to individual bits of a port.

For example the command:

\[
\text{Out#61,0}
\]

will cause the computer to send logic "0" to all the bits of port 1. Similarly the command:

\[
\text{Out#61,255}
\]

will send logic "1" to all the bits of port 1. Likewise

\[
\text{Out#61,64}
\]

will send logic "1" to bit 6 only while all the other bits remain low.
5.7 Data Transmission Techniques

The interface between the computer and the outside world is known as a port. Data enters or leaves the system through a port. There are two kinds of ports i.e. input port and output port. The input port accepts the data from the external device and presents it to the computer, while the output accepts the processed data from the computer and prepares it for use for whatever device is electrically connected.

There are two types of I/O port, serial and parallel. A serial port accepts the data from the external device in serial fashion (i.e. one bit at a time) and returns the processed data to the output device in the same way. The parallel port accepts and delivers all the multibit data words at a time, therefore these ports can operate much faster than serial ports.

Let us assume an 8 bit pattern in some register or memory which we want to output. If the device we are dealing with is capable of receiving all the 8 bits at a time (i.e. possesses 8 lines that can be used for input), we can use peripheral interface devices that transmit data in a parallel fashion (all bits at a time). This technique is known as parallel I/O and is shown in Figure 5.7.1(a). Similarly if a device is capable of transmitting eight bits in parallel, we can capture this with the help of a parallel input device and transfer it to the memory or register.

There are devices which are capable of receiving or transmitting only one bit at a time. If we still wish to receive/transmit 8 bits, this can be done serially (i.e. only one bit at a time should be sent). This would necessitate the use of a serial peripheral device to effect the serial I/O. The actual serialisation of the
(a) Parallel I/O

(b) Software serialisation

FIGURE 5.7.1(c): Hardware Serialisation
data (i.e. breaking up into individual bits) can be done by software so that only one bit at a time is sent to the device (PD), alternatively it may be done by the device itself. In the latter case 8 bit word is sent at a time to the PD, the PD then serialises the data, perhaps with the shift register and transmits one line at a time. Similarly we can receive data from serial peripheral devices. In this case the PD will wait until all the 8 bits have been captured and then make this pattern available (hardware parallelisation) or alternatively bits may be made available individually and thus merging by software.

5.7.1 Data Transmission from DVM

The Keithley digital nanovoltmeter (180 model) has a 50 pin Amphenol socket for computer controlled digital output. DVM can read a maximum of 1.999 Volts. For a voltage exceeding 1.999, the DVM will go blank, a condition which is called the overload condition. The DVM also shows polarity i.e. plus or minus. The range on the DVM from micro to millivolts or vice versa changes automatically. The decimal point has a floating position. It shifts its position automatically, i.e. it can be before the first digit, after the first digit, second digit or third digit. In all 26 bits of information have to be sent to the computer. The 16 bit information is reserved for 4 digits (4 bits $2^0, 2^1, 2^2, 2^3$ for each digit). The 10 bit information is required for decimal points 1, 2, 3 and 4, polarity, range changing and overload.

We cannot afford to send all 26 bit information in parallel. Serially it would take too long. Therefore a compromise was made between serial and parallel transmission so that 4 parallel data lines, each having in series six/seven bits of information which was thought to be the best possible solution. There are seven 7 strobe
lines one to enable each row of serial data.

The DVM has conveniently open collector data output. We have wired 1 KΩ 8 resistors, pulled up to +5V, on these outputs so that they operate at the same logical level as RWC-F interface. Each port of RWC-F interface is buffered by an octal line driver TTL chip (74 LS244). The buffers are wired so that Port 0 of the card acts as output port, which therefore output strobe signals and port 1 is used as input port, of which only 6 bits 0-4, 7 are used. Port 2 remains unused. The bits 0-3 of Port 1 receive four parallel data lines, each line consisting of six/seven bits of information. The data gives information on DVM display, decimal point, range (function), polarity and overload. To summarise:

i) data #1 gives unity in binary.
   data #2 gives tens in binary
   data #3 gives hundreds in binary
   data #4 gives thousands in binary

ii) over-range gives $1 \times 10^4$ digits.

iii) $DP_1$, $DP_2$, $DP_3$, $DP_4$ gives decimal point position.

iv) Function 1 is '1', function 2 is '0' for mV range and vice versa for mV range and function 3 remains unused.

v) Polarity is at logic '1' for plus and '0' for minus sign.

vi) Overload is at logic '1' when reading in excess of 1.999 volts.

The bit 4 of port 1 is '0' if the range changes. The bit 7 of port 1 connected to the flag is at logic '1', when the most recent data is available at the data lines. The seven bits of port 0 strobe the six/seven serial bits of data line coming $\overline{T_c}$. port 1, with active '0' i.e. '0'
enables and '1' inhibits the data. When hold #2 is '0' the DVM stops sampling the new information and display is frozen - the data must be read in this state. A flow chart of the sequence of operation of the computer program required to read the DVM will be given at the end of the chapter. The procedure is fairly simple in principle and the only point worth important consideration is that in the case of change of flag or range, the reading should be aborted and the DVM must make a fresh start. The scheme of connection of 4 data lines, range changes and flag conditions to the input port and that strobe signal to output port has been shown in Figure 5.7.2

5.7.2 DVM Interface Card (RWC-F1)

The hexadecimal address on this Real World card was set to 1. As usual all three ports (i.e. Port 0, Port 1 and Port 2) were buffered by enabled octal line tristate buffers 74 LS244, in the predrilled free area provided for the purpose on the card. A 32 pin RS edge connection was soldered with pins in the holes at the end of the card. There are various modes of operation of these ports as explained in the manual. As already explained, 26 bits of information have been serialised and provided at bits 0-3 of the port 1 (six/seven bits of information in serial on each bit). So 26 bits of information from 4 parallel data lines are received on port 1. The bits 4 and 7 of port 1 are used for range change and flag condition. The port 0 is used as output port which outputs various strobe signals. The port 2 remains unused. A fifty way ribbon cable with one end on the edge connector of RWC-F1 and the other to the amphenol plug is wired. This scheme of connection of the Real World interface card and amphenol plugs with pin numbers and colours associated with various bits of ports is shown in the Table (5.7.3). The unused pin connections of amphenol plug have not been shown. This card was initialised by the command Out#13,130.
Fig. 5.7.2 DVM Interface
TABLE 5.7.3: The Wiring Scheme of DVM Amphenol Plug to the RWC-Fl

<table>
<thead>
<tr>
<th>Keithly Digital Nano-voltmeter</th>
<th>Amphenol Pin No</th>
<th>Function</th>
<th>Ribbon Cable Colour</th>
<th>Strip Con Pin No.</th>
<th>Port/Bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keithly Digital Nano-voltmeter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RWC-Fl</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Amphenol Pin No</th>
<th>Function</th>
<th>Ribbon Cable Colour</th>
<th>Real World Interface Card (RWC-Fl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$2^0 \times 10^0$ Data#1</td>
<td>Black</td>
<td>1 (+ 5V)</td>
</tr>
<tr>
<td>2</td>
<td>$2^1 \times 10^0$ Data#1</td>
<td>White</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>$2^2 \times 10^0$ Data#1</td>
<td>Grey</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>$2^3 \times 10^0$ Data#1</td>
<td>Violet</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>$2^4 \times 10^1$ Data#2</td>
<td>Blue</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>$2^5 \times 10^1$ Data#2</td>
<td>Green</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>$2^6 \times 10^1$ Data#2</td>
<td>Yellow</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>$2^7 \times 10^1$ Data#2</td>
<td>Orange</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>$2^8 \times 10^2$ Data#3</td>
<td>Red</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>$2^9 \times 10^2$ Data#3</td>
<td>Brown</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>$2^{10} \times 10^2$ Data#3</td>
<td>Black</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>$2^{11} \times 10^2$ Data#3</td>
<td>White</td>
<td>12</td>
</tr>
<tr>
<td>13</td>
<td>$2^{12} \times 10^3$ Data#4</td>
<td>Grey</td>
<td>13</td>
</tr>
<tr>
<td>14</td>
<td>$2^{13} \times 10^3$ Data#4</td>
<td>Violet</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>$2^{14} \times 10^3$ Data#4</td>
<td>Blue</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>$2^{15} \times 10^3$ Data#4</td>
<td>Green</td>
<td>16</td>
</tr>
<tr>
<td>17</td>
<td>$2^{16} \times 10^4$ over-range</td>
<td>Yellow</td>
<td>17</td>
</tr>
<tr>
<td>19</td>
<td>DP1 (1.000)</td>
<td>Orange</td>
<td>18</td>
</tr>
<tr>
<td>20</td>
<td>DP2 (10.00)</td>
<td>Red</td>
<td>19</td>
</tr>
<tr>
<td>21</td>
<td>DP3 (100.0)</td>
<td>Brown</td>
<td>20</td>
</tr>
<tr>
<td>22</td>
<td>DP4 (1000.0)</td>
<td>Black</td>
<td>21</td>
</tr>
<tr>
<td>27</td>
<td>Output Lo</td>
<td>White</td>
<td>22</td>
</tr>
<tr>
<td>33</td>
<td>FLAG</td>
<td>Grey</td>
<td>23</td>
</tr>
<tr>
<td>34</td>
<td>Range Change</td>
<td>Violet</td>
<td>24</td>
</tr>
<tr>
<td>35</td>
<td>Function 1</td>
<td>Blue</td>
<td>25</td>
</tr>
<tr>
<td>36</td>
<td>Function 2</td>
<td>Green</td>
<td>26</td>
</tr>
<tr>
<td>37</td>
<td>Function 3</td>
<td>Yellow</td>
<td>27</td>
</tr>
<tr>
<td>38</td>
<td>Overload</td>
<td>Orange</td>
<td>28 (GND)</td>
</tr>
</tbody>
</table>

- Flag: Grey
- Range Change: Violet
- Function 1: Blue
- Function 2: Green
- Function 3: Yellow
- Overload: Orange
TABLE 5.7.3 ... continued

<table>
<thead>
<tr>
<th>Amphenol Pin No</th>
<th>Function</th>
<th>Ribbon Cable Colour</th>
<th>Real World Interface Card (RWC-Fl)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Strip Con Pin No.</td>
<td>Port/Bit</td>
</tr>
<tr>
<td>39</td>
<td>Polarity</td>
<td>Red</td>
<td>5</td>
</tr>
<tr>
<td>40</td>
<td>Trigger</td>
<td>Not connected</td>
<td>-</td>
</tr>
<tr>
<td>41</td>
<td>HOLD#2</td>
<td>Brown</td>
<td>18</td>
</tr>
<tr>
<td>43</td>
<td>Strobe over-range</td>
<td>Black</td>
<td>23</td>
</tr>
<tr>
<td>44</td>
<td>Strobe Flag</td>
<td>White</td>
<td>28 (GND)</td>
</tr>
<tr>
<td>45</td>
<td>Strobe Function</td>
<td>Grey</td>
<td>25</td>
</tr>
<tr>
<td>46</td>
<td>Strobe Data#4</td>
<td>Violet</td>
<td>22</td>
</tr>
<tr>
<td>47</td>
<td>Strobe Data#3</td>
<td>Blue</td>
<td>21</td>
</tr>
<tr>
<td>48</td>
<td>Strobe Data#2</td>
<td>Green</td>
<td>20</td>
</tr>
<tr>
<td>49</td>
<td>Strobe Data#1</td>
<td>Yellow</td>
<td>19</td>
</tr>
<tr>
<td>50</td>
<td>Strobe Dec.Pt.</td>
<td>Orange</td>
<td>24</td>
</tr>
</tbody>
</table>

Note: Pins not connected have not been shown
5.8 Multiplexing the DVM

A multiplex or data selector is a logic circuit that accepts several data inputs but allows only one at a time to get through to the output. The routing of the desired data input to the output is controlled by data select input. A multiplexer acts like a digital multi-position switch where the digital code applied to the select input control which data input will be switched to the output.

In thermal expansion experiments quite a number of measurements are required to be made by the DVM. These are:

i) Current source i.e. DVM will measure voltage drop across the standard resistance while the current from a constant current source is flowing through it. The computer will then divide this potential difference by the value of standard resistor to determine the exact value of the current going to the thermometers.

ii) There are three thermometers on the rig, one germanium thermometer CCG 577 on specimen cell, and another germanium thermometer CCG 731 on the bath. The third thermometer is the platinum resistance thermometer on the expansion/specimen cell. The DVM is required to make measurements of the voltage drop across two of these thermometers at one time. The computer will then determine the resistance by dividing the voltage drop across and the current through the respective thermometer. The temperature of the respective thermometers can then be determined from their resistance vs temperature calibration data provided by the manufacturer of the thermometer.
iii) The off balance signal from the bridge amplified by low noise amplifier and filtered by the coherent filter is fed to the phase sensitive detector. The PSD is connected to the DVM for measurement of the off balance signal.

The mercury wetted reed type RS relays (Form A) No. 348-302 were considered to be the most convenient and flexible way of multiplexing the DVM. These relays are normally open and are closed when a 5 Volt level is applied. A Real World interface card was used to drive this circuit. The relays are mounted on a separate board connected by a ribbon cable to the Real World interface card.

5.8.1 Real World Interface Card 4 (RWC-F 4)

The hexadecimal address on this card was set to 4. As usual all its ports 0, 1 and 2 were buffered by enabled octal line tristate buffers (74 LS244) in the predrilled free area of the card provided for the purpose. The initialisation command of this card was Out#43,#80. All the three ports were wired to be used as output ports. The Ports 0 and 1 were used to enable the 8 pairs of relays which are used to make different measurements by the DVM. The function of the Port 2 will be explained in the next section. A 32 pin edge connector is wired at the end of the card. The wires from all the ports through the buffers were extended and wired to the edge connector. The pins 2-9, 13-20 and 24-31 form the Ports 1, 2 and 0 respectively. The pin 1 is connected to 5V level from the computer and pin 32 is connected to the ground. The wiring configuration of this card with port/bits numbers, their function and colour of the corresponding ribbon cable is shown in Table (5.8.1).
5.8.2 Strip Board Slave Card 4

In all 22 relays (20 ordinary mercury wetted (Form A) and two mercury wetted reversing reed type relays (Form C) No.348-273 in five rows, four rows each containing five ordinary relays and one row containing two reversing relays were wired on RS strip board slave card which provides 86 pin connection at its end, 43 on each side, the component side and the track side. An RS edge connector providing 86 pins (two rows of 43 pins, one for each side, the component side and the track side), was fixed on to the card (card contains a slit at pin 37 for this purpose). The other end of the 32 way ribbon cable from the Real World interface card ports 1, i.e. pins (2-9), port 2, i.e. pins (13-20) and port 0 i.e. pins (24-31) were wired on one side of the edge connector on the slave card so as to provide logic (high or low) to all the relays. All the bits of Ports 1 and 0 are used to provide logic '1' or '0' to 8 pairs of relays (16 relays) which enable the DVM to make 8 different measurements. (See the photograph of this relay board for detail).

On the relay board were wired another stage octal line tristate chips (74 LS244) buffering the signal from RWC-F4. The reason for two stage of buffers is that of flexibility in that the card may be used for other experiments and also to compensate for any abnormal drain of current by the relay circuit. The relay board is run on an external earthed power supply isolated from the rest of the circuitry.

As it has already been explained, we need to have a constant current source for supplying current to the thermometers. According to the instruction of the manufacturer of the germinium thermometer, we need to supply different currents at different temperatures for
precise measurement of temperature and also to avoid any excessive Joule's heating effect. For this purpose, four relays (one column of four relays on one side) were connected at their outputs, the resistors of 1 KΩ, 20 KΩ, 200 KΩ and 2 MΩ. The power to this circuit can be supplied from a 2 Volt lead accumulator. Thus this circuit can give current ranges of 1 mA, 100 µA, 10 µA and 1 µA. The output of these relays and the other end of all the resistors are connected at pins 19 and 20 on the other side of the card. The pins 19 and 20 can be connected to the thermometers through a standard resistance of 1 KΩ across which the potential difference is measured to find out the exact value of current flowing through the circuitry. A particular current range can be switched by energising an appropriate relay. As is shown in Figure (5.8.2) the relay connected to bit 4 Port 2 can switch on 1 mA current when energised. Similarly the relays connected at bits 5, 6, 7 of Port 2 when energised would be able to switch on 100 µA, 10 µA and 1 µA current.

As already mentioned, two mercury wetted (Form C) reversing relays were also wired on the strip board card so as to enable the DVM to reverse the polarity of every measurement and to make this measurement again. This is particularly essential when reading the voltage drop across the thermometers because errors due to EMF's (created by inhomogenities in wires and contacts) can make an observation suspicious. The output from each relay pair is supplied to the reversing relay for this purpose so that the polarity of every measurement may be reversed. The reversing relays are energised by the logic from bit 1 of Port 2.

The subroutine that switches on 8 pair (0 to 7) of relays controlled by Port 0 and 1 is fairly simply. All relay pairs are given a number (0 to 7). When the main program wants a quantity to be measured, it sends that
number to the subroutine. The subroutine then switches on the appropriate pair of relays, takes the reading, waits for a time (see computer program for details), reverses the polarity and takes the reading again. The average of these two measurements is calculated by the computer.

