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Development of a portable electrochemical instrument for the monitoring of heavy metals.

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DEVELOPMENT OF A PORTABLE ELECTROCHEMICAL INSTRUMENT FOR THE MONITORING OF HEAVY METALS

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requirements of
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for the degree of the Master of Philosophy

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Abstract

This report describes the development of a novel, portable, electrochemical instrument capable of gathering real-time quantitative data on a range of heavy metal contaminants. The unit is being developed for use on the site of contaminated land or water and is also able to determine the oxidation state of a metal, which is a measure of the metal's toxicity. The system provides the facilities found in a traditional lab based instrument, in a hand held design. In contrast to existing commercial systems, it can stand alone without the need of a computer and expert operators.

At the present stage of development, the instrument is capable of detecting and identifying six different toxic environmental pollutants, lead, cadmium, mercury, zinc, nickel and copper with good sensitivity and precision. Two different identification techniques have been developed. The first technique is based on the statistical profile (probability density function) of oxidation potential. The second method is based on an artificial neural network. The instrument with the combination of a Geographical Position System (GPS) is capable of storing the geographical position of the sample under test. Software has been developed to combine pollutant results with geographical position, in order to produce a cartographical presentation of the pollution of an area.

Summary

Heavy metals in land and natural water may have a detrimental effect on both human health and the environment. Apart from direct health or environmental problems, water or land contamination can cause economic and financial damage. The Confederation of British Industry has estimated that as much as 200,000 hectares of land is contaminated in the UK and remediation of these areas could cost up to £20 billion. Such land includes sites previously used for heavy industries such as steel making and shipbuilding.

Monitoring heavy metals at various points in industrial processes, in natural water and at agricultural, urban and industrial sites is highly important. At present, a great deal of manpower is employed by different companies to screen for them, which usually requires numerous sample collections and the use of dedicated laboratories. The existing analytical techniques that are used for heavy metal identification require highly trained personnel to undertake time consuming data analysis and interpretation of sample collections. Furthermore, existing detection instruments are generally complicated to operate, bulky, expensive, impractical to use for on-site monitoring and often involve sample pre-treatment before measurement. A fast, reliable, relatively inexpensive portable (hand held) instrument capable of direct monitoring of heavy metal contaminants *in-situ,* which can stand alone without the need of a computer, is consequently very desirable.

This report describes the development of a portable electrochemical instrument for detecting, identifying and measuring concentrations of heavy metals in soil or water. In contrast to existing commercial systems, it is portable, easy to use, avoids expensive and time-consuming procedures, and can stand alone without the need of a computer and expert operators. The instrument at present can detect and identify six different toxic metals, namely lead, cadmium, mercury, zinc, nickel and copper. Two different identification techniques have been developed. The first technique is based on the statistical profile (probability density function) of oxidation potential. The second method is based on an artificial neural network. The instrument, combined with a Geographical Position System (GPS) is capable of storing the geographical

position of the sample under test. Software has been developed to produce a cartographical presentation of the pollution of an area. The instrument's capability of detecting metals in multi-element solutions and in soil samples has also been examined, demonstrating good results.

Publications

Patents

[1] **K. Christidis,** P.Robertson, K.Gow and P.Pollard: 'Heavy Metal Sensor: Measurement Apparatus', British Patent Application, No:0514081.9, 8 July 2005.

Peer Reviewed Journal Papers

[1] **K. Christidis,** K.Gow, P.Robertson and P.Pollard: 'Intelligent Potentiostat for Identification of Heavy Metals in Situ', *Review of Scientific Instruments, Vol. 77, 2006* .

[2] **K. Christidis,** P.Robertson, K.Gow and P.Pollard: 'On-Site Monitoring and Cartographical Mapping of Heavy Metals', *Instrumentation Science and Technology, Vol. 34, 2006.*

[3] **K. Christidis,** P.Robertson, K.Gow and P.Pollard: 'Acidity Compensation of Electrochemical Measurements for Monitoring of Heavy Metals', *Transactions of The Instrumentation Society and Control, (Accepted on 6/12/05).*

[4] **K. Christidis,** K.Gow, P.Robertson and P.Pollard: 'Intelligent Potentiostat for Identification of Heavy Metals in Situ', *Virtual Journal of Biological Research,* Feb. (2006).

[5] **K. Christidis,** K.Gow, P.Robertson and P.Pollard: 'Hand-held Voltammetric Analyser for Real-Time Monitoring of Heavy Metals', Submitted on 28/9/05 to: *IEEE Transactions on Instrumentation and Measurements.*

[6] **K. Christidis,** K.Gow, P.Robertson and P.Pollard: 'Computer-Based Identification of Heavy Metal Contaminants in Real-Time Using Anodic Striping Voltammetry', Submitted on 26/1/06 to: *Environmental Modelling and Software.*

[7] **K. Christidis,** K.Gow, P.Robertson and P.Pollard: 'Analysis of Soil samples in Situ', Submitted on 21/2/06 to: *Review of Scientific Instruments.*

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[1] **K. Christidis,** P.Robertson, K.Gow and P.Pollard, “Electrochemical Hand-held Instrument for Measuring of Heavy Metals in Situ”, *Best SET Britain,* House of Commons, 13 March 2006, London, UK.

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[3] **K. Christidis,** H. Stuart, P.Robertson, K.Gow, P.Pollard and C.McCullagh, “In-situ Heavy Metal Sensor for Contaminated Land Monitoring”, *The 10th International*

Conference on Electroanalysis, ESEAC 2004, National University of Ireland, Galway, Ireland.

[4] **K. Christidis**, H. Stuart, P.Robertson, K.Gow and P.Pollard, "A voltammetric analyser for real-time monitoring of heavy metals in situ", *Royal Society of Chemistry, Emerging Analytical Science in Scotland, 28 January 2004,* Glasgow, UK.

Table of Contents

List of Key Symbols

T_D	deposition time of the excitation signal
ΔI	differential current
E_p	oxidation potential
R_D	digital-to-analogue converter resolution
R_G	signal generator resolution
V_{DACF}	signal generator full-scale output voltage
V_P	excitation signal start potential
V_F	excitation signal final potential
V_S	step potential
P_A	pulse amplitude
P_P	pulse period
P_D	pulse duration
$\Delta\phi_w$	voltage potential across the working electrode-solution interface
$\Delta\phi_r$	voltage potential across the reference electrode-solution interface
I_{FS}	potentiostat full-scale output current
R_f	feedback resistor
V_{OS}	offset voltage
I_B	bias current
V_{DAFS}	data acquisition system full-scale voltage
R_P	potentiostat resolution
$p(f)$	probability density function of f
σ	standard deviation
μ	mean value
I_P	peak current
E_P'	normalised oxidation potential (neural network input)
I_P'	normalised peak current (neural network input)
R_{ON}	ON resistance of the analogue multiplexer
min_{Ep}	the minimum input value of E_P used for the training of the neural network
min_{Ip}	the minimum input value of I_P used for the training of the neural network
max_{Ep}	the maximum input value of E_P used for the training of the neural network
max_{Ep}	the maximum input value of I_P used for the training of the neural network

$bias_{Nn}$ bias value of n^{th} neuron

N_{ni} input of ^{nth} neuron

N_{no} output of ^{nth} neuron

w_{jk} weight of k^{th} neuron of j^{th} layer

O_{ni} input of ^{nth} neuron of output layer

O_{no} output of ^{nth} neuron of output layer

ϕ longitude

λ latitude

h altitude

$\Delta\phi$ longitude offset (from base pixel)

$\Delta\lambda$ latitude offset (from base pixel)

$\Delta x'$ longitude offset (from base pixel) converted into metres

$\Delta y'$ latitude offset (from base pixel) converted into metres

$P(x,y)$ pixel in the raster

P_B base pixel

P_{ID} pixel's identification number

A_M physical size of a map

A_V virtual size of a map

R_{xy} virtual size of a pixel

Chapter One

Introduction

1.1. Threats Posed by Heavy Metals

The presence of heavy metals in land and natural water systems has in some instances caused significant ecosystem degradation because of their toxicity to human and other biological life[1-3]. The pathways for heavy metal introduction into soil and aquatic environments are numerous[2,4-8], and include the land application of sewage sludge and municipal composts[9-11], mine wastes[12-14], dredged materials, fly ash[15,16], and atmospheric deposits[17-19]. In addition to these anthropogenic sources, heavy metals can be introduced to soils naturally as reaction products via the dissolution of metal-bearing minerals that are found in concentrated deposits[20-22]. New European Community directives, proposed in 1993, have demanded that member countries in future enforce even stricter controls on water quality, in order to protect the environment and associated biological life. Apart from the direct health or environmental problems, water or land contamination can cause economic and financial damage. The Confederation of British Industry has estimated that as much as 200,000 hectares of land is contaminated in the UK and remediation of these areas could cost up to £20 billion.

The necessity of monitoring pollutant levels at various points in industrial and recycling processes, in natural water, and at agricultural, urban and industrial sites is highly important[23].

1.2 Present Techniques for Detecting Heavy Metals

At present a great deal of highly trained personnel are employed by different companies and organisations in the assessment of different polluted areas. Usually this process requires a large number of sample collection and dedicated laboratories[24]. Among the most popular methods used for the analysis[25] of aquatic or soil samples are atomic absorption spectrometry (AAS)[26-28], inductively coupled plasma-atomic emission spectrometry (ICP-AES)[29], X-ray fluorescence (XRF)[30-33], liquid chromatography mass-spectrometry (LC-MS)[34], energy dispersive analysis (EDAX)[35,36] and electroanalysis[37,38]. The instruments used for the analysis are expensive bench-top units (Fig. 1.1) and require trained personnel to perform the analysis and to interpret the results[24,39]. These analytical systems are too bulky to be used in the field[40,41]. In a number of applications, the long time delays associated with this process are unacceptable. In addition, the majority of samples are typically negative, yet are subjected to costly laboratory analysis[42].

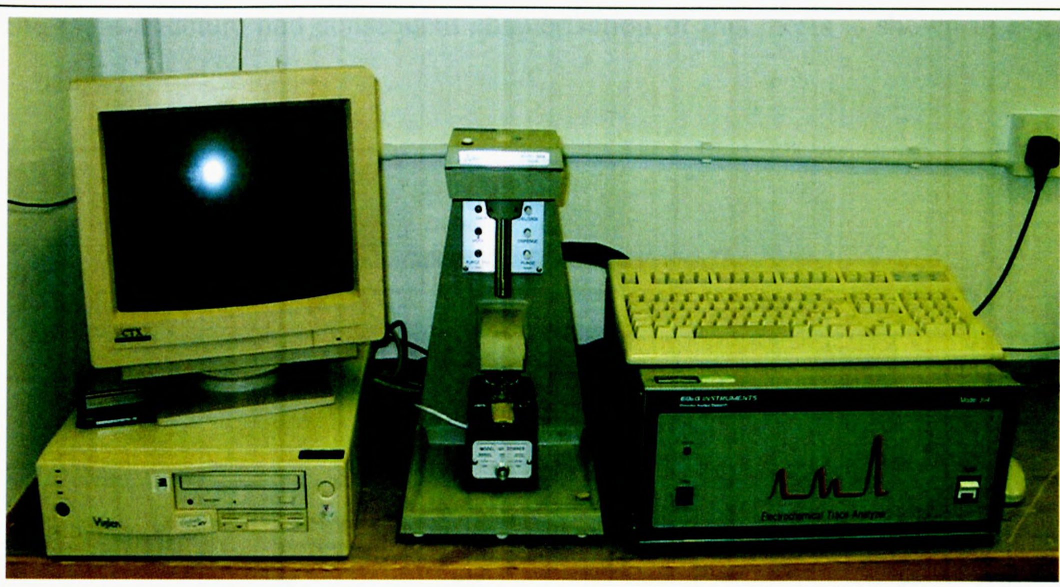


***Figure 1.1**: Electroanalytical instrument for analysis of heavy metals*

In summary, existing detection techniques are generally complicated to use, expensive, and time consuming. An inexpensive portable (hand-held) instrument capable of direct monitoring of heavy metal contaminants in the field, which can stand alone without the need of a computer, is consequently very desirable.

1.3 New Hand-Held Electrochemical Instrument

This report describes the development of an electrochemical instrument capable of gathering real-time quantitative data on a range of heavy metal contaminants. The unit is being developed for use on the site of contaminated land or water and is also able to determine the oxidation state of a metal, which is a measure of the metal's toxicity. This was the main task of this project which involved research into the following three main aspects, namely:

1. The development of a portable electrochemical instrumentation for detection of heavy metals in situ.
2. The formulation of an appropriate classification strategy for the characterisation of heavy metals in situ.
3. Cartographical mapping of the pollution

The main structure and consequent chapterisation of this thesis is shown in Fig. 1.2 below.

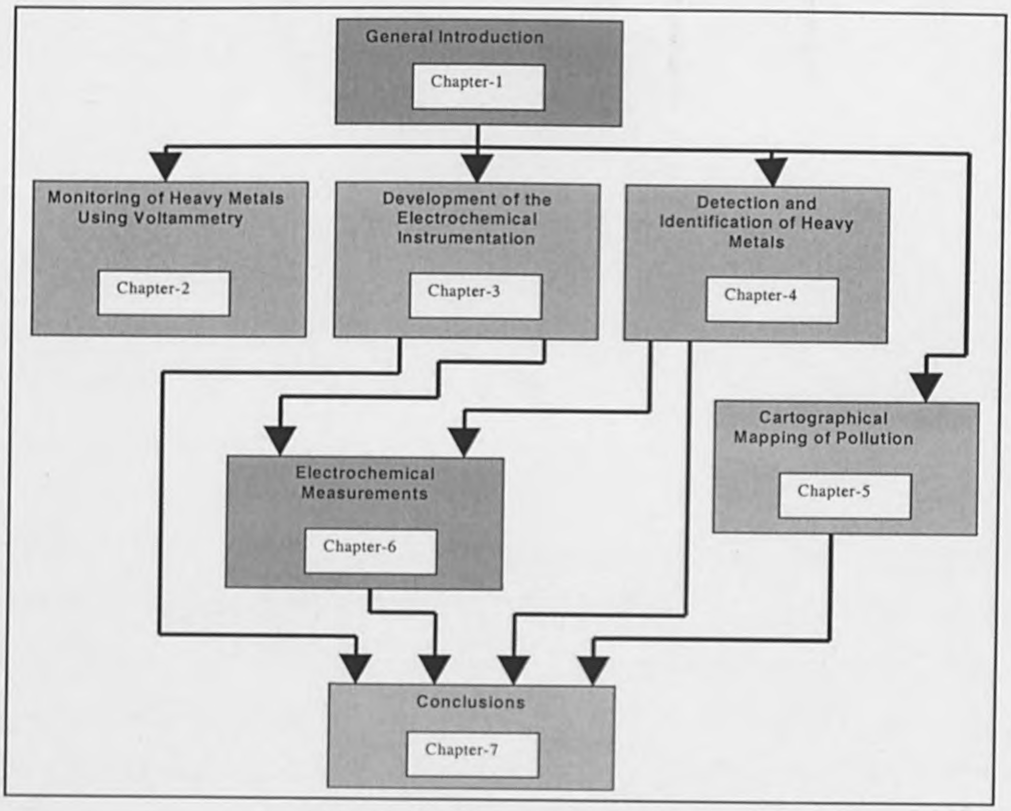


Figure 1.2: Structure of the thesis.

Chapter Two

Monitoring of Heavy Metals Using Electroanalytical Methods

2.1. Introduction

Analytical voltammetry has recently become a very important technique for metal analysis[43,44]. Ions in a solution can be measured by introducing a time-dependent potential between submerged working and reference electrodes and then measuring the current which flows through the working electrode. This current is the sum of Faradaic and non-Faradaic (background) components. The latter is the current of interest, which is the result of Redox reactions at the electrode surface:

$$Ox + ne^- \Leftrightarrow Rd \tag{2.1}$$

Where, "Ox" are the oxidised species and "Rd" are the reduced species.

Electrons either leave the electrode by reducing some oxidised species or enter the electrode by oxidising reduced species. The total Faradaic current that flows through the working electrode will therefore indicate the total rate of all such reactions occurring at the surface.

There are two main categories of voltammetric techniques, namely, potential sweep and pulse voltammetry. Potential sweep techniques consist of scanning a chosen region of potential and measuring the current response arising from the electron transfer and associated reaction. Two of the most popular potential sweep techniques used in analytical applications are cyclic voltammetry (CV)[45-47] and anodic linear-scan stripping voltammetry (ALSV)[48]. Pulse techniques are based on the application of a succession of potential steps of varying height and in forward or reverse directions. These techniques were developed largely to provide enhanced sensitivity in analytical applications as compared to potential sweep voltammetry[49-51]. Some of the most popular pulse techniques are normal pulse voltammetry (NPV)[47,51], differential pulse anodic stripping voltammetry (DPASV)[49] and square wave voltammetry (SWV)[53].

Of the different voltammetric techniques that might have been used in the development of the portable electrochemical instrument, DPASV was chosen in preference to other techniques. DPASV is a precise electrochemical method for heavy metal detection[54,55] which delivers extremely low detection limits, owing to an extremely favourable Faradaic-to-charging current ratio. Furthermore, this technique is ideally suited for this task because of its inherent simplicity and compatibility with digital microcomputer-based instruments[56].

2.2 Differential Pulse Anodic Stripping Voltammetry

The DPASV technique is a two-step process (Fig. 2.1). The first step is a fixed time pre-concentration stage (deposition), where metal ions in solution are reduced by electrolysis at a suitable applied potential to form an amalgam with the working electrode.

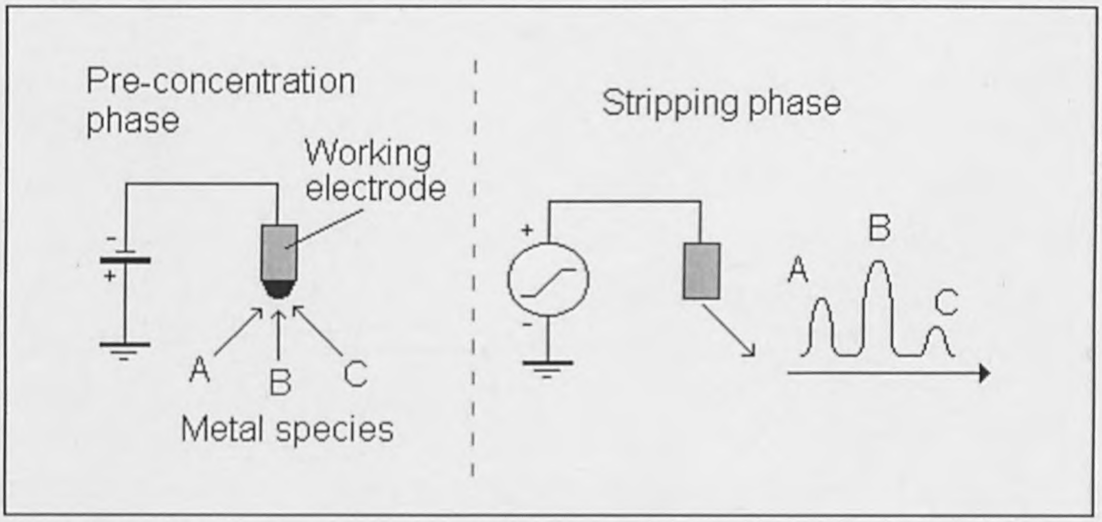


Figure 2.1: *Two stages (phases) of differential pulse anodic stripping voltammetry*

The second stage is a stripping stage, in which the metal is oxidised back into solution by means of a time-controlled excitation waveform imposed between the working and the counter electrode. The excitation signal consists of small pulses of constant amplitude superimposed upon a staircase waveform (Fig. 2.2).

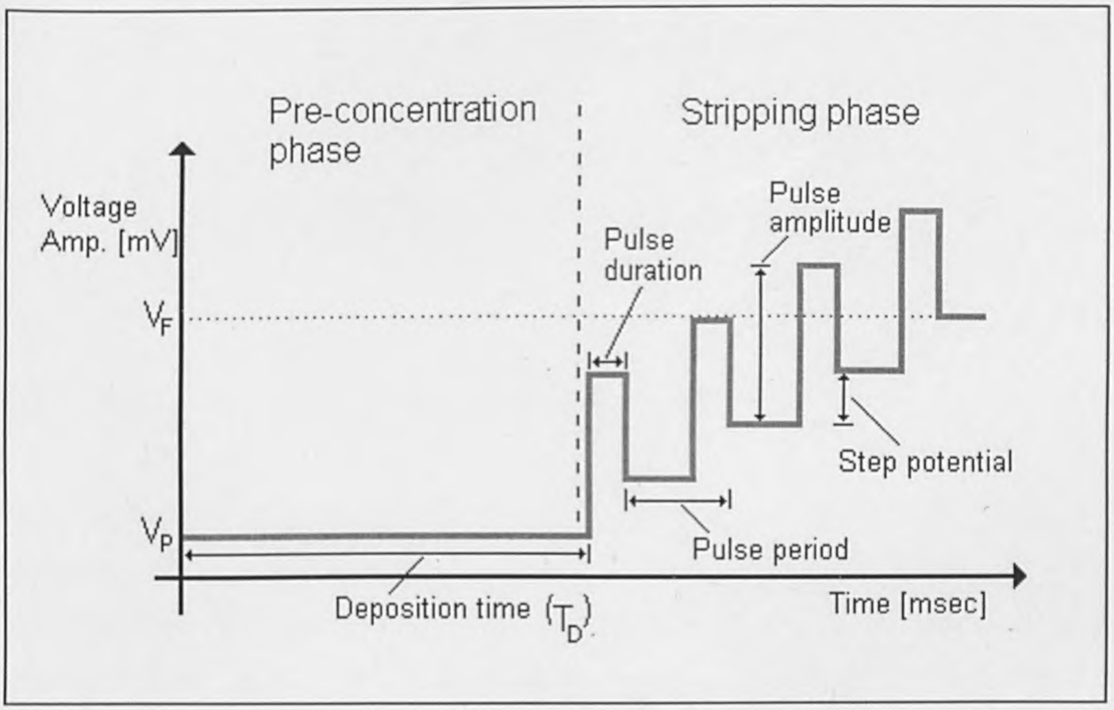


Figure 2.2: *Differential pulse anodic stripping voltammetry - excitation signal*

The current is sampled twice in each pulse period (once before the potential step, and then again just at the end of the pulse). The difference between these two current samples ($s_{2i} - s_{1i} = \Delta I$) is recorded and displayed (Fig. 2.3). This process is repeated for all of the signal pulses. As the potential approaches the lowest oxidation potential of those metals dissolved onto the electrode surface, the ions of that metal pass into solution from the electrode. The current increases rapidly and reaches a maximum value when the potential has a value corresponding to the metal's oxidation potential. As the anodic potential rises, other peaks will be observed at the oxidation potentials of the other metals which are present in the sample.

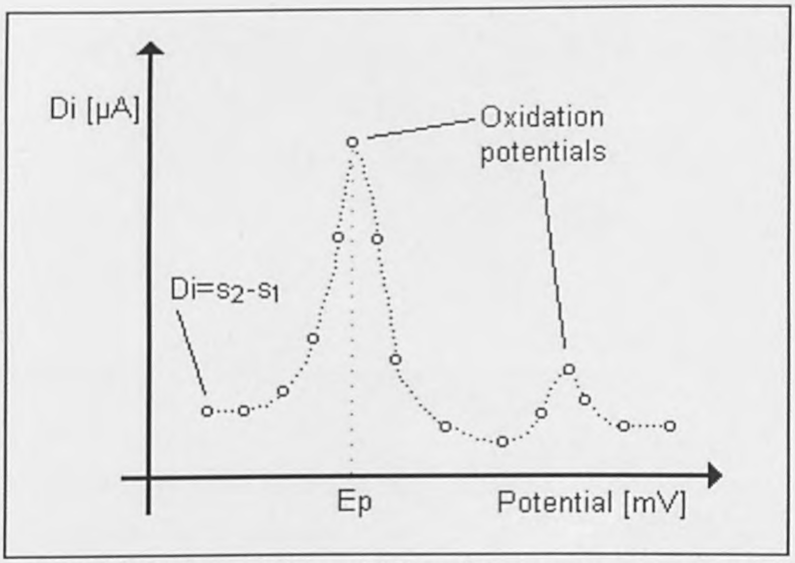


Figure 2.3: *Voltammogram – Differential current versus potential*

2.3 Sensors

The electrochemical sensor (cell) is a circuit element with electrical properties that influence the performance of the overall instrument[57]. It consists of three electrodes: the working electrode (WE), the counter electrode (CE) and a reference electrode (RE). The WE is the interface of interest and ideally, measurements would be limited to changes of this interface alone. The CE is used as an electrode from which current will pass to the WE. The RE is a non-polarisable interface that is used to measure/control the potential of the WE.

Traditional voltammetric methods involve the use of mercury based electrodes, usually in the form of a hanging mercury drop electrode (HMDE)[40,52,58], static mercury drop electrode (SMDE)[51,59] or more recently the mercury film electrode (MFEs)[60,61]. The extensive use of these electrodes is based on the advantageous analytical properties of mercury in the negative potential range[62]. However, HMDE and SMDE electrode systems have a large size due to their associated heavy motors and large mercury reservoirs[40,63]. They requires careful cleaning, prolonged oxygen removal, solution stirring during the deposition, standard additions and frequent solution replacement[63]. Apart from the large size and high cost, an important disadvantage of all mercury electrodes is the use of toxic mercury[64]. The considerable toxicity of mercury has led some countries to ban its use completely and, as a result, alternative electrode materials are sought for use in stripping analysis[65,66]. For the present application, glassy carbon[67,68] and screen printed[64,69] solid electrodes were chosen in preference to HMDE, SMDE and MFEs.

2.3.1 Electrochemical Cell with Glassy Carbon Electrode

This cell consists of three solid electrodes (Fig. 2.4). The working electrode is glassy carbon, the counter electrode is platinum and the reference electrode silver/silver chloride (3 M *NaCl*). These electrodes are commercially available and have been provided by Bioanalytical Systems Inc., (BAS) Indiana.

The working electrode is made of a carbon wire embedded in glass within a plastic rod. The sensitive portion of the electrode is a tiny circle of glassy material with surface area of 7.1mm^2 in the centre of the electrode rod. Despite its very small surface area, this electrode is very sensitive and rugged, providing reproducible results. The reference electrode is a simple system comprising of a silver wire in silver chloride solution within a glass rod. This electrode is always kept wet, usually in 3 M *NaCl* solution. The counter electrode is simply a platinum wire attached to a plastic rod with a soldered gold connector.

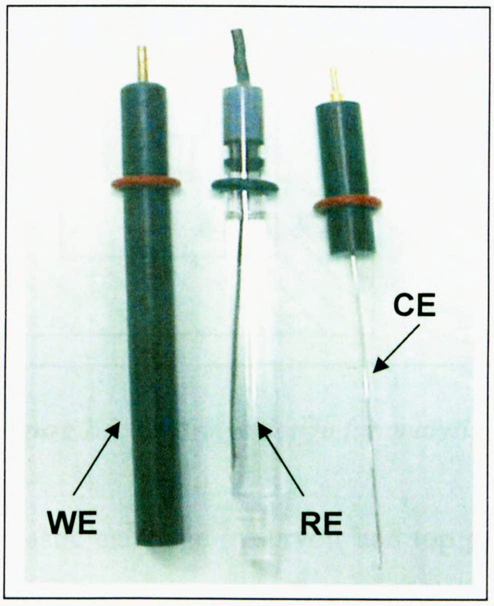


Figure 2.4: *Three electrode cell with glassy carbon working electrode, platinum counter electrode and silver/silver chloride reference electrode.*

A plastic cartridge has been designed (Fig. 2.5) to support the three electrodes for use in the field. The cartridge consists of two main parts. The top part provides the mechanical support to the electrodes and the second part (base) is the sample reservoir. The reservoir has been designed to accommodate either soil or aquatic samples.

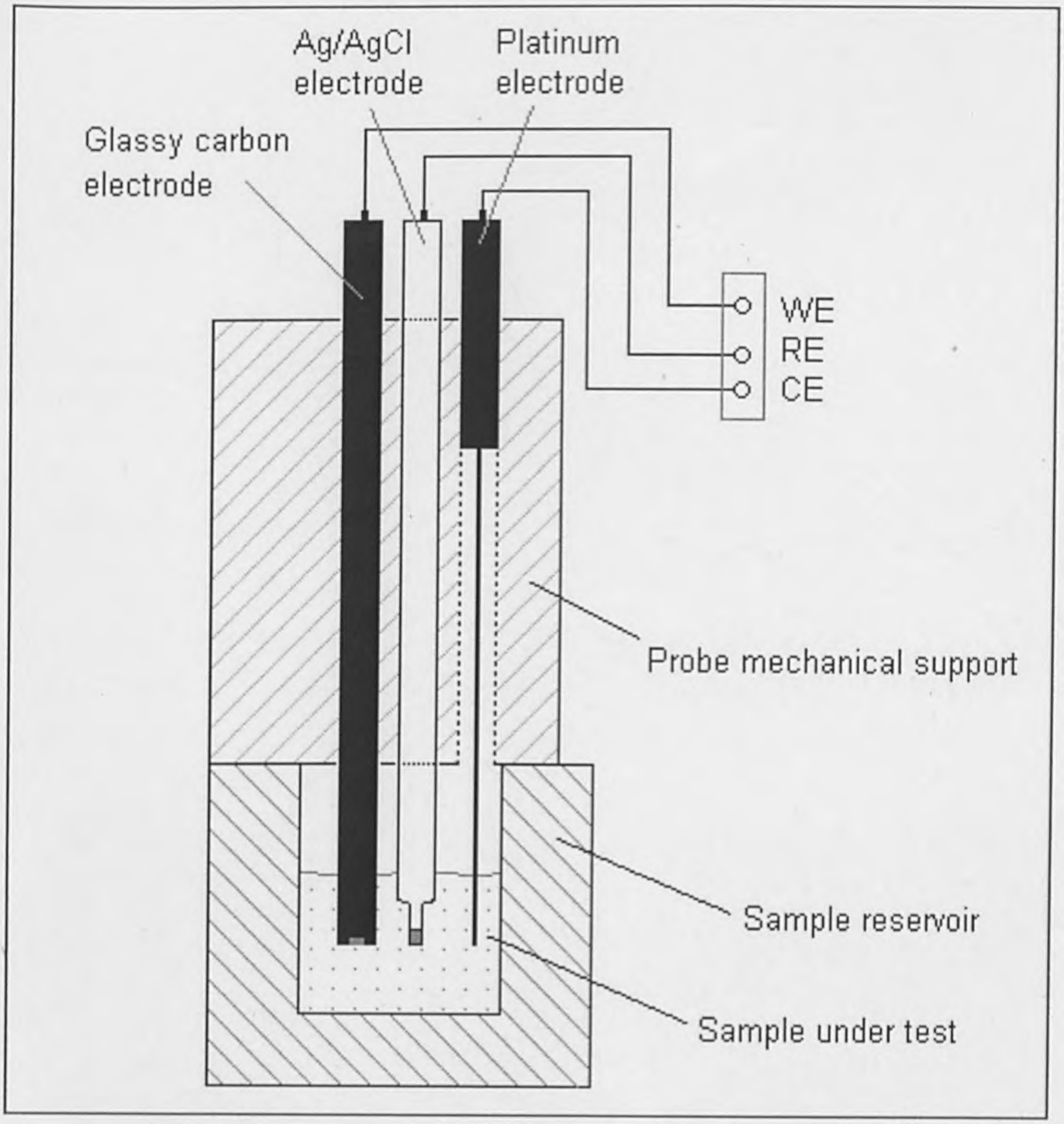
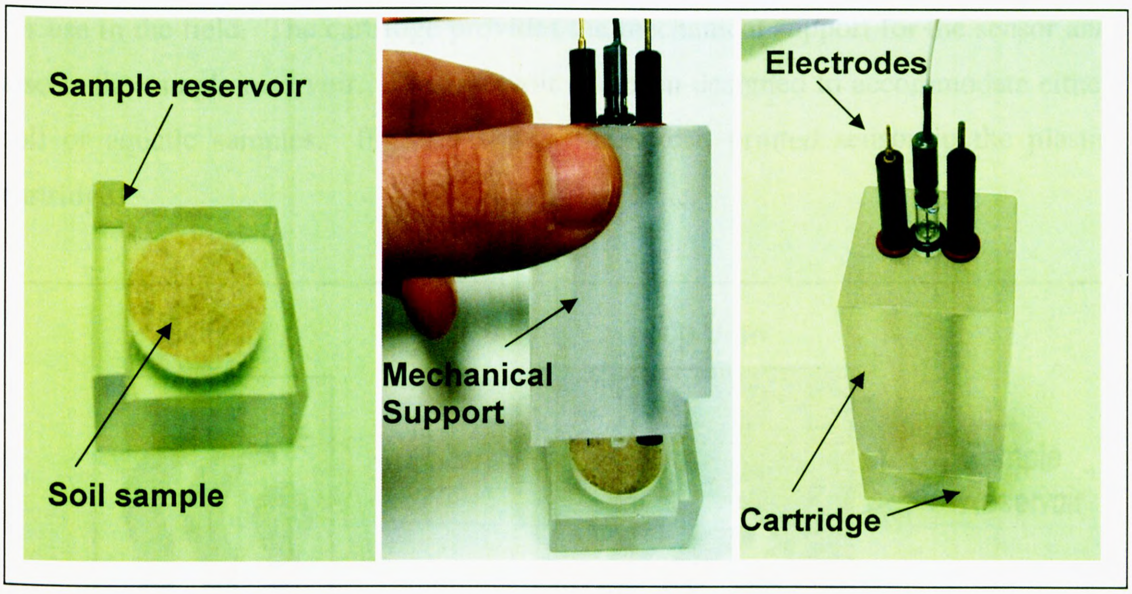


***Figure 2.5**: Cartridge design for analysis in the field*

Fig. 2.6 shows the plastic cartridge (reservoir and top part) with the three electrodes and a soil test sample.



(a) *(b)* *(c)*

Figure 2.6: *(a) sample reservoir with sample under test, (b) mechanical support, (c) plastic cartridge with the three electrodes ready for analysis*

2.3.2 Screen Printed Sensor

The three electrodes of the screen printed cell are made with specially manufactured carbon inks and are printed on ceramic plates (Fig. 2.7). These cells are inexpensive, disposable and easy to store as they have no need for special storage conditions.

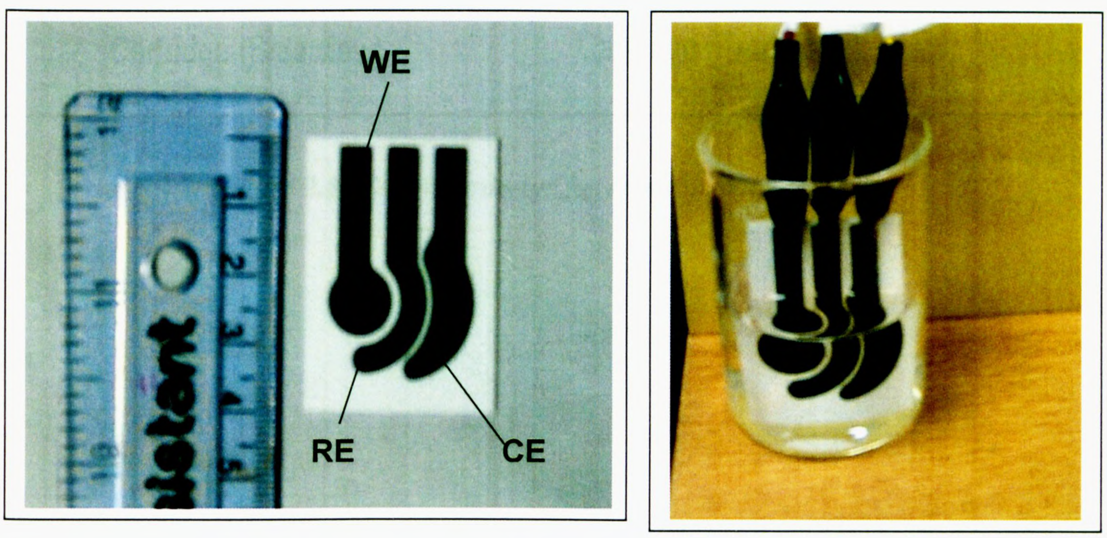


Figure 2.7: *Screen printed carbon sensor*

A plastic cartridge has been designed (Fig. 2.8) to support the screen printed sensor for use in the field. The cartridge provides the mechanical support for the sensor and also is the sample reservoir. The reservoir has been designed to accommodate either soil or aquatic samples. Fig. 2.9 shows the screen printed sensor in the plastic cartridge.

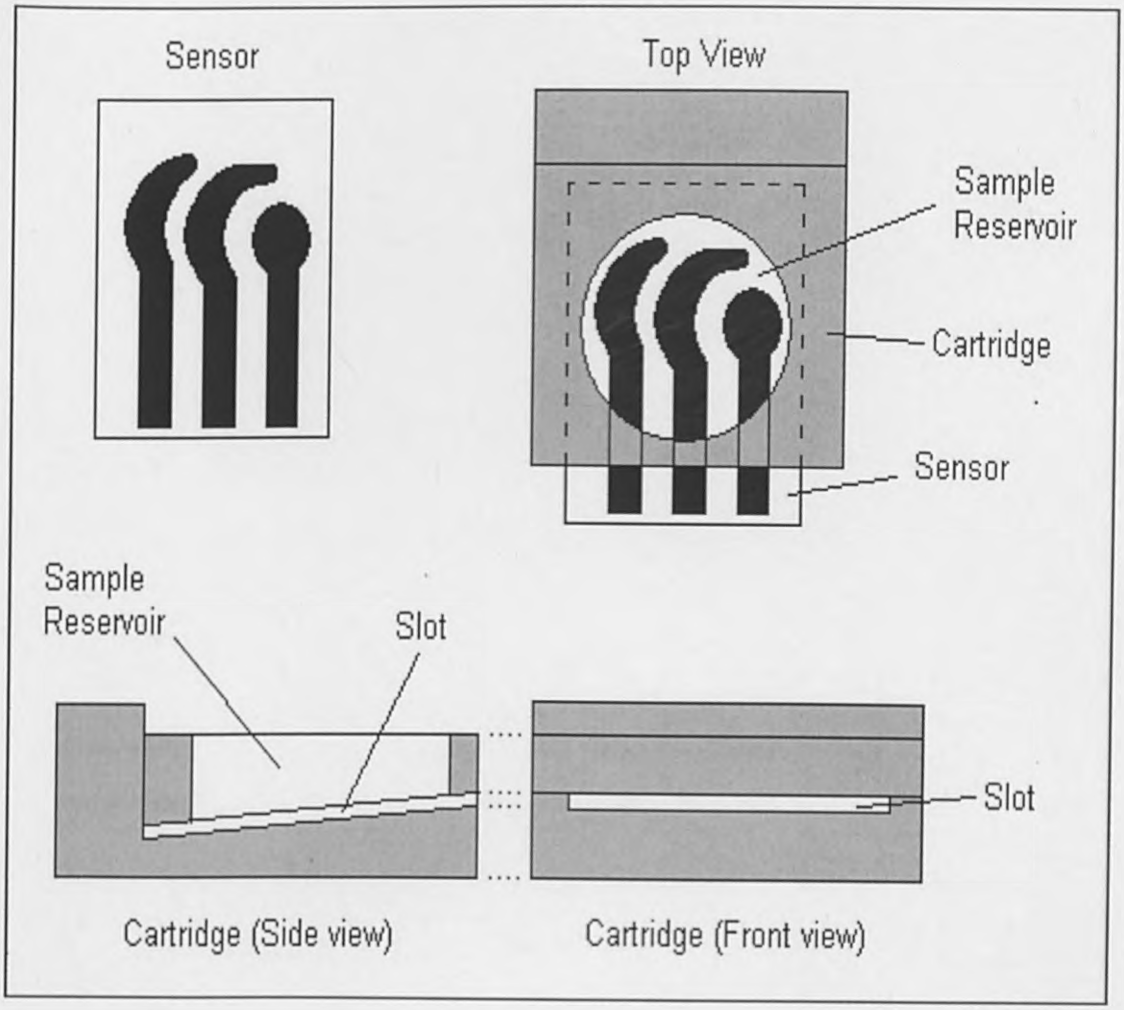


Figure 2.8: Cartridge design for screen printed sensor

***Figure 2.9**: Plastic cartridge with the screen printed sensor*

Chapter Three

Development of the Electrochemical Instrumentation

3.1 Introduction

The block diagram of the proposed instrumentation system for voltammetric analysis is shown in Fig. 3.1. It consists of five main functional parts, a signal generator, a potentiostat, a data acquisition unit, a microcontroller and a display unit.

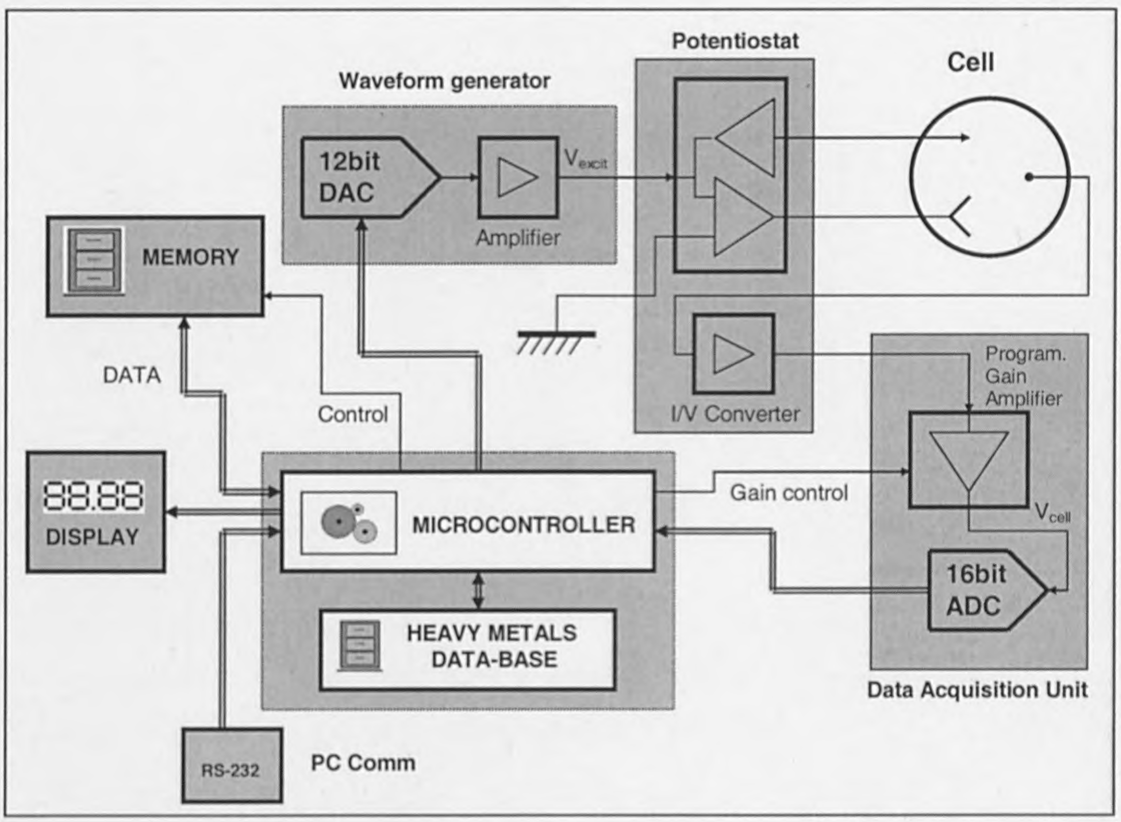


Figure 3.1: Block diagram of the electrochemical instrumentation system

More detailed examination of the design, construction, and operation of each functional part is given in the following sections.

3.2 Signal Generator

The signal generator provides the appropriate potential waveform (DPASV-excitation signal) for the cell. Fig.3.2 illustrates the circuitry of the signal generator. The heart of the system is a 16-bit microcontroller (MC68HCS12) which produces (synthesises) the excitation signal. With the use of the microcontroller *(μC)* the signal generator becomes very flexible. All of the parameters of the signal can be re-programmed and a complex waveform can be generated very easily. The signal is generated by the μC in digital form and is then converted to analogue form using a digital to analogue converter (DAC). The resolution of the DAC (R_D) is 12 bit.

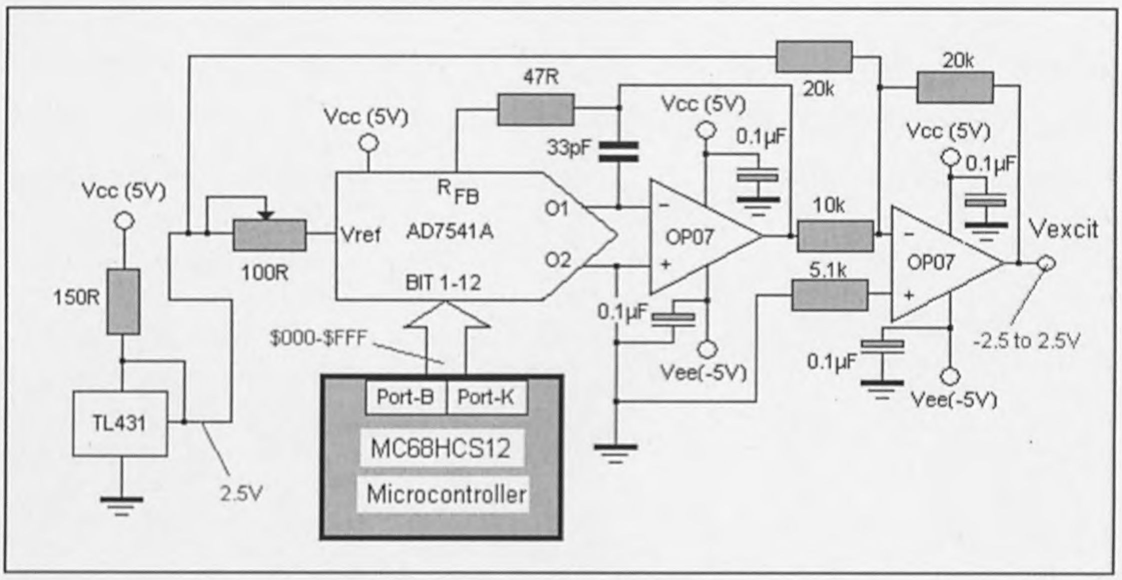


Figure 3.2: Circuitry and of the signal generator

The reference voltage (V_{ref}) which is needed to define the DAC full scale (V_{DACF}) is 2.5V, which is provided by a programmable precision reference device (TL431). Table 3.1 shows the code relationship of the DAC operation.