A 32 way flat ribbon cable was used to wire the other side of the edge connector on the strip board slave card. Out of a total 43, only 20 pins were used. The unused pins were not wired so as to avoid any stray capacitance. The pins 2-9 were used to wire the output of 8 relays connected to 8 bits of port 1 while pins 25-32 were used to wire the output of 8 relays connected to 8 bits of port 0. The pins 19 and 20 were wired as output of the current source (i.e. from where current can be supplied to the thermometer). The pins 12 and 13 were wired as output from the reversing relay when the DVM can be connected for different measurements. This wiring configuration with ribbon cable colour is shown in Table (5.8.3). At the other end of this ribbon cable was wired a 32 pin RS D type plug with wires from a pair of relays from Ports 1 and 0 in pairs (top and bottom pins). A 32 pin RS D type socket was screwed on one side of a small diecast box. The 16 wires from 8 relay pairs were extended inside the box to another 16 pin RS D type socket screwed at the front face of the diecast box. The wires from pins 19 and 20 were extended to banana sockets on the front face of the diecast box. Similarly the wires from pins 12 and 13 were extended to the banana socket for easy connection of the DVM. A sixteen colour core round cable was wired with a 16 pin RS D type plug. At the other end of each wire were wired the banana plugs for easy connection to the source of measurement (e.g. thermometer) to be made. All pairs of wires were labelled with corresponding relay pairs. The details of the pairs of wires with cable colour forming a particular relay pair
PLATE 5.8.1: RS Strip Board Slave Card 4 i.e. Relay Circuit for Multiplexing the DVM and the Current Source (Component Side)
PLATE 5.8.1(a): RS Strip Board Slave Card 4 i.e. Relay Circuit for Multiplexing the DVM and the Current Source (Track Side)
### TABLE (5.8.1): The Wiring of the Real World Card 4 to the Slave Card 4

<table>
<thead>
<tr>
<th>RWC-F4 Port</th>
<th>Bit</th>
<th>Strip Socket Pin No</th>
<th>Ribbon Cable Colour</th>
<th>Relay Pair/Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>2</td>
<td>Brown</td>
<td>Relay 7 (input-ve)</td>
</tr>
<tr>
<td>&quot;</td>
<td>6</td>
<td>3</td>
<td>Red</td>
<td>&quot; 6 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>5</td>
<td>4</td>
<td>Orange</td>
<td>&quot; 5 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>4</td>
<td>5</td>
<td>Yellow</td>
<td>&quot; 4 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>3</td>
<td>6</td>
<td>Green</td>
<td>&quot; 3 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>2</td>
<td>7</td>
<td>Blue</td>
<td>&quot; 2 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>1</td>
<td>8</td>
<td>Purple</td>
<td>&quot; 1 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>0</td>
<td>9</td>
<td>Grey</td>
<td>&quot; 0 &quot;</td>
</tr>
<tr>
<td>Slots</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>13</td>
<td>Yellow</td>
<td>1 μA select</td>
</tr>
<tr>
<td>&quot;</td>
<td>6</td>
<td>14</td>
<td>Orange</td>
<td>10 μA select</td>
</tr>
<tr>
<td>&quot;</td>
<td>5</td>
<td>15</td>
<td>Red</td>
<td>100 μA select</td>
</tr>
<tr>
<td>&quot;</td>
<td>4</td>
<td>16</td>
<td>Brown</td>
<td>1 mA select</td>
</tr>
<tr>
<td>&quot;</td>
<td>0</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>1</td>
<td>18</td>
<td>Black</td>
<td>Reversing relays</td>
</tr>
<tr>
<td>&quot;</td>
<td>2</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot;</td>
<td>3</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slots</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>7</td>
<td>24</td>
<td>Green</td>
<td>Relay 7 (input +ve)</td>
</tr>
<tr>
<td>&quot;</td>
<td>6</td>
<td>25</td>
<td>Blue</td>
<td>&quot; 6 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>5</td>
<td>26</td>
<td>Purple</td>
<td>&quot; 5 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>4</td>
<td>27</td>
<td>Grey</td>
<td>&quot; 4 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>3</td>
<td>28</td>
<td>White</td>
<td>&quot; 3 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>2</td>
<td>29</td>
<td>Black</td>
<td>&quot; 2 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>1</td>
<td>30</td>
<td>Brown</td>
<td>&quot; 1 &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>0</td>
<td>31</td>
<td>Red</td>
<td>&quot; 0 &quot;</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>+5V</td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
<td></td>
<td>Ground</td>
<td></td>
</tr>
</tbody>
</table>
FIGURE (5.8.2): DVM Multiplexing Relay Circuit and Current Source

Inputs -ve

Inputs + ve

Rev
Relay

Rev
Relay

PORT 0

PORT 2

DVM

Ext. Battery

2 MΩ

1 μA

2.00 kΩ

10 μA

2.0 kΩ

100 μA

2 kΩ

1 mA
TABLE (5.8.3): The Wiring of the Slave Card 4 to the Output Plug

<table>
<thead>
<tr>
<th>Pin No</th>
<th>Ribbon Cable Colour</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Brown</td>
<td>+5V</td>
</tr>
<tr>
<td>2</td>
<td>Brown</td>
<td>Relay pair O Port 1 (inputs +ve)</td>
</tr>
<tr>
<td>3</td>
<td>Red</td>
<td>&quot; 1 &quot;</td>
</tr>
<tr>
<td>4</td>
<td>Orange</td>
<td>&quot; 2 &quot;</td>
</tr>
<tr>
<td>5</td>
<td>Yellow</td>
<td>&quot; 3 &quot;</td>
</tr>
<tr>
<td>6</td>
<td>Green</td>
<td>&quot; 4 &quot;</td>
</tr>
<tr>
<td>7</td>
<td>Blue</td>
<td>&quot; 5 &quot;</td>
</tr>
<tr>
<td>8</td>
<td>Purple</td>
<td>&quot; 6 &quot;</td>
</tr>
<tr>
<td>9</td>
<td>Grey</td>
<td>&quot; 7 &quot;</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Red</td>
<td>Reversing relay) DVM</td>
</tr>
<tr>
<td>13</td>
<td>Orange</td>
<td>Reversing relay)</td>
</tr>
<tr>
<td>14</td>
<td>Yellow</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>White</td>
<td>Resistors I/P (current control)</td>
</tr>
<tr>
<td>20</td>
<td>Black</td>
<td>&quot; O/P &quot;</td>
</tr>
<tr>
<td>21</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Green</td>
<td>Relay pair 7 (Port O) input -ve</td>
</tr>
<tr>
<td>26</td>
<td>Blue</td>
<td>&quot; 6 &quot;</td>
</tr>
<tr>
<td>27</td>
<td>Purple</td>
<td>&quot; 5 &quot;</td>
</tr>
<tr>
<td>28</td>
<td>Grey</td>
<td>&quot; 4 &quot;</td>
</tr>
<tr>
<td>29</td>
<td>White</td>
<td>&quot; 3 &quot;</td>
</tr>
<tr>
<td>30</td>
<td>Black</td>
<td>&quot; 2 &quot;</td>
</tr>
<tr>
<td>31</td>
<td>Brown</td>
<td>&quot; 1 &quot;</td>
</tr>
<tr>
<td>32</td>
<td>Red</td>
<td>&quot; 0 &quot;</td>
</tr>
<tr>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pair</td>
<td>Colour Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Pair 0</td>
<td>Red and Green</td>
<td></td>
</tr>
<tr>
<td>Pair 1</td>
<td>Purple and Blue</td>
<td></td>
</tr>
<tr>
<td>Pair 2</td>
<td>Blue-white and Black</td>
<td></td>
</tr>
<tr>
<td>Pair 3</td>
<td>Red-black and Orange-green</td>
<td></td>
</tr>
<tr>
<td>Pair 4</td>
<td>Grey and Brown</td>
<td></td>
</tr>
<tr>
<td>Pair 5</td>
<td>Orange and Brown</td>
<td></td>
</tr>
<tr>
<td>Pair 6</td>
<td>White and Orange-Red</td>
<td></td>
</tr>
<tr>
<td>Pair 7</td>
<td>Orange-Blue and Yellow-Blue</td>
<td></td>
</tr>
</tbody>
</table>
can be seen in Table (5.8.4). The diecast box was screwed at convenient place.

5.9 Data Transmission from the Capacitance Bridge

The General Radio Co Precision Capacitance Bridge model GR 1616 has at its rear panel, a BCD capacitance output connector accompanied by 50 pin amphenol socket for digital output. It is evident from the table (5.9.1) that in order to enable the computer to read the capacitance value in the range from .1 aF to 99.9999999 pF we have to send a 36 bit information (in practice we usually have to measure not more than six or seven picofarad). Thus to measure capacitance up to the above mentioned value, 9 arms of the bridge are involved. Each arm is capable of changing digits from -1 to X (i.e. 10) in 12 steps, which means that a group of four binary bits i.e. $2^3, 2^2, 2^1, 2^0$ will be sufficient to read the capacitance on one arm. Thus an eight bit port can cover two arms. The port numbers assigned with their upper/lower nibbles is shown in the Figure (5.9.1). To summarise, the arm number, the capacitance it measures and the corresponding BCD connector pin number is given below.

<table>
<thead>
<tr>
<th>Arm No</th>
<th>Capacitance</th>
<th>BCD Connector Pin number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.1 aF</td>
<td>1,2,26,27</td>
</tr>
<tr>
<td>2</td>
<td>1 aF</td>
<td>3,4,28,29</td>
</tr>
<tr>
<td>3</td>
<td>10 aF</td>
<td>5,6,30,31</td>
</tr>
<tr>
<td>4</td>
<td>100 aF</td>
<td>7,8,32,33</td>
</tr>
<tr>
<td>5</td>
<td>1 fF</td>
<td>9,10,34,35</td>
</tr>
<tr>
<td>6</td>
<td>10 fF</td>
<td>11,12,36,37</td>
</tr>
<tr>
<td>7</td>
<td>100 fF</td>
<td>13,14,38,39</td>
</tr>
<tr>
<td>8</td>
<td>1 pF</td>
<td>15,16,40,41</td>
</tr>
<tr>
<td>9</td>
<td>10 pF</td>
<td>17,18,42,43</td>
</tr>
</tbody>
</table>
We could have sent all the 36 bits of information to the computer in parallel which would have been much faster but expensive. Therefore to economise a strip board predrilled RS card, *(hereafter referred to as input card)* was wired for receiving data from the capacitance bridge in parallel and serialising (4/5 bits in series), before presenting it to the computer.

A 36 way ribbon cable was wired to a 50 pin amphenol RS plug for plugging into the bridge amphenol socket. The unused connections of the amphenol plus were not wired to avoid any stray capacitance.

The input card provides 86 pin connections, 43 on each side, the component side and the track side. A 4-16 line decoder 74 LS154 and 8 octal line tristate TTL drives or buffers 74 LS244 were wired on the component side of this card. The pins 1, 43 are used for supplying power of +5 volt from a power supply. The 36 wires coming from the amphenol plug were divided into 5 ports, the 4 ports containing 8 bits, while the fifth port contained only 4 bit information. The pins 1, 2, 26, 27, 3, 4, 28 and 29 of the amphenol plug were wired to the pins 2-9 (port 1), the pins 5, 6, 30, 31, 7, 8, 32, 33 of the amphenol plug to the pins 10-17 (port 2), pins 9, 10, 34, 35, 11, 12, 36, 37 of the amphenol plug to pins 18-25 (port 3) and the pins 13, 14, 38, 39, 15, 16, 40, 41 of the amphenol plug to pins 26-33 of side A of the input card.

Finally the pins 17, 18, 42, 43 of the amphenol plug were wired to pins 6-9 (port 5) at side B of the input card.

As already mentioned, although for the present purpose five tristate TTL drives were sufficient to receive data
from five ports (Port 1, Port 2, Port 3, Port 4 and Port 5) of the bridge, in order to keep capacity for further use, we wired 8 octal line TTL tristate drives and a 4-16 line decoder. The eight buffers provided 8 x 8 = 64 pin connections. The input pins 2, 4, 6, 8, 11, 13, 15, 17 of 8 buffers were connected to pins 2-9 (Port 1), 10-17 (Port 2), 18-25 (Port 3) and 26-33 (Port 4) on both sides of the input card. Thus this card provided 8 x 8 = 64 lines for receiving data from the capacitance bridge.

The pins 34-36, 38 on side B (34 LSB, 38 MSB) of the input card are used for providing address to the decoder, which enables the 8 TTL drives to receive data from the capacitance bridge. The data from the capacitance bridge is received by this card in parallel on 36 pins. Here it is serialised before being presented to the computer. The pins 34-36, 38-42 (34 MSB, 42 LSB) of this card, side A, form the input port from where data is sent to the computer. The output pins 3, 5, 7, 9, 12, 14, 16, and 18 of each buffer are connected to 8 bits of the input port, so that each bit of the input port can receive 4/5 bits of information from the bridge. This is shown in Figure (5.9.5). The portwise wiring scheme of the address pins and that of the input port is shown in Figure 5.9.2. The amphenol plug pin numbers, the ribbon cable colour and corresponding pin numbers on the input card side A/B are shown in the Table (5.9.3). The terminal identification of BCD capacitance output connector is shown in Figure (5.9.1(a)).

A Real World interface card (RWC-F.3) (hereafter referred to as the bridge interface card) is used to drive the input card so that it provides 4 bit address at pins 34-36, 38 side B and receives data from the input port. The wiring scheme of the Real World interface card with ribbon cable colour of all the three ports 0, 1 and 2 is shown in Table (5.9.4).
The presentation of data from the capacitance bridge, through octal line tristate driver (buffers) to the input port is shown in the Figure (5.9.5). To summarise:

Data #A gives l/tens in binary \((.1 \text{ to } .9 \text{ aF})\)
Data #B " unit " " \((1 \text{ to } 9.9 \text{ aF})\)
Data #C " tens " " \((10 \text{ to } 99.9 \text{ aF})\)
Data #D " hundreds in binary \((100 \text{ to } 999.9 \text{ aF})\)
Data #E " thousands in binary \((1 \text{ fF} \text{ to } 9.999 \text{ fF})\)
Data #F " tens of thousands in binary \((10 \text{ fF} \text{ to } 99.999 \text{ fF})\)
Data #G " hundreds of thousands \((100 \text{ fF} \text{ to } 999.999 \text{ fF})\) in binary
Data #H " millions in binary \((1 \text{ pF} \text{ to } 9.9999999 \text{ pF})\)
Data #I " tens of millions in \((10 \text{ pF} \text{ to } 99.9999999 \text{ pF})\) binary

5.9.1 **Real World Card 3 (RWC-F3) Bridge Interface**

This Real World interface card was used to multiplex input/output. The address on this card was set to 3. As usual all the ports (i.e. Port 0, Port 1 and Port 2) were buffered by an enabled octal line tristate buffer 74 LS244 in the predrilled free area of the card. The initialisation command of this was was Out#33,#90. As already explained input card provided 8 x 8 = 64 input pins. The pins 34-36, 38-42 side A of the input card were used as input port 0 of Real World card. Similarly the port 1 of the Real World card was used as output port and pins 34-36, 38-42 side A of the output card were wired.

The output card also provides 8 x 8 = 64 output pins. Port 2 upper nibble (i.e. bits 4-7) of the Real World card was wired on the pins 34-36, 38 side B of the input card to provide a 4 bit address. Similarly port 2 lower nibble (i.e. bits 0-3) of the Real World card was wired with pins 34-36, 38 side B of the output card to provide a 4 bit
address. In the main computer program for reading the bridge there is a subroutine starting at line 6000 which can change either the upper nibble or the lower nibble without altering the other nibble. A wiring configuration of the ports of the Real World card with flat ribbon cable colour to input port, address line to input card, output port and address line of output card are shown in the Table (5.8.4). A block diagram of the input card is shown in Figure (5.8.6). The input and output cards are shown in Photographs Nos. 5.9.1 and 5.9.2.
PLATE 5.9.1: Input Card (Component Side)
PLATE 5.9.1(a): Input Card (Track Side)
PLATE 5.9.2: Output Card (Component Side)
<table>
<thead>
<tr>
<th>BCD Capacitance Output</th>
<th>BCD Connector Pin Nos</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 aF</td>
<td>1</td>
</tr>
<tr>
<td>0.2 aF</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>lower</td>
</tr>
<tr>
<td>0.4 aF</td>
<td>26</td>
</tr>
<tr>
<td>0.8 aF</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>Port 1</td>
</tr>
<tr>
<td>1 aF</td>
<td>3</td>
</tr>
<tr>
<td>2 aF</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>upper</td>
</tr>
<tr>
<td>4 aF</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>nibble</td>
</tr>
<tr>
<td>8 aF</td>
<td>29</td>
</tr>
<tr>
<td>10 aF</td>
<td>5</td>
</tr>
<tr>
<td>20 aF</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>lower</td>
</tr>
<tr>
<td>40 aF</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>nibble</td>
</tr>
<tr>
<td>80 aF</td>
<td>31</td>
</tr>
<tr>
<td>100 aF</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Port 2</td>
</tr>
<tr>
<td>200 aF</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>upper</td>
</tr>
<tr>
<td>400 aF</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>nibble</td>
</tr>
<tr>
<td>800 aF</td>
<td>33</td>
</tr>
<tr>
<td>1 fF</td>
<td>9</td>
</tr>
<tr>
<td>2 fF</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>lower</td>
</tr>
<tr>
<td>4 fF</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>nibble</td>
</tr>
<tr>
<td>8 fF</td>
<td>35</td>
</tr>
<tr>
<td>10 fF</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Port 3</td>
</tr>
<tr>
<td>20 fF</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>upper</td>
</tr>
<tr>
<td>40 fF</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>nibble</td>
</tr>
<tr>
<td>80 fF</td>
<td>37</td>
</tr>
<tr>
<td>100 fF</td>
<td>13</td>
</tr>
<tr>
<td>200 fF</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>lower</td>
</tr>
<tr>
<td>400 fF</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>nibble</td>
</tr>
<tr>
<td>800 fF</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>Port 4</td>
</tr>
</tbody>
</table>

/continued
TABLE 5.9.1 ... continued

<table>
<thead>
<tr>
<th>BCD Capacitance Output</th>
<th>BCD Connector Pin Nos</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 pF</td>
<td>15</td>
</tr>
<tr>
<td>2 pF</td>
<td>16 \text{ upper nibble}</td>
</tr>
<tr>
<td>4 pF</td>
<td>40</td>
</tr>
<tr>
<td>8 pF</td>
<td>41</td>
</tr>
<tr>
<td>10 pF</td>
<td>17</td>
</tr>
<tr>
<td>20 pF</td>
<td>18 \text{ lower nibble}</td>
</tr>
<tr>
<td>40 pF</td>
<td>42</td>
</tr>
<tr>
<td>80 pF</td>
<td>43</td>
</tr>
</tbody>
</table>
FIG. 5.9.1 (a)
TERMINAL IDENTIFICATION AT BCD CAPACITANCE OUTPUT CONNECTOR (A J13, REAR PANEL OF BRIDGE.)
FIGURE (5.9.2): Input/Output Card Connector Connections

A: Component side
B: Track side

8 lines for O/P port (Port 1 of RWC-F card)

4 bit address
From Port 2 (RWC) lower nibble

8 lines for I/P Port (Port 0 of RWC-F card)

4 bit address (from Port 2 upper nibble)
TABLE (5.9.3) Wiring Configuration of Bridge Plug to the I/P Card

<table>
<thead>
<tr>
<th>Capacitance Bridge Plug Pin No</th>
<th>BCD Capacitance</th>
<th>Ribbon Cable Colour</th>
<th>I/P Card Pin Nos</th>
<th>Side A/B</th>
<th>Port No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1 aF</td>
<td>Black</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.2 aF</td>
<td>White</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>0.8 aF</td>
<td>Purple</td>
<td>6</td>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1 aF</td>
<td>Blue</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2 aF</td>
<td>Green</td>
<td>4</td>
<td></td>
<td></td>
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TABLE (5.9.4) The Wiring Configuration of Real World CARD to the Input/Output Card

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FIGURE (5.9.5): Data Transmission from Capacitance Bridge
FIGURE 5.9.6 Block Diagram of the Input Card
5.10 Automation of the Gain of Low Noise Amplifier

At low temperatures (i.e. liquid helium temperature) where the capacitance changes are very small and the sensitivity of the capacitance bridge is very crucial, the gain of low noise amplifier is set at 90 dB and we calibrate the bridge capacitance against off balance voltage signal measured by phase sensitive detector and Keithley DVM. As the temperature rises, the capacitance of the specimen cell changes rapidly and off balance signals start reaching the maximum measurable position of 2V (by Keithley DVM) in a comparatively short time. The usual procedure is to reset the bridge capacitance at a new value bringing the off balance signal to zero volt approximately. With the rise of temperature, a stage is reached when we had to reset the bridge capacitance again and again after very short time intervals (say < half an hour). At this stage there is every likelihood that some error may creep in due to resetting of the bridge capacitance again and again. Therefore the usual procedure was to turn down the gain of the amplifier by 10/20 dB and recalibrate the bridge. For this we had to monitor the off balance signal continuously in order to enable ourselves to decide when to reduce or increase the gain of the amplifier and recalibrate the bridge.

5.10.1 Real World Interface Card 5 (RWC-F5)

For the purpose outlined above, the address on a Real World card was set to 5. As usual all the three ports on this card (Port 0, Port 1, Port 2) were buffered by enabled octal line tristate buffers 74 LS244 in predrilled free area of the card. A 32 pin RS edge connector was fitted with its pins wired at the end of the card. The wires from the buffers were extended to
the edge connector. A 32 way ribbon cable was wired with an RS plug to be plugged into the edge connector socket. The other end of the ribbon cable was wired to the RS strip board slave card. The wiring configuration with specific colours of ribbon cable to particular bits of all the ports are shown in the Table (5.10.1). The pins (2-9) (13-20) and (24-31) of the edge connector make up the Port 1, Port 2 and Port 0 respectively. On the slave strip board card, the pins (2-9), (17-24) and (33-36, 38-41) make up the Port 0, Port 1 and Port 2 respectively. The bits 0-7 of the Port 0 are wired for providing output to the relay circuit for automating the gain of the amplifier. The bit 4-7 of Port 2 were wired for O/P from DAI computer to the Real Time clock (i.e. for write operation). The bits 0-3 of Port 2 were wired for I/P from the Real Time clock to the DAI computer (i.e. read operation). The bits 0-3 of Port 1 were wired to provide 4 bit address to the clock. The bit 4 of Port 1 was wired for chip select (CS). The bits 5 and 6 were wired for read and write operation. The bit 0 was wired for F cap relay for automating the short time constant of the phase sensitive detector. The power to the buffers of all the ports was supplied from pins 1 (+ 5V) and 32 (OV) of the Real World card. The initialisation command for this was Out#53,#88.

5.10.2 RS Strip Board Slave Card 5

The circuit diagram of the amplifier gain control shows that pink and orange wires control the gain of 80 dB, 90 dB and 100 dB, while the yellow and white control the gain of 30 dB, 40 dB, 50 dB, 60 dB and 70 dB. The circuit diagram of the gain control switch is shown in the figure (5.10.3). A 9 pin RS D type socket was screwed on one side of the case of the amplifier.
The orange, yellow, pink and white leads internal to the low noise amplifier were basically connected to a rotary switch (on the front panel of the amplifier) which was used to switch on different gain positions ranging from 30 dB to 100 dB. These four leads were broken and were extended separately from the rotary switch and from the output resistor. These 8 leads, four (orange, pink, white and yellow) from the resistors and four (orange, pink, white and yellow) from the rotary switch were wired to an 8 pin RS D type socket. (The lower pins were used for wires from resistor and upper pins for wires from rotary switch). The computer control of the gain was obtained by connecting wires at the lower pins of the socket (from the resistor) to the relay circuit (this will be explained later in this section). Another D type 8 pin plug shorting its top and bottom pins was used to be plugged to have manual control of the gain of the amplifier when required. This plug simply connects the rotary switch to the output resistor as it was originally before this modification.

A computer controlled relay circuit controlling the gain of the amplifier was originally wired on the RS strip board card. As is shown in Figure (5.10.4), 8 relays have been wired with respective resistors at their output controlling the 8 gain position. The 30, 40, 50, 60 and 70 dB gain position can be straight away switched by energising the relay No. 7 (decimal equivalent 128), relay No. 6 (decimal equivalent 64), relay No. 5 (decimal equivalent 32), relay No. 4 (decimal equivalent 16) and relay No. 3 (decimal equivalent 8) respectively. The 80, 90 and 100 dB gain positions can be switched by energising a pair of relays i.e. relay pairs 3 and 2 (decimal equivalent 12) for 80 dB, relay pair 3 and 1 (decimal equivalent 10) for 90 dB and relay pair 3 and 0 (decimal equivalent 9) for 100 dB. The bits 0 to 7 of Port 0 of Real World card control the relay
circuit as is shown in Figure (5.10.5). The I/O leads to and from the amplifier gain control relay circuit on the strip board card were extended to pins 10, 12, 14 and 16. The pink and yellow leads extended to pins 10 and 16 act as I/P leads from and to the amplifier while the orange and white leads extended to pins 12 and 14 act as O/P to the amplifier (see Table 5.10.2). Approximately 4 metre long orange, pink, white and yellow leads were wired at these pins (i.e. 10, 12, 14, 16). The other ends of these leads were wired to 9 pin RS D type plug which can be plugged into a socket on one side of the amplifier. This circuit was then put to test to see if it worked and gave the same effect by energising a proper relay as that of the respective gain position on the manual rotary gain switch. To our surprise the relay circuit did not give the same effect as that by rotating the same gain position on manual switch. It seemed as if the relay circuit did not work at all. After intensive checking of the relay circuit, we came to the conclusion that it was a pick up problem due to unshielding of the very long I/O leads to the amplifier and that of the relay circuit itself. Therefore the same relay circuit was rebuilt on a small ordinary predrilled (matrix) card which was mounted on insulating pillars inside a well screened diecast box earthed to the low noise amplifier case. A 16 pin RS D type socket was fitted on one side of the box. An enabled octal line tristate buffer 74 LS244 was wired on the card inside the diecast box between the input to the relays and the output signal coming from the bits of Port 0. This buffer was used to compensate for any abnormally large drain of current by the relay circuit. The 8 input wires of the buffer were extended and wired with 8 pins of the 16 pin socket. The pin No 9 of the socket was grounded. A 9 core colour well screened cable was wired to bits 0-7 of the
Port 0 of the Real World card 5 (ninth wire was connected to ground). This cable was about 4 metres long so that the diecast box may be placed very close to the amplifier. At the other end of this cable was wired a 16 pin RS D type plug which could be plugged on to the socket on the side of the diecast box. Another 9 pin RS D type socket was screwed onto the other side of the diecast box. The I/O leads from the relay circuit were extended and wired on to this socket. On both the ends of a four core colour (orange, pink, yellow and white) about one metre long were wired 9 pin RS D type plugs with appropriate colours at appropriate pins so that one plug could be plugged to the diecast box and the other to the amplifier. This time the relay circuit worked excellently and gave exactly the same effect as that respective gain obtained by rotating the manual switch. A series of tests at almost all the gain positions were made to confirm that automation of the gain of the amplifier worked.

5.10.2.1 Real time clock

We had to monitor the different events of the experiment, e.g. when to reduce or increase the gain of the amplifier etc, therefore it was both necessary and vital to have a real time clock for the purpose. Therefore a Radiospares Co real time clock chip No. 304-548 was purchased. The real time clock chip was wired on to the strip board slave card 5.. The top view and internal block circuit diagram of the clock are shown in Figures 5.10.5(a) and 5.10.6. A four bit address \( A_0, A_1, A_2 \) and \( A_3 \) at the pins 12, 11, 10 and 9 of the clock was provided by the bits 0-3 of the port 1. The bits 4, 5 and 6 connected the \( CS \) (chip select), read and write pins of the clock. The input/output data from and to the DAI computer was buffered by an enabled octal line tristate buffer 74 LS244.
The pins 4, 5, 6 and 7 of the clock are used both for inputting and outputting data. The bits 0-3 of Port 2 are used to O/P data from the clock to the DAI computer while bits 4-7 of Port 2 are used to input data from the computer to the clock. The wiring configuration of the clock is shown in Figure (5.10.5). The oscillator is formed by an on chip inverter/amplifier with bias resistor and capacitor. A 55 - 65 pF trimmer is used to fine tune the oscillator. The oscillator output is blocked by a start/stop flip flop. When the system is powered, it is necessary to enter the correct data into the device register (address decoding for internal register is shown in Table 5.10.8) and start the clock running. The seconds, minutes, hours, days and months counters are parallel loaded with data from 4 bit data bus when correctly addressed. (CS is low and a write data strobe pulse is given). The data to be entered is set up on the 4 bit data bus, the address from the table (5.10.8) for the required register is set on the 4 bit address bus and write data strobe is sent. The CS (chip select) must be low during the read and write operations. All information is entered in the same way with the relevant addresses. To start the clock running at the required instance, a logic '1' is written at D0 at address 14, likewise writing a logic '0' will stop the clock. The data can be read from a register by using a required address as in Table (5.10.8) and applying a read strobe pulse. The data becomes available on 4 bit data bus. The clock software had to be self written. For this purpose a computer program in 'BASIC' consisting of three subroutines, one to set the clock to the user supplied date and time and the second to read data from the clock and the third to write data to the clock were written.
5.10.3 Automation of Internal Time Constant of PSD

The time constant lever of the Brook-deal phase sensitive detector has two modes of operation i.e. external and internal. The external time constant being a longer one while the internal time constant is shorter. There are two terminals at the rear panel of the phase sensitive detector where a Brookdeal external time constant 30/100 pF capacitor can be plugged for longer external time constants. When balancing or calibrating the capacitance bridge, we had to switch to an internal time constant for getting the system stabilised quickly. Similarly, the computer was made to switch on time constants from time to time. For this purpose a T cap DIL type relay No 349-434 was fitted to an ordinary matrix card which was mounted on insulating pillars inside a small diecast box.

This relay can be energised by supplying power (+5V level) at pins 1 (+5V) and 4. Normally when the relay is not energised, pins 2 and 3 are connected to pins 8 and 5 respectively. When the relay is energised by +5Volt level, the pins 2 and 3 get connected to the pins 7 and 6 respectively. The power to the relay is supplied from bit 7 of port 1 (pin 24 of the slave card). The pin 24 of the slave card is connected to pin 25. Thus the pins 1 and 4 of the relay are connected to pins 25 (+5V) and 26 (ground) of the slave board. A 0.1 pF capacitor was connected between pins 6 and 7 of the relay for short time constant. The phase sensitive detector was connected between the pins 2 and 3 of the relay. The Brookdeal external time constant 30/100 pF capacitor was connected between pins 5 and 8 of the relay. In case of logic '0' at the relay pins 1 and 4, the Brookdeal external time constant capacitor will be large i.e. time constant will be ≈ 10 seconds when logic '1'
TABLE (5.10.1) The Wiring of the Real World Interface
Card 5 with Slave card 5 Controlling the Amplifier Gain and the Clock with Ribbon Cable Colours and their Function

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<td>1</td>
<td>4</td>
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<td>7</td>
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<td></td>
<td>Purple</td>
<td>24</td>
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<tr>
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<td></td>
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<tr>
<td>13</td>
<td></td>
<td></td>
<td>Blue</td>
<td>38</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>Grey</td>
<td>39</td>
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<td>15</td>
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<td>Orange</td>
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<td></td>
<td>Grey</td>
<td>2</td>
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<td>25</td>
<td></td>
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<td>Purple</td>
<td>3</td>
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<td></td>
<td>Blue</td>
<td>4</td>
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<td>5</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
<td>Yellow</td>
<td>6</td>
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</table>

/Continued...
TABLE (5.10.1) ... continued

<table>
<thead>
<tr>
<th>RW Interface Card 5</th>
<th>Ribbon Cable Colour</th>
<th>Pin Nos on Slave Board</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge Connector Pin No</td>
<td>Port No</td>
<td>Bit Nos</td>
<td>O/P</td>
</tr>
<tr>
<td>29</td>
<td>0</td>
<td>5</td>
<td>Wired for O/P</td>
</tr>
<tr>
<td>30</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>OV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE (5.10.2) Wiring Scheme of RS Strip Board Card 5
Amplifier Gain Control and Real Time Clock

<table>
<thead>
<tr>
<th>Pin Nos</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>B₀</td>
<td>497Ω</td>
</tr>
<tr>
<td>3</td>
<td>B₁</td>
<td>1.62KΩ</td>
</tr>
<tr>
<td>4</td>
<td>B₂</td>
<td>6.49KΩ</td>
</tr>
<tr>
<td>5</td>
<td>B₃</td>
<td>215Ω</td>
</tr>
<tr>
<td>6</td>
<td>B₄</td>
<td>680Ω</td>
</tr>
<tr>
<td>7</td>
<td>B₅</td>
<td>2.26KΩ</td>
</tr>
<tr>
<td>8</td>
<td>B₆</td>
<td>8.25KΩ</td>
</tr>
<tr>
<td>9</td>
<td>B₇</td>
<td>51KΩ</td>
</tr>
<tr>
<td>10</td>
<td>Pink lead - I/P from amplifier</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>Orange lead - O/P to amplifier</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>White lead - O/P to amplifier</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>Yellow lead - I/P to amplifier</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>B₇</td>
<td>Cap relay</td>
</tr>
<tr>
<td>18</td>
<td>B₆</td>
<td>Read</td>
</tr>
<tr>
<td>19</td>
<td>B₅</td>
<td>Write</td>
</tr>
<tr>
<td>20</td>
<td>B₄</td>
<td>CS</td>
</tr>
<tr>
<td>21</td>
<td>B₃</td>
<td>A₃ Clock chip address</td>
</tr>
<tr>
<td>22</td>
<td>B₂</td>
<td>A₂</td>
</tr>
<tr>
<td>23</td>
<td>B₁</td>
<td>A₁</td>
</tr>
<tr>
<td>24</td>
<td>B₀</td>
<td>A₀</td>
</tr>
<tr>
<td>25</td>
<td>Cap relay output</td>
<td>-</td>
</tr>
<tr>
<td>26</td>
<td>Cap relay</td>
<td>-</td>
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TABLE (5.10.2) ... continued

<table>
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<td>33</td>
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<td>37</td>
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<td>38</td>
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</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>41</td>
</tr>
<tr>
<td>42</td>
</tr>
</tbody>
</table>

From Port 2 of Real World Interface Card 5

- B7: From DAI to clock
- B6: ("WRITE")
- B5: D1
- B4: D2
- B3: D3

From clock D0 (READ)

- B0: D0
- B1: D1
- B2: D2
- B3: D3

- From DAI to clock

D0

D1

D2

D3
FIGURE (5.10.3): Original Circuit Diagram Controlling the Gain of the Amplifier
FIGURE (5.10.4(b)): Relay Circuit Controlling the Gain of Low Amplifier
RS Real
Time Clock
Chip
No 304-548
(Top View)

FIGURE 5.10.5(a)
FIGURE (5.10.6): Internal Block Diagram of Clock Chip

FIGURE (5.10.7)
<table>
<thead>
<tr>
<th>Selected Counter</th>
<th>Address Bits</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_3$</td>
<td>$A_2$</td>
</tr>
<tr>
<td>0 Test only</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1 Tenth of seconds</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2 Units of seconds</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3 Tens of seconds</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4 Units of mins</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5 Tens of mins</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>6 Units of hours</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>7 Tens of hours</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>8 Units of days</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>9 Tens of days</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>10 Day of week</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>11 Units of months</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>12 Tens of months</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>13 Years</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>14 Stop/start</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>15 Interrupt status</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
FIGURE (5.10.9): Relay Circuit for Short Time Constant for Balancing the Bridge
is sent to the relay from bit 7 port 1, the PSD will be switched to 0.1 pF capacitor i.e. short time constant of ~ 3 seconds. In normal operation after a desired time interval (say a couple of seconds) when things have settled down (i.e. during the balancing operation), the sending of logic '0' will again switch the Brookdeal external time constant capacitor and the PSD will be in the usual long time constant mode. The wiring configuration of this relay is shown in Figure (5.10.9).

5.11 Automation of the Arms of the Capacitance Bridge to Balance its Capacitance against Specimen/Expansion Cell

As already explained in the introductory section of this chapter, when the off balance signal coming through the detection circuitry i.e. low noise amplifier, coherent filters and phase sensitive detectors, reaches its maximum measurable position of 2 volts (Keithley DVM is not designed to measure more than 1.999 volts) we had to reset the capacitance of the bridge manually to a new balanced position. As the temperature of expansion cell rises, the capacitance of the dilatometer starts changing rapidly, the off balance voltage starts reaching the maximum measurable position in shorter time intervals, and we had to reset the bridge again so that off balance voltage approaches 0 volts. It is worth noting that the off balance signal may go in either the positive or negative direction depending upon whether the measured capacitance is smaller or greater than the bridge setting.

At the start a linear telephone switch was thought to be a solution to our problem. A telephone switch borrowed from British Telecommunications department, containing a solenoid can be operated by a DC power supply. The switch when energised was capable of moving
upward or downward in 10 steps. The switch was mounted on a wooden board and a lever arrangement consisting of two steel rods, one horizontal and the other vertical, were built with an adaptor on the top of the switch. However this system was found to be unreliable. Therefore a small DC motor accompanied by a worm gear was tried on one of the arms of the bridge. It seemed to work. It was then a matter of refining and extending the system to other arms of the bridge. We had to automate 1, 10, 100, 10,000 and 100,000 attofarad arms. The problem was that the motor had a diameter of about 45 mm, and including its base stand it occupied a space of 50 mm. The space between consecutive arms of the bridge was about 20 mm. Therefore it was impossible to mount all the five motors in parallel on the top of the rack and extending them straight to the respective arms so that the arms could be raised or lowered. Therefore a motor worm gear assembly system was designed (see Figure 5.10.1) such that two motors on 10 and 1000 aF arms could be mounted parallel on one side of a block, the motors for 100,000 aF arm on the opposite side, while the other two motors for 1 and 1000 aF arms could be mounted at an angle of 45° to the worm wheel. For this purpose, five bearings of size 1" OD, ½" bore were fixed at suitable positions in two rows (two in one row and three in the other) in an aluminium block of dimensions 2½" x 4½" x 15 mm. On the top of these bearings were fixed five worm wheels of 35 mm diameter and about 5 mm thick. On the shaft of the motors were fixed 5 worms such that 62 revolutions of the worm would make one revolution of the worm wheel. The aluminium block was screwed on a large aluminium base plate of dimensions 10½" x 8½" x ½". The motor with base stands were screwed on the base plate such that the worm of each motor engaged firmly the respective worm wheel. The worm
wheel contained at its centre a tapped hole of 8 mm diameter. The base plate of the motor assembly system was screwed at the top of the rack (containing the bridge in its top shelf) (see the photograph for details). The 8 mm diameter threaded steel rod of suitable length reaching the respective arms were screwed in the respective worm wheels. At the lower ends of these rods were attached, with the help of small hairpins, brass rods of diameter about 5 mm and suitable length containing a hole so that these could be slipped on to the arms of the bridge. The steel rods could be raised up or lowered down thus raising up or lowering down the respective arm depending upon the direction of the motor. This mechanical system worked excellently. We simply had to develop a computer controlled relay circuit for driving these motors.