Table 3.1: *DAC operation (V_{ref} = 2.5 V).*

Binary Number in DAC	**Analogue Output**
1111 1111 1111	$V_{ref} \times (4096/2) = +2.5\ V$
1000 0000 0000	$V_{ref} \times 0 = 0\ V$
0000 0000 0000	$-V_{ref} \times (4096/2) = -2.5\ V$

Full-scale trimming can be accomplished by adjusting the value of 20 kΩ feedback resistor of the second operational amplifier. The 33 pF capacitor is used for phase compensation in order to provide stability. The generator resolution (R_G) is given by:

$$R_G = \frac{V_{DACF}}{2^{(R_D)}} = \frac{5V}{2^{12}} = 1.22\ mV \qquad (3.1)$$

Where, V_{DACF} is the full scale voltage and R_D the resolution of the DAC.

Table 3.2 shows the connection between the pins of the microcontroller ports (Port-PB and Port-PK of the evaluation T-board) and the AD7541A DAC device. Datasheets with all technical information of the DAC (AD7541A), operational amplifier (OP07), and programmable reference voltage device (TL431) are given in Appendices D1, D2 and D3 respectively.

Table 3.2: *Connection between microcontroller pins and DAC device.*

Microcontroller		**AD7541A - DAC**	
PORT	**T-Board Pin**	**Signal**	**Pin**
PB(0)	H1-24	D(0)LSB	15
PB(1)	H1-25	D(1)	14
PB(2)	H1-26	D(2)	13
PB(3)	H1-27	D(3)	12
PB(4)	H1-28	D(4)	11
PB(5)	H2-01	D(5)	10
PB(6)	H2-02	D(6)	09
PB(7)	H2-03	D(7)	08
PK(0)	H1-08	D(8)	07
PK(1)	H1-07	D(9)	06
PK(2)	H1-06	D(10)	05
PK(3)	H1-05	D(11)MSB	04

The assembly program developed to produce the ASVDP excitation signal with deposition time (T_D) of 60 sec, starting potential (V_P) -1100 mV, last potential (V_F) +500 mV, step potential (V_S) 2 mV, pulse amplitude (P_A) 25 mV, pulse period (P_P) 100 ms and pulse duration (P_D) 50 ms, is listed in Appendix B.1. The flow chart of this program is shown in Fig. 3.3 below.

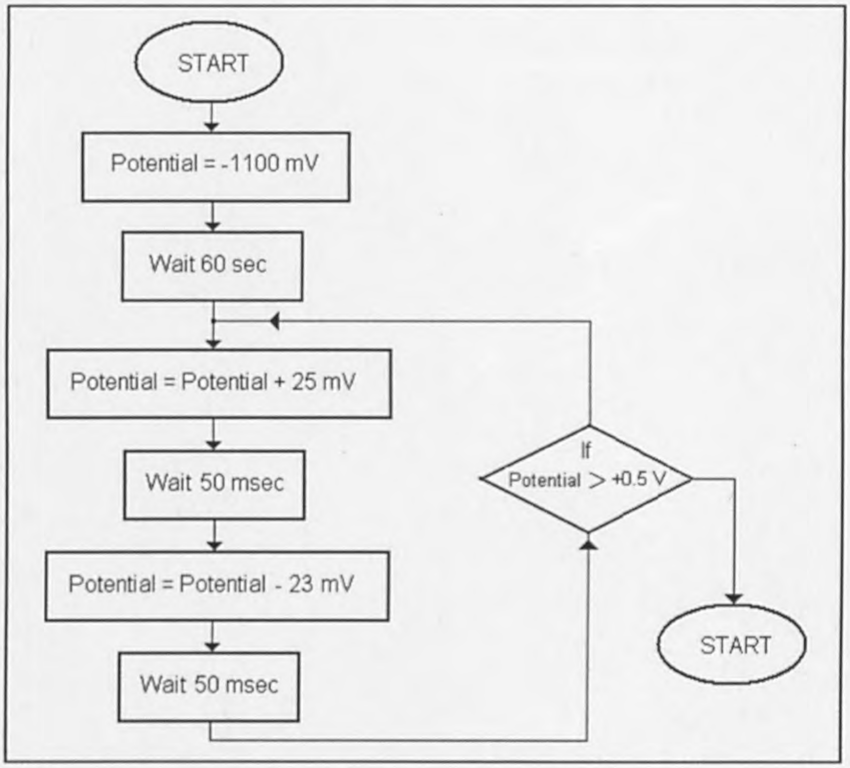
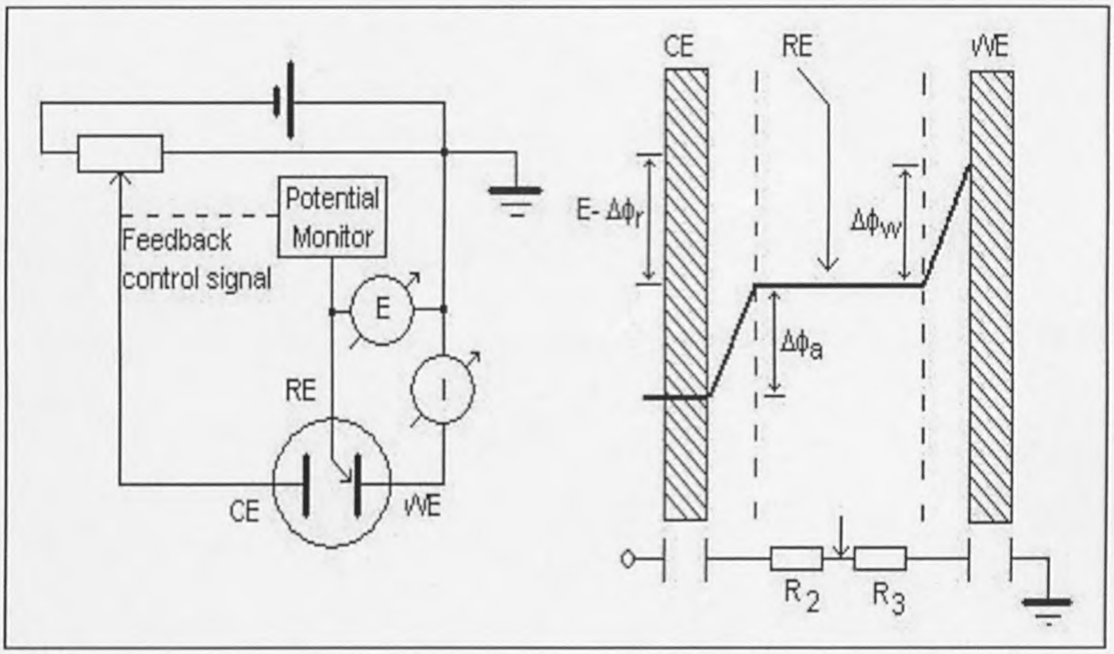


Figure 3.3: *Flow chart of signal generator program*

3.3 Potentiostat

In a potentiostat, the potential of the working electrode (vs RE) is controlled and the current flowing through the cell (via the CE) is measured. Fig. 3.4(a) shows the basic circuit for the three electrode potential control. As can be seen from this figure, *E* is the applied potential measured between RE and WE. *I* is the resulting current measured in WE. The CE allows current to flow through the cell. The RE maintains constant interfacial potential difference regardless of the current. It is also used to monitor the potential difference[70] to control $\Delta\phi_w$ relative to its own $\Delta\phi_r$[71-73] [see Fig. 3.4(b)]. The resistor R_2 is the sum of resistance of the counter electrode separator and the solution resistance between the counter and the reference electrodes. The resistor R_3, is the sum of resistance of the measuring electrode and the solution resistance between the reference and measuring electrodes[74,75]. The resistance R_2 is also referred to the literature as the uncompensated cell resistance (R_{un}). The use of the feedback control [Fig. 3.4(a)] is to compare $\Delta\phi_r$ with E. If there is a difference (error) the potential is adjusted until balance (no error) is achieved [76,77].



(a) *(b)*

Figure 3.4: *(a) Basic circuit for the three electrode potential control, (b) schematic representation of potential gradients.*

The potentiostat operation is as follows: The potentiometer [Fig.3.4(a)] is adjusted to a value to initiate reaction at WE. The potential at which reaction ensues (E with respect to RE) is monitored with the voltmeter. The current through the cell will decrease, as the reactive species is consumed at WE. This current decrease will cause E to increase. Monitoring the increase of E on the voltmeter, the potentiometer is adjusted to decrease the voltage applied to the CE until $E' = E$. The desired control point and actual control point are now very close. Fig. 3.5 shows a basic potentiostat circuit, that can be used for controlling the potential on the WE, implemented by using an operational amplifier[78-80].

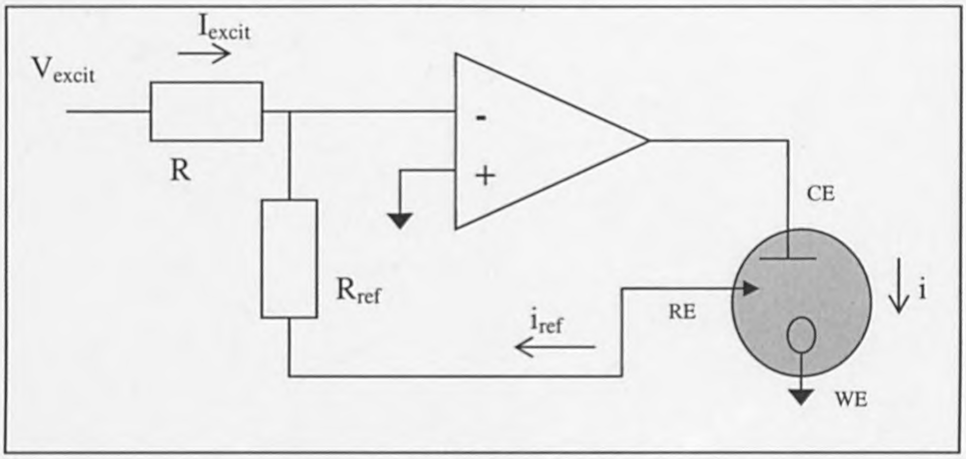


Figure 3.5: *Basic circuitry of potentiostat*

The virtual ground at the inverting input forces all currents to be zero at this point, therefore:

$$- i_{ref} = i_{excit} \quad \text{and} \quad -e_{ref} = e_{excit}\left(\frac{R_{ref}}{R_1}\right) \tag{3.2}$$

This simple arrangement has two drawbacks:

- The need to measure the current flowing into the WE
- The flow of current in RE is excessive

These are remedied using a current follower, and a voltage follower respectively[81], as shown in Fig. 3.6. The voltages e_f and V_{cell} are available for connection (to a data acquisition system, where:

$$e_f = - V_{excit} \text{ and } V_{cell} = -iR_f \tag{3.3}$$

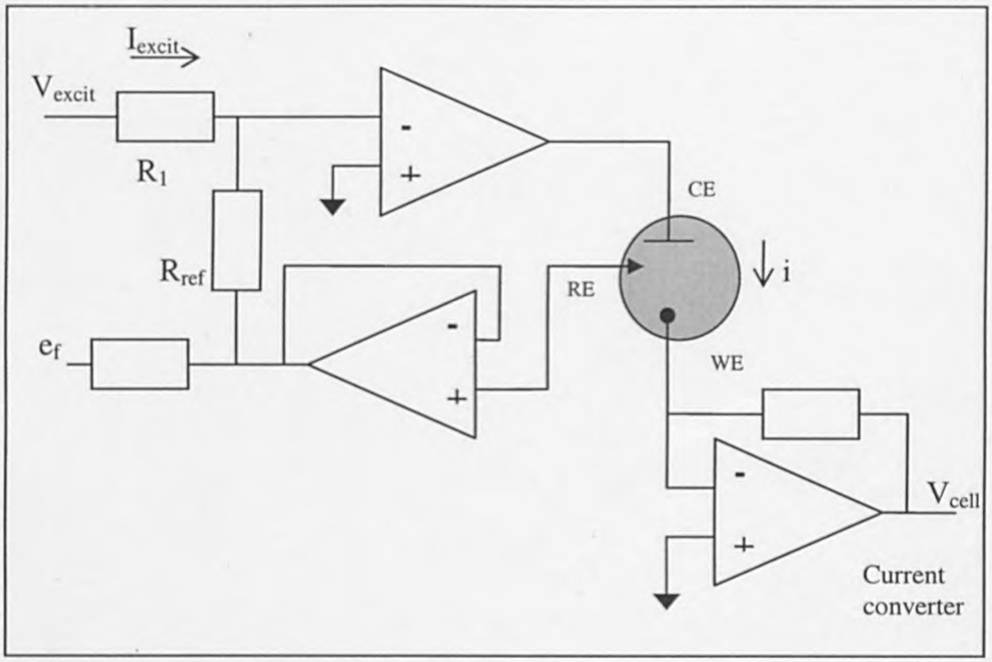


Figure 3.6*:Potentiostat circuitry*

Fig. 3.7 shows the complete circuit of the potentiostat designed for the system. The full scale current (I_{FS}) is 400 μA (-200 μA to +200 μA). The current measuring stage consists of two operational amplifiers. The first op-amp is a current to voltage converter with a gain of $10 x 10^{-3}$ ($R_f = 10\ k\Omega$). The 10 nF capacitor in the feedback loop provides some low-pass filtering (time constant, 100 μsec). The output of the op-amp (full scale) is given by:

$$V_{o1}(FS) = \mathrm{I_{FS}} \cdot \mathrm{R_f} = 400[\mu\mathrm{A}] \cdot 10 \times 10^3 [\Omega] = 4V \; (-2V \; to + 2\,\mathrm{V}) \quad (3.4)$$

where, I_{FS} is the current full scale and R_f is the feedback resistor.

The second op-amp is a voltage amplifier with a gain of 5. The output of the op-amp (full scale) is given by:

$$V_{cell}(FS) = \mathrm{V_{o1}}(FS) \cdot \mathrm{Gain} = 4[V] \cdot 5 = 20\,\mathrm{V} \; (-10V \; to + 10\,\mathrm{V}) \quad (3.5)$$

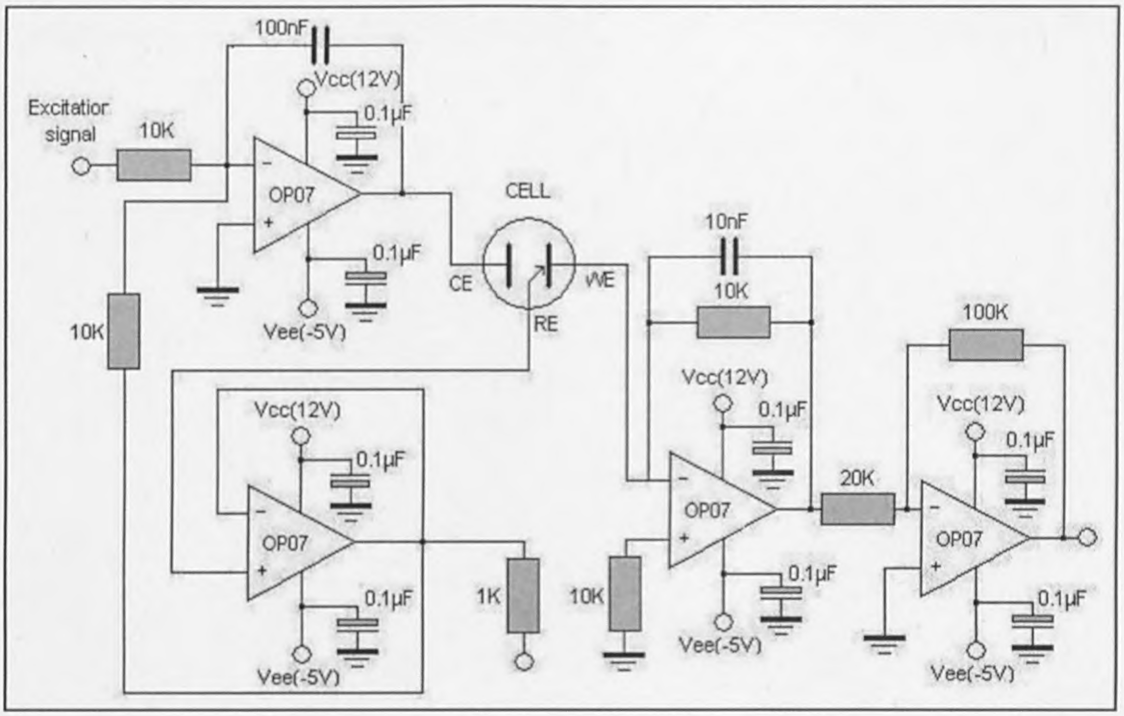


Figure 3.7: Complete circuit of the potentiostat

The specific type of the op-amps (OP07) used in the design have been chosen because of their very low offset voltage (*Vos)* and low bias current *(I_B)*. More technical information of this device is given in Appendix D.2. In order to minimise supply noise effects all operated amplifier supply connections are decoupled[82-84] using 0.1μF ceramic capacitors.

3.3.1 Variable Gain

In the previous section it has been seen that the full scale current I_{FS} is 400 μA (-200 μA to +200 μA). For low metal concentrations the amplitude of the differential (ΔI) current is very low compared to the full-scale current; I_{FS}, of the system. Therefore, the resolution R_P of the system for measuring low concentrations of metals is poor ($R_P = I_{FS} / 2^{16}$). In order to improve the resolution R_P the I_{FS} need to be decreased. In the opposite case, for measuring high concentrations of metals, the I_{FS} of the system should be high enough to fit the large current of the chemical reaction.

In order to overcome this problem, the single current-to-voltage converter (CVC) of the potentiostat (shown on Fig. 3.7) was replaced with a CVC with variable gain (Fig. 3.8).

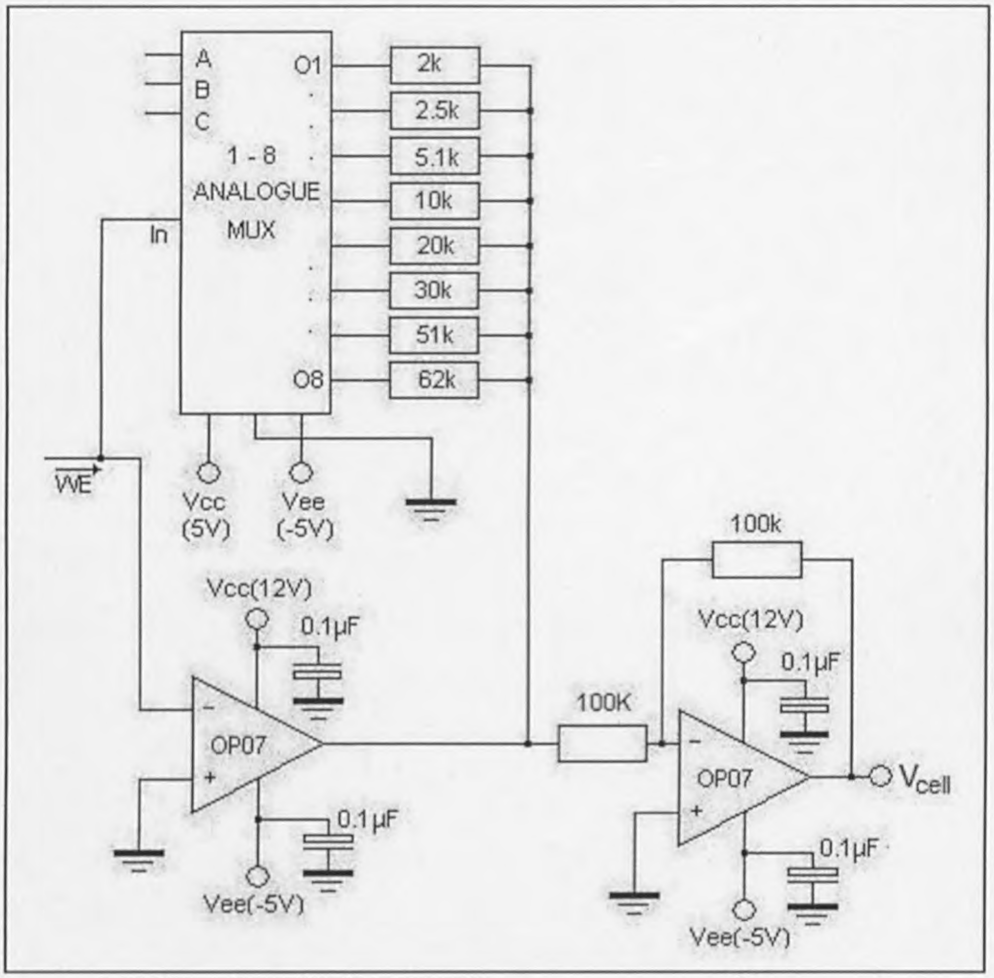


Figure 3.8: Circuit diagram of the variable gain amplifier

The gain of the CVC is determined by one of the eight different resistors connected to the output of the analogue multiplexer (4052B). The appropriate resistor (out of eight) that is used by the CVC (according to the amplitude of the measured signal) is selected by the microcontroller by controlling the analogue multiplexer. Each resistor has an associated parallel capacitor of a value chosen to preserve the 100 μsec filter time constant of this stage. (These capacitors are omitted from Fig. 3.8 to avoid unnecessary complexity). Therefore, for high current amplitude, the microcontroller will set a low gain (decrease of I_{FS}), and for a low current it will set a high gain (increase of I_{FS}). Table 3.3 shows the different values of I_{FS} (of the system) that can be set by the microcontroller. The maximum ON resistance (R_{ON}) of the analogue multiplexer (4052B) is 240 Ω. Therefore the maximum error occurs when the first resistor (2 kΩ) is selected which is 12%. The change of resistance is taken into account and compensated for within the software (for all resistors of the multiplexer).

Table 3.3: *Different I_{FS} values as set by the microcontroller.*

Resistor *[k]*	**Full Scale** *[μA]*	R_P *[nA]*
2	± 5000	152.6
2.5	± 4000	122.1
5.1	± 1961	61.0
10	± 1000	30.5
20	± 500	15.3
30	± 333	10.2
51	± 196	6.1
62	± 161	4.9

Fig. 3.9 shows the algorithm for the selection of the appropriate gain of the variable gain CVC by the microcontroller. The assembly program developed for the automatic gain control is listed in Appendix B.3. Technical information of the 4052B analogue multiplexer is given in Appendix D.4.

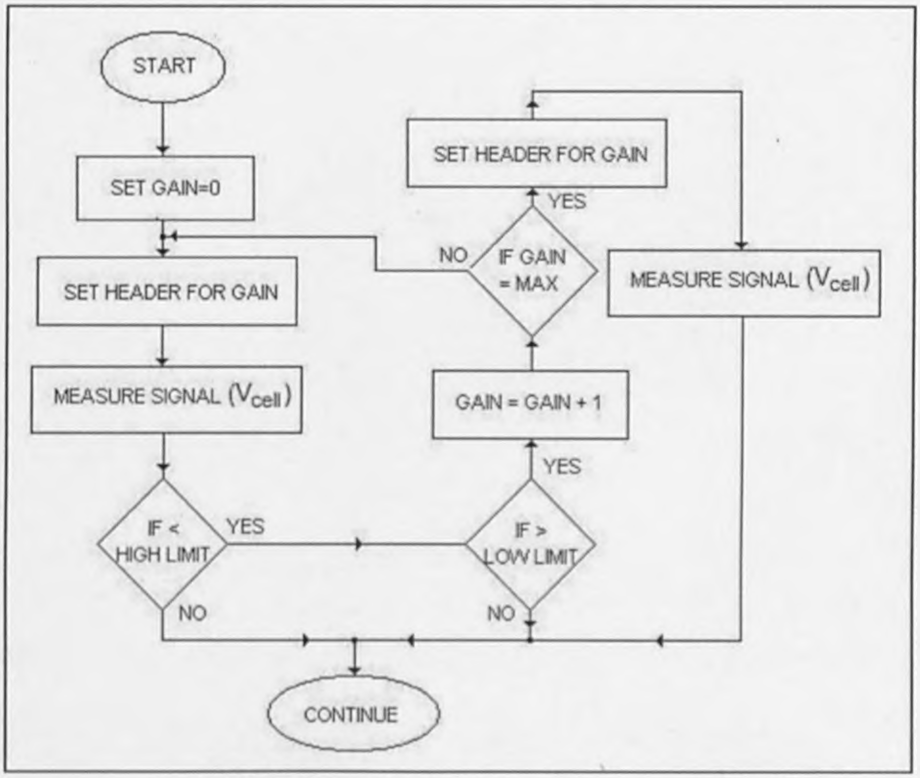


Figure 3.9: *flow chart for the variable gain amplifier*

3.4 Data Acquisition

In data acquisition, the electrochemical response, (current) is recorded at fixed time intervals by digitising it with an analogue to digital converter (ADC). Fig. 3.10 illustrates the circuitry of the data acquisition sub-system. For the signal conversion a 16-bit ADC device is used (LTC1605). The input to the ADC (output voltage from potentiostat current measuring stage) produces a 16-bit binary number each time a conversion is triggered. These numbers are stored in the microcontroller memory. The ADC operation is controlled by the microcontroller.

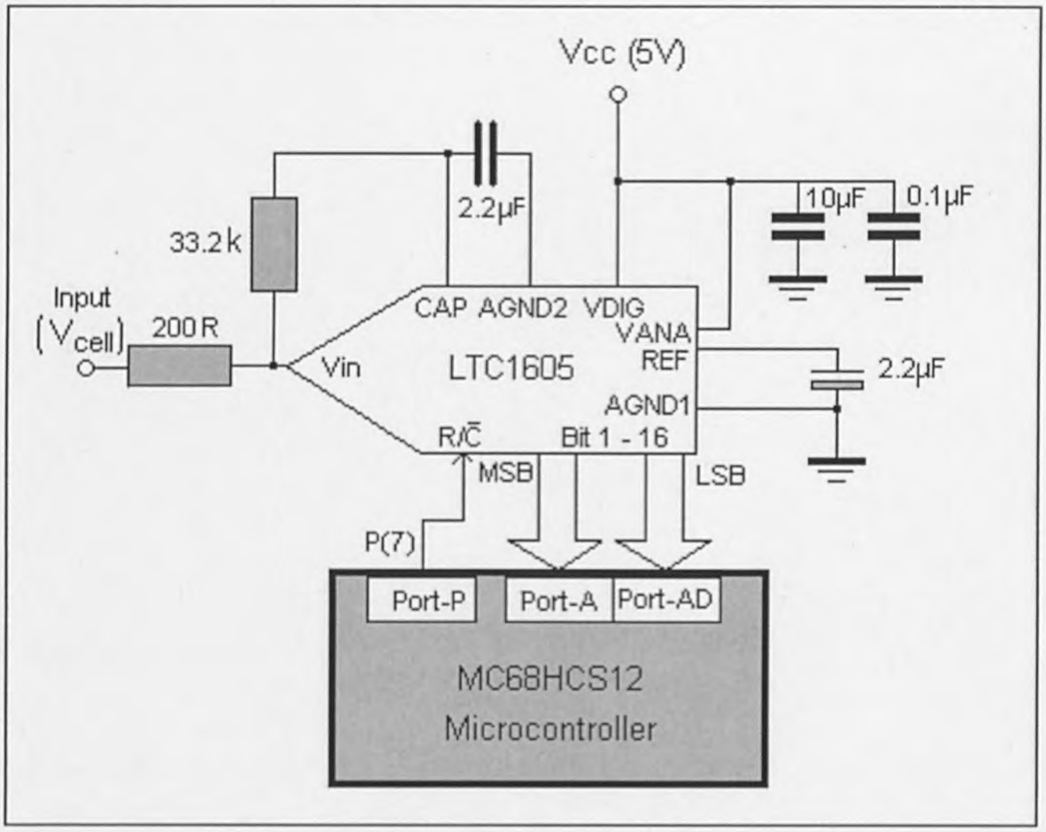


***Figure 3.10**: Circuitry for data acquisition*

The ADC uses an internal reference voltage of 2.5 V. The full-scale range (V_{DAFS}) is equal to *(±4 x Vref = ±10 V)*. Conversion start is controlled by the $R/\bar{C}$ input. A falling edge on $R/\bar{C}$ puts the internal sample-and-hold into the hold the state and starts a conversion. A rising edge on $R/\bar{C}$ enables the output data bits. Table 3.4

shows the connection between the pin of the microcontroller ports (Port-PAD1, Port-PA AND Port –PP) of the evaluation T-board) and the LTC1605 ADC device.

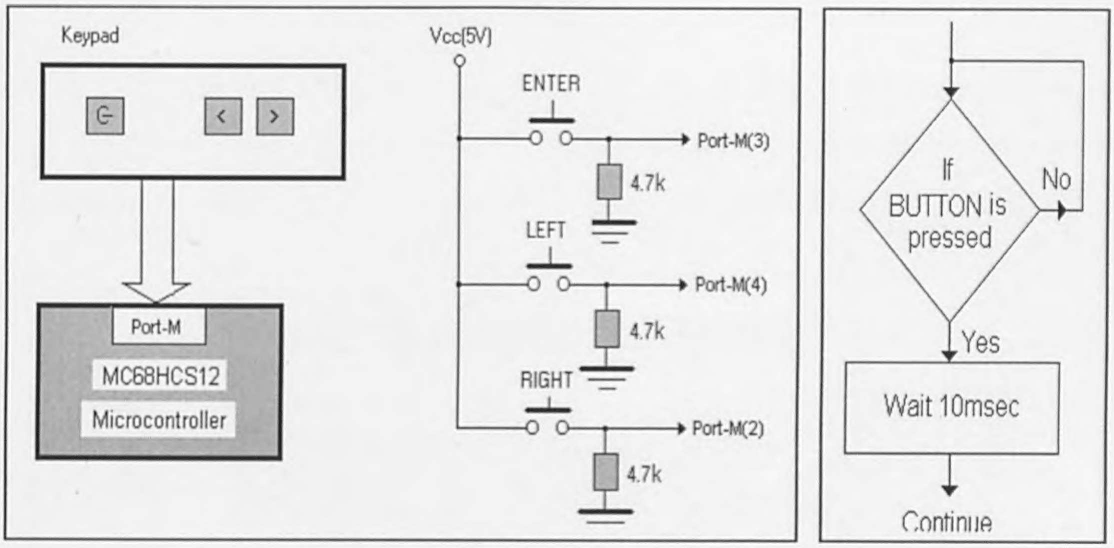
Timing diagrams for the ADC operation and more technical information for the device are given in Appendix D.5. The assembly program developed for the ADC operation is listed in Appendix B.2.

Table 3.4: *Connection between microcontroller pins and ADC device.*

Microcontroller		**LTC1605 - ADC**	
PORT	**T-Board Pin**	**Signal**	**Pin**
PAD1(0)	H3-12	D0(LSB)	22
PAD1(1)	H3-14	D1	21
PAD1(2)	H3-16	D2	20
PAD1(3)	H3-18	D3	19
PAD1(4)	H3-20	D4	18
PAD1(5)	H3-22	D5	17
PAD1(6)	H3-24	D6	16
PAD1(7)	H3-26	D7	15
PA(0)	H3-01	D8	13
PA(1)	H3-02	D9	12
PA(2)	H3-03	D10	11
PA(3)	H3-04	D11	10
PA(4)	H3-05	D12	09
PA(5)	H3-06	D13	08
PA(6)	H3-07	D14	07
PA(7)	H3-08	D15(MSB)	06
PP(7)	H4-25	R/C	24

3.5 Keypad Input

A keypad with three push buttons is used as an input to the microcontroller (Fig. 3.11). The ENTER button (key) is used to execute a command, or to start a specific process. The RIGHT and LEFT keys are used to increase/decrease the value of a parameter or to move to the next or previous command/operation. The switch bounce problem[85,86] was avoided with the addition of 10 msec delay, as shown in Fig. 3.11(b).



(a) *(b)*

Figure 3.11*(a): keypad input, (b)Timing strategy to counter switch bounce*

Table 3.5 shows the connection between the pins of the microcontroller port (Port-M of the evaluation T-board) and the key pad board.

Table 3.5*: Connection between microcontroller pin-outs and key pad board.*

Microcontroller		**Key pad**
PORT	**T-Board Pin**	
PM(2)	H4-19	Right
PM(4)	H4-17	Left
PM(3)	H4-18	Enter

3.6 Display Output

Two types of display have been used with the instrument, a simple alphanumerical display and a graphic Liquid Crystal Display (LCD). More detailed examination of the design and operation of the two displays is given in the following sections.

3.6.1 Alphanumerical Display

An LCD (TRIMODS 1543) of 2 x 20 characters (2 lines, 20 characters/line) is used to inform the user of the different stages of the process. The LCD is fully controlled by the microcontroller. Fig. 3.12 shows the LCD interface with the microcontroller.

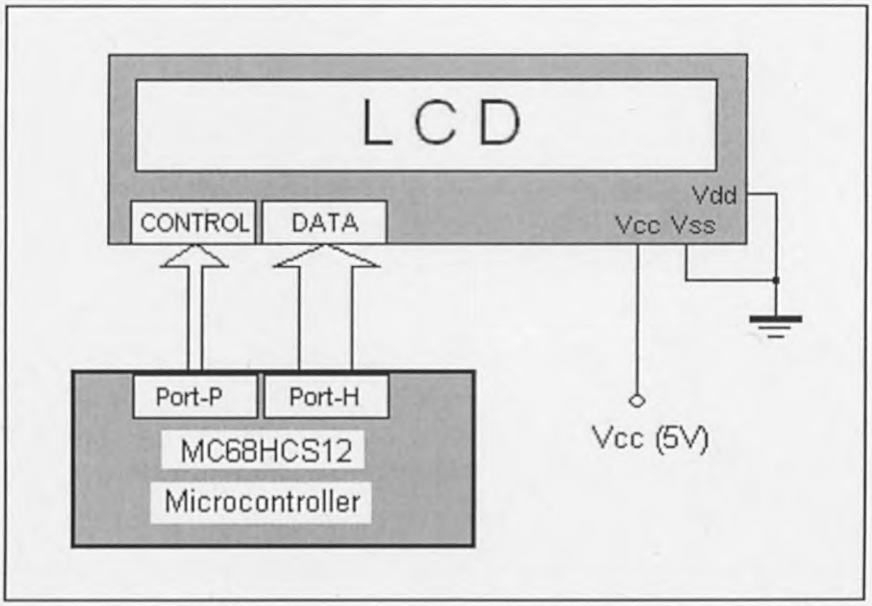


Figure 3.12: *LCD interface with the microcontroller*

Table 3.6 shows the connection between the pins of the microcontroller ports (Port-PH and Port-PP of the evaluation T-board) and the TRIMODS 1543 display.

Table 3.6: *Connection between microcontroller pins and TRIMODS display*

Microcontroller		**TRIMODS 1543**	
PORT	**T-Board Pin**	**Signal**	**Pin**
PH(0)	H2-24	Data-0	07
PH(1)	H2-23	Data-1	08
PH(2)	H2-22	Data-2	09
PH(3)	H2-21	Data-3	10
PH(4)	H2-07	Data-4	11
PH(5)	H2-06	Data-5	12
PH(6)	H2-05	Data-6	13
PH(7)	H2-04	Data-7	14
PP(2)	H1-02	RS	04
PP(4)	H4-28	R/W	06

Fig. 3.13 shows the flow chart for the initialisation of the LCD (control words and timing) to operate in 2-line increment mode, with the cursor on, and character resolution of 5x7 dots.

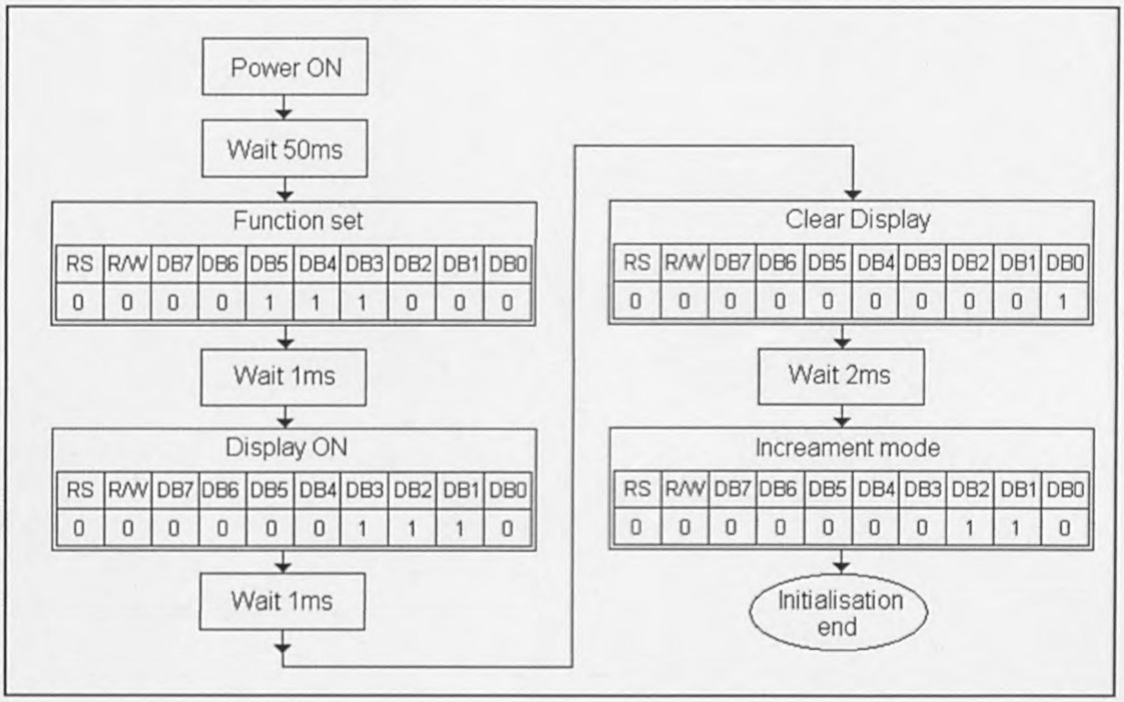


Figure 3.13: *Flow chart for LCD initialisation*

For displaying a character on the display, the "RS" control signal should be set to logic high and the "R/W" should be set to logic low. After 1 μsec, the data byte corresponding to the character to be displayed is sent to the display in ASCII format while the enable signal (E) is 'high'. The minimum time for displaying consecutive characters should be at least 500 nsec. Therefore, after sending a character byte to the display there is always 1 μsec delay before sent the next character is sent. This process is described by the flow chart of Fig. 3.14.

A datasheet with all technical information relating to the TRIMODS 1543 LCD is given in Appendix D.6. The assembly program developed for the operation of the LCD is given in Appendix B.5.

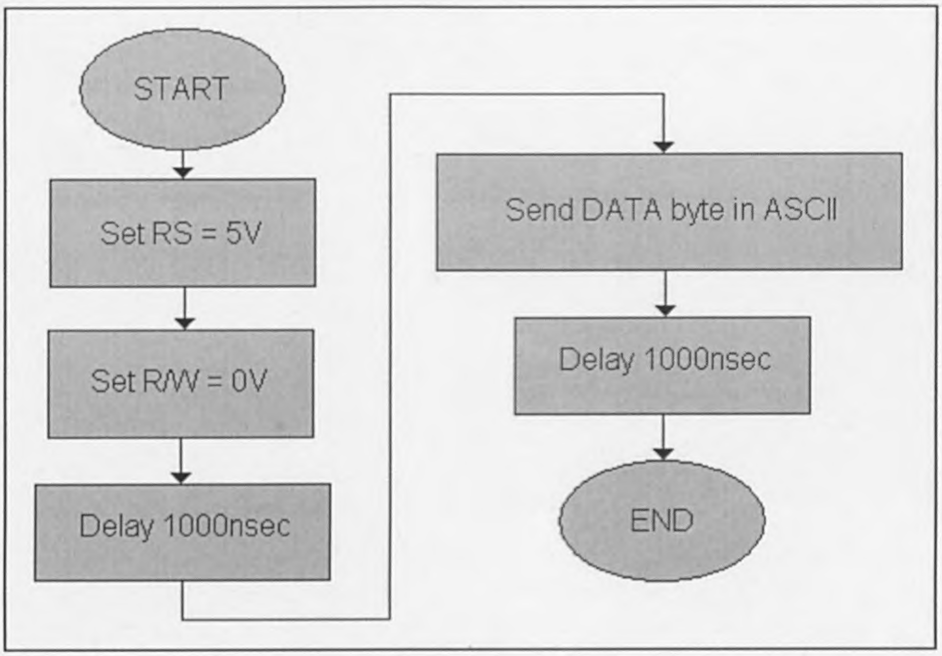


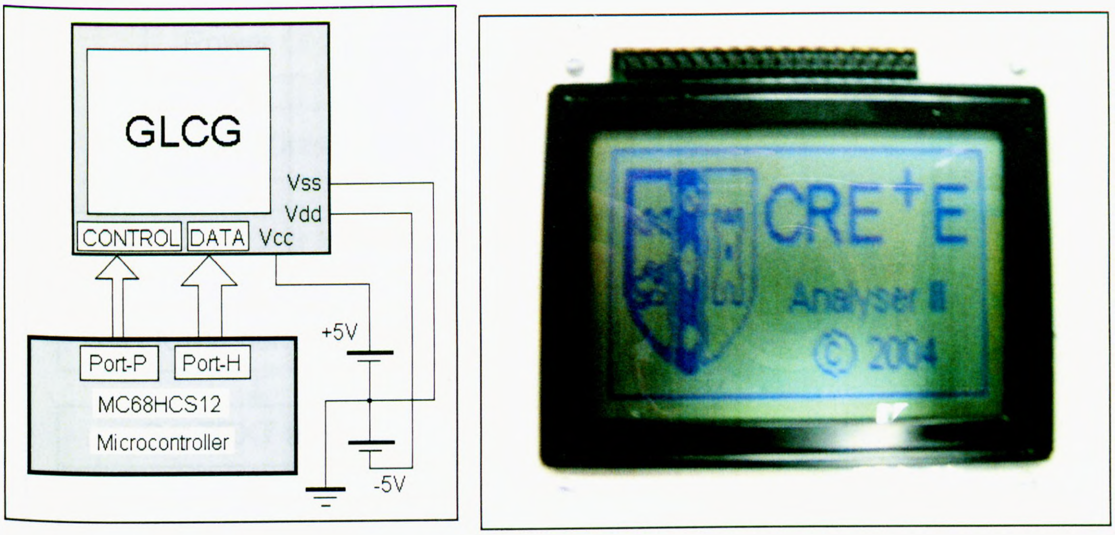
Figure 3.14: *Flow chart for displaying a character on the display*

3.6.2 Graphic Display

A Graphic liquid crystal display (POWERTIP, PG12864ERS) is used to inform the user of the different stages of the process. The advantages of using a graphic display are as follows:

- It allows the display of graphics and animations for user friendly operation
- It allows the display of the voltammogram in real time (for verification of correct operation)

The display adds flexibility to the system since the user can see the different commands/operations and can change the value of a parameter using a MENU-based operation. The GLCD (64 x 128 pixels with 8 Kbyte video RAM) is fully controlled by the microcontroller. Fig. 3.15 shows the GLCD interface with the microcontroller. Table 3.7 shows the connection between the pins of the microcontroller ports (Port-PH and Port-PP of the evaluation T-board) and the POWERTIP (PG12864ERS) display.



(a) *(b)*

Figure 3.15: *(a) GLCD interface with the microcontroller, (b) GLCD graphic output*

Table 3.7: *Connection between microcontroller pins and graphic display.*

Microcontroller		**PG 12864ERS**	
PORT	**T-Board Pin**	**Signal**	**Pin**
PH(0)	H2-24	Data-0 (LSB)	10
PH(1)	H2-23	Data-1	11
PH(2)	H2-22	Data-2	12
PH(3)	H2-21	Data-3	13
PH(4)	H2-07	Data-4	14
PH(5)	H2-06	Data-5	15
PH(6)	H2-05	Data-6	16
PH(7)	H2-04	Data-7 (MSB)	17
PP(1)	H1-03	/WR	05
PP(2)	H1-02	/RD	06
PP(3)	H1-01	/CE	07
PP(4)	H4-28	C/D	08
PP(5)	H4-27	/RST	09
PP(6)	H4-26	/FS	18

Fig. 3.16 shows the flow chart for the initialisation of the GLCD.

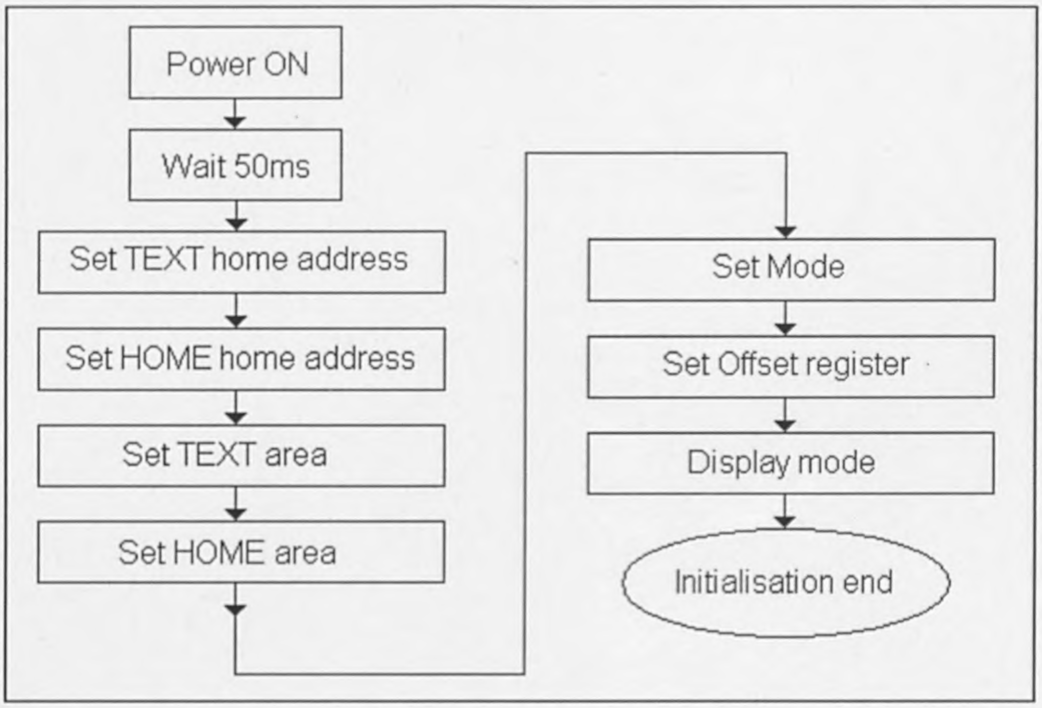


Figure 3.16: *Flow chart for GLCD initialisation*

The HOME address for the graphics was set to $0000 with $0010 area (characters per line). The TEXT address for text display was set to $0400 with $0010 area. The display was set to "OR" mode, with both graphics and text enabled and without cursor.

A datasheet with all technical information of the POWERTIP PG12864ERS LCD is given in Appendix D.7. The assembly program developed for the operation of the LCD is given in Appendix B.6.

3.7 External Memory Device

An external memory device of 64 Kbytes storage space has been designed in order to store the results during sample assessment. Since the average size of a sample is approximately 1 Kbyte, the memory device can store up to 60 samples. The heart of the memory device is a I^2C serial EEPROM (24AA512) of 512 Kbit (64 K x 8) capacity. Fig. 3.17 shows the circuitry of the memory device.

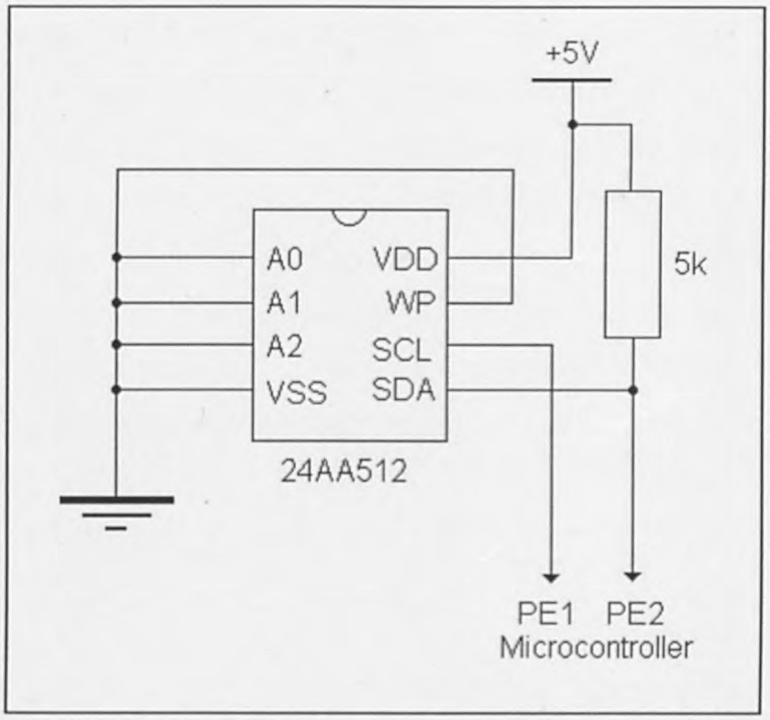


Figure 3.17: Circuitry of the external memory unit

Table 3.8 shows the connection between the pins of the microcontroller ports (Port-PJ of the evaluation T-board) and the 24AA512 serial EEPROM.

Table 3.8: Connection between microcontroller pins and serial EEPROM

Microcontroller		24AA512 - MEM	
PORT	**T-Board Pin**	**Signal**	**Pin**
PJ(0)	H1-22	DATA	05
PJ(1)	H1-21	CLK	06

The 24AA512 memory supports a bi-directional 2-wire bus I^2C protocol. The SDA terminal is used to transfer addresses and data into and data out of the device. It is an open-drain terminal, therefore, it requires a pull-up resistor to Vcc (5 kΩ for 200 kHz operation). The bus is controlled by the microcontroller (MASTER) which generates the serial clock (SCL), controls the bus access, and generates the START and STOP conditions while the serial EEPROM works as SLAVE. Both master and slave can operate as a transmitter or receiver, but the master device determines which mode is activated.

Fig. 3.18(a) shows the appropriate data format (protocol) for transmitting a byte from the microcontroller to the serial memory device. Following the START condition, the control code (four bits), the chip-select (three bits), and R/W bit (which is a logic low) are clocked onto the bus by the master transmitter (microcontroller). This indicates to the memory that the address high (most significant) byte will follow after it has generated an acknowledge bit. The next byte is the least significant address byte. After receiving another acknowledge signal from the memory, the microcontroller will transmit the data word to be written into the addressed memory location. The memory acknowledges again and the microcontroller generates a STOP condition.

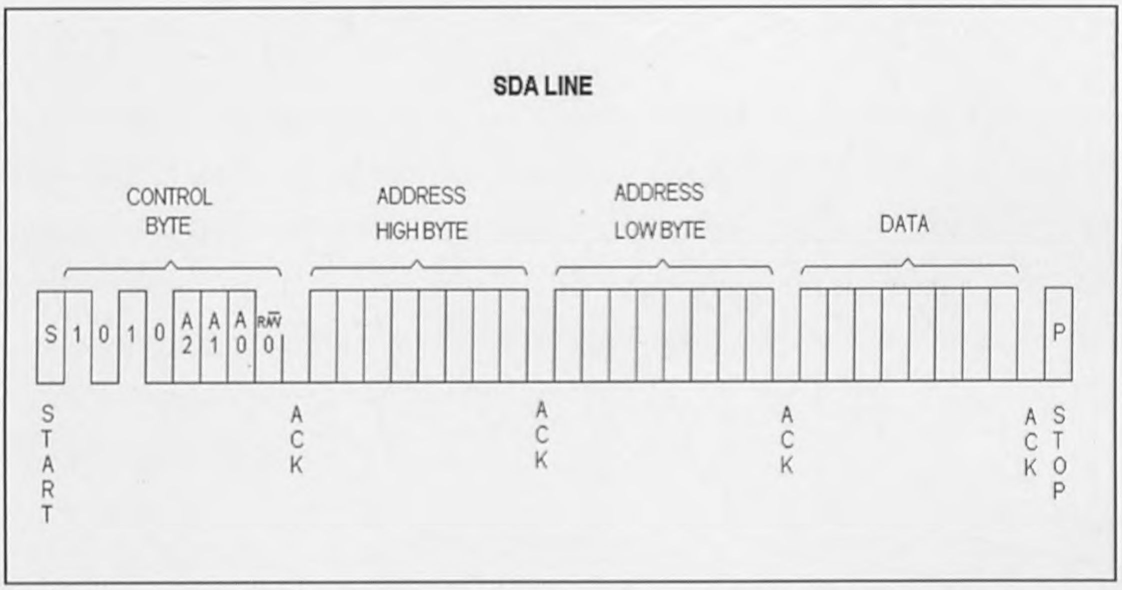


__Figure 3.18:__ (a) Data format (protocol) for transmitting a byte from the microcontroller to the serial memory.

Fig. 3.18(b) shows the appropriate data format (protocol) for transmitting a byte from the serial memory device to the microcontroller using the Sequential Reading Mode. It also shows the selection of the memory location (address) where the reading of the data is going to start. The process of the selection of the address (most significant and least significant bytes) is exactly the same as the write operation.

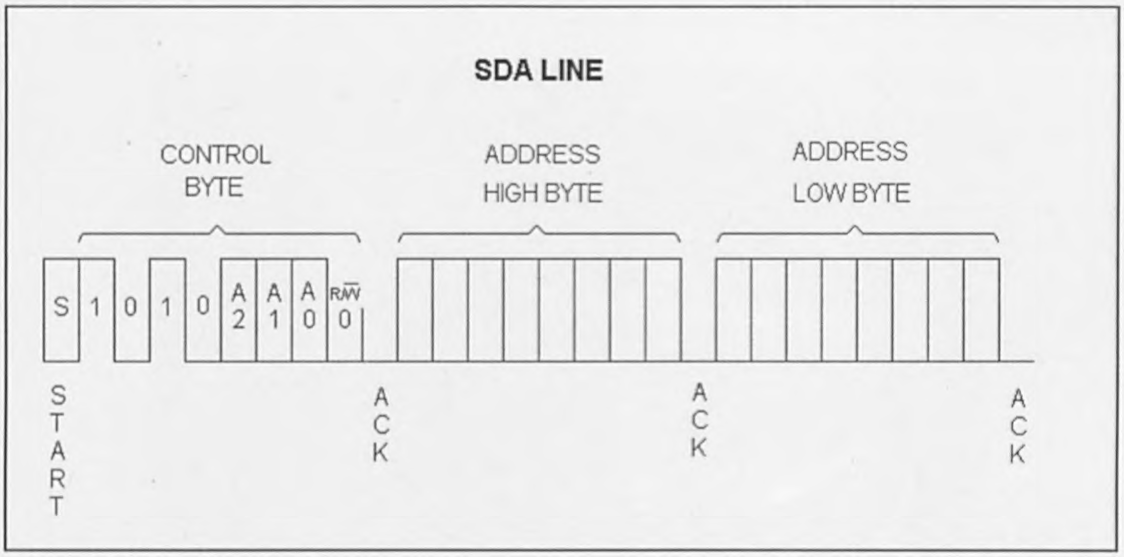


Figure 3.18: (b) Selection of memory location (addressing)

Fig. 3.18(c) shows the reading operation. The reading operation is initiated in the same way as the write operation, with the exception that the R/W bit of the control byte is set to '1'. The memory will then issue an acknowledge bit and transmit the eight bit data word. The memory will then issue another acknowledge bit and will transmit the sequentially addressed eight bit data. Following the final byte transmitted to the microcontroller, the microcontroller will not generate an acknowledge bit but will generate a STOP condition.

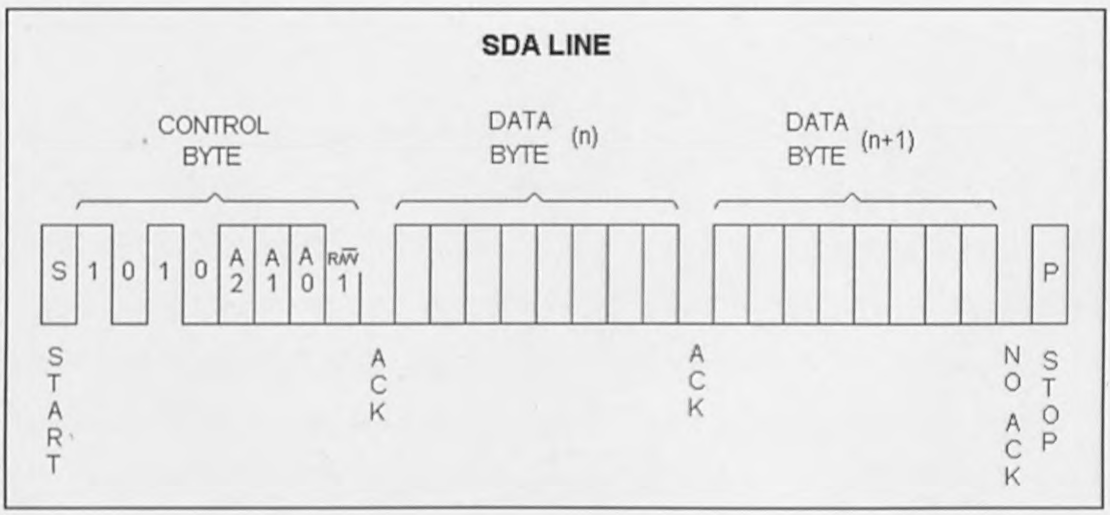


Figure 3.18:(c) Reading operation

Fig. 3.19 shows the physical size (5 cm by 2 cm) of the external memory device designed for the storage of the samples' measurements (voltammograms).

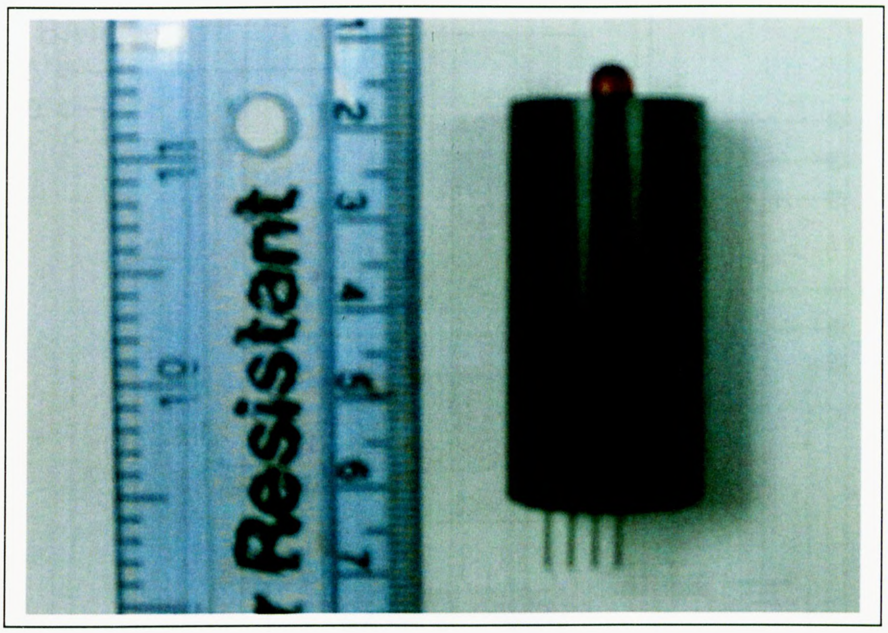


Figure 3.19: *Miniature external memory device*

A datasheet with all technical information of the 24AA512 memory device is given in Appendix D.8. The assembly program developed for the operation of this memory module is listed in Appendix B.7.

3.8 Portable Power Supply

An important characteristic of the system is its portability, which is made possible by its battery operation. The power consumption of the system is approximately 2 W (0.17 A at 12V). A TRACO TEL 3-0522 DC-to-DC converter was used to provide ±12 V supplies while LM2950 and 79LM05 regulators were used in conjunction to provide ±5 V supplies. The circuit diagram of the converter is shown in Fig. 3.20 below. A 7.2 V, 1.4 Ah battery was used for powering the two converter/inverters. The 1.4 Ah capacity of the battery is capable of providing approximately eight hours of continuous operation.

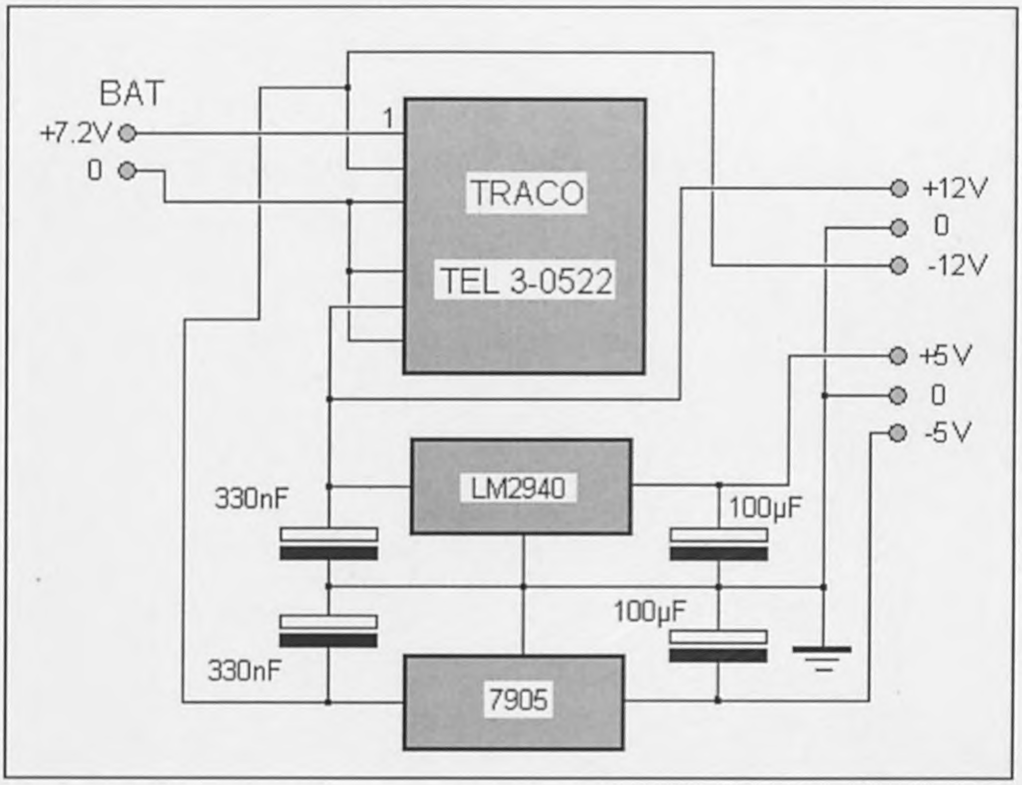


Figure 3.20: Circuit diagram of the converter / inverter

A datasheet with all technical information of the LM2940 and 7905 voltage regulators and TRACO TEL 3-0522 DC-to-DC converter device are given in Appendix D.9, D.10 and D.11 respectively

3.9 System Integration and Miniaturisation

Fig. 3.21 shows the development of the electrochemical instrumentation system with all units (power supply, microcontroller, display, keypad, potentiostat, digital-to-analogue converter, analogue-to-digital converter, and external memory module) connected together.

Fig. 3.22 shows the algorithm (flow chart) of the software which was developed for system operation. The program in assembly language is listed in appendix B.9. The program in C language for uploading and monitoring the voltammogram data on the PC is listed in appendix C.

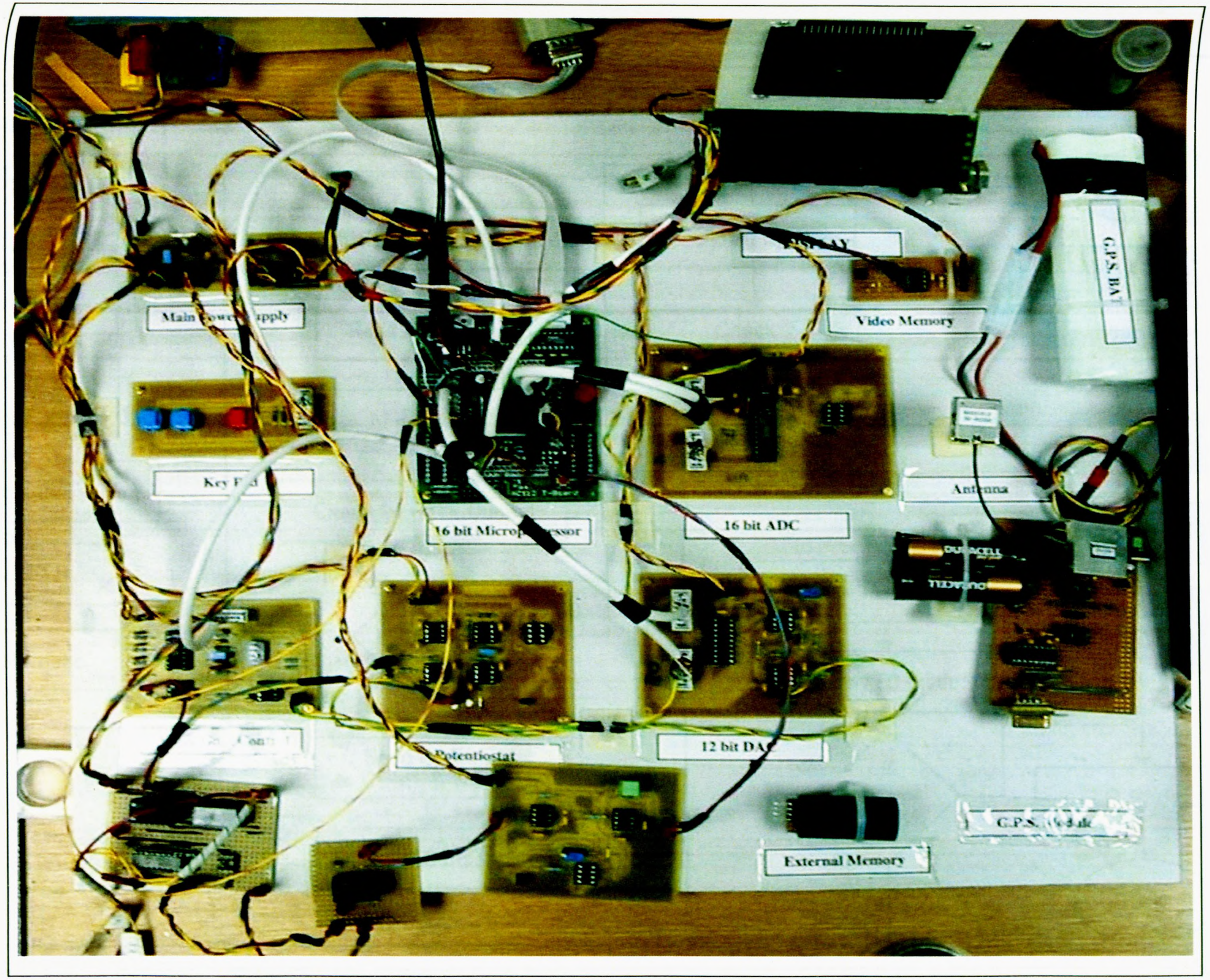


Figure 3.21: Final development of the electrochemical instrumentation system.

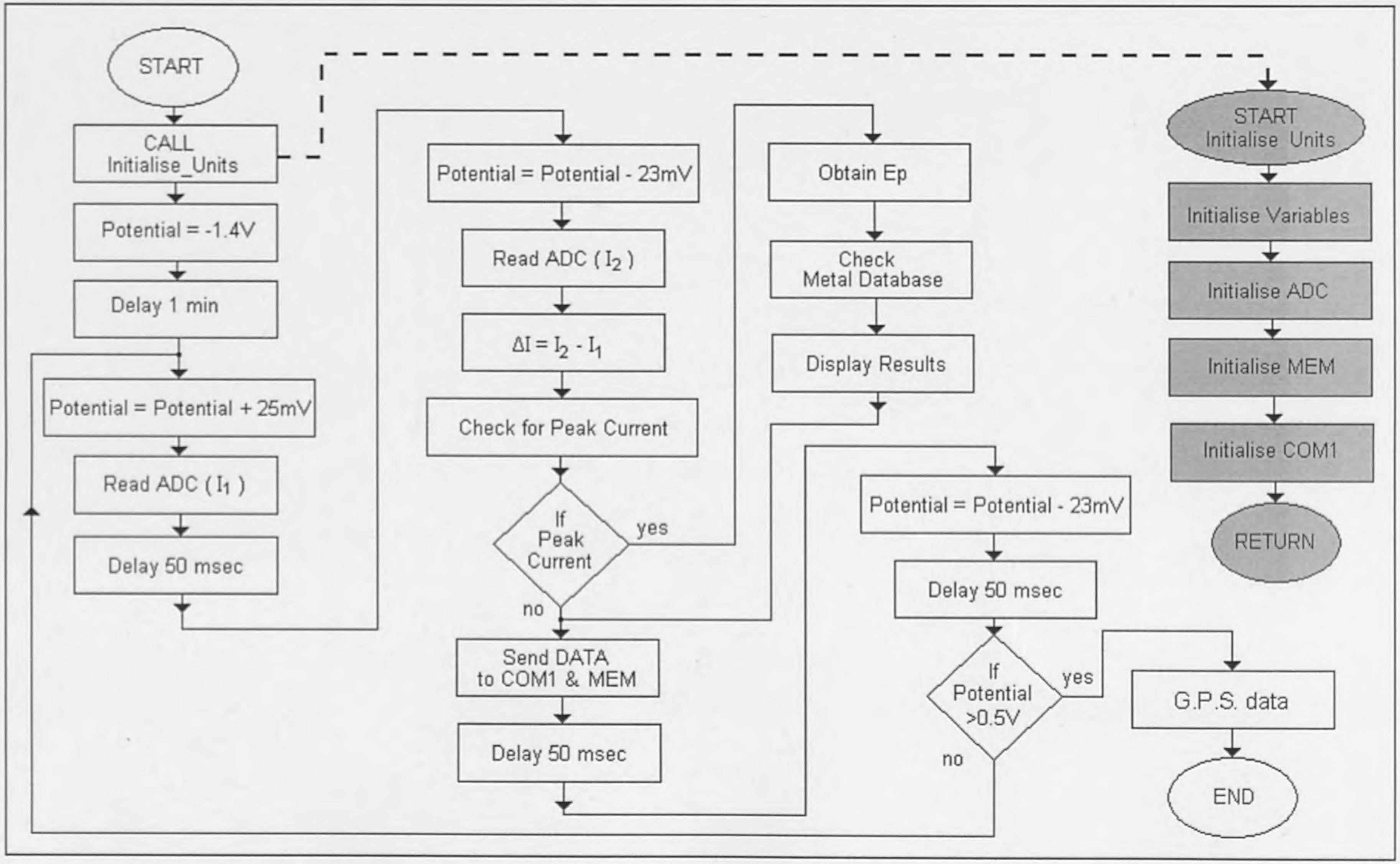


Figure 3.22: *Algorithm of the software for the system's operation*

Fig. 3.23 shows the design of the plastic box which is used to accommodate all units of the instrument, the battery and the electrochemical sensor.

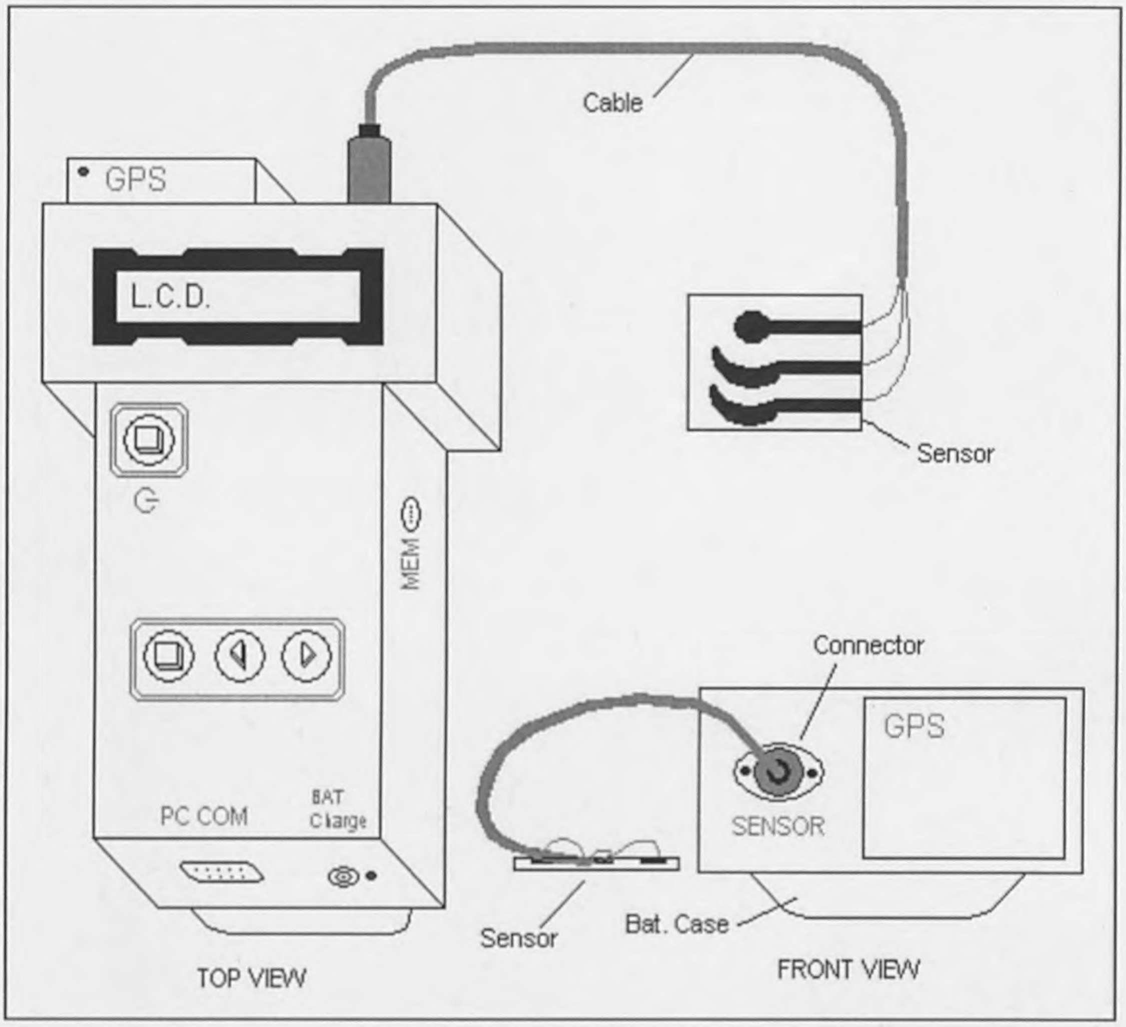


***Figure 3.23**: Design of the plastic box to accommodate all units of the instrument*

The next step of the design was to integrate the whole system shown in Fig.3.21 using only one Prototype Circuit Board (PCB). Fig. 3.24 shows the PCB design of the electrochemical system. The PCB is 17 cm long and 10.2 cm wide.

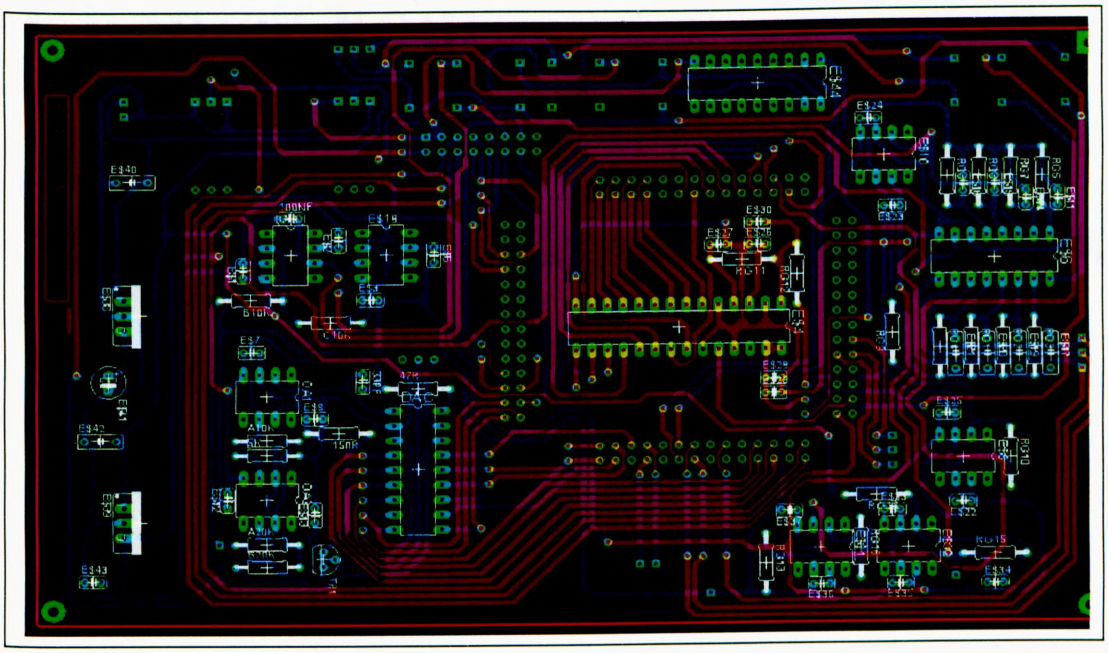


***Figure 3.24**: PCB design of the electrochemical system*

Fig. 3.25 shows the miniaturised version of the system assembled in the plastic box.

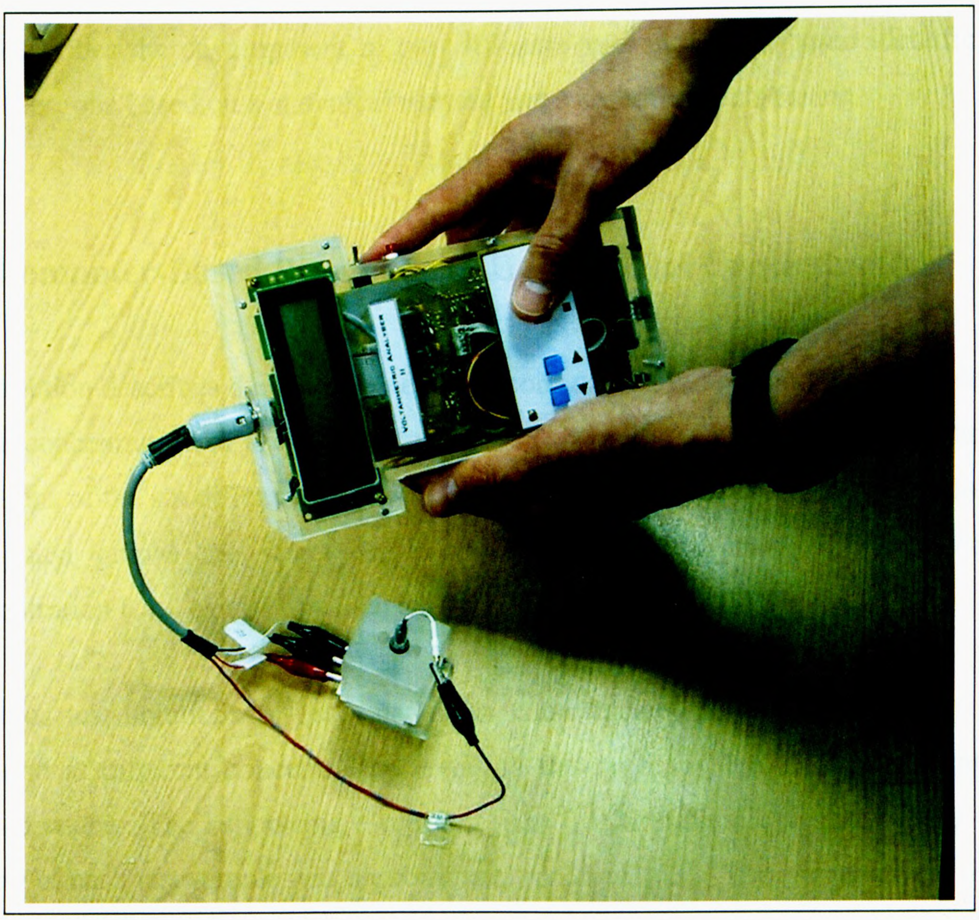


***Figure 3.25**: Electrochemical instrumentation system prototype*

Chapter Four

Microprocessor-Based Detection and Identification of Heavy Metals

4.1 Introduction

This chapter deals with the development of the appropriate microprocessor-based methods for the prediction of the concentration of six different metals namely lead, cadmium, zinc, nickel, mercury and copper. These six ions were initially chosen for examination due to their importance as environmental pollutants[87-92]. The chapter also describes the development of two different microprocessor-based identification strategies, one based on a statistical method and a second on data fusion.

4.2 Computer-Based Prediction of Heavy Metal Concentrations

This section describes the development of a computer-based method for the prediction of the concentration of six different metals. This method is based on the calibration equations of the six different metals. The coefficients of the curve-fitting equations of calibration graphs are stored in system memory; if a metal is identified, its concentration level can be obtained using these equations[93,94].

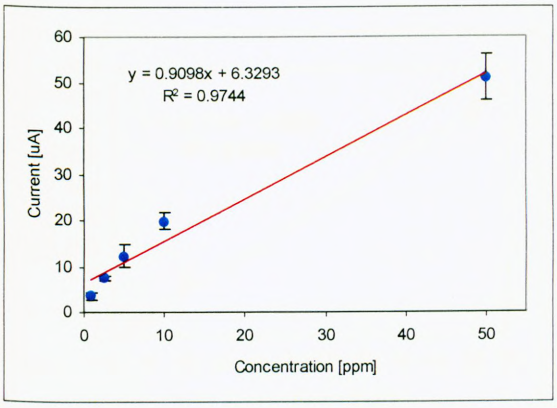
Aqueous test solutions of lead, cadmium, zinc, nickel, mercury and copper were prepared at different concentration levels in the range of 1 to 100 ppm using de-ionised water. The supporting electrolyte was 0.1 M sodium chloride (*NaCl)*. The acidity of each test sample was approximately 1.35 pH[63]. The samples were placed in a glass sample reservoir of 40 ml capacity. The pre-concentration time used for these experiments was 60 sec and the scanning voltage was in the range -1400 to +1000 mV.

Thirty two independent measurements of the electrical potential and peak current amplitude of all six metals were recorded. The instrument was also connected to a personal computer, and the results were monitored for comparison with the values obtained from the liquid-crystal display. This procedure was carried out using both electrochemical sensors (glassy carbon and screen printed).

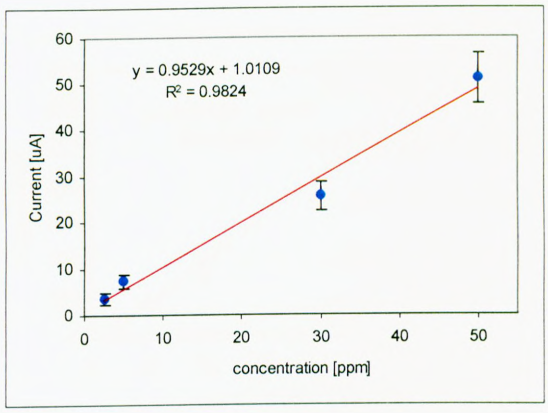
Fig. 4.1(a) to (f) shows the calibration graphs of lead, cadmium, mercury, zinc, copper and nickel respectively using the cell with the glassy carbon electrode. The full set of measurements are given in Appendix A(1-6).

Fig. 4.2(a) to (f) shows the calibration graphs of lead, cadmium, mercury, zinc, copper and nickel respectively using the screen printed cell. The full set of measurements are given in Appendix A(7-12).

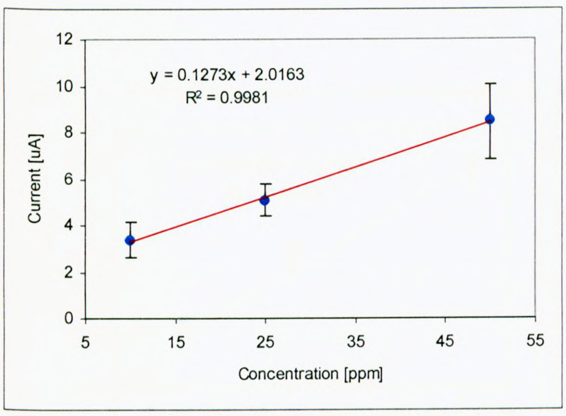
As the calibration graphs for all the metals examined are approximately linear (as shown in Fig. 4.1 and Fig. 4.2) and thus relatively reproducible, the concentration of a particular species can be obtained from the measured peak current. The calibration coefficients of the calibration equations were stored in the microcontroller memory. When a test is carried out, the metal is first identified using the identification algorithm. The amplitude of the peak current (corresponding to the oxidation potential of the identified metal) is then used with the calibration equation in order to predict the level of concentration.



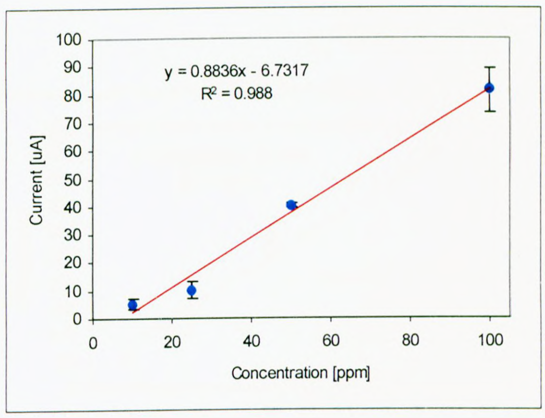
(a) Lead(ii)



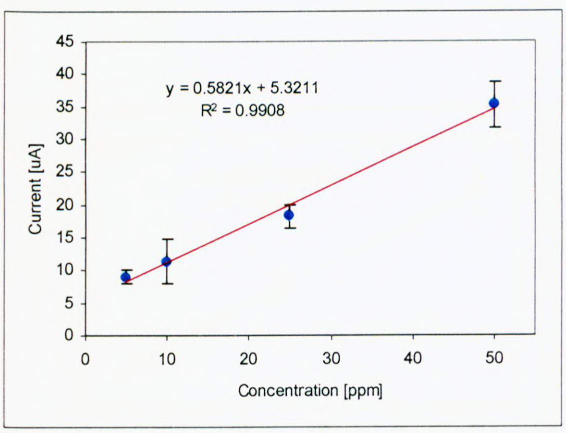
(b) Cadmium(ii)



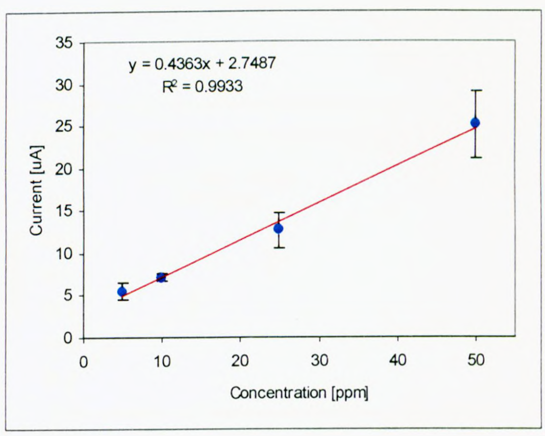
(c) Mercury(ii)



(d) Zinc(ii)

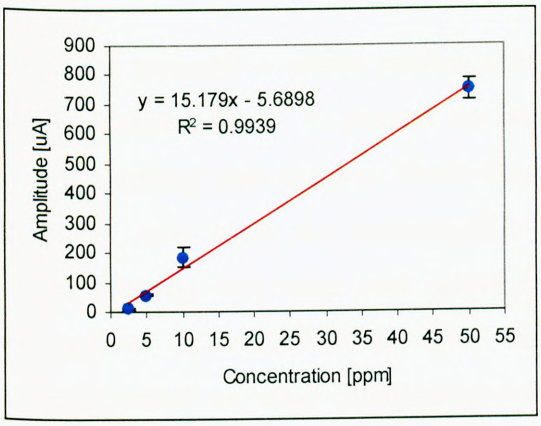


(e) Copper(ii)

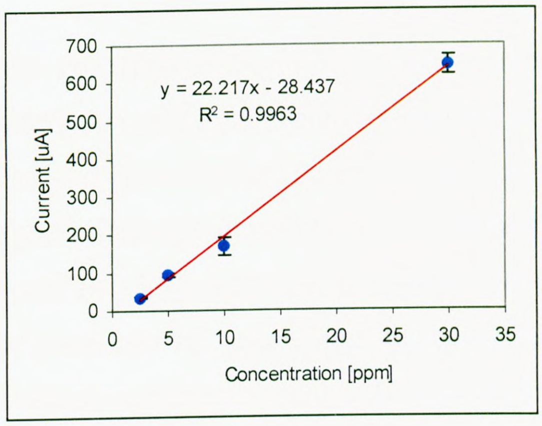


(f) Nickel(ii)

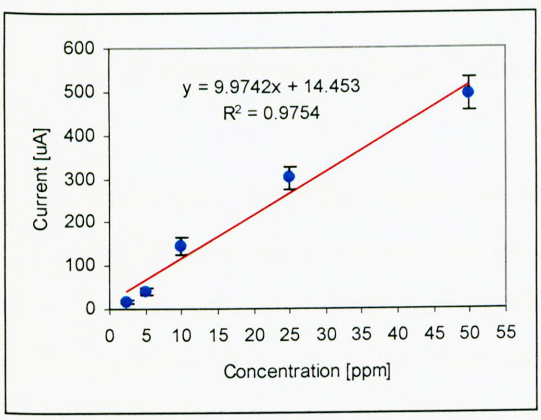
Figure 4.1: *Calibration curves of all metals using the glassy carbon electrode*



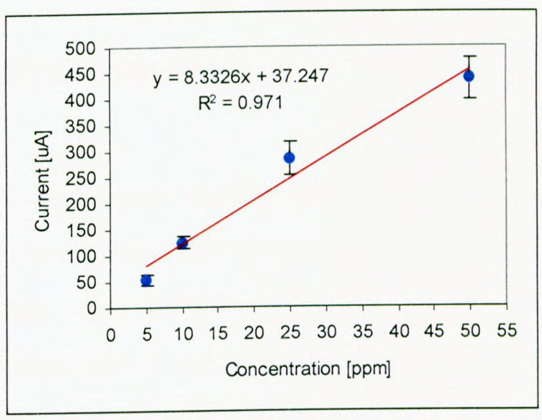
(a) Lead(ii)



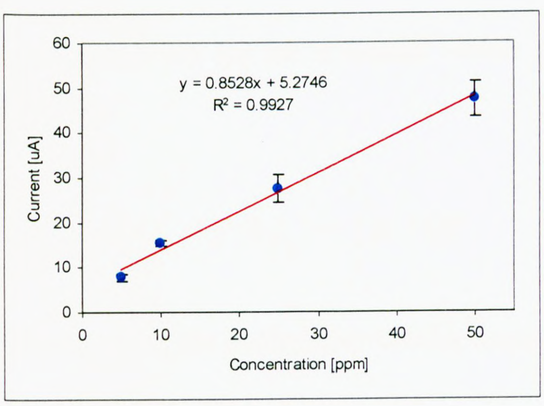
(b) Cadmium(ii)



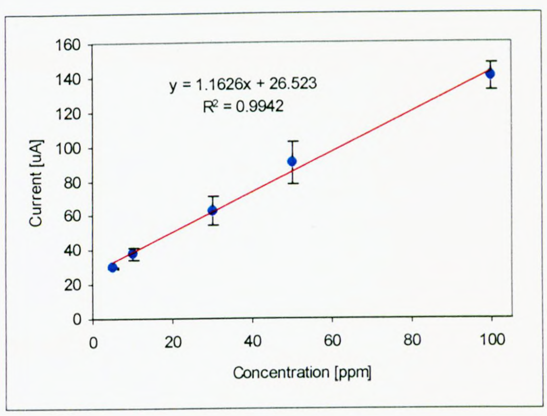
(c) Zinc(ii)



(d) Copper(ii)



(e) Nickel(ii)



(f) Mercury(ii)

Figure 4.2*: Calibration curves of the six metals using the screen printed sensor*

4.3 Identification of Heavy Metals Using a Statistical Method

Oxidation potential is widely used as a feature extraction method for the identification of electro-active ions. At present, the identification of metals requires laborious and time consuming data analysis, which must be carried out by highly trained personnel. Problems arise when the voltammetric signals relevant to neighbouring elements overlap, having very close peak potentials and very high concentration ratios. Most working in this field[95-98] solve such problems by employing mathematical methods, which are often complicated and difficult to follow or apply. To achieve the same goal, two alternative computer-based techniques, which are simple and quick to apply, have been developed. Using these techniques, six different metals can be identified.