5.11.1 Relay Circuit for Driving Motors

Several trial circuits using simple solid state relays were tried but it became clear that to handle current surges of DC motors a series of conventional relays (driven by +5V pulses to a controlling transistor) would have to be used.

A circuit containing 5 conventional relays was designed (see Figure 5.11.2) and built in a diecast box. A 7 Volt lamp power supply for driving the relays was built in the same box. This power supply was also used to drive a conventional reversing relay wired in a separate diecast box. As is shown in the circuit, each relay was buffered by a transistor at the base of which were wired two resistors 1KΩ and 10 KΩ. The 10KΩ resistor was connected to earth while at the other end of the 1KΩ resistor, a five volt level from the computer could be applied for energising the coil of the relay.
The emitter of the transistor was connected to earth while the collector was connected to one end of the coil. The collector was also connected to +ve terminal of a diode, the -ve of the diode being connected to earth. In order to have manual control of the motors, a resistor of 820Ω was connected between +ve of the power supply and the base of each transistor with a tiny on/off switch in between. The reversing relay was buffered in a similar way, but with different resistors at the base of the transistors. A 12 Volt, 2 amp power supply was built in another diecast box which could be easily plugged at contacts 7 and 13 of the reversing relay for driving the motors.

5.11.2 Real World Card (RWC-F6)

The hexadecimal address on this card was set to 6. As usual all the three ports of this card were buffered by enabled octal line tristate buffers 74 LS244 in the predrilled free area of the card. The wiring from the buffers were brought to the end of the card. A 32 pin RS edge connector was fixed at the end of the card and wiring from all the ports wired. Ports 1 and 2 were wired for output while Port 0 was wired for input. The initialisation command for this card was Out#63,#90. A seven way ribbon cable was wired to an edge connector plug for bits 0, 3-7 of Port 1 only, the seventh wire being connected to ground of the Real World card. Ports 2 and 0 remained unused. At the other end of the ribbon cable were wired 7 banana plugs. Out of these five banana plugs could be plugged into the banana sockets on one side of the diecast box driving the relay circuit, the sixth one to the socket used for ground and the seventh to the banana socket on the diecast box containing the reversing relay. The wiring configuration of the Real World card with edge
PLATE 5.11: Shows DC Motors Worm-Gear Assembly Connected to Arms of the Bridge for Balancing Operation
FIGURE 5.11.1: Motor worm-gear assembly
FIGURE (5.11.2): Relay Circuit for Driving Motors
TABLE (5.11.3) The Wiring of Real World Interface Card to the Relay Circuit for Driving Motors

<table>
<thead>
<tr>
<th>Edge Connector Pin No</th>
<th>Port No</th>
<th>Bit No</th>
<th>Ribbon Cable Colour</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (+5V)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>B7</td>
<td>Black</td>
<td>B3 - B7</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>B6</td>
<td>Brown</td>
<td>connected to</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>B5</td>
<td>Red</td>
<td>relay circuit</td>
<td>for driving</td>
</tr>
<tr>
<td>5</td>
<td>B4</td>
<td>Orange</td>
<td>motors</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>B3</td>
<td>Yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
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<td>-</td>
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<td></td>
</tr>
<tr>
<td>8</td>
<td>B1</td>
<td>Blue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>B0</td>
<td>Purple</td>
<td>Reversing relay</td>
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</tr>
<tr>
<td>10</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>B6</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>15</td>
<td>B5</td>
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<td></td>
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</tr>
<tr>
<td>16</td>
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<td></td>
</tr>
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<td>17</td>
<td>B0</td>
<td>O/P</td>
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<td>18</td>
<td>B1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
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<td></td>
<td></td>
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<tr>
<td>20</td>
<td>B3</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
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<tr>
<td>23</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
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<td>B1</td>
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<td>B3</td>
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<td></td>
</tr>
<tr>
<td>28</td>
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</tr>
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Continued..
### REAL WORLD CARD (RWC-F6)

<table>
<thead>
<tr>
<th>Edge Connector Pin No</th>
<th>Port No</th>
<th>Bit No</th>
<th>Ribbon Cable Colour</th>
<th>Function</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td></td>
<td>B5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>B6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>B7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32(G)</td>
<td></td>
<td></td>
<td>Green</td>
<td>Connected to ground of the relay circuit</td>
<td></td>
</tr>
</tbody>
</table>
connector pin Nos, Port Nos, Bit Nos and ribbon cable colour (Port 1 only) are shown in Table (5.11.3).

5.11.3 Motor/Bridge Direction Matrix

We now explain the motor direction matrix used in the computer program on which bridge balancing operation (the most difficult aspect of the dilatometer automation process) totally depends. When the bridge off balance voltage exceeds ±0.7 volts and the computer wants to balance the bridge, it senses the arm digit that currently it is working on, through the BCD interface at its rear panel and decides whether to increase or decrease the bridge capacitance in order to balance it. The negative off balance voltage means that bridge setting capacity is less than that being measured and computer should increase the bridge capacitance and vice versa.

There are three distinct stages in adjusting the balance of the capacitance bridge:

a) moving the appropriate arm by activating an electric driving motor,

b) sensing when the correct digit has been selected and stopping the driving motor and finally

c) stopping further change in bridge balance once the DVM reads an "off balance" bridge voltage < ±0.3 volts.

This section describes how the computer logically determines when a digit has been changed satisfactorily and stops the driving motor.

We start with an example of the balancing operation. Consider that the computer senses an off balance voltage of -0.9 volts (< 0.7 volts limit) whilst operating on arm 5 with a bridge reading as follows:
Bridge reading 6 7 8 7 0.9 1 0 pF
ARM% values 6 5 4 3 2

The five driven arms corresponding to different bridge digits are also shown. Because the off balance voltage is negative and \( > \) \( \text{abs}(0.7) \) volts, the computer will wish to re-balance the bridge by increasing the capacitance value of the bridge. It will do this by increasing the value of ARM5 from 7 to 8 and then immediately to 9. (The values are always changed in steps of two unless, of course, the act of increasing by two violates the maximum value of 9 or a minimum value of 0). Once it has been reset by two (from 7 to 9) the computer re-measures the off balance voltage to see if the re-balanced bridge gives an off balance voltage less than \( \pm 0.3 \) volts.

However, before the next sequence of operations is considered, we have to explain the manner in which a digit change is effected. As described in Section 5.9, the computer collects the digit information from a pair of arms at the same time (e.g. Arms 1 and 2 or 3 and 4 together). Each digit is coded as a BCD number in 4 bits, and these are combined in pairs and sent to the computer input as a byte (8 bits) of information. One digit is coded as the 4 least significant bits (least significant nibble) and the other digit is coded as the most significant 4 bits (most significant nibble). Thus the input port to the computer sees byte of information representing two digits simultaneously:

\[
\begin{align*}
2^7 & \quad 2^6 \quad 2^5 \quad 2^4 \\
\text{upper nibble} & \\
2^3 & \quad 2^2 \quad 2^1 \quad 2^0 \\
\text{lower nibble}
\end{align*}
\]
In balancing one arm or digit, the computer will only be interested in one half of the information: either the upper nibble (NIB%=1) or the lower nibble (NIB%=Ø).

Let us consider an example given above when arm 5 is being adjusted from 7 to 8. Digit 5 information will come to the input port of the computer in the lower nibble (through port 3 of the multiplexer). The BCD representation of 7 and 8 are:

\[
\begin{array}{cccc}
2^3 & 2^2 & 2^1 & 2^0 \\
7 & 0 & 1 & 1 & 1 \\
8 & 1 & 0 & 0 & 0
\end{array}
\]

so that the \(2^3\) bit increases from Ø to 1 when the change is effected. Thus to determine that a change has been effected, the computer simply watches for the 4th \((2^3)\) bit to be set (become 1). This can obviously be extended for all the digit changes as follows:

<table>
<thead>
<tr>
<th>Decimal Number</th>
<th>Binary Number (lower nibble) (2^3 2^2 2^1 2^0)</th>
<th>Bit Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0 0 0 0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0 0 0 1</td>
<td>(2^0 = 1)</td>
</tr>
<tr>
<td>2</td>
<td>0 0 1 0</td>
<td>(2^1 = 2)</td>
</tr>
<tr>
<td>3</td>
<td>0 0 1 1</td>
<td>(2^0 = 1)</td>
</tr>
<tr>
<td>4</td>
<td>0 1 0 0</td>
<td>(2^2 = 4)</td>
</tr>
<tr>
<td>5</td>
<td>0 1 0 1</td>
<td>(2^0 = 1)</td>
</tr>
<tr>
<td>6</td>
<td>0 1 1 0</td>
<td>(2^1 = 2)</td>
</tr>
<tr>
<td>7</td>
<td>0 1 1 1</td>
<td>(2^0 = 1)</td>
</tr>
<tr>
<td>8</td>
<td>1 0 0 0</td>
<td>(2^3 = 8)</td>
</tr>
<tr>
<td>9</td>
<td>1 0 0 1</td>
<td>(2^0 = 1)</td>
</tr>
</tbody>
</table>
Therefore to instruct the computer to turn off the driving motor at the moment a change has occurred, it is simply a matter of instructing the computer to de-activate the motor once the appropriate bit goes high. The "appropriate bit" can be determined by a simple table stored as the "Bridge Direction Matrix" and is stored as DIGIT% (DIGIT%,NIB%) which is 9x2 matrix. The dimension 9 carries the digit change information appropriate to each digit which is going to be changed whereas the dimension 2 enables parallel digit information to be used when monitoring a digit encoded in the upper nibble. Let us consider the situation in the upper nibble that mirrors that explained above. In this case the number will be represented in a slightly different way:

<table>
<thead>
<tr>
<th>Decimal Number Represented</th>
<th>Binary Number (upper nibble)</th>
<th>Bit changes:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$2^7$ $2^6$ $2^5$ $2^4$</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0 0 0 0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0 0 0 1</td>
<td>$2^4 = 16$</td>
</tr>
<tr>
<td>2</td>
<td>0 0 1 0</td>
<td>$2^5 = 32$</td>
</tr>
<tr>
<td>3</td>
<td>0 0 1 1</td>
<td>$2^4 = 16$</td>
</tr>
<tr>
<td>4</td>
<td>0 1 0 0</td>
<td>$2^6 = 64$</td>
</tr>
<tr>
<td>5</td>
<td>0 1 0 1</td>
<td>$2^4 = 16$</td>
</tr>
<tr>
<td>6</td>
<td>0 1 1 0</td>
<td>$2^5 = 32$</td>
</tr>
<tr>
<td>7</td>
<td>0 1 1 1</td>
<td>$2^4 = 16$</td>
</tr>
<tr>
<td>8</td>
<td>1 0 0 0</td>
<td>$2^7 = 128$</td>
</tr>
<tr>
<td>9</td>
<td>1 0 0 1</td>
<td>$2^4 = 16$</td>
</tr>
</tbody>
</table>

Thus a different bit must be monitored when using data stored in upper nibble. The "Bridge Direction Matrix" is therefore stored as:
Lower nibble (NIB%=Ø) 1, 2, 1, 4, 1, 2, 1, 8, 1
Upper nibble (NIB%=1) 16, 32, 16, 64, 16, 32, 16, 128, 16

In summary, once the computer knows the value of the digit to be changed and in which nibble the current value at this digit can be monitored, it can activate a driving motor until the relevant bit (determined by the Bridge Direction Matrix) goes high.

To decrease the bridge balance a similar process occurs. In this situation the motor is activated until the relevant bit goes low (from 1 to Ø) and this "relevant bit" can be determined by the same Bridge Direction matrix. This is best illustrated by an example: say that on ARM 5 (lower nibble input) we wished to change from digit value 4 to 3, which bit do we look at for change?

\[
\begin{array}{cccc}
2^3 & 2^2 & 2^1 & 2^0 \\
4 &=& 0 & 1 & 0 & 0 \\
3 &=& 0 & 0 & 1 & 1 \\
\end{array}
\]

Bit \(2^2\) = 4 goes low (1 → Ø) and so the motor is deactivated once this bit changes. Similarly the Bridge Direction Matrix is reproduced (although displaced by one digit) for all changes in digit values.
Similarly the binary bit changes with upper nibble when decimal digit decreases from 9 to 0 are given by:

<table>
<thead>
<tr>
<th>Decimal Number Represented</th>
<th>Binary Number (lower nibble) (2^3 \ 2^2 \ 2^1 \ 2^0)</th>
<th>Bit changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1 0 0 1</td>
<td>(2^0 = 1)</td>
</tr>
<tr>
<td>8</td>
<td>1 0 0 0</td>
<td>(2^3 = 8)</td>
</tr>
<tr>
<td>7</td>
<td>0 1 1 1</td>
<td>(2^0 = 1)</td>
</tr>
<tr>
<td>6</td>
<td>0 1 1 0</td>
<td>(2^1 = 2)</td>
</tr>
<tr>
<td>5</td>
<td>0 1 0 1</td>
<td>(2^0 = 1)</td>
</tr>
<tr>
<td>4</td>
<td>0 0 1 1</td>
<td>(2^2 = 4)</td>
</tr>
<tr>
<td>3</td>
<td>0 0 1 0</td>
<td>(2^0 = 1)</td>
</tr>
<tr>
<td>2</td>
<td>0 0 0 1</td>
<td>(2^1 = 2)</td>
</tr>
<tr>
<td>1</td>
<td>0 0 0 0</td>
<td>(2^0 = 1)</td>
</tr>
<tr>
<td>0</td>
<td>0 0 0 0</td>
<td>(2^2 = 4)</td>
</tr>
</tbody>
</table>
We now have a system for determining the value of any bridge digit and effecting a discrete change of ±1 on that digit. Several minor complications can occur in balancing the bridge that have to be catered for in the program. One obvious problem is what happens when one must increase the value of a digit when it is already at 9 (and similarly if the digit = 0 on decreasing). The computer handles this by quickly reducing the appropriate digit from 9 to 0 and then increasing the next higher digit by 1. It can continue up the chain of digit required so that it can handle the problem of increasing Arm 5 in the following situation:

<table>
<thead>
<tr>
<th>Bridge reading</th>
<th>6.9996320</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARM% Number</td>
<td>65432</td>
</tr>
</tbody>
</table>

and ending up with 7.0006320.

Similarly when the bridge is being decreased and a 0 is encountered, the value is increased quickly from 0 to 9 and the next highest digit is decreased by 1.

Rebalancing of the bridge continues until the off balance voltage falls to < abs (0.3V), reading being taken normally after a digit has been changed by 2. In one situation, however, the balance must be effected more precisely than this. If the bridge balance has not been changed for 1½ hours, the computer increases the sensitivity of the apparatus by working on a more sensitive digit (ARM%) and increasing the amplifier gain. Since the amplifier gain can be increased by a factor of 10, we must balance the bridge to < abs \( \frac{1.6}{10} \) = 0.16 volts before increasing the gain to ensure that the DVM is not overloaded. A small subroutine handles this special case of fine tuning before increasing the bridge sensitivity.
FLOW CHART OF SUBROUTINE TO READ DVM

From the main program

Put DVM in sampling mode i.e. Out#10,255

Wait

For IT% = 1 to 50

Read Port·1 Card 1 i.e. IN%=INP(#11)

Is the bit 4 of Port 1 high? i.e. no range change

Yes

X = 0.0

NEXT IT%

Read Port 1 Card 1 i.e. IN%=INP(#11)

Is the bit 7 of port 1 high? No flag fault condition

Yes

Out#10,254 i.e. Hold

No

GOSUB 9700 i.e. generate a deep note

Print range change

Wait

GOSUB 9700 i.e. Generate a deep note

No

FIGURE 5.5.3
FIGURE 5.5.3... contd

Wait
Read Port 1 Card 1

Is the bit 7 of Port 1 high? i.e. no flag fault condition

Yes
Wait
Loop I%=0
For I%=1 to 7
Strobe I% lines
Wait
Read Port 1 Card 1
IN%=INP(#11)
Read I% lines

No

Is bit 4 of Port 1 high? No range change

Yes
Store I%(I%) data lines by bits 0 to 3 Port 1
NEXT I%

No

GOSUB 9700 i.e. generate a deep note

Print flag faults

A B C D
FIGURE 5.5.3 ... continued
FLOW CHART FOR THE SUBROUTINE TO READ THE CAPACITANCE BRIDGE

Note

CD$ = Actual bridge reading
C$ = Display on the bridge
D$ = Digit on an individual arm
Display$ = actual bridge reading

From the main program

C$ = ""
CD$ = ""
i.e. set the initial values of C$ & CD$

Set all the ten values of D%(I%) = ""

J% = 1

For I% = 1 to 4

N% = I%

N$ = "M"
Upper nibble
Port 2 Card 3

GOSUB 6000
Calculate and send correct address to Port 2 upper nibble of RWC-F3 card

Send addresses

D%(J%) = INP(#30)
i.e. Read digit from Port 0 (i.e. input port of input card) and assign it with a variable D%(I%)

FIGURE 5.5.4
D$(I%)='X' if; 

\[ J\% = J\% + 2 \]

\[ \text{NEXT I\%} \]

\[ N\% = 5 \text{ i.e. 5th port of input card lower nibble} \]

GOSUB 6000 i.e. calculate and send correct address to upper nibble Port 2 (RWC - F3)

Reads the digit on arm 9 i.e. lower nibble Port 5

\[ D\%(9) = \text{INP(#30)} \text{ IAND 15} \]

Interpret 'X' and '-1' values

For I\% = 9 to 1 step -1

Read the digit string on all the arms i.e. from 1 to 9 i.e. \[ D\%(I\%) = \text{STR}$(D\%(I\%)) \]

\[ \text{Is } D\%(I\%)='X' \text{?} \]

\[ \text{Yes} \]

\[ \text{Is } D\%(I\%)=10? \text{ i.e. is the digit on an arm = 10?} \]

\[ \text{No} \]

\[ \text{Is } D\%(I\%)="1"? \text{ i.e. is the digit string on an arm = 11?} \]

\[ \text{Yes} \]

\[ \text{Is } D\%(I\%)=11? \text{ i.e. is the digit string on an arm = 11?} \]

\[ \text{No} \]

\[ \text{NEXT I\%} \]

FIGURE 5.5.4.. continued
For \( I^9 = 9 \) to \( 1 \) Step \( -1 \)

- If digit on an arm in the display string \( --> 11 \)?
  - Yes
    - Subtract 1 from the digit on the next higher arm i.e. \( D^9(I^9 + 1) = (D^9(I^9 + 1) - 1) \)
  - No
    - Digit on the previous arm (i.e. arm where digit was 11) would now be \( 9 \)
      - i.e. \( D^9(I^9) = 9 \)

- Is the digit on next higher arm \( < \emptyset \emptyset \)?
  - Yes
    - \( D^9(I^9 + 1) = 11 \)
  - No

- NEXT \( I^9 \)

For \( I^9 = 9 \) to \( 1 \) Step \( -1 \)

- Is the digit on an arm in the digit string \( --> 10 \)? i.e. \( D^9(I^9) < 10 \)?
  - Yes
    - Add 1 to the digit on next higher arm i.e. \( D^9(I^9 + 1) = (D^9(I^9 + 1) + 1) \)
  - No
    - Digit on the previous arm (i.e. where digit was before) will be \( \emptyset \)
      - \( D^9(I^9) = \emptyset \)
Add
Digit
String

For I% = 9 to 1 Step -1
C$ = C$ + D$ (I%)
NEXT I%

For I% = 9 to 1 Step -1
Temp$ = integer display on all the arms
i.e. Temp$ = STR$(D%(I))

Return separate characters of Temp$ i.e.
Temp$ = MID$(Temp$,1,1)

Actual capacitance = Temp$
 i.e. CD$ = CD$ + Temp$

NEXT I%

CD$ = 1+CD$

Display$ = Left$(CD$,LEN(CD$)-1)
 i.e. remove the first integer (i.e. ø) on the left hand and rest 9 integer form the display string

Is D%(10) = 1? i.e. digit on the 10th arm = 1

Yes

Is 1st digit on the left of CD$ <> ø?