4.3.1 Metal Identification Using Probability Density Function

An identification technique based on the probability density functions (*PDF*) of oxidation potential measurements has been developed. PDF curves have been used in the development of decision algorithms for feature selection in various applications[99-101]. Data are first arranged into a numerical order from which various statistical features are obtained, such as *minimum*, *maximum*, *mean*, *median*, and *standard deviation.* These are then used as a basis for classification.

The probability (p) for a feature which assumes a value between f_1 and f_2 is given by[102]:

$$p(f_1 \le f \le f_2) = \int_{f_1}^{f_2} p(f)df \qquad (4.1)$$

where, $p(f)$ is the probability density function of f.

In the case of Gaussian distribution[103], the probability density function p(f) is given by:

$$p(f) = \left[1/(\sigma\sqrt{2\cdot\pi})\right]\cdot e^{-(f-\mu)^2/2\cdot\sigma^2} \tag{4.2}$$

$$\mu = \sum_{i=1}^{N} \left(f_i / N\right) \tag{4.2.a}$$

$$\sigma = (1/N)\sum_{i=1}^{N} \left(f_i - \mu\right) \tag{4.2.b}$$

where, μ is the mean value and σ is the standard deviation.

Fig. 4.3 shows an example of probability density function curves for a two-class classification problem. Features 1 and 2 are limited in their capability for classifying the feature as either class 1 or 2. Feature 3 provides a clearer differentiation between class 1 and 2. Feature 4 provides an excellent marker for differentiating the two classes with 100% probability.

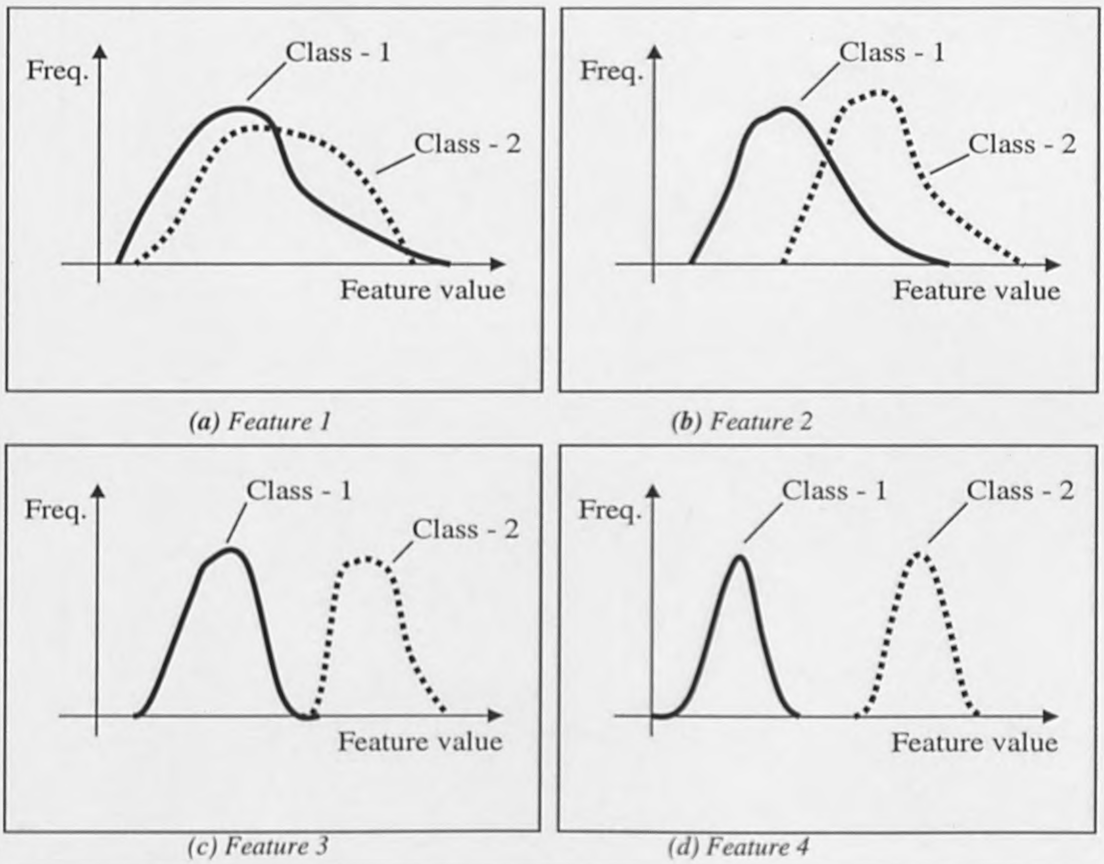


***Figure 4.3**: Sample probability density function curves for a typical two-class classification*

Considering the application of the PDF-based method to the heavy metal identification problem, as the potential of the excitation signal approaches the oxidation potential of one of the metals dissolved onto the electrode surface, the ions of that metal pass into the solution from the electrode. The current increases rapidly and reaches a maximum value (peak current) when the applied potential approximates to the metal's oxidation potential (E_p). When an actual test is carried out, the oxidation potential E_p is assessed and examined against a PDF to determine the probability of membership of that analyte with all analytes stored in a database of PDF measurements. The analyte representing the highest probability of likeliness is thus identified. Analytes identified in this way are automatically given a probability of likeliness, indicating the prediction accuracy.

Fig. 4.4 shows a block diagram for the whole process of identification by this means.

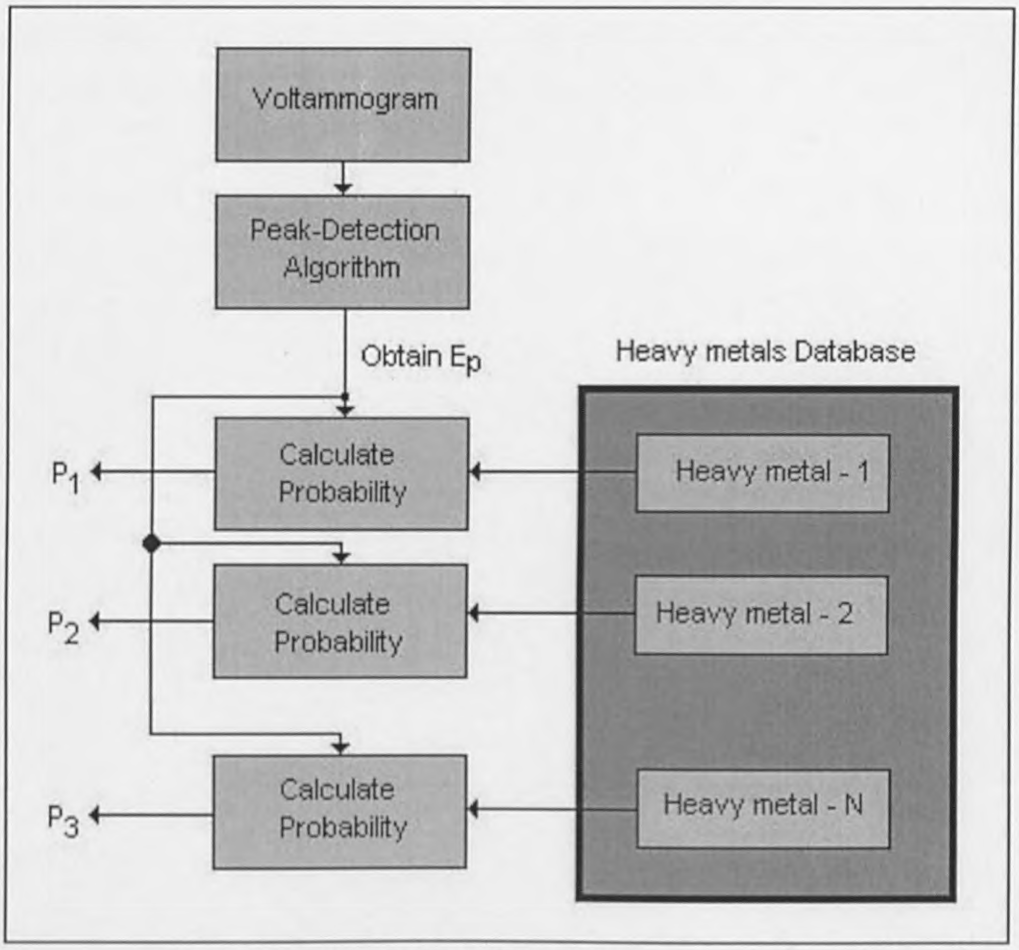


***Figure 4.4**: Process for the identification of heavy metals*

4.3.2 Development of the Statistical Method

Aqueous test solutions of lead, cadmium, zinc, nickel, mercury and copper were prepared at different concentration levels in the range of 1 to 100 ppm. These six ions were initially chosen for examination due to their importance as environmental pollutants. The solutions were prepared using de-ionised water. The supporting electrolyte was 0.1 M sodium chloride (*NaCl)*. The acidity of each test sample was approximately 1.35 pH. The samples were placed in a glass sample reservoir of 40 ml capacity. The pre-concentration time used for these experiments was 60 sec and the scanning voltage was in the range -1400 to +1000 mV.

Thirty two independent measurements of the electrical potential and peak current amplitude of all six metals were recorded. The instrument was also connected to a personal computer, and the results were monitored for comparison with the values obtained from the liquid-crystal display. This procedure was carried out using both electrochemical sensor (glassy carbon and screen printed).

Fig. 4.5 shows the resultant probability density functions of the electrical potential measurements which were estimated for the six different metals using the glassy carbon electrode. The statistical parameters are shown in table 4.1. The full set of measurements are given in Appendix A(1-6).

Fig. 4.6 shows the resultant probability density functions of the electrical potential measurements which were estimated for the six different metals using the screen printed sensor. The statistical parameters are shown in table 4.2. The full set of measurements are given in Appendix A(7-12).

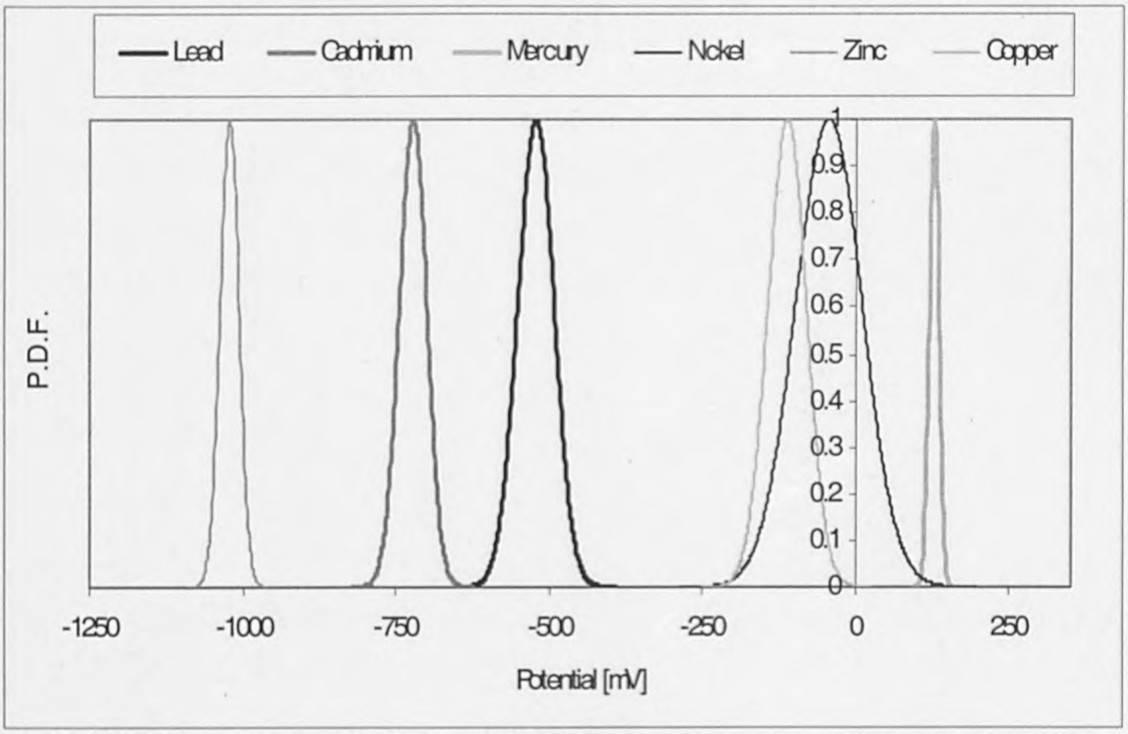


Figure 4.5: *Probability density functions of the electrical potentials of the six different metals (glassy carbon electrode).*

Table 4.1*: Statistical parameters of electrical potential measurements at acidity of ~1.35pH (glassy carbon electrode)*

Heavy metal	Oxidation potential [mV]	
	Mean μ_E	Std σ_E
Zinc (Zn^{II})	-1022	15.24
Cadmium (Cd^{II})	-722	22.27
Lead (Pb^{II})	-522	29.36
Copper (Cu^{II})	-112	31.42
Nickel (Ni^{II})	-44	54.40
Mercury (Hg^{II})	128	7.75

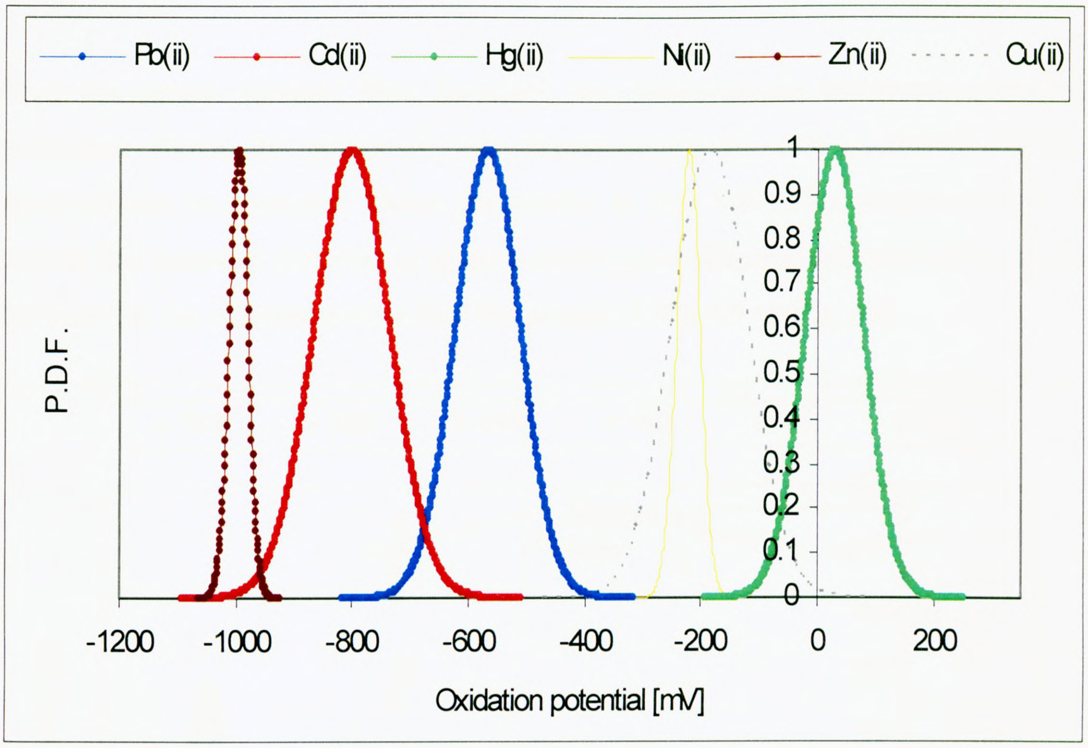


Figure 4.6: *Probability density functions of the electrical potentials of the six different metals (screen printed sensor).*

Table 4.2: *Statistical parameters of electrical potential measurements at acidity of ~1.35pH (screen printed sensor)*

Heavy metal	**Oxidation potential [mV]**	
	Mean μ_E	**Std σ_E**
Zinc (Zn^{II})	-1002	25.42
Cadmium (Cd^{II})	-821	67.99
Lead (Pb^{II})	-568	56.31
Copper (Cu^{II})	-183	64.82
Nickel (Ni^{II})	-211	28.39
Mercury (Hg^{II})	57	51.74

4.4 Identification of Metals Using Data Fusion

From the dataset obtained from the thirty two measurements described in previous technique, above, the points of peak current amplitude and associated oxidation potential can be extracted. These are plotted in Fig. 4.7. The combination of the current and potential dimensions gives a clearer (two-dimensional) view of separation between the six different metals than the graphs of Fig. 4.5 or Fig. 4.6.

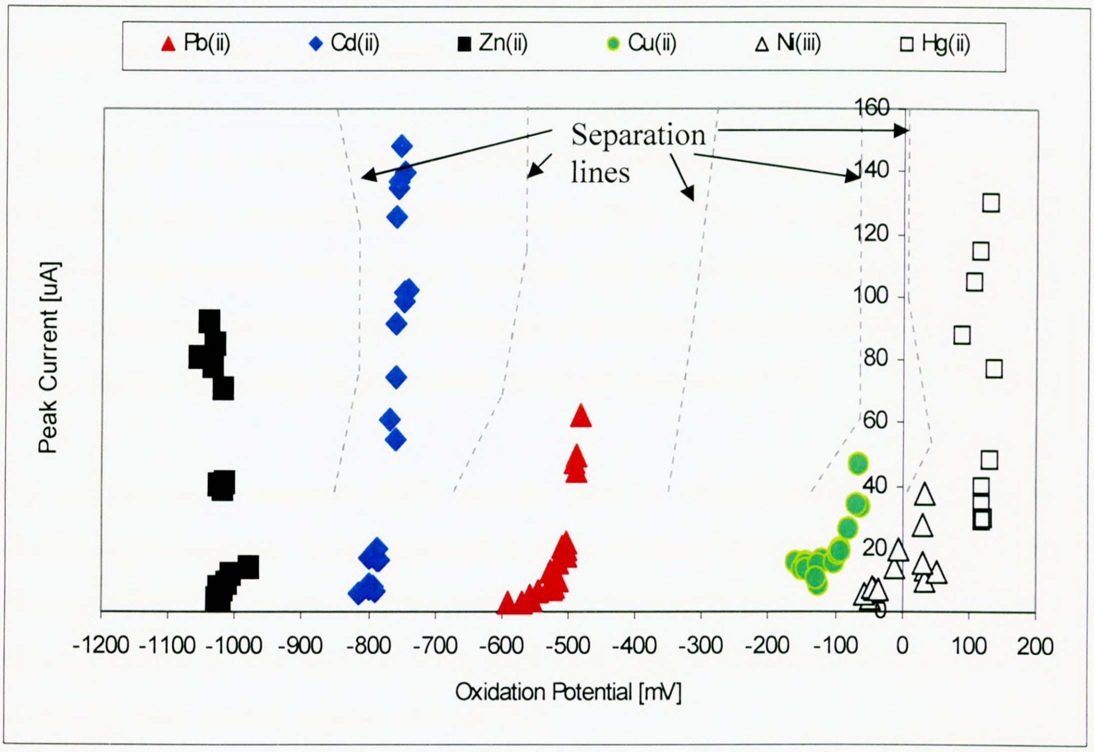


Figure 4.7: *Amplitude peak versus oxidation potential for the six different metals*

The plot of Fig. 4.7 is called a *space scatter diagram* and is well known in the field of pattern recognition[104]. The plot allows any natural clustering of the data to be seen. Clustering is a process in which a set of data is organised into groups that have strong likeness or similarity, measures described in standard textbooks on pattern recognition[105,106]. Separation problems like the one evidenced on the space scatter diagram of Fig. 4.7 can be easily solved by using artificial neural networks[107,110].

4.4.1 Identification of Heavy Metals Using a Neural Network

Artificial neural networks (ANNs) can be implemented in software, and can be trained to undertake many problems which are amenable to a distributed computational approach of this kind. The training of ANNs is performed with historical data and associated outcomes. The ANN calculates its response to test input data and compares it with a known result. The comparison result is used to adjust internal parameters within the ANN, according to a specified algorithm, in such a way as to improve its subsequent performance.

ANNs can be very useful in solving problems in classification applications where it is difficult to apply conventional software algorithms. They are usually composed of a number of interconnected nodes or 'neurons' that act as independent processing units. Each node processes input signals through a specified transformation and produces an output signal depending on prescribed threshold functions[111].

One of the most common ANN models used in classification applications is the multilayer Perceptron. It is composed of three or more layers of neurons each feeding its outputs forward to one or more nodes in the following layer. For this application, a neural network of this type has been used to classify six different heavy metals, zinc, cadmium, lead, nickel, copper and mercury.

The ANN applied in this instance has three layers of neurons, an input layer, a "hidden layer" and an output layer. The first layer, consists of two input neurons, one for the oxidation potential input and one for the peak current amplitude. The second (hidden) layer consists of seven neurons which are sufficient to solve the classification problem. The third layer consists of six outputs, one each for Lead (Pb^{II}), Cadmium (Cd^{II}), Mercury (Hg^{II}), Zinc (Zn^{II}), Nickel (Ni^{II}) and Copper (Cu^{II}). The neural network was designed and trained using NS32NET ANN development and optimisation software. After training, all weights and bias values for each neuron were obtained.

The input layer (Fig. 4.8) is defined by equations [4.3(a,b)]:

$$E_P' = (E_P - \min_{Ep})/(\max_{Ep} - \min_{Ep}) \qquad (4.3.a)$$

$$I_P' = (I_P - \min_{Ip})/(\max_{Ip} - \min_{Ip}) \qquad (4.3.b)$$

where, E_P and I_P are the inputs of the network, E_P' and I_P' are the normalised inputs, max_{Ep} and max_{Ip} are the maximum values of E_P and I_P input respectively used for training, min_{Ep} and min_{Ip} are the minimum input values used for training.

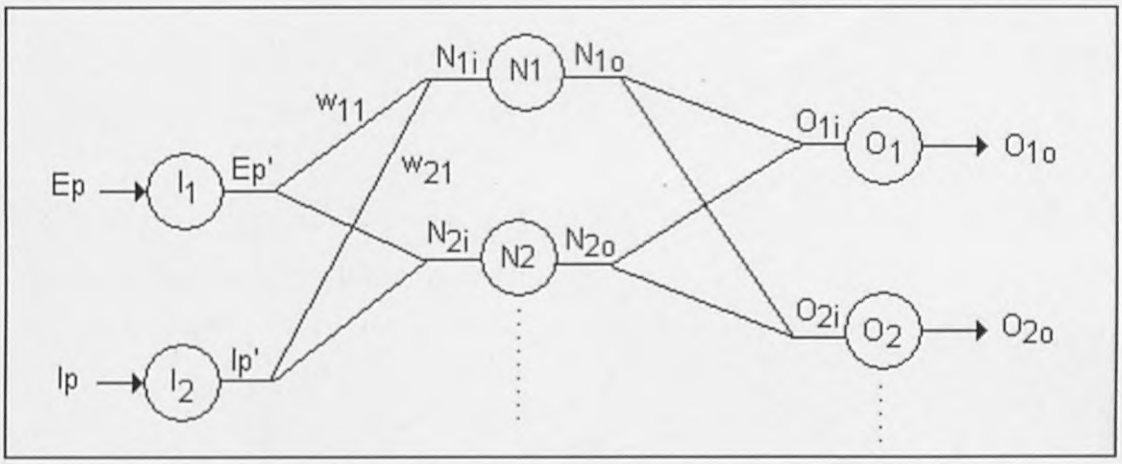


***Figure 4.8**: Neural network with three layers of neurons*

The hidden layer is defined by equations (4.4.a) and (4.4.b):

$$N1_i = (E_P' \times w_1) + (I_P' \times w_2) + bias_{N1} \qquad (4.4.a)$$

where, $N1_i$ is the input of the first neuron of the hidden layer and w_1 and w_2 are the weights.

$$N1_o = 1/(1 + e^{-N1_i}) \qquad (4.4.b)$$

where, $N1_o$ is the output of the first neuron of the hidden layer.

The output layer is defined by equation (4.5):

$$O1_o = \left[1/\left(1+e^{-O1_i}\right)\right] \times \left(\max_{O1} - \min_{O1}\right) + \min_{O1} \qquad (4.5)$$

where, $O1_o$ is the output of output layer neuron, max_{O1} is the maximum value of this output for ANN training and min_{O1} is the minimum value of this output for ANN training.

Since the weights, bias, max and min values are known after the ANN design, the next stage is to store these values into microcontroller memory. In addition, appropriate software was developed for the microcontroller which uses equations (4.3), (4.4) and (4.5) and all stored values (weights, bias, max and min) in order to obtain the output of the ANN for a given input pair (E_P, I_P).

Fig. 4.9 shows the flow chart of the operation of the electrochemical instrument for the identification of heavy metals by using a neural network.

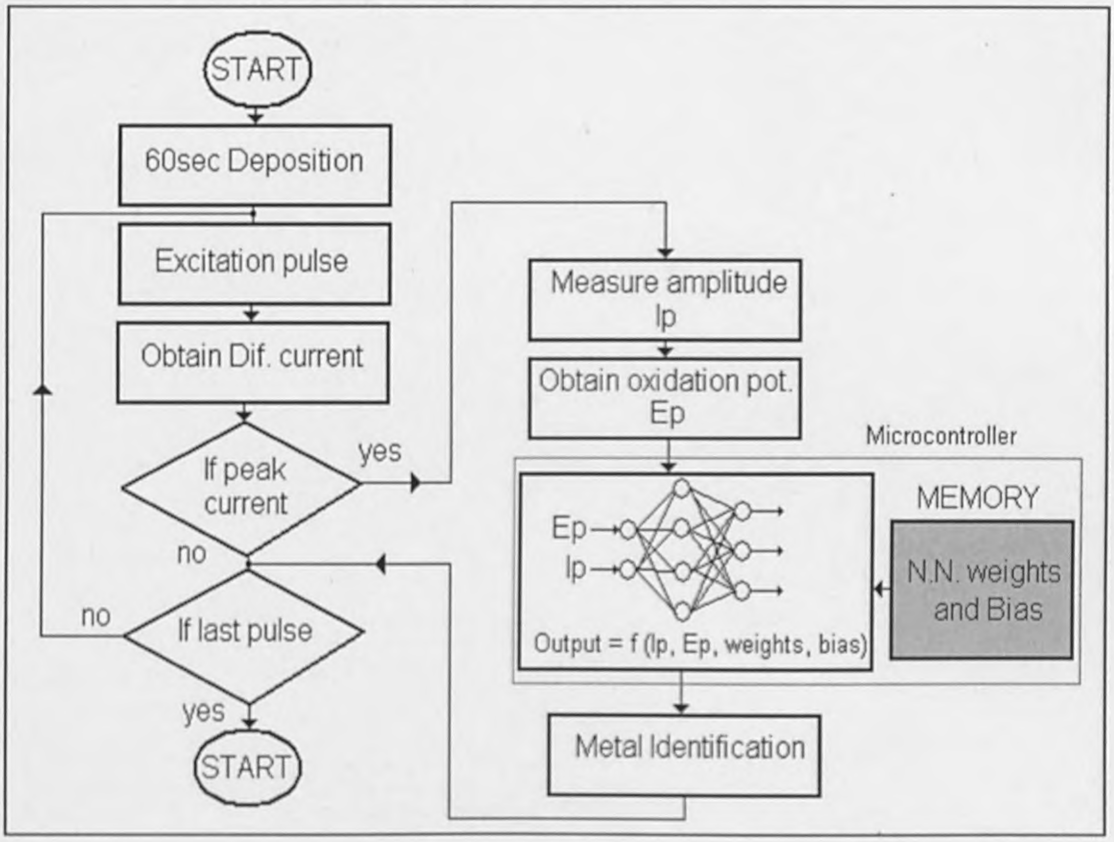


***Figure 4.9**: Flow chart of the operation of the electrochemical instrument for identification of heavy metals using a neural network.*

4.4.2 Development of the Artificial Neural Network

Test solutions of lead, cadmium, zinc, nickel, mercury and copper were prepared at different concentration levels in the range of 1 to 100 ppm. These six ions were chosen to be those for first examination due to their importance as environmental pollutants. The solutions were prepared using ionised water. The supporting electrolyte was 0.1 M sodium chloride (*NaCl*). The samples were placed in a sample reservoir with a 40 ml capacity. The pre-concentration time (deposition) was set to 60s at -1400 mV. The scanning voltage range used was from -1400 to +1000 mV, with step potential of 2 mV and pulse height of 25 mV; the scan rate was 120 ms and the pulse duration was 50 ms.

Thirty two independent measurements of the electrical potential and peak current amplitude of all six metals were recorded. The instrument was also connected to a personal computer, and the results were monitored for comparison with the values obtained from the liquid-crystal display.

The three-layer perceptron ANN was designed and trained using *"NS32NET"* ANN development software. Fig. 4.10 shows the configuration of the neural network.

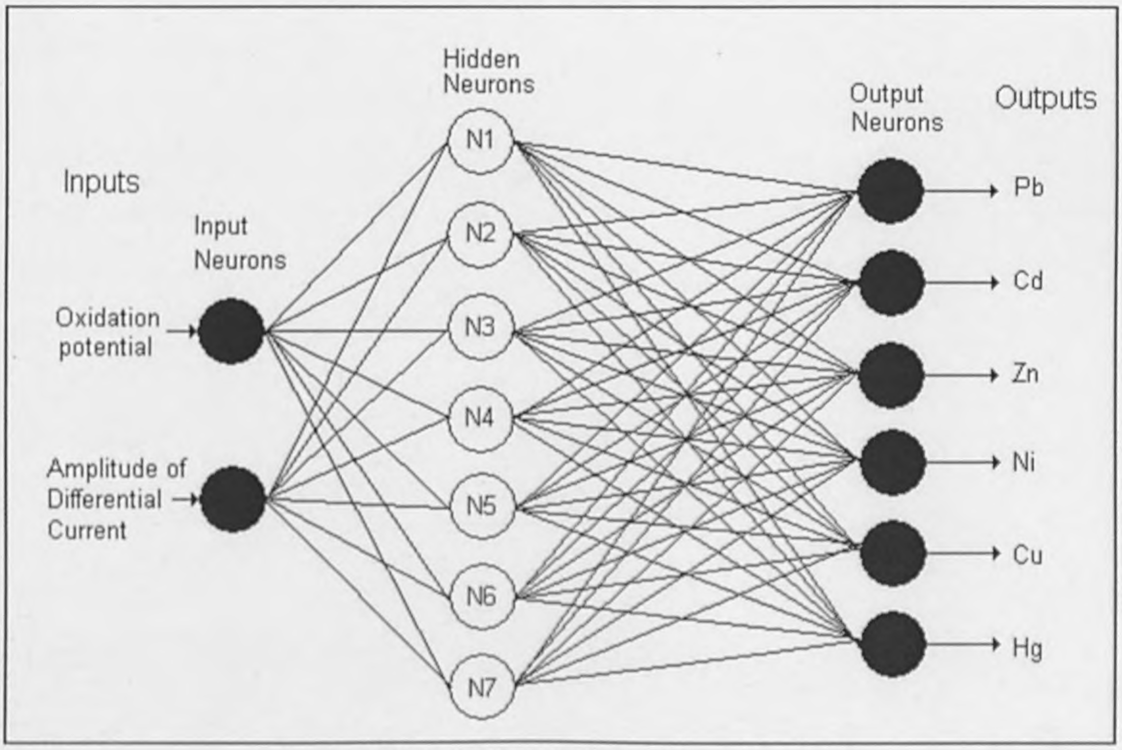


***Figure 4.10**: Configuration of the neural network*

Fig. 4.11 shows the variation of maximum, average, and minimum learning error during training. The training target was 0.012. The neural network reached the target error after 41,000 cycles.

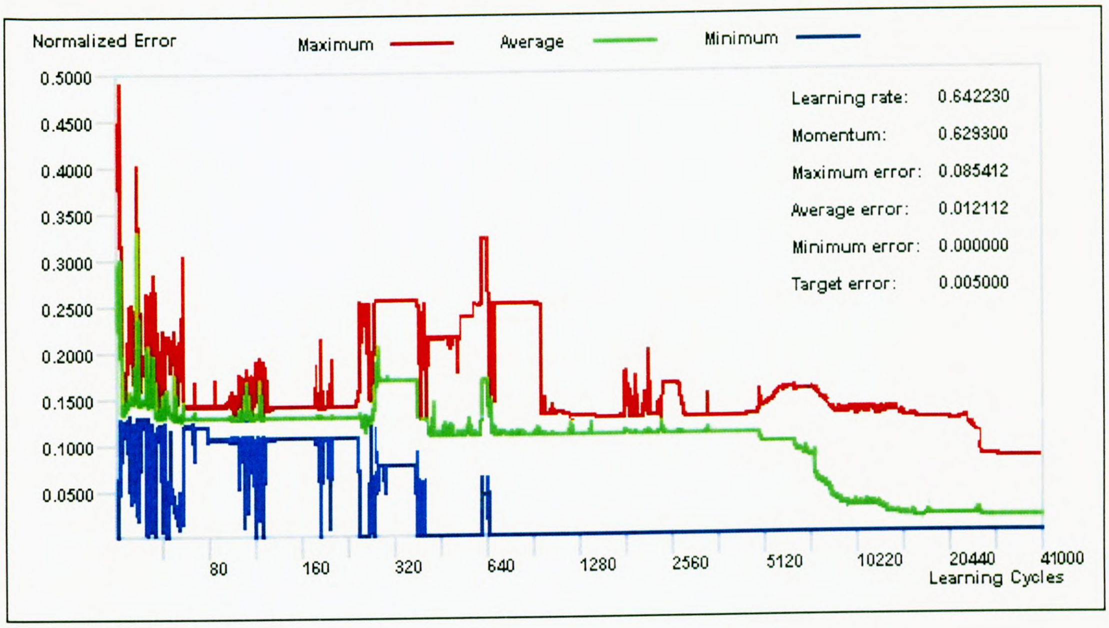


Figure 4.11*: Training error during neural network training.*

After training, all weights, bias, max and min values of each node of the ANN were obtained. The next stage of the design was to store these values into microcontroller memory. When an actual test is carried out, the peak current amplitude I_P and oxidation potential E_P of the voltammogram are first obtained. Using the I_P and E_P values and the stored weights and bias of each node, the microcontroller applies equations (4.3), (4.4) and (4.5) to obtain the outputs of the ANN, which indicate the presence of any of the six different heavy metals.

The probability of classification results, obtained from the application of the neural network, are given in Table 4.3.

Table 4.3*: Probability of classification*

Heavy Metal	Lead	Cadmium	Zinc	Nickel	Mercury	Copper
Probability [%]	100	100	100	89	100	92

As expected, lead, cadmium, zinc and mercury are classified with very good certainty (100%). For copper and nickel, the probability of identification was 92% and 89% respectively. This may be due to the network requiring refinement as it may be possible that it has converged with false minima. Such refinements would normally be carried out on a trial and error basis with parameters being gradually adjusted, but the type of software available did not allow such fine adjustments.

Chapter Five

Cartographical Mapping of Pollution

5.1. Introduction

A Global Positioning System (GPS) receiver has been added to the system. With the GPS, it is possible to store the exact geographical position of an assessed sample in the field. The GPS device is connected to the microcontroller via the serial port and uses the NEMEA GPS protocol. Geographical Information System (GIS) software has been developed which combines the pollutant results obtained by the analyser, the geographical position where the sample was taken and the map of the area of interest, so as to produce a cartographical presentation of the pollution of this area.

5.2 Global Positioning System - An overview

The Global Positioning System (GPS) is a satellite-based navigation system made up of a network of currently 27 satellites placed into orbit (approximately 20 km above earth's surface) by the U.S. Department of Defense[112,113]. It was originally intended for military applications, but in the 1980s, the government made the system available for civilian use. GPS satellites circle the earth twice a day in a very precise orbit and transmit signal information to earth. GPS receivers take this information and use triangulation to calculate the user's exact location[114]. Essentially, the GPS receiver compares the time a signal was transmitted by a satellite with the time it was received. The time difference tells the GPS receiver how far away the satellite is. With distance measurements from a few satellites, the receiver can determine the user's position and display it on the unit's electronic map.

GPS satellites transmit two low power radio signals (50 Watt or less), designated L1 and L2. Civilian GPS uses the L1 frequency of 1575.42 MHz in the UHF band. This signal contains three different bits of information, namely pseudorandom code, ephemeris data and almanac data[115,116]. The pseudo random code (PRN) is simply an I.D. code that identifies which satellite is transmitting information. Ephemeris data informs the receiver where each satellite should be at any time throughout the day. Each satellite transmits ephemeris data showing the orbital information for that satellite and for every other satellite in the system. Almanac data, which is constantly transmitted by each satellite, contains important information about the status of the satellite (healthy or unhealthy), current date and time. This part of the signal is essential for determining a position.

A GPS receiver must be locked on to the signal of at least three satellites to calculate latitude and longitude (two-dimensional position) and track movement. With four or more satellites in view, the receiver can determine the user's latitude, longitude and altitude (three-dimensional position)[117].

Each satellite transmits its current position x,y,x and its current time t. The message is received by a (station) GPS unit located at some unknown position X,Y,Z at a time $t+\Delta t$. Thus if the satellite transmits a signal at t=0 s and this signal is received 80 ms later at time $t+\Delta t$ = 80 ms, it follows that the receiver is at distance of $c\Delta t$ from the satellite, where c is the speed of light, i.e at a distance of 3×10^8 m/s $\times80\times10^{-3}$ s = 2.4×10^7 m. The satellites are equipped with highly stable clocks while each receiver has a less expensive quartz clock. This means that the clock on the receiver may run fast or slow. If fast by δt, it must subtracted from each of the Δt transit times to obtain the true transit time[118].

It is not difficult to show that three-dimensional navigation demands a minimum of four satellites. If their signalling positions are (x_1,y_1,z_1), (x_2,y_2,z_2), (x_3,y_3,z_3) and (x_4,y_4,z_4) and the measured signals $(\Delta t_1-\delta t)$, $(\Delta t_2-\delta t)$, $(\Delta t_3-\delta t)$ and $(\Delta t_4-\delta t)$, respectively (Fig.5.1), then:

$$(x_1-X)^2 + (y_1-Y)^2 + (z_1-Z)^2 = c^2 (\Delta t_1 - \delta t)^2 \quad (5.1)$$

$$(x_2-X)^2 + (y_2-Y)^2 + (z_2-Z)^2 = c^2 (\Delta t_2 - \delta t)^2 \quad (5.2)$$

$$(x_3-X)^2 + (y_3-Y)^2 + (z_3-Z)^2 = c^2 (\Delta t_3 - \delta t)^2 \quad (5.3)$$

$$(x_4-X)^2 + (y_4-Y)^2 + (z_4-Z)^2 = c^2 (\Delta t_4 - \delta t)^2 \quad (5.4)$$

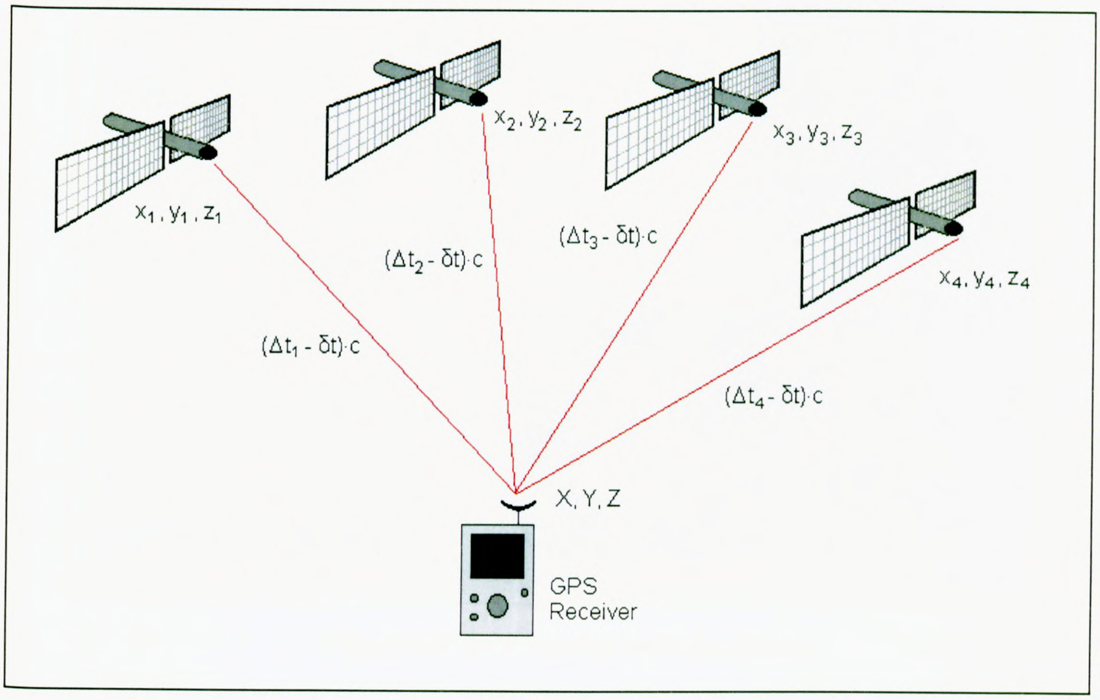


***Figure 5.1**: Calculating locations using GPS*

Once the user's position has been determined [geodetic latitude *(ϕ)*, longitude *(λ)* and altitude *(h)*], the GPS unit can calculate other information, such as speed, bearing, track, trip distance, distance to destination, sunrise and sunset times and more.

5.3 The Embedded GPS Receiver

This section deals with the use of an embedded GPS receiver, and the development of the appropriate hardware peripheral and software for its communication with the microcontroller of the electrochemical instrument.

5.3.1 Hardware Design

The Lassen SQ receiver[119] is ideal for this application because of its small size (2.5 x 2.5 cm), its low power consumption (100 mW at 3.3 V) and its compatibility with a small compact antenna (2.5 x 2.5 cm). Fig. 5.2 shows the GPS receiver with the small compact antenna.

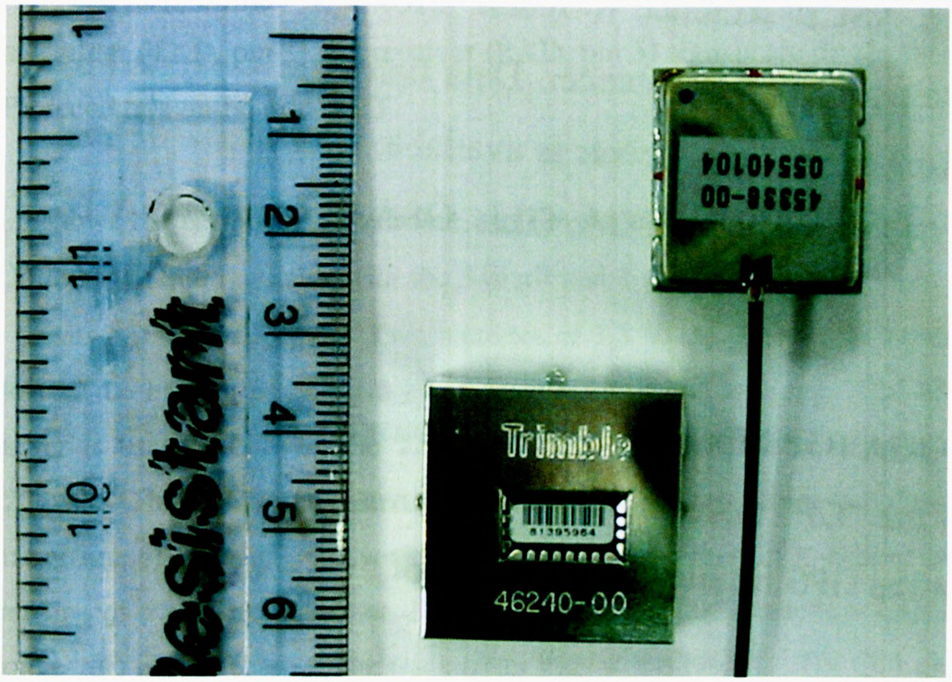


Figure 5.2: *GPS receiver with the antenna*

The receiver uses a single 8-pin (2 x 4) male header connector for both power and data I/O. The connector pin-out information is listed in table 5.1.

Table 5.1: *GPS receiver's connector signals*

Pin number	Function	Description
1	TXD A	Serial data transmit
2	GND	Ground, power signal
3	RXD A	Serial data receive
4	PPS	Pulse-per-second
5	Reserve	Not connected
6	Reserve	Not connected
7	VCC (Prime Power)	+3.0 V to 3.3 V
8	Battery backup power	+2.5 V to +3.6 V

The receiver requires +3.3 V power supply which is supplied through pin 7 (VCC) of the I/O connector. A 3 V backup battery (supplied through pin 8) is used to keep the module's RAM memory alive and to power the real-time clock when the receiver's prime power is turned off. The RAM memory is used to store the GPS almanac, ephemeris and last position. The receiver provides direct CMOS/TTL level serial I/O. The transmitter (TXD, pin 1) and receiver (RXD, pin 3) signals are driven directly by the GPS receiver's on-board UART.

Fig. 5.3 shows the peripheral circuit that was developed to support the GPS receiver. The LM7803 voltage regulator with the 330 nF and 1 μF capacitors provides +3.0 V to the power primer (VCC pin). Two batteries of 1.5 V each connected in series are used to provide backup power (pin 8) to the internal RAM memory. The MAX232 line driver is used to convert the TXD and RXD CMOS/TTL level serial data to RS232 levels. The receiver is connected to a microcontroller via the serial port. The transmitter line of the GPS receiver (pin 2 of the D-9 connector) is connected to the receiver line of the microcontroller UART device and the receiver line (pin 3 of the D-9 connector) is connected to the transmitter line of the UART. The D-9 connector can also be used to connect the GPS unit with a PC using a serial RS232 (three-wire) cable. A datasheet with all technical information of the MAX232 line driver is given in Appendix D.12.