Yes

CD$ = RIGHT$(CD$,LEN(CD$)-1)
i.e. remove leading zeros

No

No

FIGURE 5.5.4 ... continued
Tenth$ = 1st integer on right of the string CD$

Tenth$ = "." + Tenth$

Display$ = Display$ + Tenth$

i.e. Display = actual bridge distance in attofarads

RETURN

FIGURE 5.5.4 ... continued
FLOW CHART OF SUBROUTINE TO CHANGE THE BRIDGE BALANCE

From the main program

Click up % = Ø

ARMSTORE% = ARM%, i.e. Use the ARM% value supplied by the user in the initialisation

1. Print "ARM ERROR"

2. NIB% = 1
   N% = 1
   i.e. ARM 2

3. NIB% = 0
   N% = 2
   i.e. ARM 3

4. NIB% = 1
   N% = 2
   i.e. ARM 4

5. NIB% = 0
   N% = 3
   i.e. ARM 5

6. NIB% = 1
   N% = 3
   i.e. ARM 6

7. NIB% = Ø
   N% = 4
   i.e. ARM 7

8. Print "ARM ERROR"

GOSUB 6000.
Calculate and send correct address to upper nibble Port 2 of (RWC-F3)

FIGURE 5.5.5
Send address.

GOSUB 8900
Read digit % from bridge arm i.e.
DIGIT% = INP(#30)

Yes

If DIGIT% = φ and
DIR$ = "P"

Print DIR$ = DIR$

No

If DIGIT% = 9 and
DIR$ = "I"

Yes

Click up % = 1

No

If DIR$ = "D"

No

For I% = 1 to 9

GOSUB 8850 i.e.
increase the bridge capacitance by 1

TIME DELAY

NEXT I%

ARM% = ARM% + 1
increase the ARM%

If DIR$ = "I"

No

Yes

GOSUB 8800 i.e. decrease the bridge capacitance by 1

If DIR$ = "D" and
DIGIT% <> φ

Yes

GOSUB 8980 i.e. decrease the bridge capacitance by 1 more

TIME DELAY

NEXT I%

ARM% = ARM% + 1
i.e. increase arm

Print DIR$ = DIR$

Click up % = 1

For I% = 1 to 9

GOSUB 8800 i.e. Decrease the bridge capacitance by 1

TIME DELAY

NEXT I%

ARM% = ARM% + 1
i.e. increase arm

FIGURE 5.5.5 continued
GOSUB 8850
i.e. increase the bridge capacitance by one

If
DIR$ = "I"
and
DIGIT$<>9

Yes

GOSUB 8985
i.e. increase the bridge capacitance by 1 more

ARM% = ARMSTORE%
i.e. Store ARM%

WAIT

Click up% = Ø

RETURN

FIGURE 5.5.5 ... continued
FLOW CHART FOR THE SUBROUTINE TO TAKE A NUMBER STRING AND PUT IT IN THE STANDARD FORMAT

XXXXX.XXX
PLUS NEG= 1 or 0

From the main program

NEG=0

NEG=1

Is the first character on the left of ST$ a minus sign i.e. "-"?

No

For Scan%=1 to No. of characters in ST$

Go to 4600
Remove exponential

Is there anywhere exponential "E" at that position in character string?

No

NEXT SCAN$

FOR Scan%=1 to No of characters in the display string

Return the left of string beyond "." i.e. DUL$

Is this character a "."?

No

NEXT SCAN$

Return the right of the string ST$ i.e. DUR$

FIGURE 5.5.6
No

Add one zero

No

Yes

DUR$ = DUR$

Yes

Is the number of characters in the string DUR$ > 1

Add $\emptyset$ on the right of the display string.

ST$ = ST$ + $\emptyset$

Set the initial value of $\text{NOUGHTS}$ i.e., $\text{NOUGHTS} = "\"$

FOR IN$\% = \text{NO.$ of characters in ST$}$ to 11

Form string of zeros of correct length

NEXT IN$\%$

Add zeros string to the left of number string ST$

RETURN

FIGURE 5.5.6 ... continued
FLOW CHART OF THE SUBROUTINE TO CALCULATE THE ACTUAL CAPACITANCE FROM THE BRIDGE READING AND THE OFF BALANCE CAPACITANCE.

INPUT DISPLAY, C₁, OUTPUT FINAL$.

From the main program

ST$ = Display$

GOSUB 4100 i.e. take a number string and put it in standard format i.e. XXXXXXXXXX.XX
NEG=1 is negative
NEG=0 is positive

DIS$ = ST$

Print "The Display Error"

If NEG=1 i.e. string ST$ negative

ST$=STR$(C₁)
i.e. C₁=off balance capacitance

If Is the first character on the left of STR$(C₁)$ is " " blank i.e.

Remove the first character which is blank

GOSUB 4100 i.e. ST$
Take a number string and put in standard format i.e. XXXXXXXXXX.XX
NEG=1 or 0

FIGURE 5.5.7
C1$ = ST$

Initialise
FINAL$ = " "
CARRY = Ø

Remove the decimal point in DIS$

Remove the decimal point in C1$

If
NEG = Ø
i.e. if the off balance capacitance C1$ is positive

Yes

Carry = Ø

No

For IN% = ll to 1 step -1

Return the IN%th character of DIS$ = DT$

Return the IN% character of C1$ = CT$

Subtract two characters
i.e.
DIFF% = VAL(DT$) - VAL(CT$)

If CARRY = 1

IF DIFF% > 0
Yes

DIFF% = DIFF% - 2

No

If CARRY = 1

IF DIFF% < 0
Yes

SUM% = SUM% + 1

No

If DIFF% = 0

SUM% = SUM% - 10

No

SUM% = SUM% - 10

Yes

CARRY = 0

No
**Add result of summation to FINAL**: i.e.

\[ \text{FINAL} = \text{MID}(\text{DT}, l, l) + \text{FINAL} \]

**Add result of subtraction to FINAL**: 

\[ \text{FINAL} = \text{MID}(\text{DT}, l, l) \]

**Next IN**

**FINAL** = 9 left most integer of \(\text{FINAL}\)  
+ "." + 2 right most integers of \(\text{FINAL}\)  
i.e. put decimal point in correct position in \(\text{FINAL}\)

---

For \(\text{IN} = 1\) to \(8\)

**If** first integer in the left of \(\text{FINAL}\) is \(< 0\)

**Yes**

Remove the first integer on the left i.e.

\[ \text{FINAL} = \text{RIGHT}(\text{FINAL}, \text{LEN(\text{FINAL}) - 1}) \]

**Next IN**

\[ \text{FINAL} = \text{FINAL} + "aF" \]

**RETURN**

**FIGURE 5.5.7 ... continued**
FLOW CHART FOR SUBROUTINE TO SET THE CLOCK

From the main program

Send Ø to clock registers 15, 14, 13 GOSUB 6900
i.e. write 0 to the clock registers

Print "What is date"
DAY/MONTH/YEAR

GOSUB 9500
i.e. generate a bleep

Input data$

Print "Not in correct form - try again"

Are the number of characters in the date string = 8

Yes:
For I% = 1 to 8
Read the separate (i.e. one by one) characters in the date string

NEXT I%

Is 4th character in date string > 1

Yes

No

FIGURE 5.5.8
AC% = 12, GOSUB 6900
i.e. write to clock register address 12
i.e. tens of months

Is the 5th character in the date string > 9?

AC% = 11, GOSUB 6900
i.e. write to the clock register address 11
i.e. units of months

Is the 1st character in the date string > 32?

AC% = 9, GOSUB 6900
i.e. write to the clock register address 9
i.e. tens of days

Is the 2nd character in the date string > 9?

AC% = 8, GOSUB 6900
i.e. write to the clock register address 8
i.e. units of days

FIGURE 5.5.8 ... continued
231

Print "What is the time" HRS/MINS

Input TIME$

No

Is the No of characters in the time string = 5?

Yes

For I%=1 to 5

Read separate (i.e. one by one) characters in the time string

NEXT I%

Yes

Is the 1st character in the time string >2?

No

AC%=7, GOSUB 6900 i.e. write to the clock register address 7 i.e. tens of hours

Yes

Is the 2nd character in the date string >9?

No

Print "Not in correct form - try again"

FIGURE 5.5.8 ... continued
AC%=6, GOSUB 6900
i.e. write to the
clock register the
address 6
i.e. units of hours

Is the
4th
character
in the
time
string > 5?

AC%=5, GOSUB 6900
i.e. write to the
clock register the
address 5
i.e. tens of minutes

Is the
5th
character
in the
time
string > 9?

AC%=4, GOSUB 6900
i.e. write to the
clock register
address 4
units of minutes

RETURN

FIGURE 5.5.8 ... continued
FLOWCHART OF THE SUBROUTINE TO READ THE CLOCK OUTPUTS DATE$, TIME$

From the main program

For I% = 12 to 1 Step-1

AC% = I%
GOSUB 6800
i.e. reads the data from the block registers

CLOCK(I%) = DC%

NEXT I%

DATE$ = STR$(CLOCK%(9.0) x 10 + CLOCK%(8.0))

Return left of the DATE string
i.e. DATE$ = LEFT(DATE$, LEN(DATE$) - 2) + "/"

DATE2$ = STR$(CLOCK%(12.0) x 10 + CLOCK%(11.0))

DATE$ = DATE$ + mid of DATE2$
i.e. DATE$ = DATE$ + MID$(DATE2$, 1, LEN(DATE2$) - 3)

DATE$ = DATE$ + "/1982"

TIME$ = STR$(CLOCK%(7.0) x 10 + CLOCK%(6.0))

Return the left of the time string
i.e. TIME$ = LEFT(TIME$, LEN(TIME$) - 2) + "/"

FIGURE 5.5.9 ... continued
FIGURE 5.5.9 ... continued
### CHAPTER VI
RESULTS AND CONCLUSION

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<td>6.3.1</td>
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<tr>
<td>6.3.2</td>
<td>Results</td>
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CHAPTER VI

RESULTS AND CONCLUSIONS

6.1 Thermal Expansion of Chromium Doped GaAs

6.1.1 Introduction

The chromium doping of III-V group compounds semiconductors such as GaAs, Gap, Inp is known to produce semi-insulating material by compensation of shallow donors. In spite of great technological importance of chromium doped GaAs as a substrate for a large number of device fabrication, physical nature of chromium centres controlling the electrical properties of material has only recently become a subject of spectroscopic study. Chromium (Cr\(^{2+}\), Cr\(^{4+}\)) in GaAs is known to produce energy levels somewhere in the middle of the forbidden gap. The energy level at such a position in this semiconductor acts as electron traps or recombination centres. Chromium in GaAs can exist in four ionic states Cr\(^{1+}\), Cr\(^{2+}\), Cr\(^{3+}\) and Cr\(^{4+}\), of which there is particular discussion about the ground state of Cr\(^{2+}\) and Cr\(^{3+}\), which are known to be strongly coupled to the lattice.

The study of these energy levels is extremely important in determining most of the properties of the semiconductor. Literature shows evidence that various techniques such as APR, EPR, photoconductivity and many others have been employed to study the energy levels in chromium doped GaAs. In spite of employing various techniques by different authors at different times, it has not been possible to say with full confidence at what exact position chromium produces energy levels and what valence state they are in. There is only a general consensus of opinion about the systems.
There is evidence in the literature of the thermal expansion measurement of pure samples of GaAs (e.g. Novikova (1961) and that of silicon doped (e.g. White, G K (1975)), but there is little evidence in literature of thermal expansion measurements of chromium doped samples. This inspired us to measure chromium doped samples to see if there was an appreciable contribution to the thermal expansion of the chromium ion in GaAs and hence to study the level splittings of the excited states from the ground state. GaAs is a face centred cubic structure with a Debye temperature of only 345°K and is very brittle. In this respect it was considered a most difficult task to detect the presence of chromium by measuring the thermal expansion because the crystal's own contribution to thermal expansion may dominate at all temperatures.

6.1.2 Results

A chromium doped sample TI#5 of GaAs was very kindly provided by the Physics Department of Nottingham University. The sample was rectangular in shape. A special clamp was made to hold it at the bottom (see Figure 4.4) and a similar top plate (used as an electrode at higher potential) was made. An effort was made to mount the electrode at a higher potential on the top of the sample exactly parallel to the guard ring plate. The results obtained are shown in Figures 6.1.1 to 6.1.5. The results show a +ve peaked anomaly in the thermal expansion coefficient at about 5.8°K (α =+0.33 x 10^{-6}) which can be attributed to the presence of chromium, but we must say that it is very difficult to confirm this anomaly because it requires a series of measurements on a number of samples having different chromium concentrations and their comparison with the pure samples, which unfortunately could not be carried out. Moreover to date no theoretical values
GaAS:Cr

FIGURE 6.1.1: The Expansion Coefficient $\alpha$ Plotted Against Temperature for Chromium Doped GaAs
FIGURE 6.1.2: The Changes in Separation (Gap) Between Electrodes Plotted against Temperature for Chromium Doped GaAs.
FIGURE 6.1.3: The Expansion Coefficient $a$ Plotted against Temperature for Chromium Doped GaAs

GaAs:Cr
FIGURE 6.1.4: The Change in Separation Between Electrodes (Gap) Plotted against Temperature.

GaAS:Cr
GaAS:Si

(AFTER G. K. WHITE (1975))

FIGURE 6.1.5: The Expansion Coefficient Plotted Against Temperature for Silicon Doped GaAs (After G. K. White (1975) et al)
of volume dependence of energy levels of chromium in GaAs exist, so no comparison with experimental results could be made. Figure 6.1.5 shows the results of thermal expansion measurement for silicon doped GaAs measured by Smith and White (1975).

6.2 Thermal Expansion of Amorphous Arsenic

6.2.1 Introduction

Zeller and Pohl (1971) reported on the anomalous low temperature thermal properties of various amorphous solids. Stephens (1973) also mentioned similar observations for glasses. The low temperature thermal measurements have been made on a wide range of amorphous solids in recent years. Similar features have been reported in all of them. It has been observed that below 10K the specific heat is considerably larger than that calculated from measured sound velocities. At very low temperature i.e. of the order of milliKelvin, specific heat cannot be described by simple power law, however it can be explained adequately between 0.1 and 1K by a term proportional to temperature T together with a term proportional to $T^3$.

Anderson et al (1972) and Philips (1972) independently proposed a model known as "tunnelling state model" for the explanation of this anomalous behaviour of amorphous solids. This model is based on the idea of tunnelling states in glasses. In this model the quantum mechanical tunnelling of an atom or a small group of atoms from one potential minimum to the neighbouring one gives rise to small energy splitting $\epsilon$ between the ground and excited states. This energy can be compared to thermal energy at 1K and below. A wide range of such energy splitting is to be expected as a general feature of the amorphous solids and can be described by the density of states $n(\epsilon)$. 
White, G K (1975), argued that low temperature thermal expansion measurement on amorphous solids can provide a test for the tunnelling hypothesis since this mechanism should result in anomalous thermal expansion below 4°C. His argument was based on the fact that K O McLean (1972) et al and C R Case (1974) et al had already observed the tunnelling related anomalies for dilute concentrations of OH⁻ and CN⁻ in NaCl and Li⁺ in KCl.

Jones, D P et al (1978) measured specific heat of amorphous arsenic down to very low temperatures. They showed a significant departure from Debye behaviour at 1°C. They demonstrated that specific heat varies at T³ below 0.7°C and there was no sign of the linear anomaly observed in other amorphous solids. Their result (reproduced in Figure 6.2.4) shows a peaked anomaly at about 5°C in the plot of specific heat/T³ vs temperature. The literature shows little evidence of thermal expansion measurement of amorphous arsenic except Brassington, M P et al (1979) who have used our earlier data at higher temperatures from 60°C to 175°C (they found a good fit to the theory) to determine second and third order elastic constants.

These factors inspired us to measure thermal expansion of amorphous arsenic to study its peculiar behaviour.

6.2.2 Results

A sample of bulk a-As was obtained from the Mining and Chemical Products where it was prepared by condensing As in the presence of hydrogen on a heated substrate.

Due to the irregular shape of the sample, it was extremely difficult to hold this firmly at the dilatometer base and to stick a Cu plate at the top of the sample to
<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Expansion Coefficient $(K^{-4})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.965</td>
<td>-0.4127E-09</td>
</tr>
<tr>
<td>3.057</td>
<td>-0.3124E-08</td>
</tr>
<tr>
<td>3.294</td>
<td>-0.1177E-08</td>
</tr>
<tr>
<td>4.307</td>
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<tr>
<td>4.385</td>
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<td>4.495</td>
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<tr>
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<td>4.764</td>
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<td>5.700</td>
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<tr>
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<td>6.907</td>
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<td>0.1743E-08</td>
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<tr>
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<tr>
<td>17.56</td>
<td>0.5460E-09</td>
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<td>18.39</td>
<td>0.5060E-09</td>
</tr>
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<td>0.4760E-09</td>
</tr>
<tr>
<td>19.62</td>
<td>0.4560E-09</td>
</tr>
<tr>
<td>20.32</td>
<td>0.4310E-09</td>
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</tbody>
</table>

**TABLE 6.1:** The Values of Temperature and $a/T^3$ given in this Table have been plotted in Figure 6.2.4.
The Separation Between Electrodes (Gap) Plotted Against Separation
FIGURE 6.2.2: The Expansion Coefficient Plotted Against Temperature for Amorphous Arsenic
FIGURE 6.2.3: The Expansion Coefficient/T^3 Plotted Against Temperature for Amorphous Arsenic
a_\alpha S

(AFTER D.P. JONES et al (1978))

FIGURE 6.2.4: Specific Heat/T^3 Plotted Against Temperature
(after Jones, D P et al (1978))
act as an electrode at higher potential. Its top and bottom faces were ground to make them as flat as possible so that the capacitor electrodes would be parallel. For this purpose clamping plates (both for the top and bottom) were made. The details of the clamping mechanism can be seen in Chapter 4. The results obtained are presented in Figures 6.2.1 and 6.2.2. The results at higher temperatures are in general agreement with the theory. In order to compare our results at low temperature with Jones, D P et al (1978), who made specific heat and thermal conductivity measurements on a sample from the same sources, we have plotted $\alpha/T^3$ vs temperature. This is shown in Figure 6.2.3. It is seen that our results are in excellent agreement with Jones et al in that both results show a peaked anomaly at about 50 K. Our result is in agreement with Jones et al above 4.2 K, below which our data points seem to be noisy.

6.3 Thermal Expansion of Vanadium Silicate ($V_3Si$)

6.3.1 Introduction

Kohn and Vachaspati (1951) first discussed the lattice instability due to strong electron phonon coupling. Later on after the development of BCS theory various authors (e.g. Cohn et al (1967), Phillips J C (1971)) evaluated quantitatively the effect of the instability of the lattice on a variety of properties. Tyalilikosou et al (1958) and Abriksov et al (1958) established a criterion for lattice stability which is given by

$$N(\varepsilon_F) V_{BCS} < \frac{1}{x}$$

where $\varepsilon_F$ is the Fermi energy and $V$ is the volume of the lattice. It became evident that lattice instabilities
may be expected in high temperature superconductors or more precisely in materials with largest $T_c/\theta_D$ (where $T_c$ is transition temperature and $\theta_D$ is the Debye temperature) ratio. In particular, the group A15 structure, $V_3X$ and $Nb_3X$ showed some additional features such as large and strongly temperature dependent susceptibilities, large electronic specific heat (Morin et al (1963)), suggesting extremely narrow $d$ band and high density of states, thus favouring large electron-phonon coupling constants. Clogston, A M et al (1966)). Labbe, J and Friedel, J (1966) showed that lattice instability will occur in these materials (A15) if Fermi energy is close enough to the bottom of sub-band leading to excessively high density of states with decreasing temperature. The crystal will distort spontaneously to a tetragonal unit cell at some temperature $T_m'$, called the martensitic temperature. The lowering of the symmetry leads to the splitting of the degenerate $m = \pm 2$ sub-band and at the same time the lower density of states. Katsumi Akutsu et al (1976) observed an anomaly in the mixed state of $V_3Si$ single crystal in specific heat measurement. Smith et al (1975, 1976) while making thermal expansion measurements on nearly stoichiometric samples of $V_3Si$, reported that the sample contracts on warming at a temperature above $T_c = 16.5^0K$ over a span of several tens of degree Kelvin. They interpreted the corresponding negative thermal expansion coefficient as arising from anharmonic properties of the cubic lattice. Smith et al samples were polycrystalline. This inspired M Melewits et al (1978) to make measurements of thermal expansion on a single crystal of $V_3Si$ and to see if they behaved like the Smith et al samples. Milewits et al (1978) measured five single crystals of $V_3Si$ two of which displayed lattice transformation from cubic A15 phase at high temperature to tetragonal phase below $21K$, and three
of their samples remained cubic at all temperatures. Earlier Fawcett (1971) had reported large anomaly in thermal expansion coefficient $\alpha$ due to structural transformation in $V_3Si$. Fukase, T et al (1978) studied the structural transformation in single crystals of $V_3Si$ in normal and superconducting states by measuring their thermal expansion. Because the behaviour of $V_3Si$ samples are very sensitive to strain, Fukase et al therefore adopted two different methods of mounting the samples in the capacitance dilatometer (see Fukase et al (1971) for details). The samples behaved quite differently in the two methods. Work on these systems is being carried out by our collaborator in Grenoble (France) and we were asked by M Couach (private communication) to measure the thermal expansion of one of the samples of $V_3Si$ to see whether our results agreed with Fukasé et al and moreover to resolve the problem of temperature at which the transformation starts and the span of this temperature range.

6.3.2 Results

Our collaborators in the field at Grenoble very kindly provided us with a sample (axis 100). The sample was extremely short, only about 0.9 mm thick (which can be considered as the length of the sample). As already explained in Chapter 4, a semi-absolute expansion cell was used for its measurement. A special guard ring plate (used as a plane plate) was made and three identical pieces of sample were stuck (by using G E Varnish on the side of the sample, care being taken not to use varnish between the sample and plate), at an angle of $120^\circ$ around the guard plate. The central electrode of this plate was used as an electrode at high potential. For further details see Chapter 4.
FIGURE 6.3.1: Changes in Separation Between Electrode (specimen length changes in this case) Plotted Against Temperature for Vanadium Silicate

\[ \Delta g(\AA) \times 10^3 \]

monocrystal \( S_2T_3P \) \( V_2Si [001] \)
FIGURE 6.3.2: The Expansion Coefficient Plotted Against Temperature for Vanadium Silicate Sample

\[ \alpha \times 10^{-6} \]

Temperature (K)

monocrystal \( S_2T_p \) \( V_3Si \) [001]
The results obtained are presented in Figure 6.3.1 where the gap (the specimen length in this case) change has been plotted against temperature. The Figure 6.3.2 shows a plot of expansion coefficient vs temperature. Our result is in excellent agreement with Fukasè et al. Our equipment being about 100 times more sensitive than Fukasè et al, provides more precise information. We will simply outline essential features of our results. As can be seen from Figure 6.3.2, with increasing temperature $\alpha$ decreases steeply above $T_c$ (16.3$^\circ$K), and shows a $\sim$-ve peaked anomaly (negative thermal expansion $\alpha = -0.194 \times 10^{-4}$/K) at martensitic temperature $T_m = 20.7^\circ$K and then starts increasing above $30^\circ$K and more indicating a structural transformation from cubic to tetragonal. Our result reinforces Fukasè et al claim that anisotropy is confined to somewhere between $30^\circ$K and $70^\circ$K.

6.4 Conclusion

The measurement of thermal expansion on the three different samples, has demonstrated the fact that automated cryostat is working well and can produce good results. Time factors prevented us from carrying out further measurements which will need to be carried out. We would especially like to emphasise that chromium doped GaAs is very interesting and needs intensive experimental work.
APPENDIX

COMPUTER PROGRAM
APPENDIX
COMPUTER PROGRAM

1 P2%=255
5 POKE #131,1
6 COLOR 14 5 0
10 CLEAR 10000
12 PRINT "ARM%=":GOSUB 5500:INPUT ARMS%:ARM%=ARMS%:PRINT
13 BLOCK=0.0
14 DIM CAL(10.0)
15 DIM IS%(7.0),LI(7.0)
16 DIM F(2.0,70.0),X(2.0,5.0),G(10.0,2.0,7.0),H(2.0,70.0),Y(2.0,5.0)
17 DIM D%(10.0),D$(10.0)
18 DIM DIGIT%(9.0,2.0),GAIN%(10.0)
20 L%=1
21 N1=0.0:N4=0.0
22 C$=" ":CD$=" ":J%=1
25 REM INITIALISE CARD1-DVM INTERFACE
26 OUT #13,130
45 OUT #33,#90:REM SET PORT1,2-0/P*PORT0-I/P
50 REM INITIALISE CARD 4-SWITCH CONTROL
55 OUT #43,80:PO%=0:PO%=0:PO%=18
60 OUT #40,P%=OUT #41,PO%=OUT #42,P%=0
70 REM INITIALISE CARD 5-CLOCK AND AMP. GAIN
75 OUT #53,#B8
76 OUT #51,127:OUT #50,0:OUT #52,0:OUT #51=127
77 FOR J%=2 TO 6:READ GAIN%(J%):NEXT J%
78 DATA 10,8,32,128,128
79 REM 90,70,50,30,30 DB GAIN SETTINGS CORR. TO
80 REM 2, 3, 4, 5, 6 ARM% VALUES
85 PS%=GAIN%(ARM%):OUT #50,PS%
87 REM INITIALISE CARD 6
88 OUT #63,#90:OUT #61,0:REM ALL MOTORS OFF-DIR. INC.
90 GOSUB 6500:REM SET CLOCK
95 AC%=14:DC%=1:GOSUB 6900:REM START CLOCK
97 REM **SET INITIAL TIME IN STORET
98 GOSUB 6700
99 STORET=(CLOCK%(7.0)*10.0+CLOCK%(6.0)*60.0+(CLOCK%(5.0)*10.0+CLOCK%(4.0))
100 STORET=STORET-31.0
101 REM SET UP BRIDGE DIRECTION MATRIX
105 FOR I%=0 TO 1
110 FOR J%=0 TO 8
115 READ GAIN%(J%,I%)
120 NEXT J%:NEXT I%
121 REM MOTOR DIRECTION MATRIX
122 DATA 1,2,1,4,1,2,1,8,1,16,32,16,64,16,32,16,128,16
125 Motor%=0
130 REM SET UP STROBE ARRAY
135 FOR I%=1 TO 7
140 FOR J%=1 TO 7
145 L%=2*L%:IS%(I%)=254-L%
150 NEXT I%
155 N1=N1+1.0:READ F(1.0,N1),F(2.0,N1)
210 IF F(1.0, N1)<>0.0 GOTO 200
220 N1=N1-1.0
230 N4=N4+1.0:READ H(1.0, N4), H(2.0, N4)
240 IF H(1.0, N4)<>0.0 GOTO 230
250 N4=N4-1.0
330 PRINT "NEW CALIBRATION (Y/N)"
331 GOSUB 9500
332 ENVELOPE 1 15
333 Y9=GETC:IF Y9=89.0 THEN 333:IF Y9=78.0 THEN 334:GOTO 333
334 PRINT
340 IF Y$="Y" THEN GOTO 9000:REM INPUT BRIDGE CALIBRATION DATA
341 GOSUB 9500
342 PRINT "IS THIS A REAL CALIBRATION? (Y/N)"
343 Y9=GETC:IF Y9=89.0 THEN 343:IF Y9=78.0 THEN 344:GOTO 343
344 IF Y$="Y" THEN GOTO 9800:REM INPUT CAL.
345 GOTO 9900
350 ARM%=ARMSTORE27.:P507.=GAIN{l,}(ARM{l,}):OUT #50,P507.
355 PRINT
360 PRINT :PRINT "CALIBRATION COMPLETE - RESET BRIDGE"
365 PRINT "PRESS <SPACE BAR> WHEN READY TO CONTINUE"
366 PRINT
367 A=GETC:IF A=32.0 THEN 420:GOTO 367
420 PRINT
439 GOSUB 9500
440 PRINT :PRINT "HOW MANY CAPACITANCE READINGS?":INPUT U
445 PRINT
449 REM ******************************
450 REM ***START READINGS ***
451 REM ******************************
455 REM **READ THERMOMETER CURRENT**
456 PRINT "READING RELAY=":
460 RELAYS%=0:PRINT RELAYS%::GOSUB 2000
480 A=D:WAIT TIME 200
510 REM **READ 1ST THERM. VOLTAGE**
520 RELAYS%=1:PRINT RELAYS%::GOSUB 2000
540 C=D:WAIT TIME 200
550 REM **READ 2ND THERM. VOLTAGE**
560 RELAYS%=2:PRINT RELAYS%::GOSUB 2000
580 C3=D:WAIT TIME 200
600 REM **READ BRIDGE VOLTAGE U TIMES**
620 RELAYS%=3
630 PRINT RELAYS%
640 CO=0.0:WAIT TIME 50
660 FOR S=1.0 TO U
680 PRINT CHR$(64+S)::GOSUB 9500::GOSUB 2000
700 WAIT TIME 200:CO=CO+D
720 NEXT S
740 CO=CO/U
800 REM **CALCULATION OF PARAMETERS**
820 A=A/1000.0
Contd...
IERROR=0.0
IF A>1E-7 THEN 840
PRINT "CURRENT READING FAULT- A<10-7 A"
A=ISTORE:PRINT "PUT CURRENT=":A
IERROR=1.0
R=C/A
ISTORE=A
R3=C3/A
GOSUB 2300:REM CALCULATE Temp. of 1st Therm.
GOSUB 2500:REM CALCULATE Temp. of 2nd Therm.
GOSUB 2700:REM CALCULATE DELTA C
REM ********************
REM ** OUTPUT PHASE **
REM ************+********++++
POKE #131,0
PRINT :PRINT "****+***+++++++***++++++**+++*+*******++**+*+*********+++**
**********
GOSUB 6700
PRINT "DATE=":DATE$,"TIME=":TIME$
PRINT "THERMOMETERS NO.1 NO.2"
PRINT "VOLTAGE(V)=",C,C3
PRINT "CURRENT(A)=",A,A
IF IERROR=1.0 THEN PRINT "CURRENT READING FAULT (I<10-7 A) - CURRENT SET TO PREVIOUS VALUE "
PRINT "RESISTANCE(OHM)=",R,R3
PRINT "TEMPERATURES(K)=",TEMP1,TEMP2
PRINT "BRIDGE PARAMETERS ARM%=",ARM%
PRINT "Bridge PARAMETERS ARM%=",ARM%
GOSUB 5000
PRINT "Bridge Voltage=":CO;"V";TAB(32);"Bridge Display=":C$;
PRINT "DELTA C=";Cl;"aF";TAB(32);"Bridge Reading=":DISPLAY$;
aF";TAB(32);"Actual Capacitance AT Temperature=";TEMP1;"K"
GOSUB 4000:PRINT "TIME ELAPSED FROM LAST BRIDGE BALANCE=";ELAPSE;" MIN."
POKE #131,1
REM ********************
REM ** DECISION PACK **
REM ************+**************++++******
REM ** THERMOMETER CURRENT CHECK**
IF TEMP1<2.9 THEN P42=130:REM 1A SETTING
IF (TEMP1>3.1) AND (TEMP1<9.9) THEN P42=65:REM 10UA SETTING
IF (TEMP1>10.2) AND (TEMP1<39) THEN P42=34:REM 100UA SETTING
P42=18:REM 1 MA SETTING
OUT #42,P42:REM SET APPROP. CURRENT
REM **BRIDGE BALANCE CHECK**
IF ABS(CO)<0.7 THEN 1434
1320 IF CO>0.7 THEN 1350
1330 REM CO<0.7
1331 P51%=P51%+128:OUT #51,P51%
1332 DIR$="I":GOSUB 8500:REM INCREASE BRIDGE BY 1
1333 WAIT TIME 200
1334 RELAYS%=3:GOSUB 2000:REM READ CO AGAIN
1335 PRINT "BRIDGE VOLTAGE":D
1336 IF D>(-0.3) THEN 139:REM BRIDGE VOLTAGE>-0.3
1338 GOTO 1332
1339 P51%=P51%-128:OUT #51,P51%:GOTO 1400
1340 RELAYS%=3:GOSUB 2000:REM DECREASE BRIDGE BY 1
1341 WAIT TIME 200:RELAYS%=3:GOSUB 2000:REM READ CO AGAIN
1342 PRINT "BRIDGE VOLTAGE":D
1343 IF D<(0.3) THEN 138:REM BRIDGE VOLTAGE<0.3
1344 GOTO 1332
1345 P51%=P51%+128:OUT #51,P51%:GOTO 1400
1346 REM ** TIME OF LAST BRIDGE CHANGE CHECK
1347 REM **GET CURRENT TIME IN MINUTES (NOS.)
1348 CTIME=(CLOCK%(7.0)*10.0+CLOCK%(6.0)+60.0+(CLOCK%(5.0)+10.0+CLOCK%(4.0))
1349 IF CTIME<STORET THEN CTIME=CTIME+24.0+60.0:REM CORRECT FOR 24 HOUR CHANGE OVER
1350 REM **TEST FOR TIME DURATION FROM LAST BRIDGE CHANGE
1351 ELAPSE=CTIME-STORET
1352 IF (CTIME-STORET)>30.0 THEN 1610
1353 IF ARM%=6.0 THEN 1610:REM NO INCREASE IN ARM% POSSIBLE
1354 ARM%=ARM%-1:GOTO 1510
1355 IF ARM%=2 THEN 450:REM NO CHANGE DOWN POSSIBLE
1356 IF (CTIME-STORET)<90.0 THEN 450:REM NO CHANGE REQUIRED
1357 REM **CHANGE ARM BASED ON TIME ELAPSED
1358 ARM%=ARM%-1
1359 P51%=P51%-128:OUT #51,P51%:GOTO 1400
1360 RELAYS%=3:GOSUB 2000:REM READ CO=D
1361 REM **BALANCE BRIDGE AT OLD GAIN TO <0.16 BEFORE INCREASE
1362 IF ABS(D)<0.16 THEN 1500
1363 IF D>0.0 THEN 1470
1364 DIR$="I":GOTO 1472:REM D<0 INCREASE BRIDGE
1365 DIR$="D"
1366 GOSUB 8500:REM CHANGE BY ONE WITH "BLOCK"
1367 GOSUB 2000:REM READ CO=D
1368 PRINT "D":D
1369 IF ABS(D)<0.16 THEN 1500
1370 REM **NOW TEST FOR ABORT
1371 IF (DIR$="I") AND (D>0.0) THEN 1484
1372 IF (DIR$="D") AND (D<0.0) THEN 1484
1373 GOTO 1472
1374 ARM%=ARM%+1:REM RESTORE ORIGINAL ARM-ATTEMPT FAILED
1375 PRINT "CHANGE OF ARM NOT BALANCED"
1376 P51%=P51%-128:OUT #51,P51%:REM LONG T CONST.
1378 GOTO 450
1379 BLOCK=0.0
1380 CONTINUED...
TCONSTCL%=0
OUT #50,GAIN%(ARM%):REM CHANGE ARM% AND CHANGE AMPLIFIER GAIN
WAIT TIME 500:P51%=P51%-128:OUT #51,P51%=REM LONG T CONST
POKE #131,0:PRINT "CHANGE OF BRIDGE ARM TO-";ARM%
POKE #131,1:REM TURN OFF PRINTER
STORET=CTIME
GOTO 450
STOP
REM ***********************
REM **SUBROUTINE TO INPUT SIGNALS TO DVM**
REM **AND TO RETURN REVERSE POLARITY AVERAGE**
REM **REQUIRES RELAY VALUE 0-7 (RELAYS%)**
REM **OUTPUTS D=DVM READING**
REM **OPEN SHORTING LINK**
P42%=P42%-2:OUT #42,P42%
REM **OPEN CORRECT PAIR OF RELAYS**
P41%=1 SHL (RELAYS%):OUT #41,P41%
P40%=P41%:OUT #40,P40%
FOR T=1.0 TO 1000.0:NEXT T:REM DELAY TO SETTLE
IF RELAYS%=3 THEN WAIT TIME 200:REM MORE TIME FOR BRIDGE VOLTAGE
GOSUB 3000:REM READ DVM-RESULT=D
DSTORE=D:REM STORE RESULT
REM **REVERSE DVM INPUT POLARITY & REPEAT**
P42%=P42%+1:OUT #42,P42%
FOR T=1.0 TO 1000.0:NEXT T:REM DELAY TO SETTLE
IF RELAYS%=3 THEN WAIT TIME 200:REM MORE TIME FOR BRIDGE VOLTAGE
GOSUB 3000:REM READ DVM IN OPPOSITE POLARITY
OUT #40,0:OUT #41,0:WAIT TIME 5:REM OPEN CIRCUIT RELAYS
OUT #42,0:OUT #42,0:REM SWITCH OFF DVM & SHORT
D=-(DSTORE-D)/2.0
GOSUB 9700
RETURN
REM *************************************
REM ** CONVERSION OF RESISTANCE VALUES **
REM ** INTO TEMPERATURE FOR I ST THERM. **
REM *************************************
N2=0.0:IF R<(F(1.0,3.0)) THEN N2=1.0
IF R>(F(1.0,N1-2.0)) THEN N2=N1-4.0
IF N2<0.0 THEN GOTO 2400
FOR I=1.0 TO N1:IF F(1.0,I)<R THEN N2=I-2.0
NEXT I
FOR I=1.0 TO 5.0:N3=N2+I-1.0:X(1.0,I)=F(1.0,N3)
X(2.0,I)=F(2.0,N3):NEXT I
L1=R-(X(1.0,J)):(X(1.0,I)-X(1.0,J)):L2=L2*L3
NEXT J
L1=L1+L2:NEXT I:TEMP1=L1:RETURN