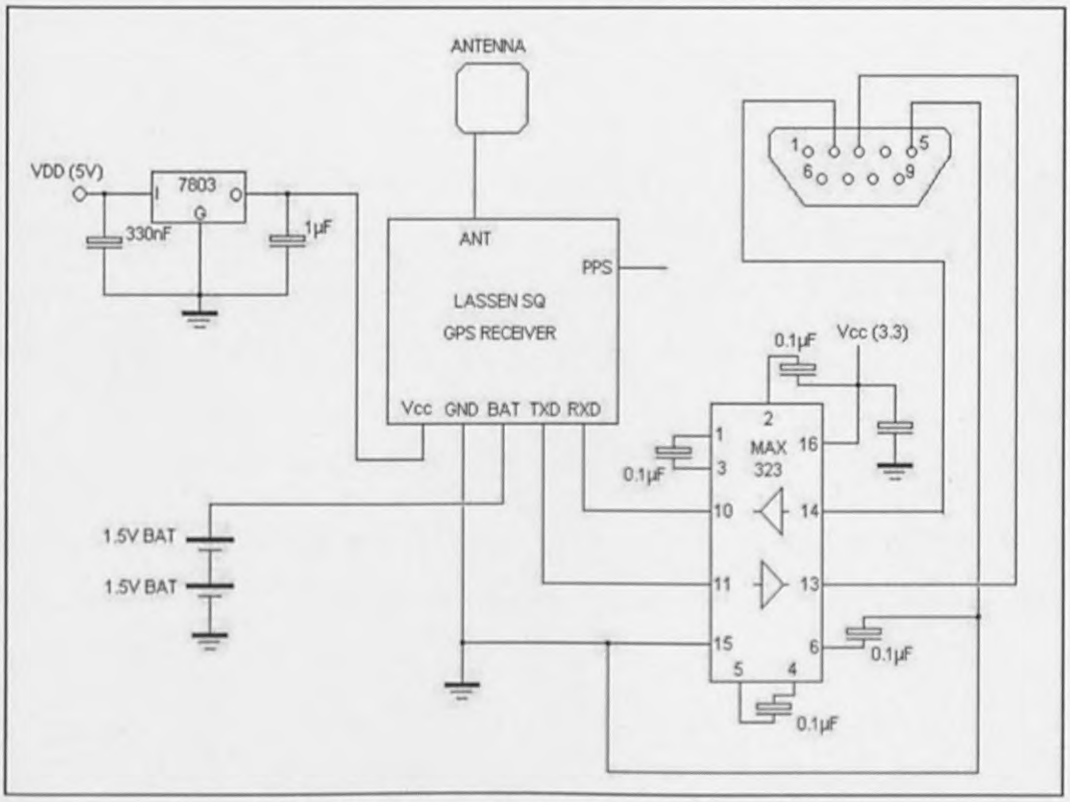


Figure 5.3: Circuit diagram of the graphical position system

5.3.2 Communication Protocol

The Lassen SQ GPS receiver uses the National Marine Electronics Association (NMEA 0183) protocol[119] which is an industry standard. NEMEA allows a single source to transmit serial data over a single twisted wire pair to one or more receivers. Table 5.2 lists the standard characteristics of the data transmission.

***Table 5.2**: NEMEA 0183 standard characteristics*

Signal Characteristic	NEMEA Standard
Baud Rate	4800
Data bits	8
Parity	None
Stop bits	1

NMEA data is output in standard ASCII sentence format. Message identifiers are used to signify what data is contained in each sentence, with data fields being separated by commas. The Lassen SQ receiver is available with firmware that supports a subset of the NMEA 0183 messages: GGA, GLL, GSA, GSV, RMC, VTC and ZDA.

For the current application the GGA (GPS fix data) message is used. This message is sent at 1 second intervals with the "GP" talker ID and checksums and includes time, position and fix related data for the GPS receiver. The format of the GGA message is listed below:

```
$GPGGA,time,latitude,longitude,quality,satellites,dilution,altitude,checksum
```

The operation of the GPS receiver was examined using the HYPERTERMINAL monitor program. When the receiver was powered up the data displayed on the PC monitor was as listed below:

```
$GPGGA,,,,0,00,,,,0
```

After approximately 2 minutes the receiver was able to connect with four different satellites and was able to obtain its geographical position. The data displayed on the PC monitor was as listed below:

```
$GPGGA,122223.02,5708.560,N,00206.080,W,1,04,1.1,56.9,M,0238*0B
```

Software was developed for the microcontroller to read the GGA ASCII data of the GPS receiver and extract the latitude and longitude. Fig. 5.4 shows the algorithm of this process.

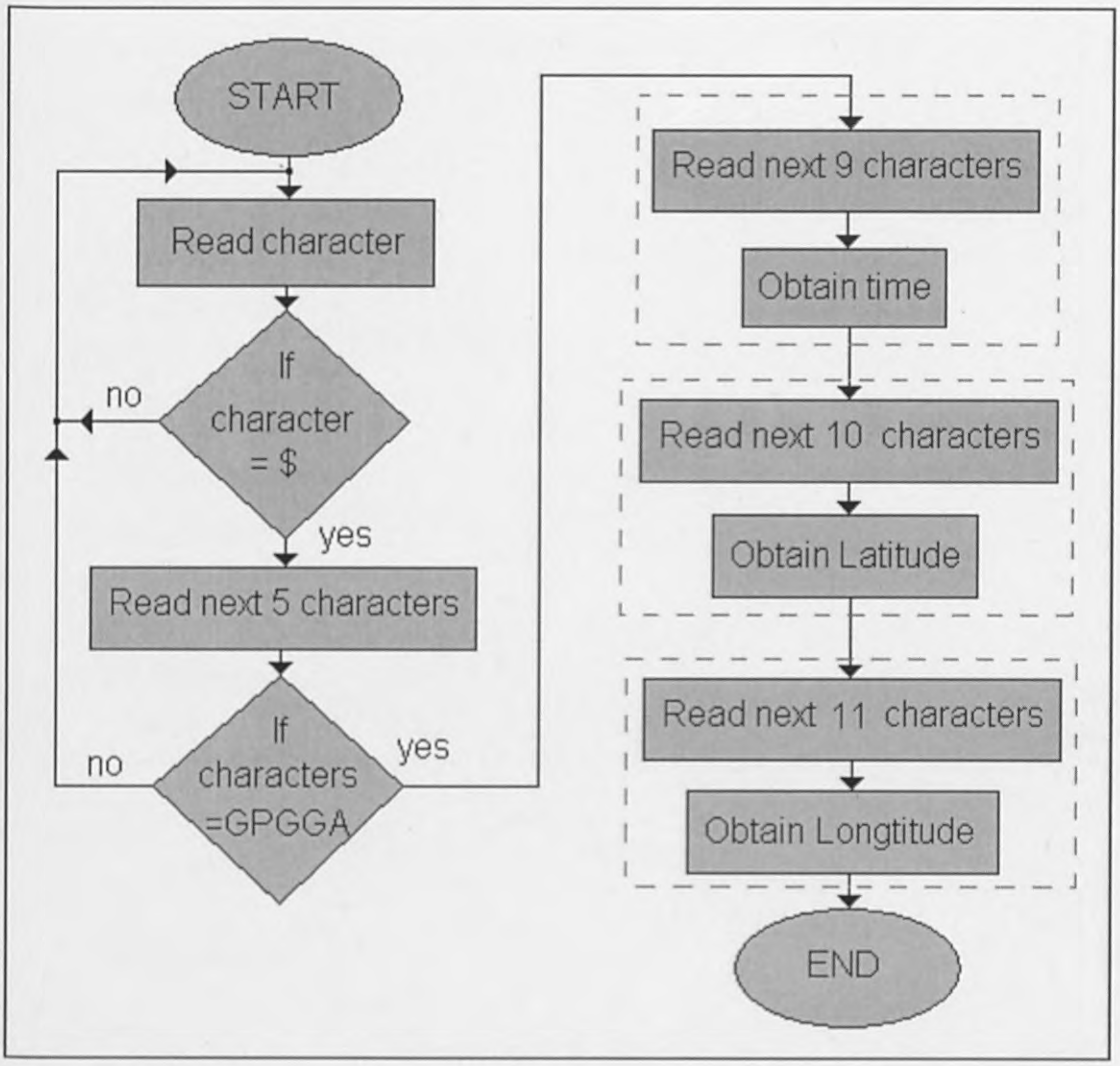


Figure 5.4: Extraction of latitude and longitude data from CGA message.

5.4 The Pollution-Mapping Software

This section deals with the development of the GIS software[120,121] to produce a map on which can be fixed sites of heavy metal pollution. The software combines the pollution results obtained by the analyser, the geographical position of the assessed sample and the map of the assessed area, so as to produce a cartographical presentation of the pollution of the area. The approach is shown in Fig. 5.5. This approach involves four main tasks as follows:

1. Map rasterising[122,123]
2. Correlation of rasterised map with GPS coordinates
3. Database of heavy metal pollution
4. Display of polluted area[124]

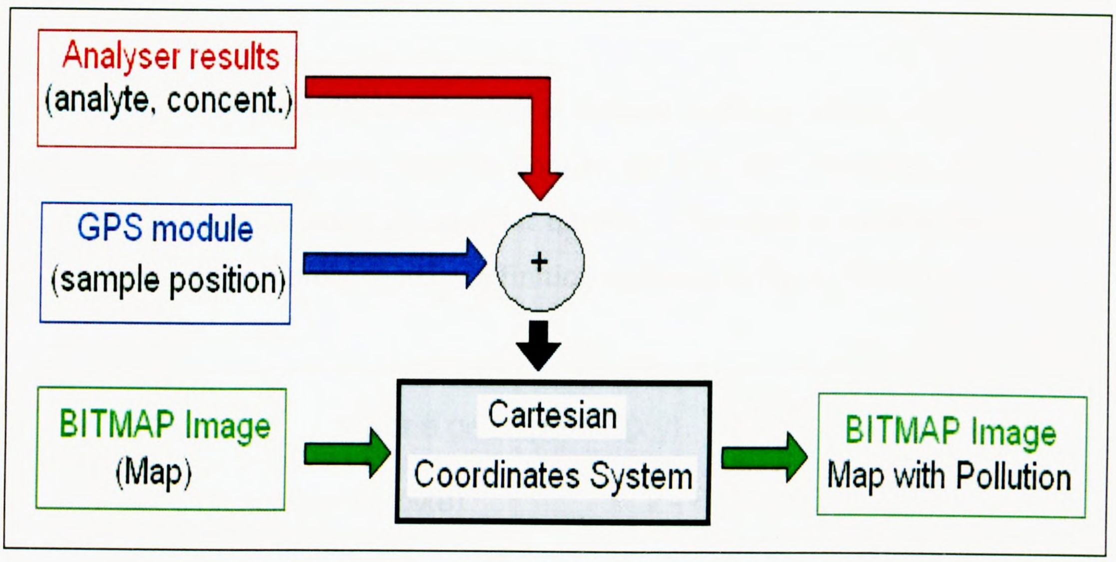


***Figure 5.5**: Pollution mapping - approach*

5.4.1 Map Rasterising

The map of the area under investigation is digitised and stored as a bitmap file. The map in digital form is represented by a two-dimensional array (raster) of size *NxM* number of pixels (Fig. 5.6).

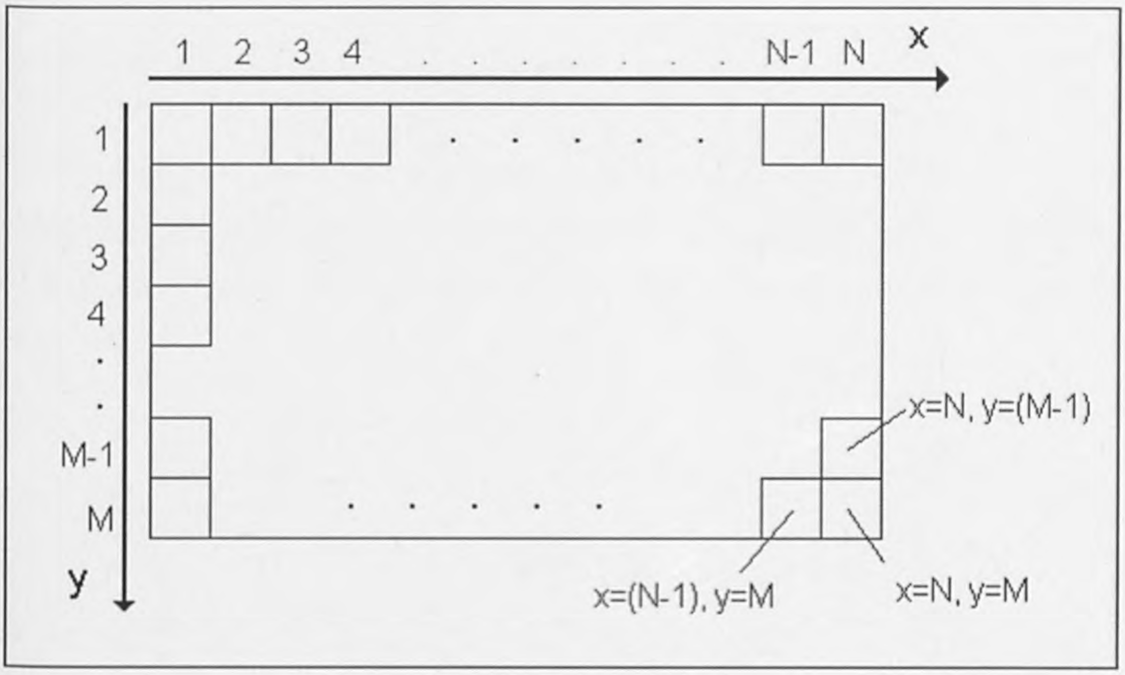


Figure 5.6: Digital image of NxM pixels

The position of a pixel (P) in the raster is defined as ($P_{x,y}$), where, $x=1,2,3...N$, and $y=1,2,3...M$. The maximum value for both M and N is 255. Therefore, both x and y numbers can be represented by an 8 bit number. The pixel's identification number (P_{ID}) is thus a 16 bit number and its definition is shown in Fig. 5.7 below:

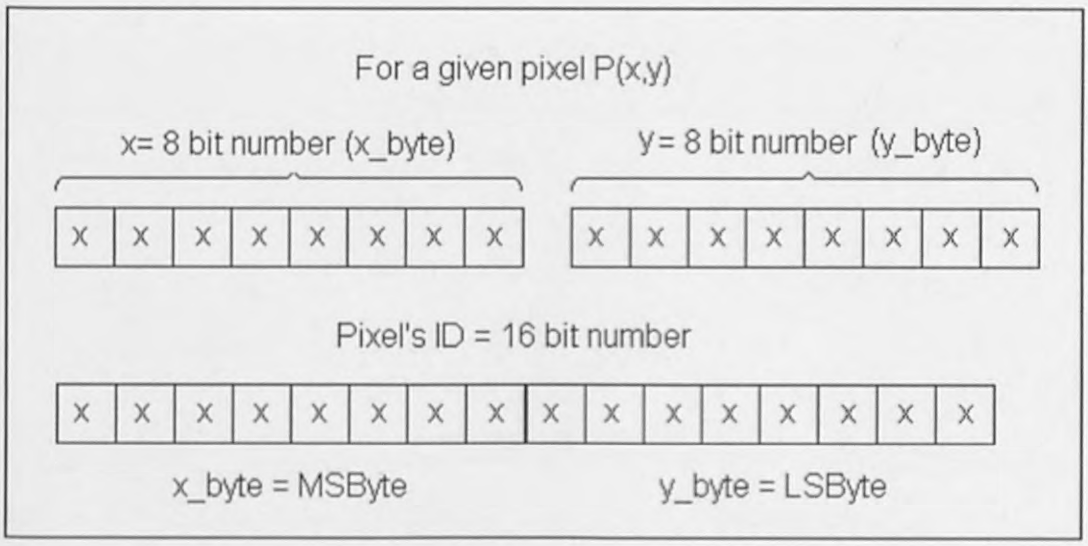


Figure 5.7: Pixel's ID number

This number is unique for every pixel in the image. The first pixel of the digital map is called base pixel P_B (where, $P_B = P(x, y)\big|_{x=1, y=1}$). The P_{ID} number of the base pixel is $257_{(10)}$ or $0101_{(hex)}$.

The graphic scale (Fs) of the digital map is defined as the ratio of a distance on the displayed map (A_M) to the corresponding distance on the ground (Av). The graphical size of a pixel (R_{xy}) is defined by the number of pixels of the image (NxM) over A_v (Fig. 5.8).

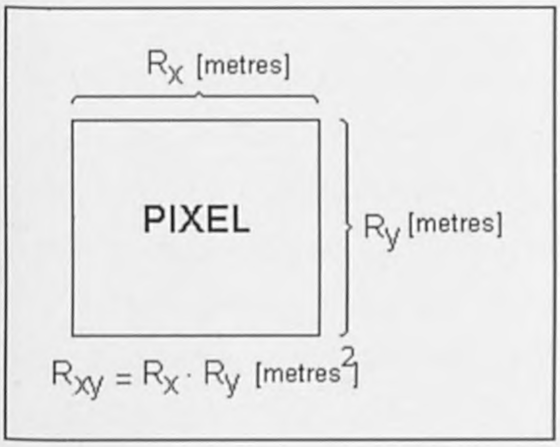


Figure 5.8*: Pixel's virtual size in metres*

5.4.2 Correlation of Rasterised Map with the GPS Coordinates

When a test is carried out in the field, the GPS receiver will obtain the geographical position (latitude and longitude) of the assessed sample. The differential latitude ($\Delta\phi$) and differential longitude ($\Delta\lambda$) are obtained from equations 5.8(a) and (b), thus:

$$\Delta\phi = \phi_s - \phi_o \quad (5.8a)$$

$$\Delta\lambda = \lambda_s - \lambda_o \quad (5.8b)$$

Where, ϕ_s is the latitude of the sample, ϕ_o is the latitude of the base pixel, λ_s is the longitude of the sample, and λ_o is the longitude of the base pixel.

The position (x,y) of the pixel $P(x,y)$ in the digital map related to the geographical position obtained by the GPS unit, can be calculated thus:

$$x = \Delta x' \, [m] \, / \, R_x \, [m] \tag{5.9a}$$

$$y = \Delta y' \, [m] \, / \, R_y \, [m] \tag{5.9b}$$

Where, $\Delta x'$ and $\Delta y'$ are the $\Delta\lambda$ and $\Delta\phi$ values in metres, and R_x and R_y define the geographical size of the pixel as shown in Fig. 5.8. By calculating the x and y co-ordinates of the pixel, its identification number P_{ID} can be obtained (Fig. 5.7).

5.4.3 Database of Heavy Metal Pollution

When a pixel of the digital map (consistent with GPS data) has been identified and its P_{ID} number is known, the user can add all appropriate heavy metal pollution-related information of this geographical point by referring it to the pixel's P_{ID} number. Table 5.3 shows the heavy metal pollution (database) created for an area under assessment. The database at the present stage has 12 fields, six for each metal and six for their concentration state. In future more fields can be added in the database for storing more information.

***Table 5.3**: Database of an assessed area.*

Pixel ID	Pb	Con. [ppm]	Cd	Con. [ppm]	Zn	Con. [ppm]	Hg	Con. [ppm]	Ni	Con. [ppm]	Cu	Con. [ppm]
$0112_{(hex)}$	yes	12	no	0	no	0	No	0	no	0	no	0
$0113_{(hex)}$	yes	14	no	0	no	0	No	0	no	0	no	0
$0114_{(hex)}$	yes	15	no	0	no	0	No	0	no	0	no	0
$0115_{(hex)}$	yes	14	no	0	no	0	No	0	no	0	no	0

5.4.4 Display of Polluted Area

The user using the database is able to plot the map of the assessed area and to display any information from the database. For example, a map might show the presence of lead pollutant with green colour (dark green low concentration, light green high concentration), and the presence of other heavy metals with other colour scales.

Fig. 5.9 shows an example of a cartographical mapping of heavy metal pollution of an assessed area (Aberdeen centre, Robert Gordon University). The green colour represents "NO" pollution and the black colour is pollution. As can be seen from this figure there is no heavy metal pollution in the database therefore there is no black area visible on the map.

Figure 5.9: *Example of a cartographical mapping of heavy metal pollution of an area under test.*

Chapter Six

Measurements

6.1 Introduction

This section deals with test analyses of soil and aqueous samples. The investigations were carried out using the portable analyser and the two different (glassy carbon and screen printed) electrochemical sensors with their new supporting plastic cartridges. All sample tests were carried out in the laboratory in ideal conditions.

6.2 Procedure for Analysing Soil and Aquatic Samples

Analysis Approach for Aquatic Samples

Fig. 6.1 illustrates the steps used for the analysis of aqueous samples. The analysis process consists of two phases, namely, sample pre-treatment and sample analysis.

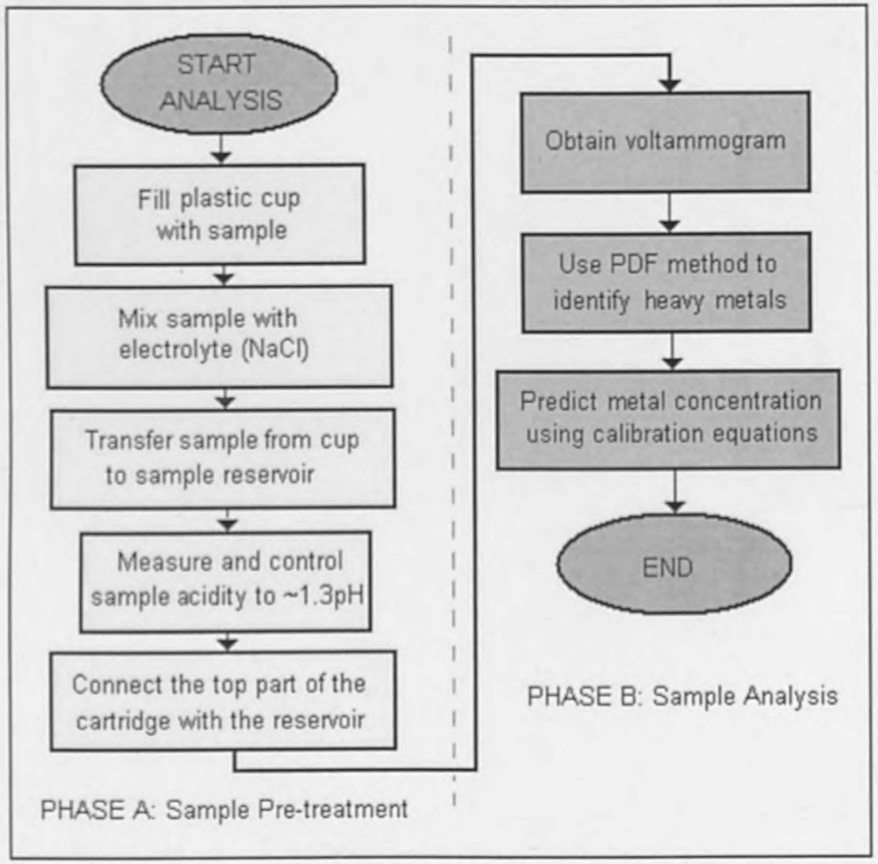


Figure 6.1: Steps in the analysis of aqueous sample

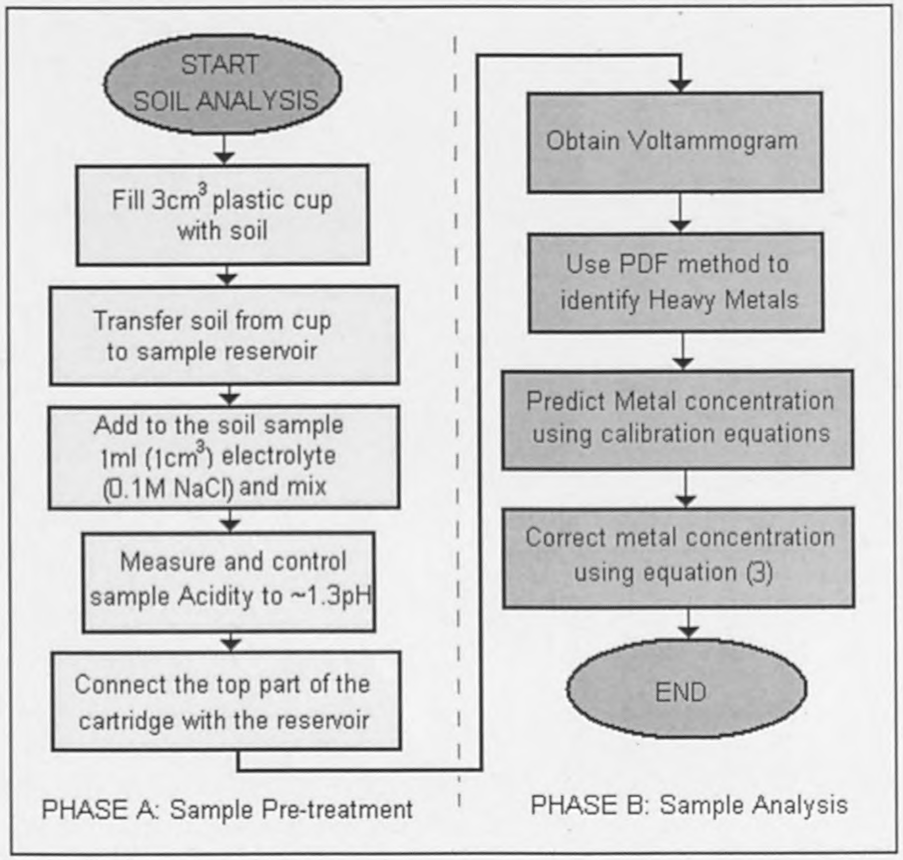


Figure 6.2: Steps in the analysis of a soil sample

Fig. 6.2 illustrates the steps used for the analysis of soil samples. The analysis process consists of two phases, namely, sample pre-treatment and sample analysis.

Using the procedure shown in Fig. 6.2 for soil analysis, the concentrations of metals will be changed (diluted) with the extra addition of supporting electrolyte by a factor C_e, such as:

$$C_e = V_{sample} / (V_{sample} + V_{electrolyte}) \quad (6.1)$$

Where, V_{sample} is the volume of the soil sample in cm^3 and $V_{electrolyte}$ is the volume of the electrolyte in cm^3. Therefore, in order to predict the real concentration of metals a correction equation needs to be used such as:

$$C_M' = C_M \times (1 / C_e) \quad (6.2)$$

where, C_M' is the corrected metal concentration, and C_M is the concentration of a metal (M) obtain by the system before correction.

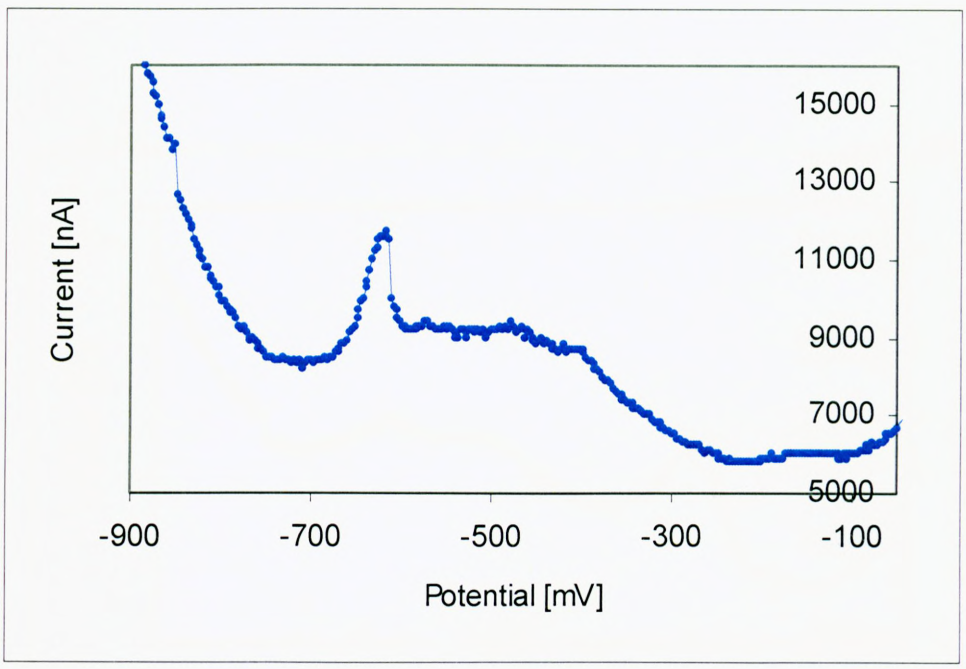
6.3 Analysis of Aqueous Samples

Test solutions of lead, cadmium, zinc, copper, nickel and mercury were prepared at different concentration levels in the range of 250 ppb to 50 ppm. The six ions selected for examination were chosen due to their importance as environmental pollutants. These solutions were diluted from a commercially available standard solution (1000 ppm in 1 M Nitric Acid). The solutions were prepared using de-ionised water with a supporting electrolyte of 0.1 M sodium chloride (*NaCl)*. The pre-concentration (deposition) time was 60sec at -1400 mV potential. The scanning voltage range used was from -1400 to +1000 mV, with step potential of 2 mV, pulse height of 25 mV, with a scan rate of 120 ms and pulse duration of 50 ms. The acidity for test samples was 1.35 pH.

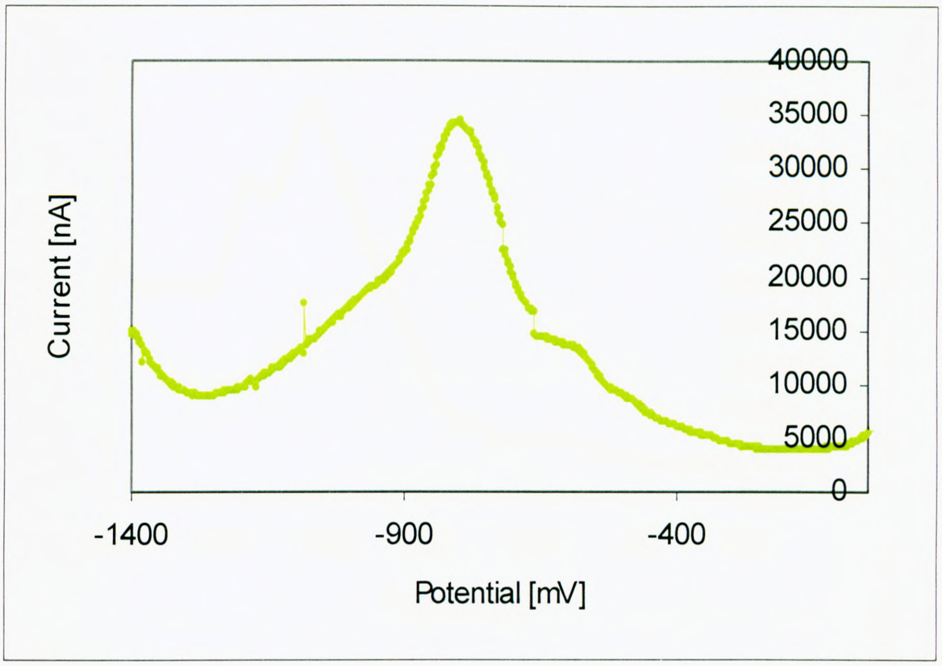
Thirty two independent measurements of the electrical potential and peak amplitude of all six metals were recorded. The instrument was also connected to a personal computer, and the results were monitored for comparison with the values obtained from the liquid-crystal display. This procedure was carried out using both the glassy carbon and screen printed electrochemical sensors.

6.3.1 Sensitivity

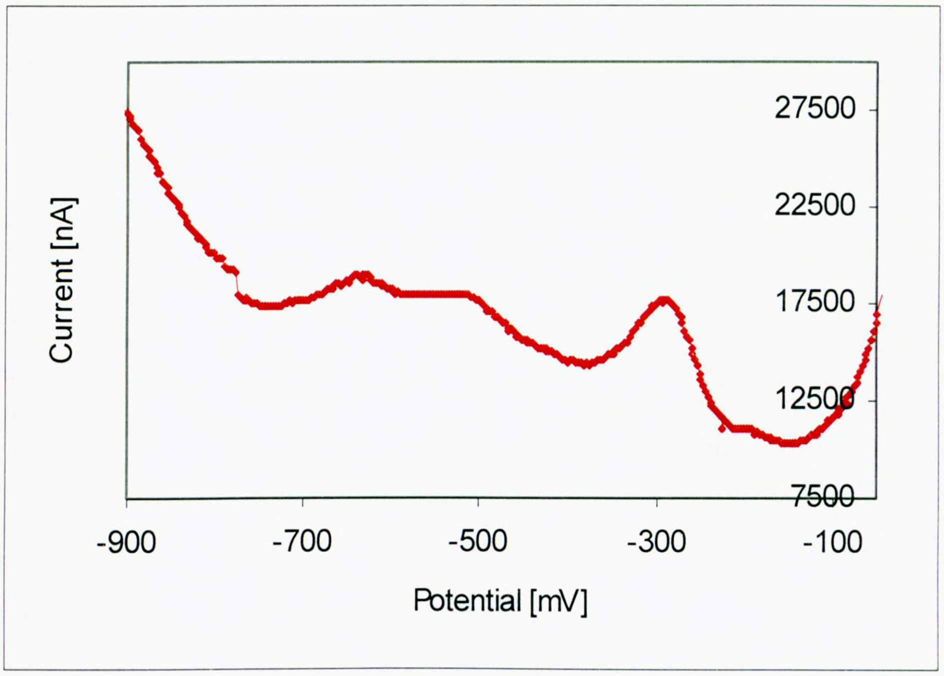
It was found that the lowest possible concentrations of metals that can be detected by the instrument using the screen printed sensor are 1 ppm for Lead(II), 1 ppm for Cadmium(II), 3 ppm for Zinc(II), 1 ppm for Copper(II), 2 ppm for Nickel(II) and 3 ppm for Mercury(II). Fig. 6.3 shows the differential-current voltammogram using the screen printed sensor for each of the above metals at their lower detectable concentration level.



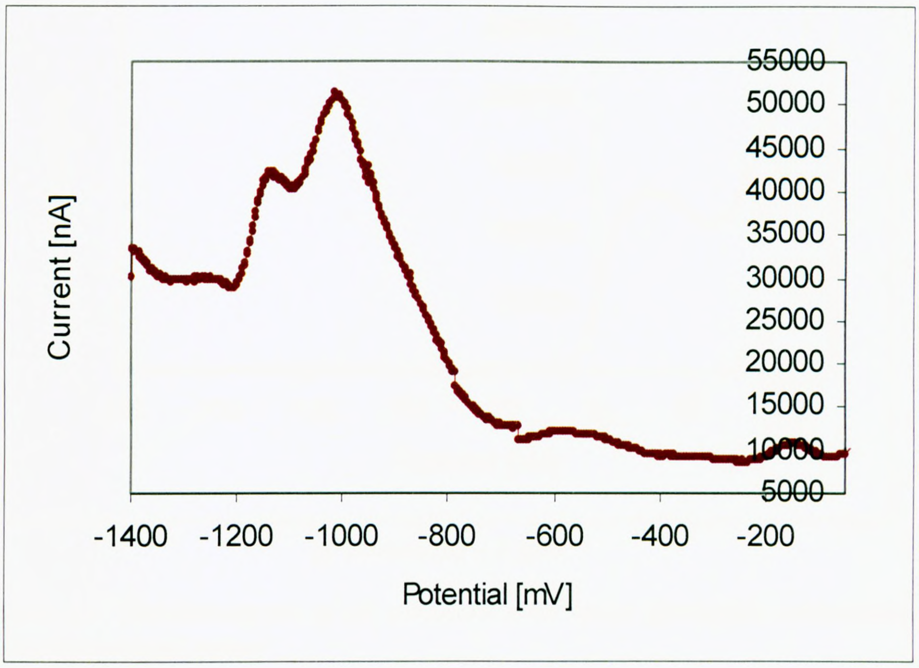
(a) Lead(II) – 1 ppm



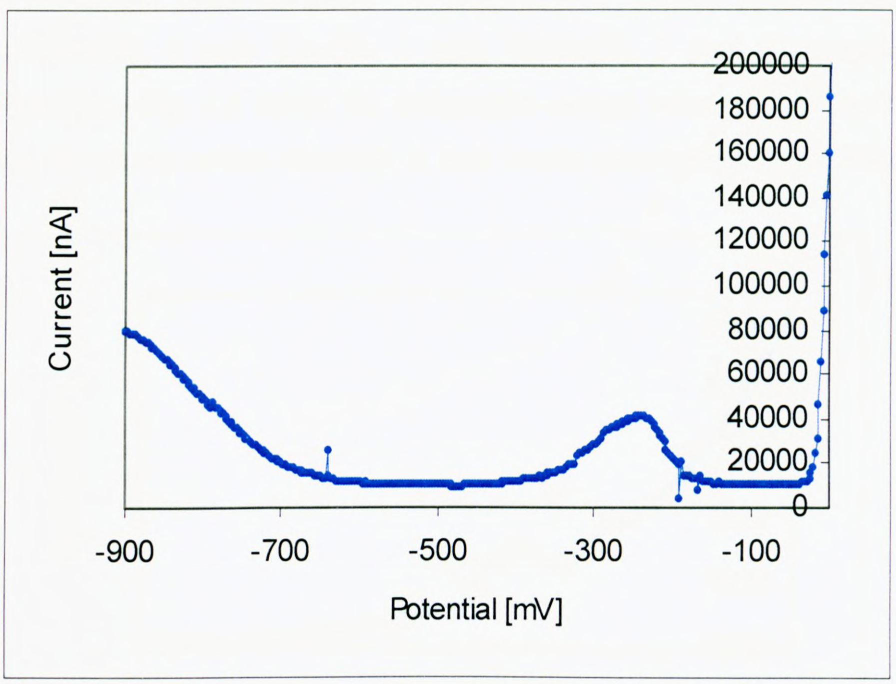
(b) Cadmium(II) – 2 ppm



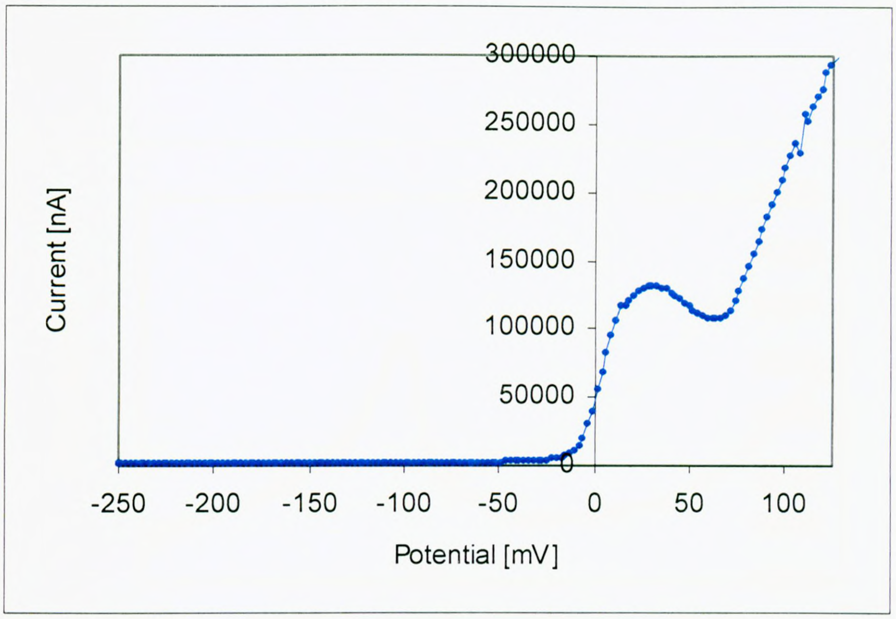
(c) Copper (II) – 1 ppm



(d) Zinc(II) – 3 ppm



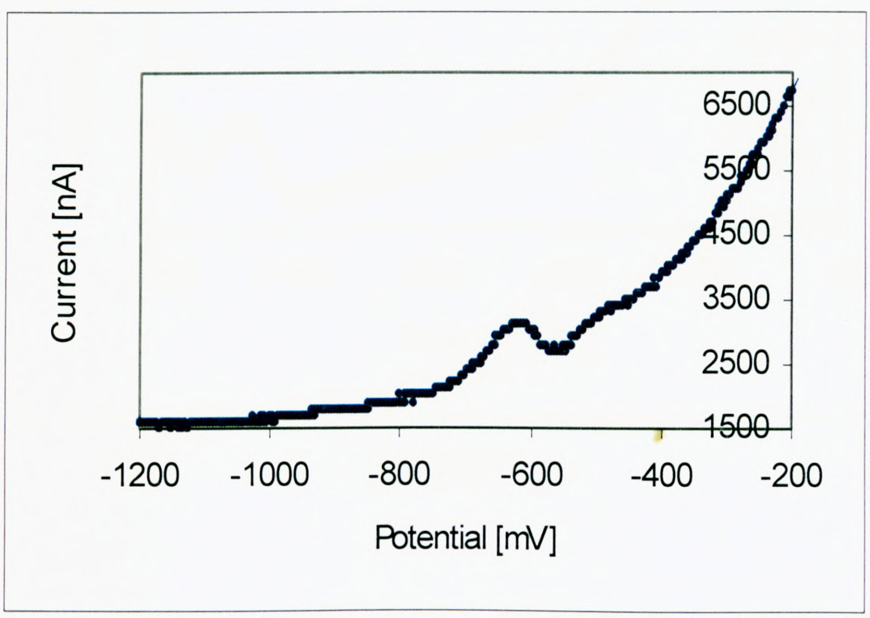
(e) Nickel(II) – 2 ppm



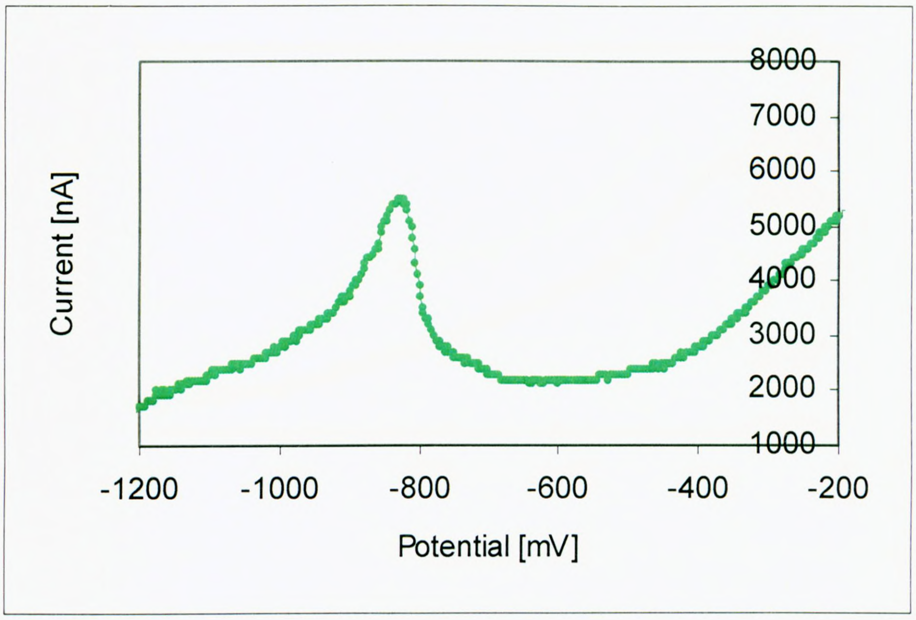
(f) Mercury(II) – 3 ppm

Figure 6.3: *Voltammogram of six metals at their lower detectable concentration level using the screen printed sensor*

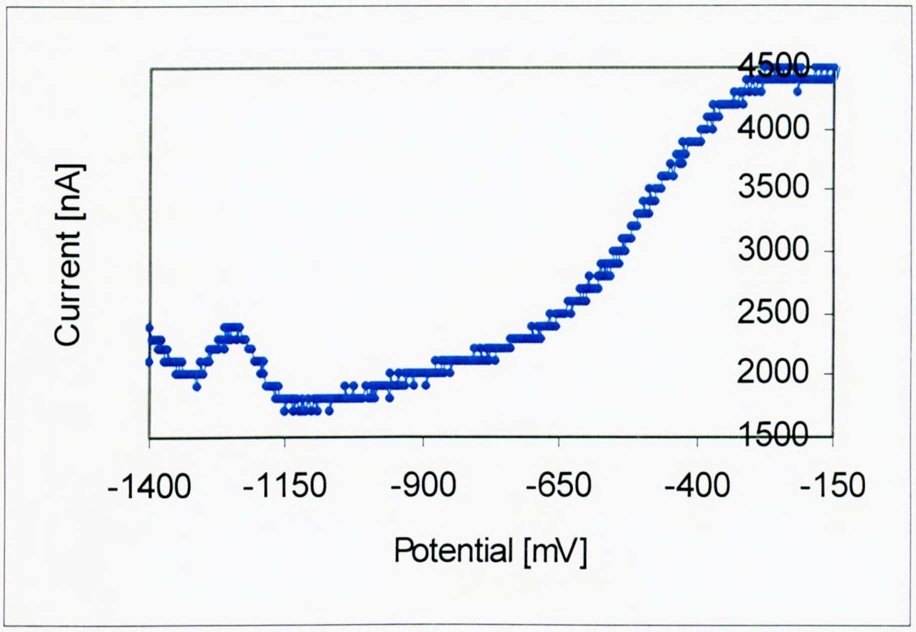
It was found that the lower possible concentrations of metals that can be detected by the instrument using the glassy carbon electrode are 500 ppb for Lead(II), 750 ppb Cadmium(II), 2 ppm Zinc(II), 1 ppm Nickel(II), 2 ppm Mercury(II) and 2 ppm Copper(II). Fig. 6.4 shows the differential-current voltammograms of all six metals using the glassy carbon electrode at their lowest possible detectable concentration.