Contd...
REM *****************************************************
REM ** CONVERSION OF RESISTANCE VALUES **
REM ** INTO TEMPERATURE FOR 2ND THERM. **
REM *****************************************************
N5=0.0:IF R3<H(1.0,3.0) THEN N5=1.0
IF R3>H(1.0,N4-2.0) THEN N5=N4-4.0
FOR I=1.0 TO N4:IF H(I.0,I)<R3 THEN N5=I-2.0
NEXT I
FOR I=1.0 TO 5.0:N6=N5+I-1.0:Y(I.0,I)=H(I.0,N6)
NEXT I
L4=0.0:FOR I=1.0 TO 5.0:L5=Y(2.0,I):FOR J=I.0 TO 5.0
IF J=I THEN GO TO 2610
L6=(R3-Y(I.0,J))/(Y(I.0,I)-Y(I.0,J)):L5=L5*L6
NEXT J
L4=L4+L5:NEXT I:TEMP2=L4:RETURN
REM *****************************************************
REM ** SUBROUTINE TO CONVERT BRIDGE **
REM *****************************************************
L1=0.0:FOR IX=1 TO 9.0:L2=G(IX,2.0,ARMX):FDR JX=I.0 TO 9.0
IF JX=IX THEN GO TO 2740
L3=(CO-G(JX,I.0,ARMX))/(G(IX,I.0,ARMX)-G(JX,I.0,ARMX)):L2=L2*L3
NEXT JX
L1=L1+L2:NEXT IX:C1=L1
RETURN
REM *****************************************************
REM ** SUBROUTINE TO READ KIETHLEY DVM **
REM *****************************************************
OUT #10,255
WAIT TIME 200
FOR IX=1 TO 50
INX=INP(#II)
IF (INX=1 AND 16)=16) THEN 3080
GOSUB 9700
PRINT "RANGE CHANGE"
WAIT TIME 125
GOSUB 9700
X=0.0
NEXT IX
INX=INP(#II)
IF (INX=1 AND 128)=128) THEN 3130
GOTO 3100
OUT #10,254
WAIT TIME 50
INX=INP(#II)
IF (INX=1 AND 128)=128) THEN 3190
GOSUB 9700
PRINT "FLAG FAULT"
3180 GOTO 3010
3190 WAIT TIME 5
3200 LOOP1X=0
3210 FOR IX=1 TO 7
3220 ISX=ISX(IX):OUT #10,ISX:REM:DVM IS STROBED
3230 WAIT TIME 3:INX=INP(#II):REM:DATA LINES ARE READ
3240 LX(IX)=(INX IAND 15):REM:STROBED DATA STORED
3250 NEXT IX
3260 OUT #10,255
3280 IF ((LX(5.0) IAND 4.0)=0.0) THEN 3300
3285 LOOP1%=LOOP1%+1:IF LOOP1%$ THEN 450
3290 PRINT "OVERLOAD":GOSUB 9700:GOTO 3200
3300 D=LX(1.0)+10.0*LX(2.0)+100.0*LX(3.0)+1000.0*LX(4.0):D=LX
3310 IF ((LX(5.0) IAND 1.0)=0.0) THEN 3330
3320 LX=LX(I.0)+10.0*LX(2.0)+100.0*LX(3.0)+1000.0*LX(4.0):D=LX
3340 D=D*IE-4
3350 IF ((LX(5.0) IAND 8.0)=8.0) THEN 3350
3360 D=D*IE-3
3370 D=D*IE-2
3380 D=D*IE-1
3390 D=D*IE-0
3410 IF ((LX(6.0) IAND 8.0)=0.0) THEN 3425
3420 D=D*IE-0
3425 ARG1X=(LX(7.0) IAND 1.0):ARG2X=(LX(7.0) IAND 2.0)
3430 IF ((ARG1X=1.0) AND (ARG2X=0.0)) THEN 3470
3440 IF ((ARG1X=0.0) AND (ARG2X=2.0)) THEN 3490
3450 PRINT "SCALE ERROR"
3460 GOTO 3020
3470 D=D*IE-3
3480 GOTO 3500
3490 D=D*IE-6
3500 RETURN
4000 REM ***************************************************************
4001 REM ** SUBROUTINE TO CALCULATE ACTUAL CAPACITANCE **
4002 REM ** FROM BRIDGE READING & OFF BALANCE CAP. **
4003 REM ** INPUT DISPLAY$,C1 OUTPUT FINAL$ IN aF **
4006 REM ***************************************************************
4015 ST$=DISPLAY$
4020 GOSUB 4100
4025 DIS$=ST$:IF NEG=1.0 THEN PRINT "DISPLAY ERROR"
4027 ST$=STR$(C1):IF LEFT$(ST$,1)=" " THEN ST$=RIGHT$(ST$,LEN(ST$)-1)
4030 GOSUB 4100:C1*=ST$
4032 FINAL$="":CARRY=0.0
4034 DIS$=LEFT$(DIS$,LEN(DIS$)-3)+RIGHT$(DIS$,2)
4035 C1*=LEFT$(C1*,LEN(C1*)-3)+RIGHT$(C1*,2)
4036 IF NEG=0.0 THEN 4060
4060 PRINT "NO SIGNAL":GOTO 262
4040 FOR INX=11 TO 1 STEP -1
4042 DT$=MID$(DIS$, (INX-1), 1); CT$=MID$(CI$, (INX-1), 1)
4044 SUM%=VAL(DT$)+VAL(CT$)
4046 IF CARRY=1 THEN SUM%=SUM%+1
4048 IF SUM%<10 THEN 4052
4050 SUM%=SUM%-10:CARRY=1.0:GOTO 4054
4052 CARRY=0.0
4054 DT$=STR$(SUM%):FINAL$=MID$(DT$, 1, I)+FINAL$
4056 NEXT INX
4058 GOTO 4080
4060 CARRY=0.0:FOR INX=11 TO 1 STEP -1
4063 DT$=MID$(DIS$, (INX-1), 1); CT$=MID$(CI$, (INX-1), 1)
4064 DIFF%=VAL(DT$)-VAL(CT$)
4066 IF CARRY=1 THEN DIFF%=DIFF%-1
4068 IF DIFF%>0 THEN 4074
4069 IF DIFF%=0 THEN 4074
4070 DIFF%=DIFF%+10:CARRY=1.0
4072 GOTO 4076
4074 CARRY=0.0
4076 DT$=STR$(DIFF%):FINAL$=MID$(DT$, 1, I)+FINAL$
4078 NEXT INX
4080 FINAL$=LEFT$(FINAL$, 9)+"."+RIGHT$(FINAL$, 2)
4092 FOR INX=1 TO 8:IF LEFT$(FINAL$, 1)<>"0" THEN 4095
4094 FINAL$=RIGHT$(FINAL$, LEN(FINAL$)-1):NEXT INX
4095 FINAL$=FINAL$+"af"
4099 RETURN
4100 REM *********************************************************
4101 REM ** SUB ROUTINE TO TAKE NUMBER STRING **
4102 REM ** AND PUT IN STANDARD FORMAT XX.XX PLUS NEG= 1 OR 0 **
4103 REM *********************************************************
4114 NEG=0.0
4120 IF LEFT$(ST$, 1)<>"-" THEN 4140
4130 NEG=1.0:ST$=RIGHT$(ST$, LEN(ST$)-1)
4140 FOR SCAN%=1 TO LEN(ST$)
4150 IF MID$(ST$, SCAN%-1, I)="E" THEN 4600
4180 NEXT SCAN%
4170 REM NO EXPONENTIAL TERM
4180 FOR SCAN%=1 TO LEN(ST$)
4190 IF MID$(ST$, SCAN%-1, I)="." THEN 4230
4200 NEXT SCAN%
4210 ST$=ST$+".00":REM NO DEC. POINT ADD .00
4220 GOTO 4400
4230 DUL$=LEFT$(ST$, SCAN%-1)
4240 DUR$=RIGHT$(ST$, LEN(ST$)-SCAN$)
4250 IF LEN(DUR$)>1 THEN 4270
4260 DUR$=DUR$+"0":GOTO 4345
4270 IF LEN(DUR$)=2.0 THEN 4400
4280 DUR$=LEFT$(DUR$, 2)
4345 GOTO 4350
264

4350 ST$=DUL$+"."+DUR$ GOTO 4400
4400 REM NOW WITH .00
4405 REM NOW FILL WITH NOUGHTS
4410 NOUGHTS$="FOR INX=LEN(ST$) TO 11:NOUGHTS$=NOUGHTS$+"0"
4415 NEXT INX:ST$=NOUGHTS$+ST$
4420 RETURN
4600 REM ** ROUTINE TO REMOVE EXPONENTAIL **
4601 IF MID$(ST$,(SCANX),1)="" THEN 4715
4605 REM +IVE EXPONENTIAL
4610 DUR$=RIGHT$(ST$,(LEN(ST$)-SCANX))
4615 DUL$=LEFT$(ST$,(SCANX-1))
4620 LENDUL%=LEN(DUL$):DURY.=VAL(DUR$)
4625 IF LENDUL%=1 THEN 4635
4630 LENDUL%=3:DUL$="0".
4635 IF (LENDUL%-2)>DUR% THEN 4685
4640 IF (LENDUL%-2)=DUR% THEN 4660
4645 REM LENDUL%-2<DUR% ADD CORRECT NO. OF 0S
4650 FOR INX=1 TO (DUR%=LENDUL%+2)
4655 DUL$=DUL$+"0":NEXT INX
4660 REM REMOVE "." 
4665 IF LENDUL%=1 GOTO 4180
4670 DUL2$=LEFT$(DUL$,1)
4675 DUL2$=DUL2$+RIGHT$(DUL$,LEN(DUL$)-2)
4677 ST$=DUL2$
4680 GOTO 4180
4685 DUL2$=LEFT$(DUL$,1)
4690 DUL2$=DUL2$+RIGHT$(DUL$,LEN(DUL$)-2)
4695 REM NOW REPLACE DEC. POINT
4705 DUL$=LEFT$(DUL2$, (DUR%+1))+"."+RIGHT$(DUL2$, (LEN(DUL2$)-DUR%+1))
4708 ST$=DUL$
4710 GOTO 4180
4715 DUR$=RIGHT$(ST$,LEN(ST$)-SCAN%-1)
4720 DUR%=VAL(DUR$)
4725 NOUGHTS$=""
4730 FOR INX=1 TO (DUR%-1)
4735 NOUGHTS$=NOUGHTS$+"0"
4740 NEXT INX
4745 DUL$=LEFT$(ST$,SCAN%-1)
4750 REM REMOVE "." IF THERE
4755 IF LEN(DUL$)>1.0 THEN 4760
4756 DUL$=NOUGHTS$+DUL$:GOTO 4775
4760 DUL2$=LEFT$(DUL$,1)
4765 DUL2$=DUL2$+RIGHT$(DUL$,LEN(DUL$)-2)
4770 DUL$=NOUGHTS$+DUL2$
4775 DUL$="0."+DUL$
4780 ST$=DUL$ GOTO 4180

Cont...
REM ************************************************
REH
** SUBROUTINE TO READ THE CAPACITANCE BRIDGE **
REH ** THROUGH PORT 0, UPPER NIBBLE & PORT2 CARD 3 **
REM ************************************************
C$="I"CD$=""
FOR I%=1 TO 10
D$(I%)=0.0:D$(I%)=" "
NEXT I%
REM *****READ BRIDGE VALUES****************
JI=1
FOR I%=1 TO 4
NI=II:N$="H":GOSUB 6000
OUT #32,P21:REH SENDS I/P ADDRESS TO UNI-PORT2
DI(JI)=INP(#30)
01(JI+1.0)=01.(JI) lAND 240.0
01(JI)=01.(JI) lAND 15.0
DI(JI+1.0)=01.(J7.+1.0) SHR 4.0
01(JI)=01.(JI) lAND 15.0
J7.=J7.+2
NEXT I%
N7.=5:GOSUB 6000:OUT #32,P21
DI(9.0)=INP(#30) lAND 15
REH ***INTERPRET 'X' AND (-1) VALUES
FOR I%=9 TO 1 STEP -1
D$(I%)=STR$(01.(I%))
D$(I%)=LEFT$(D$(I%),LEN(D$(I%))-2.0)
D$(I%)=RIGHT$(D$(I%),LEN(D$(I%))-1.0)
IF D$(I%)="10" THEN D$(I%)="X"
IF D$(I%)="11" THEN D$(I%)="(-1)"
NEXT I%
FOR I%=9 TO 1 STEP -1
IF D$(I%)<>11.0 THEN 5350
D$(I%+1.0)=D$(I%+1.0)-1.0:D$(I%)=9
IF D$(I%+1.0)<0.0 THEN 5360
GOTO 5300
NEXT I%
FOR I%=9 TO 1 STEP -1
IF D$(I%)<>10.0 THEN 5400
D$(I%+1.0)=D$(I%+1.0)+1.0:D$(I%)=0
GOTO 5360
NEXT I%
FOR I%=9 TO 1 STEP -1
IF D$(I%)<>11.0 THEN 5400
D$(I%+1.0)=D$(I%+1.0)+1.0:D$(I%)=0
GOTO 5360
NEXT I%
FOR I%=9 TO 1 STEP -1
NEXT I%
FOR I%=9 TO 1 STEP -1
NEXT I%
FOR I%=9 TO 1 STEP -1
NEXT I%
FOR I%=9 TO 1 STEP -1
NEXT I%
FOR I%=9 TO 1 STEP -1
NEXT I%
FOR I%=9 TO 1 STEP -1
NEXT I%
5510   GOTO 5490
5520   DISPLAY$=LEFT$(CD$,.LEN(CD$)-1)
5530   TENTHSS=RIGHT$(CD$,.1):TENTHSS=","+TENTHSS
5540   DISPLAY$=DISPLAY$+TENTHSS
5550   REM CS=BRIDGE DISPLAY
5560   REM DISPLAY$=ACTUAL BRIDGE BALANCE IN AF
5570   RETURN
6000   REM ************************************
6001   REM ** SUBROUTINE TO PUT DEVICE ADDRESS TO PORT2 **
6010   REM ** UPPER Nibble,N$=M -LOWER Nibble N$=L **
6020   REM ** OTHER Nibble UNCHANGED -OUTPUT VALUE=P2% **
6030   REM ** P2%=NUMBER OUTPUT TO PORT2 **
6035   REM ************************************
6040   IF N$="M" THEN 6080
6050   IF N$<"L" THEN PRINT "NIBBLE NOT SET";RETURN
6060   S$=P2% IAND 240:S%=N$ IAND 15:P2%=S% IOR S2%
6070   GOTO 6090
6080   S$=P2% IAND 15:N$=N$ SHR 4:S%=N% IAND 240:P2%=S% IOR S2%
6090   RETURN
6500   REM ************************************
6501   REM ** SUBROUTINE TO SET CLOCK **
6502   REM ************************************
6505   DC%=0:AC%=15:GOSUB 6900
6510   DC%=0:AC%=14:GOSUB 6900
6515   DC%=2:AC%=13:GOSUB 6900
6520   PRINT "WHAT IS THE DATE? 
6525   PRINT "DAY/MONTH/YEAR"
6530   PRINT " 
6533   GOSUB 9500
6535   INPUT DATES
6540   PRINT
6545   IF LEN(DATES)=8.0 THEN 6555
6550   PRINT "NOT IN CORRECT FORM - TRY AGAIN";GOTO 6520
6555   FOR 1%=1 TO 8:DATE$(1%)=MIDS(DATES,IX-1,1):NEXT 1%
6560   DC%=VAL(DATES(4.0)):IF DCX>1.0 THEN 6550:AC%=12:GOSUB 6900
6565   DC%=VAL(DATES(5.0)):IF DCX>9.0 THEN 6550:AC%=11:GOSUB 6900
6570   DCX=VAL(DATES(1.0)):IF DCX>3.0 THEN 6550:ACX=9:GOSUB 6900
6575   DCX=VAL(DATES(2.0)):IF DCX>9.0 THEN 6550:ACX=8:GOSUB 6900
6578   PRINT
6580   PRINT "WHAT IS THE TIME? 
6585   PRINT "HRS/MINS"
6590   PRINT * 
6595   PRINT *
6600   INPUT TIMES
6605   PRINT
6610   IF LEN(TIMES)=5.0 THEN 6620
6615   PRINT "NOT IN CORRECT FORM - TRY AGAIN";GOTO 6580
6620   FOR 1%=1 TO 5
6625   TIMES$(1%)=MIDS(TIMES,IX-1,1)
6630  NEXT  IX
6635  DCX=VAL(TIME$(1.0));IF  DCX>2.0  THEN  6615:ACX=7:GOSUB  6800
6640  DCX=VAL(TIME$(2.0));IF  DCX>9.0  THEN  6615:ACX=6:GOSUB  6800
6645  DCX=VAL(TIME$(4.0));IF  DCX>5.0  THEN  6615:ACX=5:GOSUB  6800
6650  DCX=VAL(TIME$(5.0));IF  DCX>9.0  THEN  6615:ACX=4:GOSUB  6800
6660  RETURN
6700  REM  ************************************************************
6701  REM  **  SUBROUTINE  TO  READ  CLOCK  **
6702  REM  **  OUTPUT  DATE$  TIME$  **
6703  REM  ************************************************************
6705  FOR  IX=12  TO  1  STEP  -1
6710  ACX=IX:GOSUB  6900
6715  DCX=VAL(TIME$(IX)):IF  DCX>NEXT  IX
6720  DATE$=STR$(CLOCK$:9.0)*10.0+CLOCK$:8.0)
6725  DATE$=LEFT$(DATE$,LEN(DATE$)-2)/""
6730  DATE2$=STR$(CLOCK$:12.0)*10.0+CLOCK$:11.0)
6735  DATE$=DATE$+MID$(DATE2$,1,LEN(DATE2$)-3)
6740  DATE$=DATE$+/1982"
6745  TIME$=STR$(CLOCK$:7.0)*10.0+CLOCK$:6.0)
6750  TIME$=LEFT$(TIME$,LEN(TIME$)-2)/""
6755  TIME2$=STR$(CLOCK$:5.0)*10.0+CLOCK$:4.0)
6760  TIME$=TIME$+MID$(TIME2$,1,LEN(TIME2$)-3)/""
6765  TIME2$=STR$(CLOCK$:3.0)*10.0+CLOCK$:2.0)
6770  TIME$=TIME$+MID$(TIME2$,1,LEN(TIME2$)-3)/""
6775  TIME2$=STR$(CLOCK$:1.0))
6780  TIME$=TIME$+MID$(TIME2$,1,LEN(TIME2$)-3)
6785  RETURN
6800  REM  ************************************************************
6801  REM  **  SUBROUTINE  TO  READ  DATA  FROM  CLOCK  REG.**
6802  REM  **  INPUTS  ACX(ADDRESS)  OUTPUT  DCX(DATA)  **
6803  REM  ************************************************************
6805  P51X=112+ACX:OUT  #51,P51X
6810  P51X=P51X-16:OUT  #51,P51X
6815  P51X=P51X-64:OUT  #51,P51X
6820  DCX=INP(#52):DCX=DCX  IAND  240
6822  DCX=DCX  SHR  4
6825  IF  DCX<>15.0  THEN  6835
6830  DCX=DCX  SHR  4
6835  DCX=DCX  SHR  4
6840  OUT  #51,P51X
6850  DCX=INP(#51):IF  DCX<15.0  THEN  GOTO  6835
6855  DCX=DCX  SHR  4
6860  DCX=DCX  SHR  4
6865  DCX=DCX  SHR  4
6870  DCX=DCX  SHR  4
6875  DCX=DCX  SHR  4
6880  DCX=DCX  SHR  4
6885  DCX=DCX  SHR  4
6890  DCX=DCX  SHR  4
6895  DCX=DCX  SHR  4
6900  REM  ************************************************************
6901  REM  **  SUBROUTINE  TO  WRITE  TO  CLOCK  REGISTER  ***
6902  REM  **  INPUTS  ACX(ADDRESS)  DCX(DATA)  ***
6903  REM  ************************************************************
6905  P52X=DCX
6910  P51X=P51X+80:OUT  #51,P51X
6915  P51X=DCX  IAND  240
6920  OUT  #52,P52X
6925  P51X=P51X-32:OUT  #51,P51X
6930  P51X=P51X-32:OUT  #51,P51X
6935  OUT  #51,127:RETURN
REM *******************************************
REM CALIBERATION DATA OF 1ST GERMIUM / PLATINUM
REM THERMOMETER ON THE EXPANSION CELL
REM *******************************************
DATA 0.01443, 4.220
DATA 0.03221, 13.083
DATA 0.03793, 14.060
DATA 0.05454, 16.076
DATA 0.07832, 18.086
DATA 0.11195, 20.147
DATA 0.24473, 25.265
DATA 0.44571, 30.173
DATA 0.72591, 35.172
DATA 1.08154, 40.249
DATA 1.94453, 50.259
DATA 2.9483, 60.287
DATA 4.0182, 70.285
DATA 5.0964, 80.104
DATA 6.2150, 90.221
DATA 7.3167, 100.208
DATA 10.0360, 125.134
DATA 12.7415, 150.371
DATA 15.3773, 175.309
DATA 17.8722, 200.132
DATA 20.5588, 225.108
DATA 23.1255, 250.104
DATA 25.47103, 273.119
DATA 25.48714, 273.280
DATA 28.1998, 300.112
DATA 0, 0
REM *******************************************
REM CALIBERATION DATA OF 2ND GERMIUM
REM THERMOMETER ON THE BATH
REM *******************************************
DATA 4.2864, 125.681, 4.9136, 100.188
DATA 5.1002, 95.487, 5.3481, 90.24
DATA 5.6046, 85.678, 5.9645, 80.35
DATA 6.3708, 75.409, 6.8639, 70.495
DATA 7.5204, 65.235, 8.2746, 60.249
DATA 9.3686, 55.010, 10.5952, 50.359
DATA 12.3733, 45.285, 14.8339, 40.223
DATA 16.3368, 37.804, 18.1374, 35.458
DATA 21.3368, 32.122, 23.8326, 30.067
DATA 27.952, 27.371, 32.119, 25.247
DATA 39.444, 22.452, 48.125, 20.095
DATA 53.357, 18.982, 58.498, 18.075
DATA 65.391, 17.043, 73.457, 16.050
DATA 84.021, 14.998, 96.419, 14.019
DATA 112.52, 13.022, 133.67, 12.019
DATA 162.09, 11.013, 179.47, 10.522

Cont'd
DATA 200.99.10.004.225.72.9.501
DATA 251.57.9.054.286.39.8.544
DATA 328.43.8.032.379.76.7.516
DATA 435.11.7.054.286.39.8.544
DATA 567.44.6.214.659.0.5.774
DATA 752.5.5.401.866.5.5.026
DATA 1033.7.4.590.1114.5.4.417
DATA 1219.7.4.216.1358.0.3.992
DATA 1489.3.3.810.1631.1.3.640
DATA 1858.8.3.413.2068.1.3.241
DATA 2369.7.3.037.2790.3.2.815
DATA 3415.3.2.571.4106.1.2.375
DATA 4935.0.2.201.6107.0.2.022
DATA 8314.0.1.799.11762.0.1.588
DATA 13950.0.1.497.0.0
REM ***********************************
REM **SUBROUTINE TO CHANGE THE BRIDGE BALANCE**
REM ***********************************
CLICKUPX=0
REM DIR$='D' FOR REDUCED CAPACITANCE VALUE
REM DIR$='I' FOR INCREASED CAPACITANCE VALUE
ARMSTOREX=ARM7.
ON ARMX GOTO 8560.B565.8570.8572.8574.8576.8578.8580.8560
PRINT "ARM ERROR":GOTO 8580:REM ARMX=I.B&9 NOT USED
NIB7.=I:NX=I:GOTO 8580:REM PORT 1 UPPER NIBBLE
NIBX=0:NX=2:GOTO 8580:REM PORT 2 LOWER NIBBLE
NIB7.=0:NX=3:GOTO 8580:REM PORT 3 LOWER NIBBLE
NIB7.=I:N7.=3:GOTO 8580:REM PORT 3 UPPER NIBBLE
NIB7.=0:N7.=4:REM PORT 4 LOWER NIBBLE
N$="M":GOSUB 6000:OUT #32.P2X:REM SENDS CORRECT I/P ADDRESS TO PORT 2
GOSUB 8900:REM READ DIGIT
IF (DIGITX=0) AND (DIR$="D") THEN 8710
IF (DIGITX=9) AND (DIR$="I") THEN 8750
IF DIR$="D" THEN GOSUB 8800:REM DECREASE BY 1
IF (DIR$="D") AND (DIGITX<>0) THEN GOSUB 8980:REM DECREASE BY ONE MORE IF <>0
IF (DIR$="I") THEN GOSUB 8850:REM INCREASE BY 1
IF (DIR$="I") AND (DIGITX<>9) THEN GOSUB 8855:REM INCREASE BY ONE MORE IF <>0
ARM%=ARMSTORE%
WAIT TIME 200
CLICKUPX=0
RETURN
PRINT "8710.DIR$=";DIR$;CLICKUPX=I:FOR IX=1.0 TO 9.0:GOSUB 8850:X=0.0 :NEXT IX:REM INCREASE TO 9
8720 PRINT "8750.DIR$=";DIR$;CLICKUPX=I:FOR IX=1.0 TO 9.0:GOSUB 8800:X=0.0 :NEXT IX:REM DECREASE TO 0
8760 ARM%=ARM%+1:GOTO 8550
270

8761 REM ****************************
8800 REM ** SUBROUTINE TO DECREASE BY 1 **
8801 REM ****************************
8805 WAIT TIME 50
8810 GOSUB 8800: DIGITSTOREX = DIGITX
8820 BITX = DIGITX((DIGITX-1.0).AND.15): REM BIT WATCH FOR CHANGE
8825 PRINT "8825.BITX=":BITX
8830 MOTORX = 1: SHL ARMX: MOTORX = MOTORX+1: REM CHOOSE MOTOR-DIRECTION DECREASE
8835 OUT #61, MOTORX: WAIT #30, BITX, BITX: WAIT TIME 30: OUT #61, 0
8840 GOSUB 8800: IF DIGITX = DIGITSTOREX - 1 THEN RETURN
8843 WAIT TIME 50
8845 GOTO 8835
8849 REM ****************************
8850 REM ** SUBROUTINE TO INCREASE BY 1 **
8851 REM ****************************
8855 WAIT TIME 100
8860 GOSUB 8800: DIGITSTOREX = DIGITX
8870 BITX = DIGITX( DIGITX . AND. 15): REM BIT WATCH FOR CHANGE
8875 PRINT "8875.BITX=":BITX
8880 MOTORX = 1: SHL ARMX: REM CHOOSE MOTOR-DIRECTION INCREASE
8885 PRINT "8885.MOTORX=":MOTORX
8890 OUT #61, MOTORX: WAIT #30, BITX, 0: WAIT TIME 50: OUT #61, 0
8893 WAIT TIME 50
8895 GOSUB 8800: IF DIGITX = DIGITSTOREX + 1 THEN RETURN
8896 IF DIGITX > DIGITSTOREX + 1 THEN RETURN
8897 GOTO 8890
8899 REM ****************************
8900 REM ** SUBROUTINE TO READ DIGITX **
8901 REM ** FROM CAPACITANCE BRIDGE **
8902 REM ****************************
8905 WAIT TIME 50
8910 DIGITX = INP(#30)
8920 IF NIBX = 0 THEN DIGITX = DIGITX AND 15
8930 IF NIBX = 0 THEN GOTO 8950
8940 IF NIBX < 1.0 THEN PRINT "NIBBLE ERROR"
8950 DIGITX = DIGITX AND 240: DIGITX = DIGITX SHR 4
8960 PRINT "DIGITX( "ARMX" )=":DIGITX
8970 RETURN
8979 REM ** SUBROUTINE TO BLOCK DIGIT INCREASE ON CHANGE UP
8980 IF CLICKUPX = 1 THEN RETURN
8982 GOSUB 8800
8983 RETURN
8985 IF CLICKUPX = 1 THEN RETURN
8987 GOSUB 8850
8988 RETURN

Contd...
9000 REM **********************************************************************
9010 REM ** SUBROUTINE TO INPUT BRIDGE CALIBRATION DATA **
9020 REM **********************************************************************
9025 PRINT
9030 PRINT "INPUT CALIBRATION DATA FOR BRIDGE"
9033 PRINT
9035 PRINT "SET BRIDGE TO 'CAL' AND 0.00000000PF"
9037 PRINT "SET TIME CONSTANT TO <INT> AND 10 SECS."
9040 RELAYS% = 3
9045 PRINT
9050 PRINT "90 dB VALUES - ARM% = 2": ARM% = 2: GOSUB 9300
9055 PRINT
9060 PRINT "70 dB VALUES - ARM% = 3": ARM% = 3: GOSUB 9300
9065 PRINT
9070 PRINT "50 dB VALUES - ARM% = 4": ARM% = 4: GOSUB 9300
9075 PRINT
9080 PRINT "30 dB VALUES - ARM% = 5": ARM% = 5: GOSUB 9300
9085 PRINT
9090 ARM% = 6
9100 FOR GIX = 1 TO 9
9110 G(GIX, 1.0, 6.0) = G(GIX, 1.0, 5.0): G(GIX, 2.0, 6.0) = G(GIX, 2.0, 5.0)
9120 NEXT GIX
9200 PRINT "CALIBRATION DATA"
9210 POKE #131, 0
9220 FOR ARM% = 2 TO 6
9230 PRINT "ARM% = "; ARM%;
9240 PRINT "DELTA CAP.","VOLTAGE"
9250 FOR GIX = 1 TO 9
9260 PRINT G(OIr., 2.0, ARM%), G(OIr., 1.0, ARM%)
9270 NEXT GIX
9280 PRINT: NEXT ARM%
9290 POKE #131, 1
9295 GOTO 350
9300 REM ** SUBROUTINE TO INPUT DATA
9302 OUT #50, OAINX(ARM%): REM 0/P CORRECT GAIN SETTING
9305 PRINT: GOSUB 9500
9310 FOR GIX = 1 TO 9
9330 READ CAP: PRINT "CAPACITANCE VALUE TO BE SET ON BRIDGE= "; CAP
9340 PRINT "SET BRIDGE NOW - PRESS <SPACE BAR> WHEN READY"
9350 A = GETC: IF A = 32.0 THEN 9355: GOTO 9350
9355 WAIT TIME 200
9371 D1 = 0.0: K% = 0
9372 FOR J% = 1 TO 3: GOSUB 2000: K% = K% + 1: PRINT CHR$(64 + K%);: D1 = D1 + D: WAIT TIME 100: NEXT J%
9373 D1 = D1 / 3.0
9376 SOUND 1 1 15 0 FREQ(4000.0): WAIT TIME 15
9377 SOUND 1 1 15 0 FREQ(3000.0): WAIT TIME 30: SOUND OFF
9380 G(GIX, 1.0, ARM%) = D1: G(GIX, 2.0, ARM%) = CAP
9385 PRINT G(GIX, 1.0, ARM%), G(GIX, 2.0, ARM%), ARM%, GI%
9390 NEXT GIX
9395 RETURN
** REM ** CALIBRATION CAP. VALUES

** DATA ** -7.1, -1.03, -5, -1.75, -3, -3.55, -1.22, -5.1, -0.63, -1.8, 1.7, 1.9, 1.05

** DATA ** -70.1, -1.67, -50, -0.67, -12, -1.24, -30, -0.75, -1.12, -0.8, -0.38

** DATA ** 10, 0.30, 45, 0.50, 85, 0.20, 1, 0.70, 1.29, 0.90, 1.71

** DATA ** -700, -1.72, -500, -1.28, -300, -0.85, -100, -0.41

** DATA ** 100, 0.65, 300, 0.59, 700, 0.36, 900, 0.18

** DATA ** -7000, -1.7, -5000, -1.27, -3000, -0.83, -1000, -0.4

** DATA ** 1000, 0.78, 3000, 0.47, 7000, 0.13, 9000, 0.177

** REM ** SUBROUTINE TO GENERATE BLEEP **

** ENVELOPE 0 15; 0.10; **

** SOUND 0 0 15 **

** FREQUENCY 4000.0; WAIT TIME 25 **

** SOUND OFF; RETURN **

** REM ** SUBROUTINE TO GENERATE DEEP NOTE **

** ENVELOPE 0 15; 0.15; **

** SOUND 0 0 15 1 **

** FREQUENCY 500.0; WAIT TIME 40 **

** SOUND OFF; RETURN **

** REM ** ROUTINE TO MANUALLY INPUT CALIBRATION DATA **

** PRINT " INPUT CALIBRATION POINTS MANUALLY" **

** FOR ARMX=2 TO 5 **

** FOR CIX=1 TO 9 **

** READ CAP **

** PRINT "CAPACITANCE VALUE=", CAP **

** GCCIX.1.0.ARMX)=D1: GCCIX.2.0.ARMX)=CAP **

** NEXT CIX **

** NEXT ARMX **

** FOR CIX=1 TO 9 **

** G(CIX,1.0,ARMX)=D1: G(CIX,2.0,ARMX)=CAP **

** NEXT CIX **

** NEXT ARMX **

** FOR ARMX=2 TO 5 **

** FOR CIX=1 TO 9 **

** READ CAP: G(CIX,2.0,ARMX)=CAP: READ VOLT: G(CIX,1.0,ARMX)=VOLT: **

** NEXT CIX **

** NEXT ARMX **

** FOR ARMX=2 TO 5 **

** FOR CIX=1 TO 9 **

** G(CIX,1.0,6.0)=G(CIX,1.0,5.0): G(CIX,2.0,6.0)=G(CIX,2.0,5.0) **

** NEXT CIX **

** GOTO 350 **

** FOR ARMX=2 TO 5 **

** FOR CIX=1 TO 9 **

** G(CIX,1.0,6.0)=G(CIX,1.0,5.0): G(CIX,2.0,6.0)=G(CIX,2.0,5.0) **

** NEXT CIX **

** GOTO 9200 **

** RELAYSX=2 **

** P42X=18 **

** OUT #42, P42X **

** OUT #40, 0: OUT #41, 0 **

** GOSUB 2000 **

** GOTO 9980 **

** STOP **
REFERENCES
REFERENCES


DCE Microcomputer system and designer handbook and instruction manual.