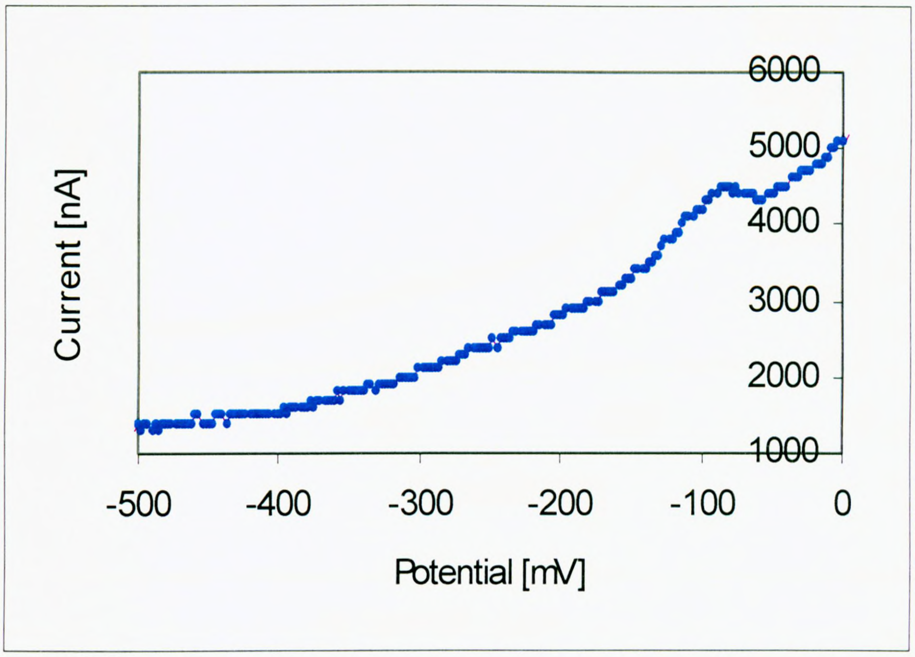
(a) Lead(II) – 500 ppb



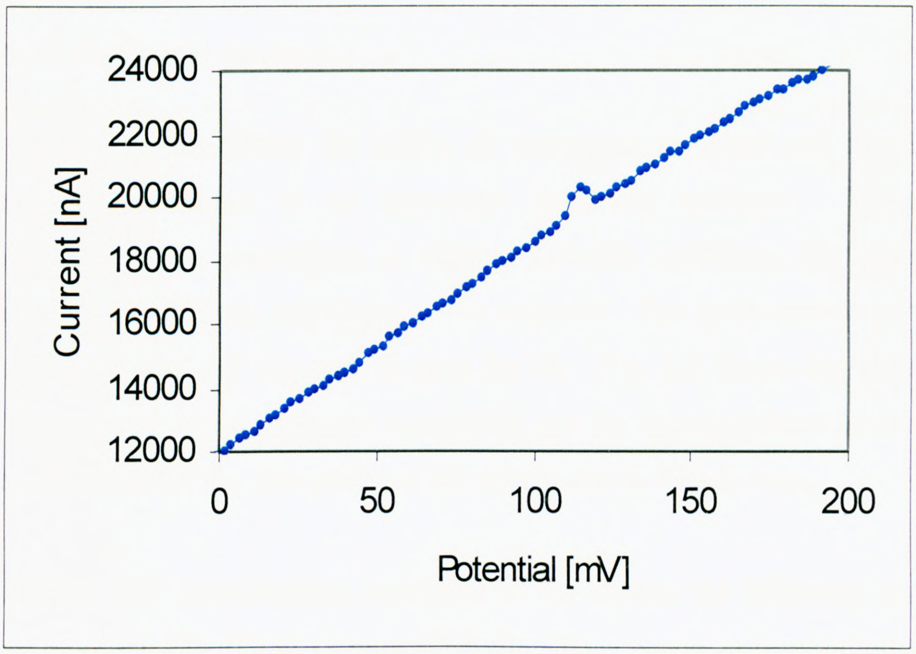
(b) Cadmium(II) – 750 ppb



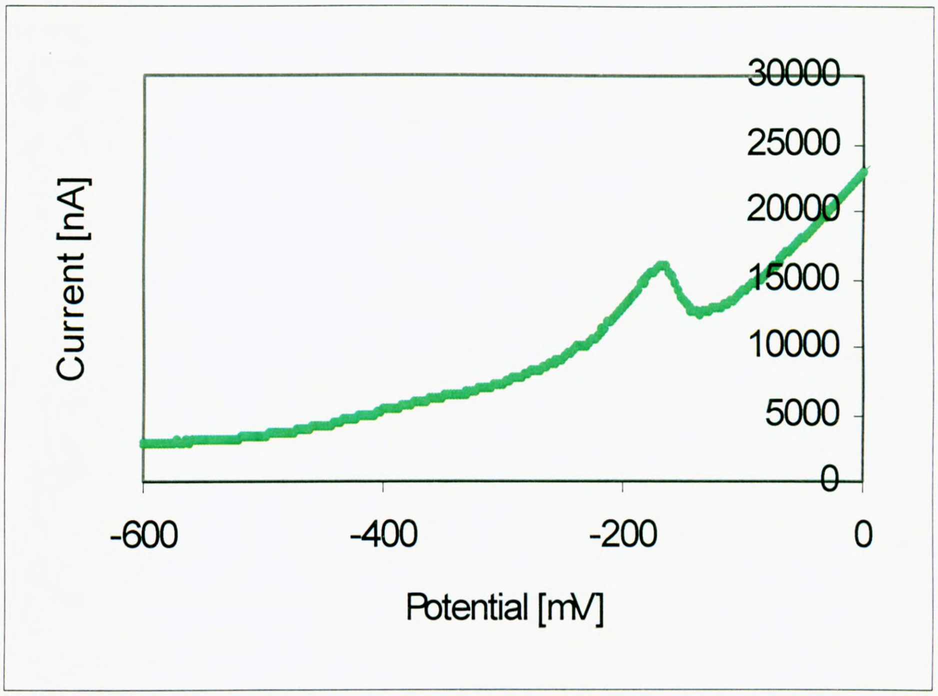
(c)Zinc(II) – 2 ppm



(d) Nickel(II) – 1 ppm



(e) Mercury(II) – 2 ppm



(b) Copper(II) – 2 ppm

***Figure 6.4**: Differential-current voltammogram of six metals at lower possible detectable concentration using the glassy carbon sensor*

6.3.2 Multi-Metal Analysis

In addition to sensitivity, the ability of instrument to detect and identify metals in multi-metal mixtures is an extremely important attribute. This ability was investigated in an experiment in which a solution containing four different metals, Zinc, Lead, Cadmium, and Copper, was prepared. The concentration of metals was 5 ppm for *Pb*, *Cd* and *Cu*, and 10 ppm for *Zn*. Fig. 6.5 shows the differential pulse voltammogram taken using the instrument and the screen printed sensor. As can be seen from Fig.6.5 the four peaks of the metals can be clearly seen.

Using the PDF identification algorithm of the system the following results (metals) were reported: Zinc(II) at 12 ppm, Cadmium(II) at 4 ppm concentration, Lead(II) at 6 ppm concentration and Copper(II) at 3 ppm concentration. The four metals have been easily identified by the instrument and their concentration has been obtained with maximum error of 2 ppm.

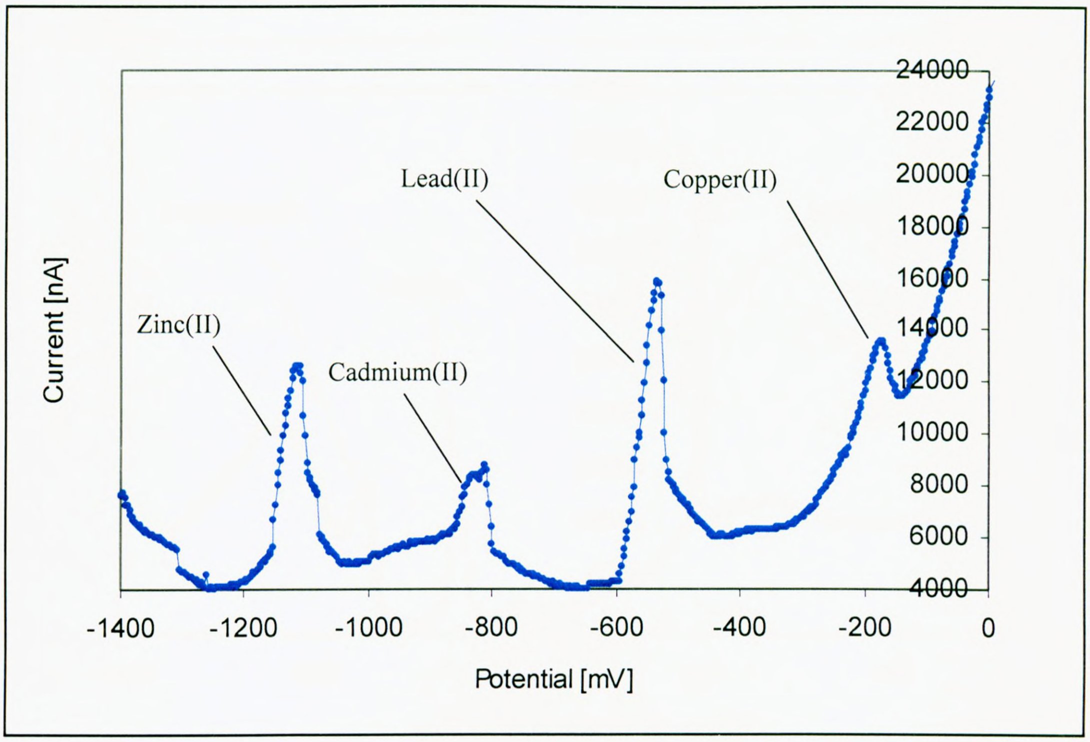


Figure 6.5: *Voltammogram for a solution with a multi-metal mixture containing Lead, Cadmium, Copper at 5 ppm and Zinc at 10 ppm.*

Another solution was prepared, containing three different metals, Lead, Cadmium, and Mercury. The concentration of all three metals was 10 ppm. Fig. 6.6 shows the differential pulse voltammogram obtained using the instrument and the glassy carbon electrode. As can be seen from the figure, a peak corresponding to each of the three metals can be clearly seen. Using the system's PDF identification algorithm, the following results were reported: Cadmium(II) at 12 ppm concentration, Lead(II) at 7 ppm concentration and Mercury(II) at 13 ppm concentration. In summary, it was found that the three metals were clearly identified by the instrument and their concentrations were reported with a maximum error of 3 ppm.

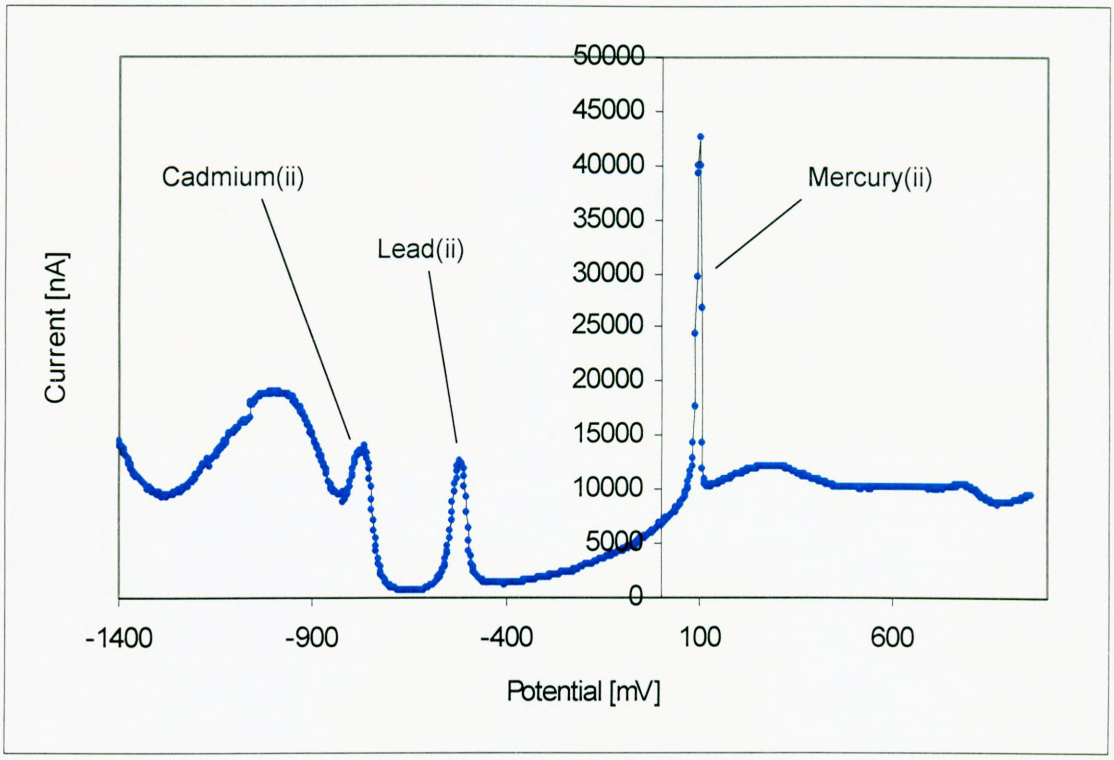
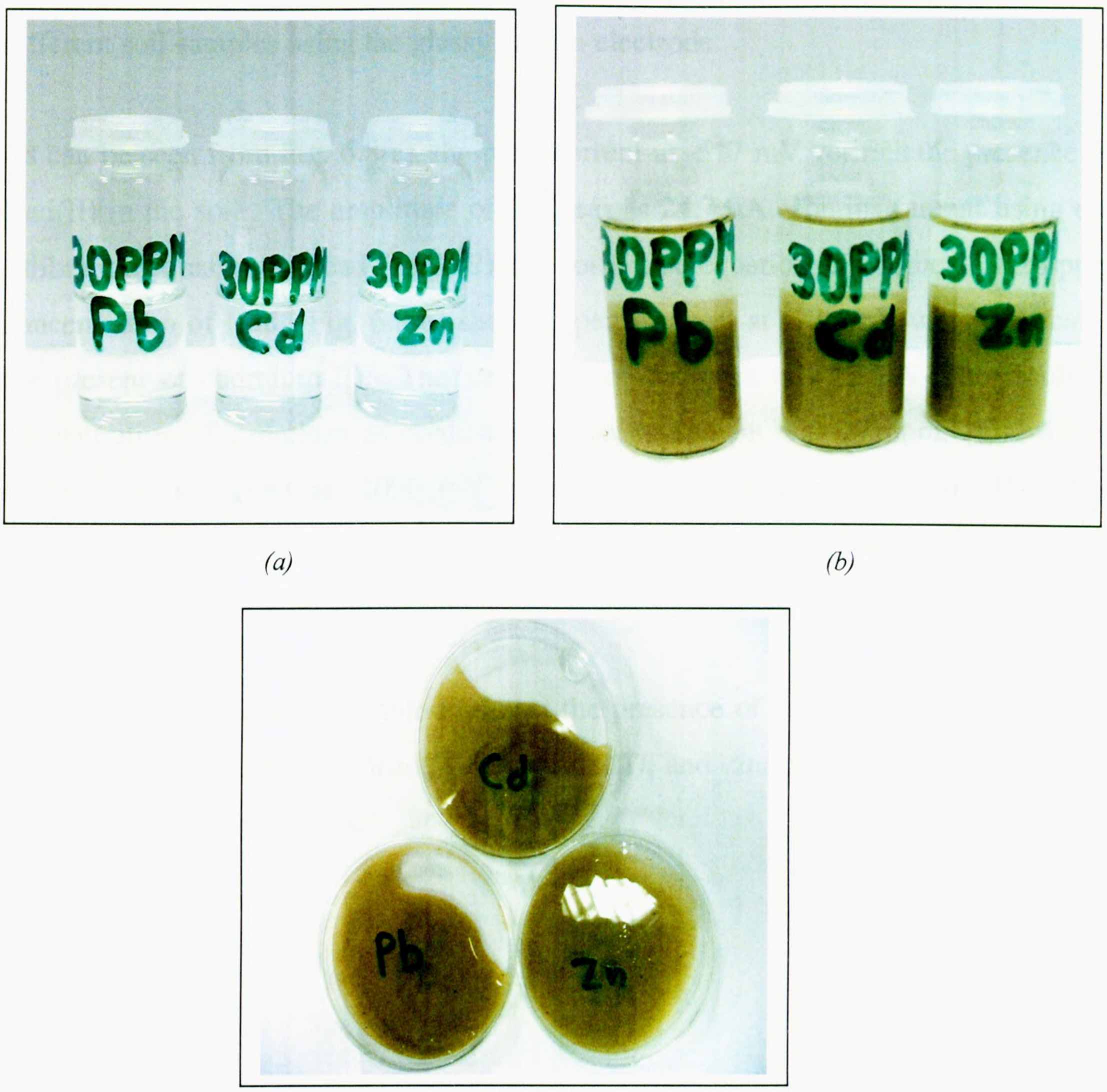


Figure 6.6: *Differential pulse voltammogram for a solution with a multi-metal mixture containing Cadmium, Lead and Mercury at 10 ppm*

6.4 Analysis of Soil Samples

6.4.1 Preparation of Soil Samples

Three 10 ml metal solutions of lead, cadmium, and zinc were prepared at concentrations of 30 ppm [Fig. 6.7(a)]. The solutions were made up using de-ionised water and standard metal solutions. The supporting electrolyte was 0.1 M sodium chloride (*NaCl*). 10 cm^3 of clear sand was added to each of the three different bottles of metal solutions. The aqueous solution and sand in each bottle were mixed well [Fig. 6.7(b)], and then left to dry as shown in Fig. 6.7(c).



(a) (b)

(c)

Figure 6.7*:(a) Three 10 ml aqueous solutions of 30 ppm lead, cadmium and zinc, (b) aqueous solutions mixed with clear sand, (c) dried soil samples.*

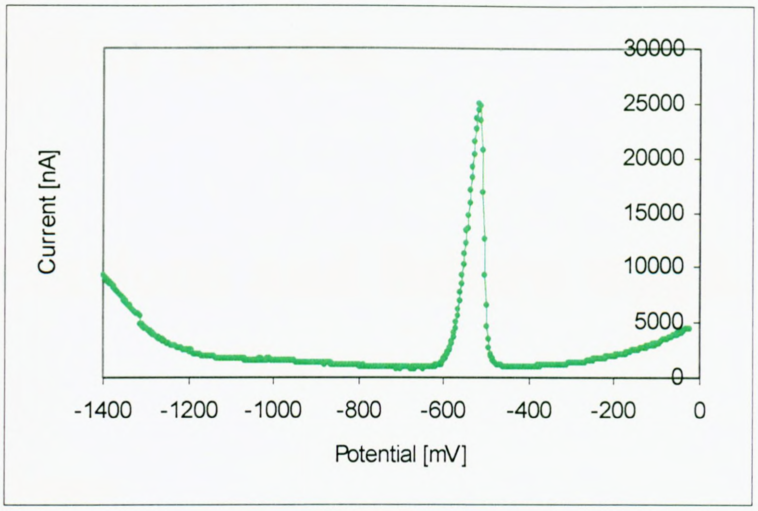
6.4.2 Analysis

3 cm^3 volume of the first soil sample (lead) was measured by using a 3 cm^3 plastic cup and transferred to the sample reservoir. 1 ml (1 cm^3) of 0.1 M *NaCl* electrolyte was then added and mixed with the sample in the reservoir. The acidity of the sample was controlled to approximately 1.35 pH by adding a few drops of 1M nitric acid. The pre-concentration time used for the analysis was 60 sec and the scanning voltage was in the range -1400 to +1000 mV. The same process was repeated for sample two (cadmium) and three (zinc).

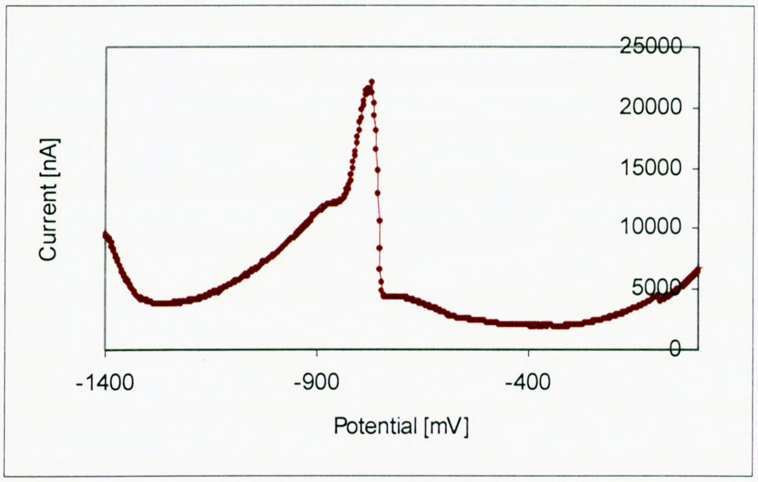
Fig. 6.8 (a),(b) and (c) shows the voltammograms from the analysis of the three different soil samples using the glassy carbon electrode.

As can be seen from Fig. 6.8(a), the peak current at -517 mV verifies the presence of lead(II) in the soil. The amplitude of the peak is 24.7 μA. The instrument using the calibration equation for lead (Table 2) and correction equation (3) predicted a 26 ppm concentration of lead. Fig. 6.8(b) shows a peak current at -774 mV which indicates the present of cadmium(II). The amplitude of the peak is 21.2 μA. The resultant concentration of cadmium as predicted by the instrument was 27 ppm. Fig. 6.8(c) shows a peak current at -1090 mV which indicates the present of zinc(II). The amplitude of the zinc peak is 11.3 μA. The resultant concentration of zinc as predicted by the instrument was 27 ppm.

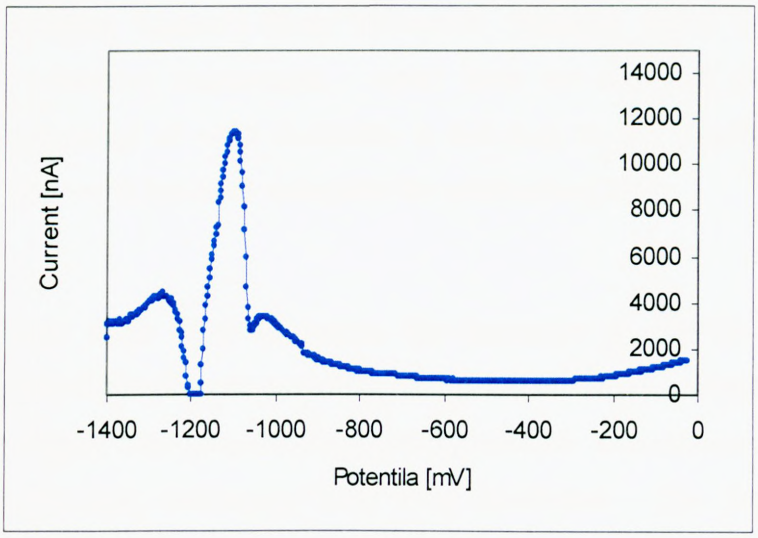
Therefore, the analyser was able to detect the presence of each of the three different metals in the soil samples [lead(II), cadmium(II), and zinc(II)] and also was able to predict their concentrations.



(a) Lead



(b) Cadmium



(c) Zinc

Figure 6.8: *Voltammograms from the three different soil samples using the glassy carbon electrode.*

Chapter Seven

Conclusions and future work

7.1 Conclusions

A portable (hand-held) electrochemical instrument capable of gathering real-time quantitative data on a range of heavy metal contaminants has been developed. The unit is being developed to identify heavy metals contamination of land or water and is also able to determine the oxidation state of the target metals, which is a measure of their toxicity. The system provides the facilities found in a traditional lab based instrument, but in a hand held design. In contrast to existing commercial systems, it can stand alone without the need of a computer and expert operators. The system uses Differential Pulse Anodic Stripping Voltammetry (DPASV) which is a precise and sensitive analytical method with excellent limits of detection. The sensor (cell) uses solid (screen-printed and glassy carbon) working electrodes rather than the more common Hanging Mercury Drop Electrodes (HMDE) which are used by most traditional laboratory instruments. Apart from the size and cost difference, an important advantage of solid electrodes is that they do not require the use of toxic mercury. This work has been submitted for publication[125].

At the present stage of development, the instrument is capable of detecting and identifying six different toxic environmental pollutants, lead, cadmium, mercury, zinc, nickel and copper, with good sensitivity and precision. Two different microprocessor-based identification techniques have been developed. The first identification technique is based on statistical information (Probability Density Function) of oxidation potentials of the above six metals. When an actual test is carried out, the oxidation potential E_p is assessed and examined against a PDF to determine the probability of membership of that analyte with all analytes stored in a database of

PDF measurements. The analyte representing the highest probability of likeliness is thus identified. Analytes identified in this way are automatically given a probability of likeliness, indicating the prediction accuracy. A database has been created from practical measurements which contains statistical information of the six different heavy metals. At present there are two sets of data, one set using the glassy carbon electrode and a second set using the screen printed sensor. This work has been submitted for publication[126].

The second identification technique is based on an intelligent machine-based-method using a multi-layer perceptron neural network consisting of three layers of neurons. The artificial neural network was implemented using a 16-bit microcontroller and was trained to identify the six different metals. The probability of classification was very good (100%) for lead, cadmium, zinc and mercury. For copper and nickel was 92% and 89% respectively. This work has been published[127,128].

The instrument with the combination of a Geographical Position System (GPS) is capable of storing the geographical position of the sample under test. Software has been developed to combine pollutant results with geographical position, in order to produce a cartographical presentation of the pollution of an area. The instrument's capability of detecting metals in multi-element solutions and in soil samples has also been examined, demonstrating good results. This work has been published[129].

Finally, other parts of this research have been submitted for publication to various peer reviewed journals[130,131]. All aspects of the research have been patented[132].

7.2 Future work

At present, the instrument has been used successfully to analyse both soil and aqueous samples in laboratory conditions. The next stage of this project is the use of the instrument in the field. This will require some further development of the sampling chamber and further miniaturisation of the instrument for in situ usage.

The instrument will be taken to various contaminated places in order to assess its capability to detect and to identify different types of heavy metals, in situ. At that stage the instrument (hardware and software) and the sensor cartridge will be in their final form. Therefore, the final clarifications and additions to the patent application will be made at that point.

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Appendix A: Tables with Results

A.1. Peak current amplitude and oxidation potential, for lead(II): Using glassy carbon electrode.

Sample No	Concentration [ppm]	Amplitude [μA]	Oxidation Pot. [mV]
01	1	3.10	-592
02	1	4.65	-558
03	1	3.80	-553
04	1	3.50	-568
05	1	2.70	-568
06	2.5	6.68	-546
07	2.5	7.20	-529
08	2.5	7.25	-524
09	2.5	7.93	-537
10	2.5	7.12	-525
11	5	10.48	-522
12	5	10.15	-516
13	5	12.19	-523
14	5	15.55	-528
15	5	12.75	-527
16	10	17.70	-524
17	10	19.52	-517
18	10	21.70	-518
19	10	20.00	-522
20	10	20.38	-526
21	50	49.35	-516
22	50	51.01	-519
23	50	47.52	-502
24	50	44.72	-504
25	50	62.18	-502
26	100	98.53	-509
27	100	100.89	-505
28	100	110.65	-487
29	100	92.32	-482
30	100	93.45	-490
31	100	102.21	-487
32	100	108.87	-486

A.2. Peak current amplitude and oxidation potential, for cadmium(II): Using glassy carbon electrode.

Sample No	Concentration [ppm]	Amplitude [μA]	Oxidation Pot. [mV]
01	2.5	3.6	-768
02	2.5	3.4	-768
03	2.5	2.5	-770
04	2.5	3	-779
05	2.5	2.5	-775
06	2.5	3.9	-773
07	2.5	6.1	-769
08	5	8.02	-762
09	5	6.05	-763
10	5	5.48	-759
11	5	8.55	-760
12	5	6.9	-751
13	5	8.23	-758
14	5	8.91	-755
15	30	32.1	-741
16	30	20.6	-746
17	30	22.7	-732
18	30	25.5	-742
19	30	28.15	-739
20	30	26.45	-725
21	30	25.34	-732
22	50	51.2	-712
23	50	59.8	-703
24	50	43.5	-708
25	50	45.63	-712
26	50	56.82	-715
27	50	51.6	-720
28	50	49.3	-709
29	100	105.72	-722
30	100	101.28	-720
31	100	98.3	-710
32	100	94.7	-711

A.3. Peak current amplitude and oxidation potential, for zinc(II): Using glassy carbon electrode.

Sample No	Concentration [ppm]	Amplitude [μA]	Oxidation Pot. [mV]
01	10	4.4	-1002
02	10	4.9	-1005
03	10	3.5	-1009
04	10	7.2	-980
05	10	7.18	-1007
06	10	4	-1024
07	10	3.9	-1019
08	25	14.25	-1012
09	25	12	-1019
10	25	9.02	-1012
11	25	6.75	-1019
12	25	7.3	-1022
13	25	13.11	-1022
14	25	7.9	-1029
15	50	40.43	-1004
16	50	40.2	-1007
17	50	38.75	-1024
18	50	41.3	-1019
19	50	40.1	-1012
20	50	39.01	-1019
21	50	41.4	-1024
22	50	39.33	-1019
23	50	40.72	-1017
24	100	85.05	-1022
25	100	71.03	-1031
26	100	77.7	-1019
27	100	92.32	-1034
28	100	80.45	-1041
29	100	84.2	-1032
30	100	78.02	-1048
31	100	72.01	-1034
32	100	91.5	-1034

A.4. Peak current amplitude and oxidation potential, for mercury(II): Using glassy carbon electrode.

Sample No	Concentration [*ppm*]	Amplitude [*μA*]	Oxidation Pot. [*mV*]
01	5	29.17	120
02	5	29.65	122
03	5	29.42	128
04	5	29.12	132
05	5	29.34	129
06	5	29.23	131
07	5	29.52	129
08	5	29.49	130
09	5	29.12	132
10	10	39.67	118
11	10	35.45	127
12	10	40.53	132
13	10	33.24	134
14	10	38.11	128
15	10	39.09	136
16	10	42.34	129
17	10	32.03	129
18	10	37.42	130
19	30	60.78	132
20	30	51.55	137
21	30	74.02	128
22	30	65.87	133
23	30	63.12	128
24	30	60.02	132
25	50	95.54	105
26	50	88.34	88
27	50	104.21	134
28	50	76.27	137
29	100	145.39	115
30	100	132.06	130
31	100	148.78	132
32	100	134.12	130

A.5. Peak current amplitude and oxidation potential, for copper(II): Using glassy carbon electrode.

Sample No	Concentration [*ppm*]	Amplitude [*μA*]	Oxidation Pot. [*mV*]
01	10	8.43	-158
02	10	11.23	-150
03	10	10.02	-143
04	10	8.5	-143
05	10	8.2	-127
06	10	8.1	-144
07	10	8.8	-132
08	10	8.01	-143
09	10	18.52	-135
10	10	8.48	-129
11	10	10.42	-118
12	25	9.5	-119
13	25	12.45	-125
14	25	9.02	-126
15	25	12.22	-123
16	25	10.22	-125
17	25	15.68	-122
18	25	17.34	-121
19	25	19.9	-118
20	25	18.8	-124
21	25	17.61	-116
22	25	18.36	-123
23	50	22.01	-97
24	50	16.34	-94
25	50	33.12	-92
26	50	39.12	-80
27	50	33.3	-65
28	50	34.08	-63
29	50	40.99	-65
30	50	31.12	-62
31	50	36.24	-64
32	50	32.16	-63

A.6. Peak current amplitude and oxidation potential, for nickel(II): Using glassy carbon electrode.

Sample No	Concentration [*ppm*]	Amplitude [μA]	Oxidation Pot. [*mV*]
01	5	6.82	-48
02	5	6.11	-41
03	5	6.02	-4
04	5	4.81	-22
05	5	5.79	-59
06	5	5.09	-52
07	5	4.92	-47
08	5	4.82	-35
09	10	6.86	-6
10	10	7.74	-7
11	10	7.75	-11
12	10	7.07	-4
13	10	7.34	-30
14	10	7.12	-34
15	10	6.77	-6
16	10	6.79	-12
17	25	13.62	-156
18	25	15.82	-178
19	25	12.91	-176
20	25	14.35	-145
21	25	11.24	-102
22	25	11.34	-123
23	25	10.56	-23
24	25	10.26	-12
25	50	22.98	-4
26	50	19.02	-6
27	50	27.48	-10
28	50	32.99	-23
29	50	24.23	-18
30	50	23.49	-11
31	50	24.56	-3
32	50	24.98	-12

A.7. Peak current amplitude and oxidation potential, for lead(II): Using the screen printed sensor.

Sample No	Concentration [*ppm*]	Amplitude [*μA*]	Oxidation Pot. [*mV*]
01	2.5	7.6	-602
02	2.5	15.1	-623
03	2.5	14.1	-616
04	2.5	8.1	-622
05	2.5	12.32	-612
06	2.5	12.8	-622
07	2.5	11.6	-602
08	2.5	11.6	-608
09	5	55.65	-611
10	5	59.42	-612
11	5	56.73	-609
12	5	60.25	-611
13	5	56.11	-601
14	5	55.31	-602
15	5	59.09	-598
16	5	60.22	-592
17	10	153	-521
18	10	226.1	-522
19	10	167.1	-521
20	10	224.3	-526
21	10	223.4	-523
22	10	160	-523
23	10	159.1	-533
24	10	162.3	-522
25	50	747.9	-501
26	50	747.8	-502
27	50	796.3	-504
28	50	700.1	-511
29	50	710.2	-511
30	50	780.2	-502
31	50	709.5	-504
32	50	782.7	-503

A.8. Peak current amplitude and oxidation potential, for cadmium(II): Using the screen printed sensor.

Sample No	Concentration [*ppm*]	Amplitude [μA]	Oxidation Pot. [*mV*]
01	2.5	37.22	-755
02	2.5	32.91	-760
03	2.5	36.25	-776
04	2.5	31.05	-745
05	2.5	31.98	-746
06	2.5	35.66	-739
07	2.5	37.26	-722
08	2.5	32.11	-728
09	5	94.82	-777
10	5	94.82	-756
11	5	100.1	-799
12	5	89.23	-782
13.	5	90.34	-789
14	5	102.7	-774
15	5	91.73	-782
16	5	95.03	-824
17	10	168.7	-845
18	10	168.7	-848
19	10	143	-833
20	10	187	-834
21	10	139	-856
22	10	198	-869
23	10	190	-857
24	10	152	-877
25	30	648.4	-914
26	30	639.2	-902
27	30	679	-916
28	30	611	-927
29	30	612	-900
30	30	654	-909
31	30	678	-918
32	30	630	-922

A.9. Peak current amplitude and oxidation potential, for zinc(II): Using the screen printed sensor.

Sample No	Concentration [*ppm*]	Amplitude [*μA*]	Oxidation Pot. [*mV*]
01	5	47.21	-1002
02	5	68.12	-1048
03	5	58.67	-1011
04	5	44.27	-1016
05	5	62.78	-1023
06	5	45.87	-1029
07	5	43.78	-1036
08	5	56.11	-1026
09	10	124.6	-961
10	10	122.1	-964
11	10	139.8	-965
12	10	112.6	-959
13	10	240.1	-971
14	10	109.9	-957
15	10	132.8	-968
16	10	112.7	-958
17	25	302.8	-995
18	25	304.2	-1009
19	25	243.2	-1003
20	25	327.2	-1011
21	25	249.9	-994
22	25	271.2	-1012
23	25	272.6	-1008
24	25	312.7	-1021
25	50	398.9	-997
26	50	389.2	-1016
27	50	446.1	-1023
28	50	420.1	-1013
29	50	486.2	-1005
30	50	478.2	-1009
31	50	470.9	-1021
32	50	396.8	-1022

A.10. Peak current amplitude and oxidation potential, for mercury: Using the screen printed sensor.

Sample No	Concentration [*ppm*]	Amplitude [μA]	Oxidation Pot. [*mV*]
01	5	30.22	19
02	5	32.56	11
03	5	29.67	13
04	5	33.52	25
05	5	31.08	23
06	5	31.12	11
07	10	40.98	21
08	10	41.34	14
09	10	37.56	13
10	10	36.67	15
11	10	42.78	12
12	10	36.78	11
13	30	50.31	29
14	30	55.22	23
15	30	51.27	21
16	30	65.12	34
17	30	71.06	23
18	30	72.32	64
19	50	72.66	87
20	50	73.99	64
21	50	74.72	83
22	50	92.25	78
23	50	89.2	78
24	50	71.01	61
25	50	97.99	73
26	100	136.6	122
27	100	155.2	132
28	100	141.1	138
29	100	134	145
30	100	149	132
31	100	151.1	127
32	100	140	129

A.11. Peak current amplitude and oxidation potential, for copper(II): Using the screen printed sensor.

Sample No	Concentration [*ppm*]	Amplitude [μA]	Oxidation Pot. [*mV*]
01	2.5	14.11	-268
02	2.5	21.09	-256
03	2.5	15.54	-261
04	2.5	20.03	-269
05	2.5	12.64	-264
06	2.5	22.42	-262
07	5	47.12	-243
08	5	32.05	-256
09	5	46.23	-252
10	5	30.42	-257
11	5	49.56	-261
12	5	32.09	-254
13	10	170.2	-196
14	10	167	-184
15	10	150.6	-189
16	10	134.2	-182
17	10	120.1	-183
18	10	126.7	-181
19	25	320.5	-146
20	25	280.1	-137
21	25	332	-138
22	25	287.5	-148
23	25	334	-139
24	25	269.2	-135
25	25	289.6	-137
26	50	540	-91
27	50	445.1	-92
28	50	546.3	-95
29	50	471.2	-91
30	50	493.6	-98
31	50	479.5	-94
32	50	470.3	-93

A.12. Peak current amplitude and oxidation potential, for nickel: Using the screen printed sensor.

Sample No	Concentration [*ppm*]	Amplitude [μA]	Oxidation Pot. [*mV*]
01	5	6.52	-268
02	5	6.32	-255
03	5	8.21	-253
04	5	8.03	-255
05	5	8.79	-259
06	5	8.12	-245
07	5	6.08	-239
08	5	6.23	-235
09	10	16.32	-210
10	10	16.21	-209
11	10	16.98	-211
12	10	16.35	-221
13	10	17.99	-219
14	10	17.82	-223
15	10	17.95	-208
16	10	17.02	-214
17	25	22.08	-198
18	25	21.56	-201
19	25	23.76	-196
20	25	22.05	-183
21	25	27.92	-194
22	25	31.44	-192
23	25	29.28	-199
24	25	35.71	-193
25	50	41.01	-184
26	50	43.29	-188
27	50	41.56	-182
28	50	47.92	-186
29	50	55.99	-188
30	50	59.12	-183
31	50	58.09	-175
32	50	43.25	-179

Appendix B

Software developed in ASSEMBLY language

B.1. Excitation Signal

```
****************************************************************
*
*              School of Engineering
*       The Robert Gordon University, Aberdeen
****************************************************************
*
*           File name: excitation.asm (ok)
*           Author:      KONSTANTINOS CHRISTIDIS
*           Created:     02/03/2004
****************************************************************
*
*                  M68HCS12  Assembler Source File
* Description : Produce excitation signal
*               PON=50mS and POFF=70ms
*               Range:-1.4 to +1.0V
****************************************************************
* DAC:        PORT B - [DDDD DDDD], LSB DATA for DAC
*             PORT K - [xXXX DDDD], MSB DATA for DAC
****************************************************************

COPCTL              EQU     $003C               ; COP Control Register
****************************************
* STARTING ADDRESS FOR DATA
****************************************
                    ORG     $3700               ; DATA: RAM starting address
***********
* I/O PORTS
***********
PORTB               EQU     $0001               ; DAC: LSB DATA
DDRB                EQU     $0003
PORTK               EQU     $0032               ; DAC: MSB DATA
DDRK                EQU     $0033
**********
* DAC DATA
**********
VOLT_M              DB      #0                  ;$3000: Voltage variable for DAC (MSByte)
VOLT_L              DB      #0                  ;$3001: Voltage variable for DAC (LSByte)
VOLT_M_AUX          DB      #0                  ;Voltage var. to support Sensor MASK control
VOLT_L_AUX          DB      #0                  ;Voltage var. to support Sensor MASK control
;****************************************
;* STARTING ADDRESS FOR THE PROGRAM
;****************************************
                    ORG     $1000               ; PROGRAM: RAM starting address
;********************************
;* Initialisation - Set variables
;********************************
START:
                    CLR     COPCTL              ; Clear COP
                    LDS     #$3BFF              ; Set STAC register
;***************
;* Set I/O ports
;***************
                    BSET    DDRB,#%11111111             ; Set port-B OUTPUT
                    BSET    DDRK,#%00001111             ; Set port-K OUTPUT
;**********************************
;* Initial voltage (-1.4V)(#0901)
;**********************************
                    LDD     #0901
                    STD     VOLT_M
                    STD     VOLT_M_AUX
                    BSET    VOLT_M_AUX,#%00010000       ; Connect sensor-1 (S1)
                    LDD     VOLT_M_AUX
                    STAA    PORTK                       ; Sent also Control (S1=1)
                    STAB    PORTB
```

```
;*****************************
;* Deposition timer for 1 min
;*****************************
                LDD     #1200           ; 1200 x 50msec = 1min DELAY
LOOP50:         JSR     DELAY10
                DEC
                CPD     #0
                BHI     LOOP50
                RTS
;*******************
;* REPEAT PROCESS
;*******************
LOOP:           NOP
;**********************************************
;* 50 msec step up (21bits ~1.22 x 21 = 25.62mV)
;**********************************************
                LDD     VOLT_M
                ADDD    #21
                STD     VOLT_M
                STD     VOLT_M_AUX
                BSET    VOLT_M_AUX,#%00010000     ; Connect sensor-1 (S1)
                LDD     VOLT_M_AUX
                STAA    PORTK                     ; Sent also Control (S1=1)
                STAB    PORTB
                JSR     DELAY50
;***************************************
;* 50 sec step down (19 bit 1.22x19=23.18)
;***************************************
                LDD     VOLT_M                    ; Load current voltage potential
                SUBD    #19                       ; Add 20bits to current potential
                STD     VOLT_M                    ; Store new potential
                STD     VOLT_M_AUX
                BSET    VOLT_M_AUX,#%00010000     ; Connect sensor-1 (S1)
                LDD     VOLT_M_AUX
                STAA    PORTK                     ; Sent also Control (S1=1)
                STAB    PORTB                     ; LSB DAC output
                JSR     DELAY50                   ; Wait for 50msec
                JSR     DELAY10
                JSR     DELAY10
;*****************************************************
;* Check if reach potential +0.0V (2048) or +1.0V (2867)
;*****************************************************
                LDD     VOLT_M          ; Load current voltage potential
                CPD     #2867           ; 1.0V Step potential 2 = 1.0V
                LBLO    LOOP            ; If no, repeat process GO to LOOP
                                        ; If yes, continue
;**********************************************************
;****************** END OF MAIN ***************************
;**********************************************************
LOOPGQ:         BRA     LOOPGQ          ; Continuously repeat, END

;************************************
;*
;*      SUBRUTINE: DELAY50
;*      INFO:      Delay for 50ms
;*      PASS:       No
;*      RETURNE:   No
;************************************
DELAY50:        PSHA
                LDAA    #5              ; 5 x 10msec DELAY
LOOP50:         JSR     DELAY10
                DECA
                CMPA    #0
                BHI     LOOP50
                PULA
                RTS

;************************************
;*
;*      SUBRUTINE: DELAY10
;*      INFO:      Delay for 10ms
;*      PASS:       No
;*      RETURNE:   No
;************************************
DELAY10:        LDX     #40625          ;10msec execution time
LOOP10:         DEX
                CPX     #$00
                BHI     LOOP10
                LDX     #REGBS
                RTS
;**************************
;*
;*              END OF CODE
;**************************
```

B.2. Data acquisition

```
**************************************************************
*              School of Engineering
*       The Robert Gordon University, Aberdeen
**************************************************************
*            File name: adc.asM
*            Author:      KONSTANTINOS CHRISTIDIS
*            Created:     14/02/2004
**************************************************************
*                  M68HCS12  Assembler Source File
* Description : ADC driver and Data acquisition
**************************************************************
* ADC:       PORT A   - [DDDD DDDD], MSB DATA for ADC
*            PORT AD1 - [DDDD DDDD], LSB DATA for ADC
*            PORT P7  - CONTROL DATA for ADC
**************************************************************

COPCTL          EQU     $003C           ; COP Control Register
***********
* I/O PORTS
***********
PORTAD1         EQU     $012F           ; ADC: LSB DATA
ENBL_AD1 EQU    $012D
PORTA           EQU     $0000           ; ADC: MSB DATA
DDRA            EQU     $0002
PORTP           EQU     $0258           ; ADC: CONTROL
DDRP            EQU     $025A
;*****************************************
;* STARTING ADDRESS FOR THE PROGRAM
;*****************************************
                ORG     $1000           ; PROGRAM: RAM starting address
;********************************
;* Initialisation - Set variables
;********************************
START:          CLR     COPCTL          ; Clear COP
                LDS     #$3BFF          ; Set STAC register
;***************
;* Set I/O ports
;***************
                CLR     DDRA                    ; Set port-A INPUT
                BSET    ENBL_AD1,#%11111111     ; Enable port-AD1 (INPUT)
                BSET    DDRP,#%11111100         ; Set port-P OUTPUT
LOOP:           JSR     READADC
                JSR     DELAY50
                JMP     LOOP                    ; Continuously read ADC
;************************************
;*     SUBRUTINE: DELAY50
;*     INFO:      Delay for 50ms
;*     PASS:        No
;*     RETURNE:   No
;************************************
DELAY50:        PSHA
                LDAA    #5              ; 5 x 10msec DELAY
LOOP50:         JSR     DELAY10
                DECA
                CMPA    #0
                BHI     LOOP50
                PULA
                RTS
;************************************
;*     SUBRUTINE: DELAY10
;*     INFO:      Delay for 10ms
;*     PASS:        No
;*     RETURNE:   No
;************************************
DELAY10:        LDX     #40625          ;10msec execution time
LOOP10:         DEX
                CPX     #$00
                BHI     LOOP10
                LDX     #REGBS
                RTS
;**********************************
;*     SUBRUTINE: READADC
;*     INFO:      Read ADC Converter
;*     PASS:        No
;*     RETURNE:   Register-D
;**********************************
READADC:      BSET      PORTP,#%10000000        ; Initial stage (Conversion=OFF)
                JSR     DELAY01
                BCLR    PORTP,#%10000000        ; Conversion=ON
```

```
            NOP
            NOP
            NOP
            BSET    PORTP,#%10000000        ; Conversion=OFF
            JSR     DELAY01                 ; Wait for BUSY signal
            LDAA    PORTA                   ; Read MSByte
            LDAB    PORTAD1                 ; Read LSByte
            RTS
;*************************************
;*    SUBRUTINE: DELAY01
;*    INFO:      Wait for 100usec
;*    PASS:      No
;*    RETURNE:   No
;*************************************
DELAY01:    LDX     #1016                   ; 100 usec execution time
LOOP25:     DEX
            CPX     #$00
            BHI     LOOP25
            RTS
;***************************
;*          END OF CODE
;***************************
```

B.3. Gain control

```
**************************************************************
*             School of Engineering
*     The Robert Gordon University, Aberdeen
**************************************************************
*           File name:      gain_cnt.asm
*           Author:         KONSTANTINOS CHRISTIDIS
*           Created:        12/08/2004
**************************************************************
*                 M68HCS12  Assembler Source File
* Description : Gain
**************************************************************
* ADC:      PORT A   - [DDDD DDDD], MSB DATA for ADC
*             PORT AD1 - [DDDD DDDD], LSB DATA for ADC
*           PORT P7  - CONTROL DATA for ADC
* GAIN:     PORT T - [XXAB CXXX] 3bits Input KEYPAD
**************************************************************

COPCTL          EQU     $003C           ; COP Control Register
****************************************
* STARTING ADDRESS FOR DATA
****************************************
                ORG     $3700           ; DATA: RAM starting address
***********
* I/O PORTS
***********
PORTAD1         EQU     $012F           ; ADC: LSB DATA
ENBL_AD1 EQU    $012D
PORTA           EQU     $0000           ; ADC: MSB DATA
DDRA            EQU     $0002
PORTP           EQU     $0258           ; LCD:3-BIT CONTROL
DDRP            EQU     $025A
PORTT           EQU     $0240           ; GAIN: 3-BIT DATA
DDRT            EQU     $0242
**********
* ADC DATA
**********
SMP_16M         DW      #0              ;$0802: ADC sample storage (MSWord)
SMP_16L         DW      #0              ;
SAMPLE_M DW     #0
****************
* AUTOMATIC GAIN
****************
GN_PNT1         DB      #0
GN_PNT2         DB      #0
GAIN            DB      #0              ;$0870
GAIN0           DB      #%00000000
GAIN1           DB      #%00001000      ;$0870
GAIN2           DB      #%00010000      ;$0870
GAIN3           DB      #%00011000      ;$0870
GAIN4           DB      #%00100000      ;$0870
GAIN5           DB      #%00101000      ;$0870
GAIN6           DB      #%00110000      ;$0870
GAIN7           DB      #%00111000      ;$0870
GN_RES          DW      #0              ;$0000
GN_RES0         DW      #31623          ;$0872
```

```
GN_RES1         DW      #25914          ;$0872
GN_RES2         DW      #14698          ;$0872
GN_RES3         DW      #7722           ;$0872
GN_RES4         DW      #2959           ;$0872
GN_RES5         DW      #2322           ;$0872
GN_RES6         DW      #1722           ;$0872
GN_RES7         DW      #811            ;$0872
X_SAMPLA DW     #0              ;$0874
X_SAMPLB DW     #0              ;$0874
X_SAMPL0 DW     #0              ;$0874
X_SAMPL1 DW     #0              ;$0874
X_SAMPL2 DW     #0              ;$0874
X_SAMPL3 DW     #0              ;$0874
X_SAMPL4 DW     #0              ;$0874
X_SAMPL5 DW     #0              ;$0874
X_SAMPL6 DW     #0              ;$0874
X_SAMPL7 DW     #0              ;$0874
SMP_M16M DW     #0              ;
SMP_M16L DW     #0              ;
SAMPL_MM dw     #0              ;
DIV_FLG1 DB     #0              ;1=div10, 10=div1000
DIV_FLG2 DB     #0              ;0=Less than 500.00uA,1=Higher than 500.00uA
RES_PPM         DW      #0
;*****************************************
;* STARTING ADDRESS FOR THE PROGRAM
;*****************************************
                ORG     $1000           ; PROGRAM: RAM starting address
;*******************************
;* Initialisation - Set variables
;*******************************
START:          CLR     COPCTL          ; Clear COP
                LDS     #$3BFF          ; Set STAC register
;***************
;* Set I/O ports
;***************
                CLR     DDRA                    ; Set port-A INPUT
                BSET    ENBL_AD1,#%11111111     ; Enable port-AD1 (INPUT)
                BSET    DDRP,#%11111100         ; Set port-P OUTPUT
                BSET    DDRT,#%00111000         ; Set port-T OUTPUT
LOOPGQ:         NOP
;*****************************************
;* GAIN CONTROL
;* Read ADC, HIGH sample
;*****************************************
                JSR     GN_CNT2
;*****************************************
;* GAIN CONTROL
;* Find best tuning
;*****************************************
                LDAA    GN_PNT2
                LSLA
                STAA    GN_PNT1
                LDY     #X_SAMPL0
                LDAA    GN_PNT1
NTXT2:          CMPA    #0
                BEQ     VELE2
                DECA
                INY
                BRA     NTXT2
VELE2:          LDD     0,Y
                STD     X_SAMPLA
                LDY     #GN_RES0
                LDAA    GN_PNT1
NTXT3:          CMPA    #0
                BEQ     VELE3
                DECA
                INY
                BRA     NTXT3
VELE3:          LDD     0,Y
                STD     GN_RES
;*********************************
;* MULTIPLY SAMPLE A WITH RESOLUTION
;*********************************
                LDD     X_SAMPLA
                LDY     GN_RES
                EMUL                    ;X_SAMPLEA*GAIN_RES*100=(Y:D)
                STD     SMP_M16L
                STY     SMP_M16M
;*********************************
;* MULTIPLY SAMPLE B WITH RESOLUTION
;*********************************
                LDD     X_SAMPLB
                LDY     GN_RES
                EMUL                    ;X_SAMPLEB*GAIN_RES*100=(Y:D)
                STD     C_SMP16L
                STY     C_SMP16M
;*************************************************
;* Calculate difference NUMBER 1 - NUMBER 2 [method II]
;*************************************************
```

```
                LDD     SMP_M16L
                SUBD    C_SMP16L
                STD     SMP_16L
                BCC     NEXT
                LDD     C_SMP16M
                ADDD    #1
                STD     C_SMP16M
NEXT:           LDD     SMP_M16M
                SUBD    C_SMP16M
                STD     SMP_16M
;******************************************
;* Multiply sample with resolution
;******************************************
                LDY     SMP_16M
                LDD     SMP_16L
                LDX     #10000
                EDIV                    ;(Y:D)/100=Y.D
                STY     SAMPLE_M        ;Store results
                STY     SAMPL_MM
                movb    #100,DIV_FLG1   ;Set division /100
                ldd     SAMPLE_M
;****************
; Repeat Process
;****************
                BRA     LOOPGQ          ; Continuously repeat
;***********************************************
;* Subroutine:   GN_ADC
;* Note:   Gain control for ADC
;***********************************************
GN_ADC:         STAA    PORTT
                JSR     DELAY001        ; Delay 200nsec
                JSR     READADC         ; Read ADC for gain 000
                JSR     NEGPOS          ; Negative and positive shift results on D-REGISTER
                RTS
;***********************************************
;* Subroutine:   GAIN_CNT
;* Note:   Gain control for ADC FOR FIRST SAMPLE
;***********************************************
GAIN_CNT:       MOVB    #0,GN_PNT1
                LDAA    GAIN0
                JSR     GN_ADC
                STD     X_SAMPL0        ; Store sample for gain 000
                CPD     #51491          ; +9.8(*0.8)
                LBHS    NO_GN
                CPD     #14044          ; -9.8(*0.8)
                 LBLS   NO_GN
                MOVB    #1,GN_PNT1
                LDAA    GAIN1
                JSR     GN_ADC
                STD     X_SAMPL1        ; Store sample for X gain
                CPD     #43375          ; +5(*0.8)
                LBHS    NO_GN
                CPD     #22160          ; -5(*0.8)
                LBLS    NO_GN
                MOVB    #2,GN_PNT1
                LDAA    GAIN2
                JSR     GN_ADC
                STD     X_SAMPL2        ; Store sample for X gain
                CPD     #38174          ; +2.5(*0.7)
                LBHS    NO_GN
                CPD     #27361          ; -2.5(*0.7)
                LBLS    NO_GN
                MOVB    #3,GN_PNT1
                LDAA    GAIN3
                JSR     GN_ADC
                STD     X_SAMPL3        ; Store sample for X gain
                CPD     #34888          ;+0.98(*0.7)
                LBHS    NO_GN
                CPD     #30647          ;-0.98(*0.7)
                LBLS    NO_GN
                MOVB    #4,GN_PNT1
                LDAA    GAIN4
                JSR     GN_ADC
                STD     X_SAMPL4        ; Store sample for X gain
                CPD     #34358          ;+0.735(*0.7)
                LBHS    NO_GN
                CPD     #31177          ;-0.735(*0.7)
                LBLS    NO_GN
                MOVB    #5,GN_PNT1
                LDAA    GAIN5
                JSR     GN_ADC
                STD     X_SAMPL5        ; Store sample for X gain
                CPD     #33849          ; +0.5(*0.7)
                LBHS    NO_GN
                CPD     #31686          ; -0.5(*0.7)
                LBLS    NO_GN
                MOVB    #6,GN_PNT1
                LDAA    GAIN6
                JSR     GN_ADC
```

```
                STD     X_SAMPL6        ; Store sample for X gain
                CPD     #33308          ; +0.25(*0.7)
                 LBHS    NO_GN
                CPD     #32227          ; -0.25(*0.7)
                LBLS    NO_GN
                MOVB    #7,GN_PNT1
                LDAA    GAIN7
                JSR     GN_ADC
                STD     X_SAMPL7        ; Store sample for X gain
NO_GN:          RTS
;*********************************************
;* Subroutine:   GN_CNT2
;* Note:   Gain control for ADC FOR SECOND SAMPLE
;*********************************************
GN_CNT2: MOVB   #0,GN_PNT2
                LDAA    GAIN0
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
                CPD     #51491          ; +9.8(*0.8)
                LBHS    NO_GN1
                CPD     #14044          ; -9.8(*0.8)
                LBLS    NO_GN1
                LDAA    GN_PNT1
                CMPA    GN_PNT2
                LBLS    NO_GN1
                MOVB    #1,GN_PNT2
                LDAA    GAIN1
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
                CPD     #43375          ; +5(*0.8)
                LBHS    NO_GN1
                CPD     #22160          ; -5(*0.8)
                LBLS    NO_GN1
                LDAA    GN_PNT1
                CMPA    GN_PNT2
                LBLS    NO_GN1
                MOVB    #2,GN_PNT2
                LDAA    GAIN2
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
                CPD     #38174          ; +2.5(*0.7)
                LBHS    NO_GN1
                CPD     #27361          ; -2.5(*0.7)
                LBLS    NO_GN1
                LDAA    GN_PNT1
                CMPA    GN_PNT2
                LBLS    NO_GN1
                MOVB    #3,GN_PNT2
                LDAA    GAIN3
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
                CPD     #34888          ;+0.98(*0.7)
                LBHS    NO_GN1
                CPD     #30647          ;-0.98(*0.7)
                LBLS    NO_GN1
                LDAA    GN_PNT1
                CMPA    GN_PNT2
                LBLS    NO_GN1
                MOVB    #4,GN_PNT2
                LDAA    GAIN4
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
                CPD     #34358          ;+0.735(*0.7)
                LBHS    NO_GN1
                CPD     #31177          ;-0.735(*0.7)
                LBLS    NO_GN1
                LDAA    GN_PNT1
                CMPA    GN_PNT2
                LBLS    NO_GN1
                MOVB    #5,GN_PNT2
                LDAA    GAIN5
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
                CPD     #33849          ; +0.5(*0.7)
                LBHS    NO_GN1
                CPD     #31686          ; -0.5(*0.7)
                LBLS    NO_GN1
                LDAA    GN_PNT1
                CMPA    GN_PNT2
                LBLS    NO_GN1
                MOVB    #6,GN_PNT2
                LDAA    GAIN6
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
                CPD     #33308          ; +0.25(*0.7)
                LBHS    NO_GN
                CPD     #32227          ; -0.25(*0.7)
                LBLS    NO_GN1
                LDAA    GN_PNT1
```

```
                CMPA    GN_PNT2
                LBLS    NO_GN1
                MOVB    #7,GN_PNT2
                LDAA    GAIN7
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for X gain
NO_GN1:         RTS
;***************************************
;*      SUBRUTINE: DELAY50
;*      INFO:      Delay for 50ms
;*      PASS:       No
;*      RETURNE:   No
;***************************************
DELAY50:        PSHA
                LDAA    #5              ; 5 x 10msec DELAY
LOOP50:         JSR     DELAY10
                DECA
                CMPA    #0
                BHI     LOOP50
                PULA
                RTS
;***************************************
;*      SUBRUTINE: DELAY10
;*      INFO:      Delay for 10ms
;*      PASS:       No
;*      RETURNE:   No
;***************************************
DELAY10:        LDX     #40625          ;10msec execution time
LOOP10:         DEX
                CPX     #$00
                BHI     LOOP10
                LDX     #REGBS
                RTS
;*************************************
;*      SUBRUTINE: READADC
;*      INFO:      Read ADC Converter
;*      PASS:       No
;*      RETURNE:   Register-D
;*************************************
READADC:        BSET    PORTP,#%10000000        ; Initial stage (Conversion=OFF)
                JSR     DELAY01
                BCLR    PORTP,#%10000000        ; Conversion=ON
                NOP
                NOP
                NOP
                BSET    PORTP,#%10000000        ; Conversion=OFF
                JSR     DELAY01                 ; Wait for BUSY signal
                LDAA    PORTA                   ; Read MSByte
                LDAB    PORTAD1                 ; Read LSByte
                RTS
;***************************************
;*      SUBRUTINE: DELAY01
;*      INFO:      Wait for 100usec
;*      PASS:       No
;*      RETURNE:   No
;***************************************
DELAY01:        LDX     #1016                   ; 100 usec execution time
LOOP25:         DEX
                CPX     #$00
                BHI     LOOP25
                RTS
;***************************
;*              END OF CODE
;***************************
```

B.4. Keypad control

```
*****************************************************************
*               School of Engineering
*       The Robert Gordon University, Aberdeen
*****************************************************************
*           File name:   keypad.asm
*           Author:      KONSTANTINOS CHRISTIDIS
*           Created:     21/09/2004
*****************************************************************
*                  M68HCS12  Assembler Source File
* Description : Keypad operation (drivers)
*****************************************************************
* KEYPAD:   PORT M - [XXX(<) (E)(>)XX] 3bits Input KEYPAD
*****************************************************************
COPCTL          EQU     $003C           ; COP Control Register

****************************************
```

```
* STARTING ADDRESS FOR DATA
******************************************
                ORG     $3700           ; DATA: RAM starting address
***********
* I/O PORTS
***********
PORTM           EQU     $0250
DDRM            EQU     $0252           ; KEYPAD: 3-BIT DATA
;******************************************
;* STARTING ADDRESS FOR THE PROGRAM
;******************************************
                ORG     $1000           ; PROGRAM: RAM starting address
;*******************************
;* Initialisation - Set variables
;*******************************
START:          CLR     COPCTL          ; Clear COP
                LDS     #$3BFF          ; Set STAC register
;***************
;* Set I/O ports
;***************
                BCLR    DDRM,#%00011100 ; Set M2,M3,M4 INPUTS
;***************
LOOP:           LDAA    #$00
                JSR     ENT_BTN         ; Read ENTER bout-on
                JSR     DELAY10
                LDAA    #$FF
                JSR     ENT_BTN         ; Read ENTER bout-on
                JSR     DELAY10
                BRA     LOOPGQ          ; Continuously repeat, END
;**************************************
;*      SUBRUTINE: DELAY10
;*      INFO:       Delay for 10ms
;*      PASS:        No
;*      RETURNE:    No
;**************************************
DELAY10:        LDX     #40625          ;10msec execution time
LOOP10:         DEX
                CPX     #$00
                BHI     LOOP10
                LDX     #REGBS
                RTS
;**********************************************
;*      SUBRUTINE: ENT_BTN
;*      INFO:       Wait to press Enter button
;**********************************************
ENT_BTN:        NOP
INTROD8: LDAA   PORTM                   ; Read ENTER bout-on
                ANDA    #%00001000      ; READ M4 PIN
                CMPA    #%00001000
                BNE     INTROD8
                RTS
;***************************
;*              END OF CODE
;***************************
```

B.5. Alphanumerical display

```
**************************************************************
*               School of Engineering
*       The Robert Gordon University, Aberdeen
**************************************************************
*           File name:  display_1.asM
*           Author:         KONSTANTINOS CHRISTIDIS
*           Created:        21/05/2004
**************************************************************
*                   M68HCS12  Assembler Source File
* Description : Alphanumerical display drivers
**************************************************************
* LCD:      PORT H - [DDDD DDDD], DATA for LCD
*           PORT P - [xXXC CCxx], CONTROL FOR LCD
**************************************************************

COPCTL          EQU     $003C           ; COP Control Register
******************************************
* STARTING ADDRESS FOR DATA
******************************************
                ORG     $3700           ; DATA: RAM starting address
***********
* I/O PORTS
***********
```

```
PORTH           EQU     $0260           ; LCD: 8-BIT DATA
DDRH            EQU     $0262
PORTP           EQU     $0258           ; LCD:3-BIT CONTROL
DDRP            EQU     $025A
;*******************************************
;* STARTING ADDRESS FOR THE PROGRAM
;*******************************************
                ORG     $1000           ; PROGRAM: RAM starting address
;*********************************
;* Initialisation - Set variables
;*********************************
START:          CLR     COPCTL          ; Clear COP
                LDS     #$3BFF          ; Set STAC register
;***************
;* Set I/O ports
;***************
                MOVB    #$FF,DDRH       ; Set port-H OUTPUT
                BSET    DDRP,#%11111100 ; Set port-P OUTPUT
;*****************
;* Initialise LCD
;*****************
                LDAA    #%00111000      ; 8bit, 2line 5x7dot
                JSR     CNTLCT
                LDAA    #%00001110      ; Display control
                JSR     CNTLCT
                LDAA    #%00000001      ; Clear LCD
                JSR     CNTLCT
                LDAA    #%00000110      ; Increment
                JSR     CNTLCT
;***********************
;* Print Welcome on LCD
;***********************
                JSR     CLR_LCD         ; Clear LCD
                LDY     #MSG_Wa
                JSR     CHAR_STR
                JSR     LINE_LCD        ; Next line
                LDY     #MSG_Wb
                JSR     CHAR_STR

LOOP:           BRA     LOOP
**********************************************
* SUBROUTINE:   D_CHAR
* FUNCTION:
**********************************************
D_CHAR:         JSR     PRNLCD
                RTS
;*************************************
;*      SUBRUTINE: CLR_LCD
;*      INFO:      Clear LCD
;*      PASS:      No
;*      RETURNE:   No
;*************************************
CLR_LCD: LDAA   #%00000001              ; Clear LCD
                JSR     CNTLCT
                RTS
;*************************************
;*      SUBRUTINE: LINE_LCD
;*      INFO:      Next Line (LCD)
;*      PASS:      No
;*      RETURNE:   No
;*************************************
LINE_LCD:       LDAA    #%11000000      ; Next line
                JSR     CNTLCT
                RTS
;*************************************
;*      SUBRUTINE: CNTLCT
;*      INFO:      Control output to LCD
;*      PASS:      Register-A, data
;*      RETURNE:   No
;*************************************
CNTLCT:         LDAB    #%00000000      ; CONTROL: (E=0,R/W=0,RS=0)
                STAB    PORTP
                STAA    PORTH
                JSR     DELAYLCD
                LDAB    #%00000100      ; CONTROL: (E=1,R/W=0,RS=0)
                STAB    PORTP
                JSR     DELAYLCD
                RTS
;*************************************
;*      SUBRUTINE: PRNLCD
;*      INFO:      Data output to LCD
;*      PASS:      Register-A, data
;*      RETURNE:   No
;*************************************
PRNLCD:         LDAB    #%00010000      ; CONTROL: (E=0,R/W=0,RS=0)
                STAB    PORTP
                STAA    PORTH
                JSR     DELAYLCD
                LDAB    #%00010100      ; CONTROL: (E=1,R/W=0,RS=1)
```

```
            STAB     PORTP
            JSR      DELAYLCD
            RTS
;****************************************
;*     SUBRUTINE: DELAYLCD
;*     INFO:      Delay for LCD operation
;*     PASS:        No
;*     RETURNE:   No
;****************************************
DELAYLCD:   JSR      DELAY10         ;10msec execution time
            RTS
****************************************
* Subroutine:  CHAR_STR
* Description: This subroutine prints
*              a character string
****************************************
CHAR_STR:   NOP
TXT_LOOP:   LDAA     0,Y
            CMPA     #$FF
            BEQ      TXT_END1
            JSR      PRNLCD
            INY
            BRA      TXT_LOOP
TXT_END1:   RTS
;**************************************
;*          CHARACTERS FOR DISPLAY
;**************************************
MSG_Wa      FCC      "Volt. Analyser-I "
            FCB      $FF
MSG_Wb      FCC      "R.G.U. 2004. "
            FCB      $FF
;****************************
;*          END OF CODE
;****************************
```

B.6. Graphic display

```
*****************************************************************
*                School of Engineering
*       The Robert Gordon University, Aberdeen
*****************************************************************
*             File name:   glcd.asm
*             Author:      KONSTANTINOS CHRISTIDIS
*             Created:     02/02/2005
*****************************************************************
*                   M68HCS12  Assembler Source File
* Description : GLCD drivers and operation example
* LCD:       PORT C - [DDDD DDDD], DATA for LCD
*            PORT H - [XXXX XCCC], CONTROL DATA for LCD
**************************************************************
            ORG      $F000           ; Starting Address inchip EEPROM
COPCTL      EQU      $0016           ; COP Control Register
PORTC       EQU      $0004           ; Data for LCD
PORTH       EQU      $0024           ; Control DATA for LCD
REGBS       EQU      $0000           ;REGISTER BASE ADDRESS.
;***************
;* Set I/O ports
;***************
            MOVB     #$FF,$0006      ; Set port-C OUTPUT
            MOVB     #$FF,$0025      ; Set port-H OUTPUT
****************
* INTITIALISE LCD
****************
        ;PREPARE FOR RESET
            LDAB     #%00110110      ;(Rst=OFF,COM=off,E=ON,R=OFF,W=OFF)
            STAB     PORTH           ;CONTROL OUTPUT
            JSR      DELAY50
        ;SET RESET ON FOR SIX CYCLES
            LDAB     #%00010110      ;(Rst=ON,COM=off,E=ON,R=OFF,W=OFF)
            STAB     PORTH           ;CONTROL OUTPUT
            JSR      DELAY50
        ;SET RESET OFF
            LDAB     #%00110110      ;(Rst=OFF,COM=off,E=ON,R=OFF,W=OFF)
            STAB     PORTH           ;CONTROL OUTPUT
            JSR      DELAY50
        ;SET ENABLE OFF
            LDAB     #%00111110      ;(Rst=OFF,COM=off,E=OFF,R=OFF,W=OFF)
            STAB     PORTH           ;CONTROL OUTPUT
;**********************************
```

```
;*Set GRAPHICS HOME address at $0000
;***********************************
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$00                ;WRITE LS BYTE DATA OF #$0000
                JSR     WR_DATA
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$00                ;WRITE MS BYTE DATA OF #$0000
                JSR     WR_DATA
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$42                ;WRITE COMMAND
                JSR     WR_COMND
;**************************
;*Set GRAPHICS AREA SET - $0010
;**************************
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$10                ;WRITE 1ST BYTE DATA OF #$0010
                JSR     WR_DATA
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$00                ;WRITE 2ND BYTE DATA OF #$0010
                JSR     WR_DATA
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$43
                JSR     WR_COMND
;*******************************
;*Set TEXT HOME address AT $0400
;*******************************
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$00                ;WRITE 1ST BYTE DATA OF #$0400
                JSR     WR_DATA
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$04                ;WRITE 2ND BYTE DATA OF #$0400
                JSR     WR_DATA
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$40
                JSR     WR_COMND
;***************************
;*Set TEXT AREA SET - $0010
;***************************
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$10                ;WRITE 1ST BYTE DATA OF #$0010
                JSR     WR_DATA
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$00                ;WRITE 2ND BYTE DATA OF #$0010
                JSR     WR_DATA
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$41
                JSR     WR_COMND
;**************************
;*Set MODE SET
;**************************
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #%10000000          ;"OR" MODE
                JSR     WR_COMND
;**************************
;*Set DISPLAY MODE
;**************************
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #%10011100          ;($98),GRAPH=ON,TEXT=ON,CURSOR=OFF
                JSR     WR_COMND
;***********************
;* Print Welcome on LCD
;***********************
                JSR     CLR_PLOT
                JSR     CLR_SCREEN
                LDD     #$0000
                STD     ADDPNT_M
                JSR     SET_ADD_PNT         ;POINTER ADDRESS
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$B0                ;AUTO WRITE MODE ON
                JSR     WR_COMND
                LDY     #$F59D              ;STARTING ADDRESS OF GRAPH DATA
                LDx     #1024               ;1024 POSITIONS
LOP_1B:         pshx
                JSR     ST_CH_2             ;READ STATUS 2
                LDAA    0,Y
                JSR     WR_DATA
                INY
                pulx
                dex
                CPx     #$00
                BHI     LOP_1B
                JSR     ST_CH_2             ; READ STATUS 2
                LDAA    #$B2                ; AUTO WRUTE MODE RESET
                JSR     WR_COMND
LOOPG           BRA     LOOPG               ; Continuously repeat, END
;*************************************
;*      SUBRUTINE: DELAY50
;*      INFO:       Delay for 50ms
;*      PASS:       No
```

```
;*      RETURNE:   No
;****************************************
DELAY50:        LDX     #65000          ;50 msec execution time
LOOP50:         DEX
                CPX     #$00
                BHI     LOOP50
                LDX     #REGBS
                RTS
;****************************************
;*      SUBRUTINE: DELAY_01
;*      INFO:      Delay for 50ms
;*      PASS:      No
;*      RETURNE:   No
;****************************************
DELAY_01:       LDX     #1300           ;1 msec execution time
LOOP_010:       DEX
                CPX     #$00
                BHI     LOOP_010
                LDX     #REGBS
                RTS
;****************************************
;*      SUBRUTINE: DELAY01
;*      INFO:      Wait for 100usec
;*      PASS:      No
;*      RETURNE:   No
;****************************************
DELAY01:        LDX     #325            ; 100 usec execution time
LOOP25:         DEX
                CPX     #$00
                BHI     LOOP25
                RTS
;****************************************
;*      SUBRUTINE: DELAY02
;*      INFO:      Wait for 770usec
;*      PASS:      No
;*      RETURNE:   No
;****************************************
DELAY02:        LDX     #1000           ; 770 usec execution time
LOOP77:         DEX
                CPX     #$00
                BHI     LOOP77
                RTS
****************************************
* Subroutine:  CHAR_STR
* Description: This subroutine prints
*              a character string
****************************************
CHAR_STR:       LDD     #$0430          ;start at 3rd line
                STD     ADDPNT_M
                JSR     SET_ADD_PNT
                JSR     ST_CHECK        ;READ STATUS
                LDAA    #$B0            ;AUTO WRITE MODE ON
                JSR     WR_COMND
TXT_LOOP:       LDAA    0,Y
                CMPA    #$FF
                BEQ     TXT_END1
                JSR     ST_CH_2         ;READ STATUS 2
                LDAA    0,Y
                JSR     WR_DATA
                INY
                BRA     TXT_LOOP
TXT_END1:       JSR     ST_CH_2         ;READ STATUS 2
                LDAA    #$B2            ;AUTO WRUTE MODE RESET
                JSR     WR_COMND
                RTS
;*******************************************************
;*      SUBRUTINE: ST_CH_2
;*      INFO:      Status check 2
;*******************************************************
ST_CH_2:        MOVB    #$00,$0006              ; Set port-A INPUT
                LDX     #$0000
                BSET    #$24,X,#%00010000       ;SET COM OFF (1)
                BCLR    #$24,X,#%00000100       ;SET RD ON (0)
                BCLR    #$24,X,#%00001000       ;SET CE ON (0)
LOOP_N2:        LDAA    PORTC
                ANDA    #%00001000
                CMPA    #%00001000
                BNE     LOOP_N2
                BSET    #$24,X,#%00001000       ;SET CE OFF (1)
                BSET    #$24,X,#%00000100       ;SET RD OFF (1)
                MOVB    #$FF,$0006              ;Set port-A OUTPUT
                RTS
;*******************************************************
;*      SUBRUTINE: ST_CHECK
;*      INFO:      Status check
;*******************************************************
ST_CHECK:       MOVB    #$00,$0006              ;Set port-A INPUT
                LDX     #$0000
                BSET    #$24,X,#%00010000       ;SET COM OFF (1)
```

```
LOOP_N1:        BCLR    #$24,X,#%00000100       ;SET RD ON (0)
                BCLR    #$24,X,#%00001000       ;SET CE ON (0)
                NOP
                NOP
                NOP
                LDAA    PORTC
                BSET    #$24,X,#%00001000       ;SET CE OFF (1)
                BSET    #$24,X,#%00000100       ;SET RD OFF (1)
                ANDA    #%00000011
                CMPA    #%00000011
                BNE     LOOP_N1
                MOVB    #$FF,$0006              ;Set port-A OUTPUT
                RTS
;********************************************************
;*      SUBRUTINE: WR_DATA
;*      INFO:      Write data
;********************************************************
WR_DATA:        LDX     #$0000
                STAA    PORTC                   ;DATA OUTPUT
                BCLR    #$24,X,#%00010000       ;SET COM=OFF (0)
                nop
                BCLR    #$24,X,#%00001000       ;SET CE=ON (0)
                nop
                BCLR    #$24,X,#%00000010       ;SET WR=ON (0)
                nop
                nop
                NOP
                NOP
                BSET    #$24,X,#%00000010       ;SET WR=OFF (1)
                nop
                BSET    #$24,X,#%00001000       ;SET CE=OFF (1)
                BSET    #$24,X,#%00010000       ;SET COM  (1)
                RTS
;***************************************
;*      SUBRUTINE: WR_COMND
;*      INFO:      Write command
;***************************************
WR_COMND:       LDX     #$0000
                STAA    PORTC                   ;DATA OUTPUT
                BSET    #$24,X,#%00010000       ;SET COM=ON (1)
                nop
                BCLR    #$24,X,#%00001000       ;SET CE=ON (0)
                nop
                BCLR    #$24,X,#%00000010       ;SET WR=ON (0)
                nop
                nop
                NOP
                BSET    #$24,X,#%00000010       ;SET WR=OFF (1)
                nop
                NOP
                BSET    #$24,X,#%00001000       ;SET CE=OFF (1)
                RTS
;***************************************
;*      SUBRUTINE: SET_ADD_PNT
;*      INFO:      Set ADDRESS POINTER
****************************************
SET_ADD_PNT:    JSR     ST_CHECK        ;READ STATUS
                LDAA    ADDPNT_L
                JSR     WR_DATA
                JSR     ST_CHECK        ;READ STATUS
                LDAA    ADDPNT_M
                JSR     WR_DATA
                JSR     ST_CHECK        ;READ STATUS
                LDAA    #$24
                JSR     WR_COMND
                RTS
;***************************************
;*      SUBRUTINE: CLR_SCREEN
;*      INFO:      Set ADDRESS POINTER
****************************************
CLR_SCREEN:     LDD     #$0400
                STD     ADDPNT_M
                JSR     SET_ADD_PNT
                JSR     ST_CHECK        ;READ STATUS
                LDAA    #$B0            ;AUTO WRITE MODE ON
                JSR     WR_COMND
                LDx     #128            ;128 POSITIONS = 16 X 8
LOOP_B1:        pshx
                JSR     ST_CH_2         ;READ STATUS 2
                LDAA    #$00
                JSR     WR_DATA
                pulx
                dex
                CPx     #$00
                BHI     LOOP_B1
                JSR     ST_CH_2         ;READ STATUS 2
                LDAA    #$B2            ;AUTO WRUTE MODE RESET
                JSR     WR_COMND
                RTS
```

```
;***************************************
;*      SUBRUTINE: CLR_PLOT
;*      INFO:      Set ADDRESS POINTER
;***************************************
CLR_PLOT:       LDD     #$0000
                STD     ADDPNT_M
                JSR     SET_ADD_PNT
                JSR     ST_CHECK            ;READ STATUS
                LDAA    #$B0                ;AUTO WRITE MODE ON
                JSR     WR_COMND
                LDx     #1024               ;1024 POSITIONS = 16 X 64
LOPO_B1:        pshx
                JSR     ST_CH_2             ;READ STATUS 2
                LDAA    #$00
                JSR     WR_DATA
                pulx
                dex
                CPx     #$00
                BHI     LOPO_B1
                JSR     ST_CH_2             ;READ STATUS 2
                LDAA    #$B2                ;AUTO WRUTE MODE RESET
                JSR     WR_COMND
                RTS
;****************************
;*              END OF CODE
;****************************
                ORG     $FBFE               ; Reset vector address
                DW      START               ; Code starting address

                ;ORG    $F200
        FCB     $0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0
        FCB     $7f,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$fe
        FCB     $40,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $40,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $40,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $40,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$ff,$fd,$fe,$ff,$ff,$c0,$0,$0,$0,$0,$0,$c,$0,$0,$2
        FCB     $43,$ff,$fd,$fe,$80,$0,$40,$0,$0,$0,$0,$0,$c,$0,$0,$2
        FCB     $43,$ff,$fd,$fe,$80,$0,$40,$0,$0,$0,$0,$0,$c,$0,$0,$2
        FCB     $43,$80,$5,$fe,$80,$0,$40,$0,$0,$0,$0,$0,$c,$0,$0,$2
        FCB     $43,$80,$5,$fe,$40,$0,$40,$7e,$1f,$f0,$7f,$f0,$ff,$c3,$ff,$82
        FCB     $43,$80,$4,$e3,$40,$0,$41,$ff,$1f,$f8,$7f,$f0,$ff,$c3,$ff,$82
        FCB     $43,$80,$2,$c3,$40,$0,$41,$c3,$98,$1c,$60,$0,$c,$3,$0,$2
        FCB     $43,$80,$2,$99,$40,$0,$43,$1,$d8,$c,$60,$0,$c,$3,$0,$2
        FCB     $43,$80,$2,$d9,$40,$0,$47,$0,$d8,$c,$60,$0,$c,$3,$0,$2
        FCB     $43,$80,$2,$c3,$40,$0,$46,$0,$18,$1c,$60,$0,$c,$3,$0,$2
        FCB     $43,$87,$1e,$e7,$4e,$dc,$46,$0,$1f,$f8,$7f,$e0,$0,$3,$ff,$2
        FCB     $43,$8e,$3c,$fe,$ca,$d4,$46,$0,$1f,$f0,$7f,$e0,$0,$3,$ff,$2
        FCB     $43,$b2,$c5,$fe,$8a,$d4,$46,$0,$18,$60,$60,$0,$0,$3,$0,$2
        FCB     $43,$cb,$15,$fe,$8b,$f4,$46,$0,$18,$70,$60,$0,$0,$3,$0,$2
        FCB     $43,$a2,$c5,$fe,$88,$4,$47,$0,$d8,$30,$60,$0,$0,$3,$0,$2
        FCB     $43,$9a,$35,$fe,$88,$4,$43,$1,$98,$38,$60,$0,$0,$3,$0,$2
        FCB     $43,$96,$2d,$fe,$44,$8,$43,$c3,$98,$1c,$60,$0,$0,$3,$0,$2
        FCB     $43,$80,$2,$ff,$44,$8,$41,$ff,$18,$c,$7f,$f0,$0,$3,$ff,$82
        FCB     $43,$80,$2,$f7,$44,$8,$40,$7e,$18,$e,$7f,$f0,$0,$3,$ff,$82
        FCB     $43,$80,$2,$e7,$44,$c8,$40,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$80,$2,$c7,$44,$c8,$40,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$80,$4,$83,$44,$c8,$40,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$80,$5,$82,$84,$c8,$40,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$83,$15,$92,$84,$8,$40,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$86,$75,$82,$84,$8,$40,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$8d,$d5,$c2,$84,$8,$40,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$8f,$34,$e6,$44,$4,$40,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$f8,$f4,$e7,$48,$4,$40,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $43,$c0,$ea,$e7,$48,$c4,$40,$0,$80,$0,$40,$0,$0,$a,$80,$2
        FCB     $43,$a0,$a,$e7,$49,$24,$40,$1,$40,$0,$40,$0,$0,$a,$80,$2
        FCB     $43,$b5,$ca,$ff,$49,$24,$40,$1,$47,$8e,$51,$38,$e5,$a,$80,$2
        FCB     $43,$9f,$1a,$ff,$49,$24,$40,$1,$44,$51,$51,$45,$16,$a,$80,$2
        FCB     $41,$c6,$14,$ff,$49,$24,$80,$2,$24,$4f,$4a,$31,$f4,$a,$80,$2
        FCB     $41,$df,$f5,$fe,$8f,$3c,$80,$3,$e4,$51,$4a,$9,$4,$a,$80,$2
        FCB     $40,$fc,$5,$fe,$80,$1,$0,$4,$14,$53,$44,$45,$14,$a,$80,$2
        FCB     $40,$e0,$5,$fe,$80,$1,$0,$4,$14,$4d,$44,$38,$e4,$a,$80,$2
        FCB     $40,$70,$5,$fe,$80,$2,$0,$0,$0,$0,$4,$0,$0,$0,$0,$2
        FCB     $40,$70,$4,$fe,$80,$2,$0,$0,$0,$0,$8,$0,$0,$0,$0,$2
        FCB     $40,$38,$2,$ff,$40,$4,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $40,$1c,$2,$e3,$40,$8,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $40,$e,$2,$c1,$40,$10,$0,$0,$0,$18,$0,$0,$0,$0,$0,$2
        FCB     $40,$7,$2,$c1,$40,$20,$0,$0,$0,$e7,$0,$0,$0,$0,$0,$2
        FCB     $40,$3,$82,$c1,$40,$40,$0,$0,$1,$0,$80,$e3,$8e,$8,$0,$2
        FCB     $40,$1,$e4,$c3,$40,$80,$0,$0,$2,$38,$41,$14,$51,$18,$0,$2
        FCB     $40,$0,$fd,$e6,$81,$0,$0,$0,$4,$44,$20,$14,$51,$28,$0,$2
        FCB     $40,$0,$7d,$fe,$82,$0,$0,$0,$4,$40,$20,$14,$51,$28,$0,$2
        FCB     $40,$0,$1d,$fe,$8c,$0,$0,$0,$4,$40,$20,$24,$51,$48,$0,$2
        FCB     $40,$0,$d,$fe,$b0,$0,$0,$0,$4,$44,$20,$44,$51,$7c,$0,$2
        FCB     $40,$0,$1,$fe,$c0,$0,$0,$0,$2,$38,$40,$84,$51,$8,$0,$2
        FCB     $40,$0,$0,$fe,$0,$0,$0,$0,$1,$0,$81,$f3,$8e,$8,$0,$2
        FCB     $40,$0,$0,$3c,$0,$0,$0,$0,$0,$e7,$0,$0,$0,$0,$0,$2
        FCB     $40,$0,$0,$0,$0,$0,$0,$0,$0,$18,$0,$0,$0,$0,$0,$2
        FCB     $40,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
```

```
        FCB     $40,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $40,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $40,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$2
        FCB     $7f,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$ff,$fe
        FCB     $0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0,$0
```

B.7. I^2C serial EEPROM

```
****************************************************************
*               School of Engineering
*       The Robert Gordon University, Aberdeen
****************************************************************
*           File name:     memory.asm
*           Author:        KONSTANTINOS CHRISTIDIS
*           Created:       13/5/2004
****************************************************************
*                   M68HCS12  Assembler Source File
*           PORT F - [xxxx xx(C)(D)], Memory module
************************************************************
                ORG     $F000               ; Starting Address in-chip EEPROM
COPCTL          EQU     $0016               ; COP Control Register
PORTF           EQU     $0030               ; Memory module
;**************************
POINTER         EQU     $0870
;*              STORE DATA          $0872-76, 77-7B, 7C-80, (80)
;******************************
;* Initialisation - Set variables
;******************************
START:          CLR     COPCTL              ; Clear COP
                LDS     #$0BFF              ; Set stac register
;**************
;* Set I/O ports
;**************
                MOVB    #$FF,$0032          ; Set port-F OUTPUT
;**************************************
;* Write number #10 into Memory module
;**************************************
                LDD     #10
                JSR     WR_MODULE
LOOPG           BRA     LOOPG               ; Continuously repeat, END

;**************************************************
;*      SUBRUTINE: MEM_PC
;*      INFO:      Setting the memory address for sample
;*      PASS:      -
;*      RETURNE:   -
;**************************************************
SHORT_ADD:      CLRA
                LDAB    SAMP_MEM ; A:B = 0:SAMPLE
                LDY     #1000
                EMUL
                STD     MEM_ADD_M           ; Memory Address Counter
                ADDD    #OFFSET
                STD     ADD_OFST
                RTS
;************************************
;*      SUBRUTINE: DELAY50
;*      INFO:      Delay for 50ms
;*      PASS:      No
;*      RETURNE:   No
;************************************
DELAY50:        LDX     #65000              ;50 msec execution time
LOOP50:         DEX
                CPX     #$00
                BHI     LOOP50
                LDX     #REGBS
                RTS
;************************************
;*      SUBRUTINE: DELAY01
;*      INFO:      Wait for 100usec
;*      PASS:      No
;*      RETURNE:   No
;************************************
DELAY01:        LDX     #325                ; 100 usec execution time
LOOP25:         DEX
                CPX     #$00
                BHI     LOOP25
                RTS
;************************************
```

```
;*      SUBRUTINE: DELAY02
;*      INFO:      Wait for 770usec
;*      PASS:      No
;*      RETURNE:   No
;**************************************
DELAY02:        LDX     #1000           ; 770 usec execution time
LOOP77:         DEX
                CPX     #$00
                BHI     LOOP77
                RTS
*****************************************
* Subroutine:  WR_MODULE
* Description: Write result to mem. module
*****************************************
WR_MODULE:      LDX     #REGBS
                JSR     STRTBIT         ;GOTO STRTBIT SUBROUTINE
                LDAA    #%10100000      ;LOAD CONTROL BYTE INTO
                STAA    TXBUFF          ;TXBUFF FOR OUTPUT TO SEEPROM
                JSR     TXBYTE          ;OUTPUT 1 BYTE TO SEEPROM
                LDAA    MEM_ADD_M       ;GET MSB ADDRESS AND LOAD IN
                STAA    TXBUFF          ;TXBUFF FOR OUTPUT
                JSR     TXBYTE          ;OUTPUT 1 BYTE TO SEEPROM
                LDAA    MEM_ADD_L       ;GET LSB ADDRESS AND LOAD IN
                STAA    TXBUFF          ;TXBUFF FOR OUTPUT
                JSR     TXBYTE          ;OUTPUT 1 BYTE TO SEEPROM
                LDAA    SAMPLE_M        ;DATA BYTE TO OUTPUT IS $A5
                STAA    TXBUFF
                JSR     TXBYTE          ;OUTPUT 1 BYTE TO SEEPROM
                LDAA    SAMPLE_L        ;DATA BYTE TO OUTPUT IS $A5
                STAA    TXBUFF
                JSR     TXBYTE          ;OUTPUT 1 BYTE TO SEEPROM
                JSR     STOPBIT         ;SEND STOP BIT TO BEGIN INTERNAL WRITE CYCLE
                RTS
*****************************************
* Subroutine:  STARTBIT
* Description: Start bit output subroutine
*****************************************
STRTBIT:        LDAA    #%00000111
                STAA    DDRF            ;PORT C ALL INPUTS EXCEPT BITS 0,1,2
                LDAA    #CHIDHI         ;SET SCLK AND SDATA HI
                STAA    PORTF
                NOP                     ;OBEY PROPER START BIT SETUP TIME
                NOP
                NOP
                NOP
                NOP
                BCLR    PFOFF,X,#SDAMASK ;SET DATA LOW FOR STOP BIT
                NOP                     ;OBEY PROPER START BIT HOLD TIME
                NOP
                NOP
                NOP
                BCLR    PFOFF,X,#SCKMASK ;SET CLK LO
                RTS                     ;END START BIT SUBROUTINE
*****************************************
* Subroutine:  STOPBIT
* Description: Stop bit output subroutine
*****************************************
STOPBIT:        LDAA    #%00000111
                STAA    DDRF            ;PORT C ALL INPUTS EXCEPT FOR BITS 0,1
                BCLR    PFOFF,X,#SDAMASK ;MAKE SURE DATA BIT IS LOW
                BSET    PFOFF,X,#SCKMASK ;CLK BIT HI
                NOP                     ;OBEY PROPER STOP BIT SETUP TIME
                NOP
                NOP
                NOP
                BSET    PFOFF,X,#SDAMASK ;DATA BIT HI CAUSES STOP BIT
                RTS                     ;END STOP BIT SUBROUTINE
*****************************************
* Subroutine:  INBIT
* Description: This routine reads in one
*                  bit from the data line
*****************************************
INBIT:          LDAA    #%00000110              ;SET SDATA AS INPUT AND KEEP
                STAA    DDRF                    ;SCLK AS OUTPUT
                CLR     EE_IN                   ;GUESS INPUT IS A 0
                BSET    PFOFF,X,#SCKMASK        ;SET CLK BIT HI
                NOP                             ;WAIT TO READ INPUT
                LDAA    PORTF                   ;GET INPUT FROM SDATA
                BCLR    PFOFF,X,#SCKMASK        ;BRING CLK LO AFTER PORT READ
                BITA    #DIMASK                 ;SEE IF INPUT IS 1 OR 0
                BEQ     DONEIN                  ;INPUT IS A ZERO
                LDAA    #$FF                    ;INPUT BIT IS ACTUALLY A 1
                STAA    EE_IN                   ;STORE BACK IN EE_IN
DONEIN:         RTS
*****************************************
* Subroutine:  OUTBIT
* Description: This routine writes out one
*              bit to the sdata line
*****************************************
```

```
OUTBIT:         LDAA    #%00000111
                STAA    DDRF                    ;BOTH CLK AND DATA ARE OUTPUTS
                LDAA    TXBUFF                  ;WHAT ARE WE TRYING TO OUTPUT,
                BITA    #DOMASK                 ;A 1 OR 0?
                BEQ     LOWOUT                  ;EE_OUT BIT IS 0
                BSET    PFOFF,X,#SDAMASK        ;HIGH NEEDS TO BE SENT OUT
                BRA     CONTOUT
LOWOUT:         BCLR    PFOFF,X,#SDAMASK        ;SEND OUT A LOW
CONTOUT: BSET   PFOFF,X,#SCKMASK                ;SET CLOCK BIT
                NOP                             ;WAIT PROPER SCLK HI TIME
                NOP
                BCLR    PFOFF,X,#SCKMASK        ;CLR CLOCK BIT AND THEN
                BCLR    PFOFF,X,#SDAMASK        ;SET DATA BIT TO 0 FOR NEXT TX
                RTS
*****************************************
* Subroutine:   TXBYTE
* Description: This routine outputs 1 byte
*               of data out the sdata pin
*****************************************
TXBYTE:         LDAB    #8                      ;SET BIT COUNTER
TXBIT:          JSR     OUTBIT                  ;SEND 1 BIT
                ROL     TXBUFF                  ;GET NEXT BIT READY TO XMIT
                DECB
                CMPB    #$00                    ;HAVE WE OUTPUT ALL 8 BITS
                BNE     TXBIT                   ;NO, THEN SEND NEXT BIT
                JSR     INBIT                   ;RECEIVE ACK BIT
                LDAA    EE_IN
                BITA    #DIMASK                 ;TEST IF INPUT IS 0 OR 1
                BEQ     DONETX                  ;IF ACK IS LOW, GO TO END OF TXBYTE
                BSET    PFOFF,X,#LEDMASK        ;TURN ON ACK FAILED LED
DONETX:         RTS
*****************************************
* Subroutine:   RXBYTE
* Description: This subroutine receives
*               1 byte from SEEPROM
*****************************************
RXBYTE:         LDAB    #8              ;LOAD BIT COUNTER IN ACCB
RXBIT:          ROL     RXBUFF          ;GET READY TO RECEIVE NEXT BIT
                LDAA    RXBUFF          ;GUESS THAT INPUT BIT IS 0
                ANDA    #%11111110
                STAA    RXBUFF          ;WRITE ACCA BACK TO RXBUFF
                JSR     INBIT           ;RECIEIVES 1 BIT
                LDAA    EE_IN           ;IS IN BIT A 1 OR A 0?
                BITA    #DIMASK
                BEQ     CONTRX
                LDAA    RXBUFF          ;GET RXBUFF INPUT
                ORAA    #%00000001      ;SET INPUT BIT TO 1
                STAA    RXBUFF
CONTRX:         DECB
                CMPB    #$00            ;HAVE WE OUTPUT ALL 8 BITS
                BNE     RXBIT           ;NO, THEN SEND NEXT BIT
                RTS
;****************************
;*              END OF CODE
;****************************
                ORG     $FBFE           ;Reset vector address
                DW      START           ;Code starting address
```

B.8. Program Vr.1.01

```
***************************************************************
*               School of Engineering
*       The Robert Gordon University, Aberdeen
***************************************************************
*               File name:   pr_vr101.asm
*               Author:      KONSTANTINOS CHRISTIDIS
*               Created:     07/04/2005
***************************************************************
*                       M68HCS12  Assembler Source File
* Description : System operation (for prototype)
*
*                PON=50mS and POFF=70ms
*                Range:-1.4 to +1.0V
***************************************************************
* LCD:          PORT H - [DDDD DDDD], DATA for LCD
*               PORT P - [xXXC CCxx], CONTROL FOR LCD
*               PORT P - [xccC CCxx], CONTROL FOR LCD
*
* KEYPAD:       PORT M - [XXX(<) (E)(>)XX] 3bits Input KEYPAD
* SWEATCH:      PORT M5 - ON=PC, OFF=GPS
* DAC:          PORT B - [DDDD DDDD], LSB DATA for DAC
*               PORT K - [xXXX DDDD], MSB DATA for DAC
* ADC:          PORT A   - [DDDD DDDD], MSB DATA for ADC
*               PORT AD1 - [DDDD DDDD], LSB DATA for ADC
```

```
*           PORT P7  - CONTROL DATA for ADC
* GAIN:     PORT T - [XXAB CXXX] 3bits Input KEYPAD
* SCI:      PORT S
* MEMORY:   PORT J - [XXXX XX,CLK,DATA], I2C MEMORY MODULE
* RELAYS:   PORT K - [XX(S2)(S1) XXXX], CONTROL FOR RELAYS
*******************************************************************

COPCTL          EQU     $003C           ; COP Control Register
******************************************
* STARTING ADDRESS FOR DATA
******************************************
                ORG     $3700           ; DATA: RAM starting address
************
* I/O PORTS
************
PORTAD1         EQU     $012F           ; ADC: LSB DATA
ENBL_AD1 EQU    $012D
PORTA           EQU     $0000           ; ADC: MSB DATA
DDRA            EQU     $0002
PORTB           EQU     $0001           ; DAC: LSB DATA
DDRB            EQU     $0003
PORTK           EQU     $0032           ; DAC: MSB DATA
DDRK            EQU     $0033
PORTM           EQU     $0250
DDRM            EQU     $0252           ; KEYPAD: 3-BIT DATA
PORTH           EQU     $0260           ; LCD: 8-BIT DATA
DDRH            EQU     $0262
PORTP           EQU     $0258           ; LCD:3-BIT CONTROL
DDRP            EQU     $025A
PORTT           EQU     $0240           ; GAIN: 3-BIT DATA
DDRT            EQU     $0242
PORTJ           EQU     $0268           ; MEMORY
DDRJ            EQU     $026A
PORTS           EQU     $0248
DDRS            EQU     $024A
PORTAD0         EQU     $008F           ; build in ADC
********
* SCI-0
********
SC0BDH          EQU     $00C8           ; SCI Baud Rate Control Register High
SC0BDL          EQU     $00C9           ; SCI Baud Rate Control Register Low
SC0CR1          EQU     $00CA           ; SCI Control Register 1
SC0CR2          EQU     $00CB           ; SCI Control Register 2
SC0SR1          EQU     $00CC           ; SCI Status Register 1
SC0SR2          EQU     $00CD           ; SCI Status Register 2
SC0DRH          EQU     $00CE           ; SCI Data Register High
SC0DRL          EQU     $00CF           ; SCI Data Register Low
BIT1            EQU     %00000010       ; SCI - TXD0
BIT0            EQU     %00000001       ; SCI - RXD0
BIT5            EQU     %00100000       ; SCI
BIT7            EQU     %10000000       ; SCI
BIT32           EQU     %00001100       ; SCI
***********
* DAC DATA
***********
VOLT_M          DB      #0              ;$3000: Voltage variable for DAC (MSByte)
VOLT_L          DB      #0              ;$3001: Voltage variable for DAC (LSByte)
VOLT_M_AUX      DB      #0              ;Voltage var. to support Sensor MASK control
VOLT_L_AUX      DB      #0              ;Voltage var. to support Sensor MASK control
***********
* ADC DATA
***********
SMP_16M         DW      #0              ;$0802: ADC sample storage (MSWord)
SMP_16L         DW      #0              ;
SAMPLE_M DW     #0
*********************
* NUMBER TO CHARACTER
*********************
DIGIT1          DB      #0              ;$0804: 1st Digit Number Address (LSB)
DIGIT2          DB      #0              ;$0805: 2nd Digit Number Address
DIGIT3          DB      #0              ;$0806: 3rd Digit Number Address
DIGIT4          DB      #0              ;$0807: 4th Digit Number Address
DIGIT5          DB      #0              ;$0808: 5th Digit Number Address (MSB - 16bits)
RESULTS         DW      #0              ;$0809: 16 bits result Address (for division)
****************
* PEAK ALGORITHM
****************
AMPLITUDE       DW      #0              ;$080B: PEAK CURRENT
COUNTER         DW      #0              ;$080D: Counter (sample point)????????????
**************************
* CONVERT TO UNSIGNED NUMBER
**************************
ADD_M           DB      #0              ;$0810: Aux address for pos - neg shift (MSB)
ADD_L           DB      #0              ;$0811: Aux address for pos - neg shift (LSB)
*****************
* CHARACTERISATION
*****************
***********
* DBASE-GCE
```

```
************
PBMAX       DW    #9500       ; Pb max rng (14000-5250=8750, +750=9250)
PBMIN       DW    #8000       ; Pb min rng (14000-5250=8750, -750=8000)
CDMAX       DW    #6860       ; Cd max rng (14000-7740=6260, +600=6860)
CDMIN       DW    #5660       ; Cd min rng (14000-7740=6260, -600=5660)
HGMAX       DW    #15570      ; Hg max rng (14000+1270=15270, +250=15570)
HGMIN       DW    #15020      ; Hg min rng (14000+1270=15270, -250=15020)
ZNMAX       DW    #4200       ; Zn max rng (14000-10400=3600, +750=4350)
ZNMIN       DW    #3000       ; Zn min rng (14000-10400=3600, -750=2850)
NI1MAX      DW    #6760       ; Ni1 max rng (14000-8540=5460, +1300=6760)
NI1MIN      DW    #4160       ; Ni1 min rng (14000-8540=5460, -1300=4160)
NI2MAX      DW    #15190      ; Ni2 max rng (14000-310=13690, +1500=15190)
NI2MIN      DW    #12190      ; Ni2 min rng (14000-310=13690, -1500=12190)
CU1MAX      DW    #6140       ; Cu1 max rng (14000-8610=5390, +1250=6640)
CU1MIN      DW    #4640       ; Cu1 min rng (14000-8610=5390, -1250=4140)
CU2MAX      DW    #10840      ; Cu2 max rng (14000-3410=10590, +250=10840)
CU2MIN      DW    #10340      ; Cu2 min rng (14000-3410=10590, -250=10340)
CU3MAX      DW    #13530      ; Cu3 max rng (14000-1220=12780, +750=13530)
CU3MIN      DW    #12030      ; Cu3 min rng (14000-1220=12780, -750=12030)
CHR_FLG     DB    #0          ; Characterisation flag
POTEN       DW    #0          ;$0820: 16 bit Potential variable
COUNTMAX DW #0                ;$0822: 16 bit Max Counter (potential)
SINFLAG     DB    #0          ;$0824: Ditermination of sign OFF=-
PEAK        DB    #0          ;$0825:
C_SMP16M DW #0                ;$0826: Varible for current sample
C_SMP16L DW #0                ;
CNT_ADDR    DW    #0          ;$0828: 16 bit Address counter
TIMER_60 DW #0                ;$082A: 16 bit Timer variable for deposition
************
* I2C COMMS
************
PFOFF       EQU   $0030       ;OFFSET FROM CONTROL REG BEG.
DDRF        EQU   $0032       ;F PORT DIRECTION REGISTER.
REGBS       EQU   $0000       ;REGISTER BASE ADDRESS.
TXBUFF      DB    #0          ;$082C
EE_IN       DB    #0          ;$082D
MEM_ADD_M   DB    #0          ;$082E
MEM_ADD_L   DB    #0          ;$082F
RXBUFF      DB    #0          ;$0830
MEM_DATA_M  DB    #0          ;$0831
MEM_DATA_L  DB    #0          ;$0832
CNT_2       DW    #0          ;$0833
CHIDHI      EQU   %00000011   SET BOTH CLK AND DATA HI
CHIDLO      EQU   %00000010   SET CLK HI AND DATA LO
CLODHI      EQU   %00000001   SET CLK LO AND DATA HI
CLODLO      EQU   %00000000   SET CLK AND DATA BOTH LO
DIMASK      EQU   %00000001   BIT MASK FOR DATA IN BIT
DOMASK      EQU   %10000000   BIT MASK FOR DATA OUT BIT
SDAMASK     EQU   %00000001   BIT MASK FOR SERIAL DATA
SCKMASK     EQU   %00000010   BIT MASK FOR SERIAL CLOCK
LEDMASK     EQU   %00000100   BIT MASK FOR ACK FAILED LED
OFFSET      EQU   #900
P_2         DB    #0          ;$0835
A_MIN       DW    #0          ;$0836
A_MIN_1     DW    #0          ;$0838
MINPOS      DW    #1          ;$083A
MINPOS_1 DW #1                ;$083C
P_FLAG      DW    #0          ;$083E
CNT_X       DW    #1          ;$0840
I           DW    #0          ;$0842
DATA_1      DW    #0          ;$0844
DATA_2      DW    #0          ;$0846
DATA_3      DW    #0          ;$0848
DATA_4      DW    #0          ;$084A
OLD_DATA DW #0                ;$084C
MIN         DW    #0          ;$084E
MAX         DW    #0          ;$0850
MIN_1       DW    #0          ;$0852
MAX_1       DW    #0          ;$0854
AMP         DW    #0          ;$0856
DEF         DW    #0          ;$0858
AV_MIN      DW    #0          ;$085A
AMP_2       DW    #0          ;$085C
FLAG        DB    #1          ;$085E
P           DB    #1          ;$085F
SAMP_MEM DB #0                ;$0860: Sample to store in memory
CNT_1       DW    #0          ;$0861
ADATA_1     DW    #0          ;$0863
ADATA_2     DW    #0          ;$0865
ADATA_3     DW    #0          ;$0867
ADATA_4     DW    #0          ;$0869
CNT_PR      DW    #0          ;$086B
F           DW    #0          ;$086D
;ALG1_THR   DW    #40         ; Threshold 4.0uA - Scr. Pr. Sensor II
ALG1_THR DW #5                ; Threshold 0.5uA - Carb. Paste Sensor
ADD_OFST DW #0                ;$086E: Base Address for counting sample
*****************
* AUTOMATIC GAIN
*****************
```

```
GN_PNT1         DB      #0
GN_PNT2         DB      #0
GAIN            DB      #0              ;$0870
GAIN0           DB      #%00000000
GAIN1           DB      #%00001000      ;$0870
GAIN2           DB      #%00010000      ;$0870
GAIN3           DB      #%00011000      ;$0870
GAIN4           DB      #%00100000      ;$0870
GAIN5           DB      #%00101000      ;$0870
GAIN6           DB      #%00110000      ;$0870
GAIN7           DB      #%00111000      ;$0870
GN_RES          DW      #0              ;$0000
GN_RES0         DW      #31623          ;$0872
GN_RES1         DW      #25914          ;$0872
GN_RES2         DW      #14698          ;$0872
GN_RES3         DW      #7722           ;$0872
GN_RES4         DW      #2959           ;$0872
GN_RES5         DW      #2322           ;$0872
GN_RES6         DW      #1722           ;$0872
GN_RES7         DW      #811            ;$0872
X_SAMPLA DW     #0                      ;$0874
X_SAMPLB DW     #0                      ;$0874
X_SAMPL0 DW     #0                      ;$0874
X_SAMPL1 DW     #0                      ;$0874
X_SAMPL2 DW     #0                      ;$0874
X_SAMPL3 DW     #0                      ;$0874
X_SAMPL4 DW     #0                      ;$0874
X_SAMPL5 DW     #0                      ;$0874
X_SAMPL6 DW     #0                      ;$0874
X_SAMPL7 DW     #0                      ;$0874
SMP_M16M DW     #0                      ;
SMP_M16L DW     #0                      ;
SAMPL_MM dw     #0                      ;
DIV_FLG1 DB     #0                      ;1=div10, 10=div1000
DIV_FLG2 DB     #0                      ;0=Less than 500.00uA,1=Higher than 500.00uA
RES_PPM         DW      #0
******************************
* ARRAY (RAM) FOR PEAK STORAGE
******************************
                ORG     $3900
POINTER         DW      #$3902          ;STORE DATA $3902-06, 07-0B, 0C-10, (00)
;*******************************************
;* STARTING ADDRESS FOR THE PROGRAM
;*******************************************
                ORG     $1000           ; PROGRAM: RAM starting address
;*******************************
;* Initialisation - Set variables
;*******************************
START:          CLR     COPCTL          ; Clear COP
                LDS     #$3BFF          ; Set stac register
;***************
;* Set I/O ports
;***************
                CLR     DDRA                    ; Set port-A INPUT
                BSET    ENBL_AD1,#%11111111     ; Enable port-AD1 (INPUT)
                BSET    DDRB,#%11111111         ; Set port-B OUTPUT
                BSET    DDRK,#%00001111         ; Set port-K OUTPUT
                MOVB    #$FF,DDRH                       ; Set port-H OUTPUT
                BSET    DDRP,#%11111100         ; Set port-P OUTPUT
                BSET    DDRT,#%00111000         ; Set port-T OUTPUT
                BSET    DDRJ,#%00000011         ; Set J0,J1 OUTPUTS
                BCLR    DDRM,#%00011100         ; Set M2,M3,M4 INPUTS
                BSET    DDRM,#%00100000         ; Set M5 OUTPUT
                BSET    DDRK,#%00110000         ; Set K4,K5 OUTPUTs
;*****************
;* Initialise LCD
;*****************
                LDAA    #%00111000      ; 8bit, 2line 5x7dot
                JSR     CNTLCT
                LDAA    #%00001110      ; Display control
                JSR     CNTLCT
                LDAA    #%00000001      ; Clear LCD
                JSR     CNTLCT
                LDAA    #%00000110      ; Increment
                JSR     CNTLCT
;**********************************************
;* Parking - Initial voltage (0V)(#2048)
;* DISCONECT SENSORS
;**********************************************
                LDD     #2048
                STD     VOLT_M
                STAA    PORTK           ;S1 and S2 bits of portK are low
                STAB    PORTB
;****************************************
;* Initialise Detection Algorithm Variables
;****************************************
                LDD     #1              ;A:B=0:1
                STAA    P_2             ;p_2=0, 0-start 1-peak, 2-high/low
                STD     MINPOS          ;minpos=1;
```

```
                STD     MINPOS_1 ;minpos_1=1;
                STD     CNT_X           ;CNT_X=1;
                STAB    P               ;P=1;
                STAB    FLAG            ;FLAG=1;
                STAB    DIV_FLG2        ;Set to higher than 500uA;
                MOVW    #$3902,POINTER
                LDAA    #$FF
                LDY     POINTER
PLACES:         STAA    0,Y             ;One place (8bit) $0000
                INY
                CPY     #$39ff          ;Initialise from $3902 - $39FF
                BLO     PLACES
;*************************
;* Clear general variables
;*************************
                CLRA
                CLRB
                STD     MAX             ; Clear Maximum sample
                STD     COUNTER         ; Clear Counter
                STD     CNT_ADDR        ; Address counter
                STAA    SAMP_MEM        ; Sample to store in the memory
                STD     MEM_ADD_M       ; Memory Address Counter
;**********************************************************
; ******* Main Program ********
;**********************************************************
;***********************
;* Print Welcome on LCD
;***********************
                JSR     CLR_LCD         ; Clear LCD
                LDY     #MSG_Wa
                JSR     CHAR_STR
                JSR     LINE_LCD        ; Next line
                LDY     #MSG_Wb
                JSR     CHAR_STR
                JSR     ENT_BTN         ; Read ENTER bout-on
;*************************
;* Initialise SCI-1 to 4800
;*************************
                JSR     INIT_SCI        ; Initialise SCI
;*************************
;* Print Wait 1 min on LCD
;*************************
                JSR     CLR_LCD         ; Clear LCD
                LDY     #MSG_1a
                JSR     CHAR_STR
                JSR     LINE_LCD        ; Next line
                LDY     #MSG_1b
                JSR     CHAR_STR
;**************************************
;* Initial voltage (-1.4V)(#0901)
;**************************************
                LDD     #0901
                STD     VOLT_M
                STD     VOLT_M_AUX
                BSET    VOLT_M_AUX,#%00010000     ; Connect sensor-1 (S1)
                LDD     VOLT_M_AUX
                STAA    PORTK                     ; Sent also Control (S1=1)
                STAB    PORTB
;****************************
;* Deposition timer for 1 min
;****************************
                LDD     #60
                STD     TIMER_60        ; Clear deposition timer
LOOP6:          JSR     TIMER
                CLRA
LOOP8:          JSR     DELAY50         ; Clear time counter
                INCA
                CMPA    #15             ; 260ms + 15 x 50ms = ~1s
                BLO     LOOP8
                LDD     TIMER_60
                DECB
                STD     TIMER_60
                CMPB    #0
                BHI     LOOP6
;*************************
;* Print on LCD WORKING...
;*************************
                JSR     CLR_LCD         ; Clear LCD
                LDY     #MSG_2
                JSR     CHAR_STR
;*****************
;* REPEAT PROCESS
;*****************
;**************************************
;* GAIN CONTROL
;* Read ADC, LOW sample
;**************************************
LOOP:           JSR     GAIN_CNT
;*********************************************
```

```
;* 50 msec step up (21bits ~1.22 x 21 = 25.62mV)
;***********************************************
                LDD     VOLT_M
                ADDD    #21
                STD     VOLT_M
                STD     VOLT_M_AUX
                BSET    VOLT_M_AUX,#%00010000     ; Connect sensor-1 (S1)
                LDD     VOLT_M_AUX
                STAA    PORTK                     ; Sent also Control (S1=1)
                STAB    PORTB
                JSR     DELAY50
;*****************************************
;* GAIN CONTROL
;* Read ADC, HIGH sample
;*****************************************
                JSR     GN_CNT2
;*****************************************
;* GAIN CONTROL
;* Find best tuning
;*****************************************
                LDAA    GN_PNT2
                LSLA
                STAA    GN_PNT1
                LDY     #X_SAMPL0
                LDAA    GN_PNT1
NTXT2:          CMPA    #0
                BEQ     VELE2
                DECA
                INY
                BRA     NTXT2
VELE2:          LDD     0,Y
                STD     X_SAMPLA
                LDY     #GN_RES0
                LDAA    GN_PNT1
NTXT3:          CMPA    #0
                BEQ     VELE3
                DECA
                INY
                BRA     NTXT3
VELE3:          LDD     0,Y
                STD     GN_RES
;***********************************
;* MULTIPLY SAMPLE A WITH RESOLUTION
;***********************************
                LDD     X_SAMPLA
                LDY     GN_RES
                EMUL                    ;X_SAMPLEA*GAIN_RES*100=(Y:D)
                STD     SMP_M16L
                STY     SMP_M16M

;***********************************
;* MULTIPLY SAMPLE B WITH RESOLUTION
;***********************************
                LDD     X_SAMPLB
                LDY     GN_RES
                EMUL                    ;X_SAMPLEB*GAIN_RES*100=(Y:D)
                STD     C_SMP16L
                STY     C_SMP16M
;****************************************************
;* Calculate difference NUMBER 1 - NUMBER 2 [method II]
;****************************************************
                LDD     SMP_M16L
                SUBD    C_SMP16L
                STD     SMP_16L
                BCC     NEXT
                LDD     C_SMP16M
                ADDD    #1
                STD     C_SMP16M
NEXT:           LDD     SMP_M16M
                SUBD    C_SMP16M
                STD     SMP_16M
;*******************************************
;* Multiply sample with resolution
;*******************************************
                LDY     SMP_16M
                LDD     SMP_16L
                LDX     #10000
                EDIV                    ;(Y:D)/100=Y.D
                STY     SAMPLE_M        ;Store results
                STY     SAMPL_MM
                movb    #100,DIV_FLG1   ;Set division /100
;*****************************************
;* Sent result to PC via serial SCI-0
;*****************************************
                LDAA    #11             ; Sent byte 11 (control word to start process)
                JSR     OUT_CHAR
                LDAA    #11             ; Sent byte 11 for second time in case is lost
                JSR     OUT_CHAR
                LDAA    DIV_FLG1        ; Load first byte - gain, to transmit
```

```
        JSR     OUT_CHAR
        LDD     SAMPL_MM        ; Load 5 digit data - difference
        JSR     CONV
        LDAA    DIGIT1
        JSR     OUT_CHAR
        LDAA    DIGIT2
        JSR     OUT_CHAR
        LDAA    DIGIT3
        JSR     OUT_CHAR
        LDAA    DIGIT4
        JSR     OUT_CHAR
        LDAA    DIGIT5
        JSR     OUT_CHAR
        LDD     GN_RES          ; Load 5 digit data - difference
        JSR     CONV
        LDAA    DIGIT1
        JSR     OUT_CHAR
        LDAA    DIGIT2
        JSR     OUT_CHAR
        LDAA    DIGIT3
        JSR     OUT_CHAR
        LDAA    DIGIT4
        JSR     OUT_CHAR
        LDAA    DIGIT5
        JSR     OUT_CHAR
        LDD     X_SAMPLB        ; Load 5 digit data - difference
        JSR     CONV
        LDAA    DIGIT1
        JSR     OUT_CHAR
        LDAA    DIGIT2
        JSR     OUT_CHAR
        LDAA    DIGIT3
        JSR     OUT_CHAR
        LDAA    DIGIT4
        JSR     OUT_CHAR
        LDAA    DIGIT5
        JSR     OUT_CHAR
        LDD     X_SAMPLA        ; Load 5 digit data - difference
        JSR     CONV
        LDAA    DIGIT1
        JSR     OUT_CHAR
        LDAA    DIGIT2
        JSR     OUT_CHAR
        LDAA    DIGIT3
        JSR     OUT_CHAR
        LDAA    DIGIT4
        JSR     OUT_CHAR
        LDAA    DIGIT5
        JSR     OUT_CHAR
;***************************
;*  Peak detection algorithm
;***************************
        JSR     ALGO1
;***********************************
;* 50 sec step down (19 bit 1.22x19=23.18)
;***********************************
        LDD     VOLT_M                  ; Load current voltage potential
        SUBD    #19                     ; Add 20bits to current potential
        STD     VOLT_M                  ; Store new potential
        STD     VOLT_M_AUX
        BSET    VOLT_M_AUX,#%00010000   ; Connect sensor-1 (S1)
        LDD     VOLT_M_AUX
        STAA    PORTK                   ; Sent also Control (S1=1)
        STAB    PORTB                   ; LSB DAC output
        JSR     DELAY50                 ; Wait for 50msec
        JSR     DELAY10
        JSR     DELAY10
;*******************************
;* Counter increment by (2x1.2mV)
;*******************************
        LDD     COUNTER                 ; Add 2.4mV
        ADDD    #24
        STD     COUNTER
;***********************************
;* Counter for memory module Address
;***********************************
        LDD     MEM_ADD_M               ; Memory address increase 2 positions
        ADDD    #2
        STD     MEM_ADD_M
;****************************************
;* Check if reach potential +0.0V (2048) or +1.0V (2867)
;****************************************
        LDD     VOLT_M          ; Load current voltage potential
        CPD     #2867           ; 1.0V Step potential 2 = 1.0V
        LBLO    LOOP            ; If no, repeat process GO to LOOP
                                ; If yes, continue
;***************************
;* Terminate COMM Module
;***************************
```

```
                LDAA    #12
                JSR     OUT_CHAR
                LDAA    #12
                JSR     OUT_CHAR
;****************************
;* Disconnect Sensor-1 (CELL)
;****************************
                BCLR    PORTK,#%00010000 ; Disconnect sensor-1 (S1)
;******************************
;* Print on LCD End of Process
;******************************
                JSR     CLR_LCD          ; Clear LCD
                LDY     #MSG_3
                JSR     CHAR_STR
                jsr     ENT_BTN          ; Read ENTER bout-on
;*****************************
;* Print Ready FOR peak search
;*****************************
                JSR     CLR_LCD          ; Clear LCD
                LDY     #MSG_6a
                JSR     CHAR_STR
                JSR     LINE_LCD         ; Next line
                LDY     #MSG_6b
                JSR     CHAR_STR
                JSR     ENT_BTN          ; Read ENTER bout-on
;*************************************
;* Print on LCD Results peak & position
;*************************************
                MOVW    #$3902,POINTER
                CLR     PEAK
TR_AGAIN:       LDY     POINTER
                LDAA    0,Y
                CMPA    #$FF
                BEQ     LV_LOOP
                STAA    SINFLAG
                LDD     1,Y
                STD     POTEN
                LDD     3,Y
                STD     AMPLITUDE
                LDD     5,Y
                STD     CNT_PR
                INC     PEAK
                JSR     PRDATA           ; PRINT AMP_2 and CNT_1
                JSR     ENT_BTN          ; Read ENTER bout-on
                JSR     CHARACT          ; Print Characterisation results
                JSR     ENT_BTN          ; Read ENTER bout-on
                LDD     POINTER
                ADDD    #7
                STD     POINTER
                BRA     TR_AGAIN
LV_LOOP: LDAA   PEAK
                BEQ     NO_PEAK
                JSR     CLR_LCD          ; Clear LCD
                LDY     #MSG_3           ; End Message
                JSR     CHAR_STR
                BRA     LOOPGX
NO_PEAK: JSR    CLR_LCD                  ; Clear LCD
                LDY     #MSG_TR1         ; Print "No Analyte Match"
                JSR     CHAR_STR
LOOPGX:         JSR     ENT_BTN          ; Read ENTER bout-on
;******************************
;* Print on LCD End of Process
;******************************
                JSR     CLR_LCD          ; Clear LCD
                LDY     #MSG_3
                JSR     CHAR_STR
                jsr     ENT_BTN          ; Read ENTER bout-on
;***************
;END OF PROCESS
;***************
LOOPGQ:         BRA     LOOPGQ           ; Continuously repeat, END
;**********************************************
;* Subroutine:  GN_ADC
;*
;* Note:  Gain control for ADC
;**********************************************
GN_ADC:         STAA    PORTT
                JSR     DELAY001         ; Delay 200nsec
                JSR     READADC          ; Read ADC for gain 000
                JSR     NEGPOS           ; Negative and positive shift results on D-REGISTER
                RTS
;**********************************************
;* Subroutine:  GAIN_CNT
;*
;*      Note:  Gain control for ADC FOR FIRST SAMPLE
;**********************************************
GAIN_CNT:       MOVB    #0,GN_PNT1
                LDAA    GAIN0
                JSR     GN_ADC
```

```
                STD     X_SAMPL0        ; Store sample for gain 000
                CPD     #51491          ; +9.8(*0.8)
                LBHS    NO_GN
                CPD     #14044          ; -9.8(*0.8)
                LBLS    NO_GN
                MOVB    #1,GN_PNT1
                LDAA    GAIN1
                JSR     GN_ADC
                STD     X_SAMPL1        ; Store sample for X gain
                CPD     #43375          ; +5(*0.8)
                LBHS    NO_GN
                CPD     #22160          ; -5(*0.8)
                LBLS    NO_GN
                MOVB    #2,GN_PNT1
                LDAA    GAIN2
                JSR     GN_ADC
                STD     X_SAMPL2        ; Store sample for X gain
                CPD     #38174          ; +2.5(*0.7)
                LBHS    NO_GN
                CPD     #27361          ; -2.5(*0.7)
                LBLS    NO_GN
                MOVB    #3,GN_PNT1
                LDAA    GAIN3
                JSR     GN_ADC
                STD     X_SAMPL3        ; Store sample for X gain
                CPD     #34888          ;+0.98(*0.7)
                LBHS    NO_GN
                CPD     #30647          ;-0.98(*0.7)
                LBLS    NO_GN
                MOVB    #4,GN_PNT1
                LDAA    GAIN4
                JSR     GN_ADC
                STD     X_SAMPL4        ; Store sample for X gain
                CPD     #34358          ;+0.735(*0.7)
                LBHS    NO_GN
                CPD     #31177          ;-0.735(*0.7)
                LBLS    NO_GN
                MOVB    #5,GN_PNT1
                LDAA    GAIN5
                JSR     GN_ADC
                STD     X_SAMPL5        ; Store sample for X gain
                CPD     #33849          ; +0.5(*0.7)
                LBHS    NO_GN
                CPD     #31686          ; -0.5(*0.7)
                LBLS    NO_GN
                MOVB    #6,GN_PNT1
                LDAA    GAIN6
                JSR     GN_ADC
                STD     X_SAMPL6        ; Store sample for X gain
                CPD     #33308          ; +0.25(*0.7)
                LBHS    NO_GN
                CPD     #32227          ; -0.25(*0.7)
                LBLS    NO_GN
                MOVB    #7,GN_PNT1
                LDAA    GAIN7
                JSR     GN_ADC
                STD     X_SAMPL7        ; Store sample for X gain
NO_GN:          RTS
;*************************************************
;* Subroutine:  GN_CNT2
;*
;*      Note:   Gain control for ADC FOR SECOND SAMPLE
;*************************************************
GN_CNT2: MOVB   #0,GN_PNT2
                LDAA    GAIN0
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
                CPD     #51491          ; +9.8(*0.8)
                LBHS    NO_GN1
                CPD     #14044          ; -9.8(*0.8)
                LBLS    NO_GN1
                LDAA    GN_PNT1
                CMPA    GN_PNT2
                LBLS    NO_GN1
                MOVB    #1,GN_PNT2
                LDAA    GAIN1
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
                CPD     #43375          ; +5(*0.8)
                LBHS    NO_GN1
                CPD     #22160          ; -5(*0.8)
                LBLS    NO_GN1
                LDAA    GN_PNT1
                CMPA    GN_PNT2
                LBLS    NO_GN1
                MOVB    #2,GN_PNT2
                LDAA    GAIN2
                JSR     GN_ADC
                STD     X_SAMPLB        ; Store sample for gain 000
```

```
        CPD     #38174          ; +2.5(*0.7)
        LBHS    NO_GN1
        CPD     #27361          ; -2.5(*0.7)
        LBLS    NO_GN1
        LDAA    GN_PNT1
        CMPA    GN_PNT2
        LBLS    NO_GN1
        MOVB    #3,GN_PNT2
        LDAA    GAIN3
        JSR     GN_ADC
        STD     X_SAMPLB        ; Store sample for gain 000
        CPD     #34888          ;+0.98(*0.7)
        LBHS    NO_GN1
        CPD     #30647          ;-0.98(*0.7)
        LBLS    NO_GN1
        LDAA    GN_PNT1
        CMPA    GN_PNT2
        LBLS    NO_GN1
        MOVB    #4,GN_PNT2
        LDAA    GAIN4
        JSR     GN_ADC
        STD     X_SAMPLB        ; Store sample for gain 000
        CPD     #34358          ;+0.735(*0.7)
        LBHS    NO_GN1
        CPD     #31177          ;-0.735(*0.7)
        LBLS    NO_GN1
        LDAA    GN_PNT1
        CMPA    GN_PNT2
        LBLS    NO_GN1
        MOVB    #5,GN_PNT2
        LDAA    GAIN5
        JSR     GN_ADC
        STD     X_SAMPLB        ; Store sample for gain 000
        CPD     #33849          ; +0.5(*0.7)
        LBHS    NO_GN1
        CPD     #31686          ; -0.5(*0.7)
        LBLS    NO_GN1
        LDAA    GN_PNT1
        CMPA    GN_PNT2
        LBLS    NO_GN1
        MOVB    #6,GN_PNT2
        LDAA    GAIN6
        JSR     GN_ADC
        STD     X_SAMPLB        ; Store sample for gain 000
        CPD     #33308          ; +0.25(*0.7)
        LBHS    NO_GN
        CPD     #32227          ; -0.25(*0.7)
        LBLS    NO_GN1
        LDAA    GN_PNT1
        CMPA    GN_PNT2
        LBLS    NO_GN1
        MOVB    #7,GN_PNT2
        LDAA    GAIN7
        JSR     GN_ADC
        STD     X_SAMPLB        ; Store sample for X gain
NO_GN1: RTS
************************************************
* SUBROUTINE:  D_CHAR
* FUNCTION:
************************************************
D_CHAR:         JSR     PRNLCD
                RTS
************************************************
* SUBROUTINE:  IN_CHAR
* FUNCTION:    Receives typed character into register A.
************************************************
IN_CHAR: LDAA   SC0SR1          ; Check status reg (RDRF in bit 5)
         ANDA   #BIT5           ; Check if receive buffer full
         BEQ    IN_CHAR         ; Wait until data present
         LDAA   SC0DRL          ; Data -&gt; A register
         STAA   CHAR
         RTS                    ; Return from subroutine
;************************************************
;* SUBROUTINE:  OUT_CHAR
;* FUNCTION:    Receives typed character into register A.
;************************************************
OUT_CHAR:       NOP
LP_LP:          BRCLR   SC0SR1,#$80,LP_LP
                STAA    SC0DRL
                RTS                     ; Return from subroutine
;**************************************************
;*      SUBRUTINE: INIT_SCI
;*      INFO:      Baud rate 4800, 8 data bits, 1 stop
;*      PASS:      No
;*      RETURNE:   No
;**************************************************
INIT_SCI:       BSET    DDRS,#%00000010 ; Set data direction to output for
                BCLR    DDRS,#%00000001 ; PortS bit1 (Tx) and input PortS bit0 (Rx)
                LDAA    #$01            ; Set baud rate to 4800
```

```
                STAA    SC0BDH              ; (25)16MHz/2 / 16 / 104 = 4.800kHz
                LDAA    #$46                ; SCP1:SCP0=11  SCR2:SCR1:SCR0=011
                STAA    SC0BDL              ; set baud rate to 4800
                LDAA    #0                  ; 1 start/stop bit, 8 data bits
                STAA    SC0CR1              ; no wakeup
                LDAA    #BIT32              ; Enable Tx and Rx;
                STAA    SC0CR2              ; all interrupts diabled
                LDAA    SC0SR1
                STD     SC0DRH
                RTS
;***************************************
;*      SUBRUTINE: CLR_LCD
;*      INFO:       Clear LCD
;*      PASS:        No
;*      RETURNE:    No
;***************************************
CLR_LCD: LDAA       #%00000001              ; Clear LCD
                JSR     CNTLCT
                RTS
;***************************************
;*      SUBRUTINE: LINE_LCD
;*      INFO:       Next Line (LCD)
;*      PASS:        No
;*      RETURNE:    No
;***************************************
LINE_LCD:       LDAA    #%11000000          ; Next line
                JSR     CNTLCT
                RTS
;***************************************
;*      SUBRUTINE: CNTLCT
;*      INFO:       Control output to LCD
;*      PASS:        Register-A, data
;*      RETURNE:    No
;***************************************
CNTLCT:         LDAB    #%00000000          ; CONTROL: (E=0,R/W=0,RS=0)
                STAB    PORTP
                STAA    PORTH
                JSR     DELAYLCD
                LDAB    #%00000100          ; CONTROL: (E=1,R/W=0,RS=0)
                STAB    PORTP
                JSR     DELAYLCD
                RTS
;***************************************
;*      SUBRUTINE: PRNLCD
;*      INFO:       Data output to LCD
;*      PASS:        Register-A, data
;*      RETURNE:    No
;***************************************
PRNLCD:         LDAB    #%00010000          ; CONTROL: (E=0,R/W=0,RS=0)
                STAB    PORTP
                STAA    PORTH
                JSR     DELAYLCD
                LDAB    #%00010100          ; CONTROL: (E=1,R/W=0,RS=1)
                STAB    PORTP
                JSR     DELAYLCD
                RTS
;***************************************
;*      SUBRUTINE: DELAY50
;*      INFO:       Delay for 50ms
;*      PASS:        No
;*      RETURNE:    No
;***************************************
DELAY50:        PSHA
                LDAA    #5                  ; 5 x 10msec DELAY
LOOP50:         JSR     DELAY10
                DECA
                CMPA    #0
                BHI     LOOP50
                PULA
                RTS
;***************************************
;*      SUBRUTINE: DELAY10
;*      INFO:       Delay for 10ms
;*      PASS:        No
;*      RETURNE:    No
;***************************************
DELAY10:        LDX     #40625              ;10msec execution time
LOOP10:         DEX
                CPX     #$00
                BHI     LOOP10
                LDX     #REGBS
                RTS
;***************************************
;*      SUBRUTINE: DELAYLCD
;*      INFO:       Delay for LCD operation
;*      PASS:        No
;*      RETURNE:    No
;***************************************
DELAYLCD:       JSR     DELAY10             ;10msec execution time
```

```
                RTS
;*************************************
;*     SUBRUTINE: READADC
;*     INFO:      Read ADC Converter
;*     PASS:      No
;*     RETURNE:   Register-D
;*************************************
READADC:        BSET    PORTP,#%10000000 ; Initial stage (Conversion=OFF)
                JSR     DELAY01
                BCLR    PORTP,#%10000000        ; Conversion=ON
                NOP
                NOP
                NOP
                BSET    PORTP,#%10000000        ; Conversion=OFF
                JSR     DELAY01                 ; Wait for BUSY signal
                LDAA    PORTA            ; Read MSByte
                LDAB    PORTAD1                 ; Read LSByte
                RTS
;***************************************
;*     SUBRUTINE: DELAY01
;*     INFO:      Wait for 100usec
;*     PASS:      No
;*     RETURNE:   No
;***************************************
DELAY01:        LDX     #1016            ; 100 usec execution time
LOOP25:         DEX
                CPX     #$00
                BHI     LOOP25
                RTS
***************************************
;*     SUBRUTINE: DELAY001
;*     INFO:      Small recovery delay
;*     PASS:       No
;*     RETURNE:   No
;***************************************
DELAY001:       nop     ; 40 nsec execution time each
                nop
                nop
                nop
                nop     ; 200 nsec overall execution time
                rts
;***************************************
;*     SUBRUTINE: DELAY02
;*     INFO:      Wait for 770usec
;*     PASS:      No
;*     RETURNE:   No
;***************************************
DELAY02:        LDX     #3125            ; 770 usec execution time
LOOP77:         DEX
                CPX     #$00
                BHI     LOOP77
                RTS
;***********************************************
;*     SUBRUTINE: CONV
;*     INFO:      Convert decimal number to ASCII
;*     PASS:      Register-D
;*     RETURNE:   DIGIT1,DIGIT2,DIGIT3,DIGIT4,DIGIT5.
;***********************************************
CONV:           CLR     DIGIT1           ; Clear all digits variables
                CLR     DIGIT2
                CLR     DIGIT3
                CLR     DIGIT4
                CLR     DIGIT5
                CPD     #0
                BEQ     LP
                LDX     #10
                IDIV
                STAB    DIGIT1           ; Check first digit
                STX     RESULTS
                LDD     RESULTS
                CPD     #0
                BEQ     LP
                LDX     #10
                IDIV
                STAB    DIGIT2           ; Check second digit
                STX     RESULTS
                LDD     RESULTS
                CPD     #0
                BEQ     LP
                LDX     #10
                IDIV
                STAB    DIGIT3           ; Check third digit
                STX     RESULTS
                LDD     RESULTS
                CPD     #0
                BEQ     LP
                LDX     #10
                IDIV
                STAB    DIGIT4           ; Check fourth digit
```

```
                STX     RESULTS
                LDD     RESULTS
                STAB    DIGIT5          ; Check fifth digit
LP:             BSET    DIGIT1,#%00110000; ASCII conversion
                BSET    DIGIT2,#%00110000; ASCII conversion
                BSET    DIGIT3,#%00110000; ASCII conversion
                BSET    DIGIT4,#%00110000; ASCII conversion
                BSET    DIGIT5,#%00110000; ASCII conversion
                RTS
;**************************************************
;*     SUBRUTINE: TIMER
;*     INFO:      Count Deposition time
;*     PASS:      TIMER_60
;*     RETURNE:   None
;**************************************************
TIMER:          JSR     CLR_LCD         ; Clear LCD
                LDY     #MSG_Ta         ; TEXT "Wait: "
                JSR     CHAR_STR
                LDD     TIMER_60 ; Load Timer
                JSR     CONV
                LDAA    DIGIT3          ; No of digit on LCD 8/20
                JSR     PRNLCD
                LDAA    DIGIT2          ; No of digit on LCD 7/20
                JSR     PRNLCD
                LDAA    DIGIT1          ; No of digit on LCD 8/20
                JSR     PRNLCD
                LDY     #MSG_Tb         ; TEXT " sec "
                JSR     CHAR_STR
                RTS
;**************************************************
;*     SUBRUTINE: NEGPOS
;*     INFO:      Negative and positive shift
;*     PASS:      Register-D
;*     RETURNE:   Register-D
;**************************************************
NEGPOS:         CPD     #$7FFF          ; 01111111-FF (negative)
                BLE     POS             ; Positive number
                COMA                    ; A complement
                COMB                    ; B compliment
                STD     ADD_M           ; ADD_M
                LDD     #$7FFF
                SUBD    ADD_M           ; Obtain shift
                BRA     NEG
POS:            ADDD    #$7FFF          ; Shift UP
NEG:            RTS
;**************************************************
;*     SUBRUTINE: ENT_BTN
;*     INFO:      Wait to press Enter button
;**************************************************
ENT_BTN:        NOP
INTROD8:        LDAA    PORTM           ; Read ENTER bout-on
                ANDA    #%00001000      ; READ M4 PIN
                CMPA    #%00001000
                BNE     INTROD8
                RTS
;******************************************************
;*     SUBRUTINE: CHARACT
;*     INFO:      Print Characterisation results on LCD
;*     PASS:       MAX, THRES, POTEN, PBMIN, PBMAX....
;*     RETURNE:   No
;******************************************************
CHARACT: CLR    CHR_FLG
                LDD     CNT_PR          ; Check for Pb
                CPD     PBMIN
                BLO     END011A
                CPD     PBMAX
                BHI     END011A
                JSR     CLR_LCD         ; Clear LCD
                MOVB    #1,CHR_FLG
                LDY     #MSG_CHRa       ; Display "Contmin. LEAD (Pb) "
                JSR     CHAR_STR
                LDD     #1137           ; A=1.137 X 1000
                JSR     PRN_PPM
END011A: LDD    CNT_PR                  ; Check for Cd
                CPD     CDMIN
                BLO     END011B
                CPD     CDMAX
                BHI     END011B
                JSR     CLR_LCD         ; Clear LCD
                MOVB    #1,CHR_FLG
                LDY     #MSG_CHRb       ; Display "Contm. CADMIUM (Cd) "
                JSR     CHAR_STR
                LDD     #2084           ; A=2.084 X 1000
                JSR     PRN_PPM
END011B: LDD    CNT_PR                  ; Cheak for Hg
                CPD     HGMIN
                BLO     END011C
                CPD     HGMAX
                BHI     END011C
```

```
            JSR      CLR_LCD          ; Clear LCD
            MOVB     #1,CHR_FLG
            LDY      #MSG_CHRc        ; Display "Contmin. MERCURY (Hg) "
            JSR      CHAR_STR
            LDD      #983             ; A=0.983 X 1000
            JSR      PRN_PPM
END011C: LDD CNT_PR                   ; Cheak for Zn
            CPD      ZNMIN
            BLO      END011D
            CPD      ZNMAX
            BHI      END011D
            JSR      CLR_LCD          ; Clear LCD
            MOVB     #1,CHR_FLG
            LDY      #MSG_CHRd        ; Display "Contmin. ZINK (Zn) "
            JSR      CHAR_STR
            LDD      #718             ; A=0.718 X 1000
            JSR      PRN_PPM
END011D: LDD CNT_PR                   ; Cheak for Ni-1
            CPD      NI1MIN
            BLO      END011E
            CPD      NI1MAX
            BHI      END011E
            JSR      CLR_LCD          ; Clear LCD
            MOVB     #1,CHR_FLG
            LDY      #MSG_CHRe        ; Display "Contmin. NICKEL (Ni-1) "
            JSR      CHAR_STR
            LDD      #698             ; A=0.698 X 1000
            JSR      PRN_PPM
END011E: LDD CNT_PR                   ; Cheak for Ni-2
            CPD      NI2MIN
            BLO      END011F
            CPD      NI2MAX
            BHI      END011F
            JSR      CLR_LCD          ; Clear LCD
            MOVB     #1,CHR_FLG
            LDY      #MSG_CHRf        ; Display "Contmin. NICKEL (Ni-2) "
            JSR      CHAR_STR
            LDD      #570             ; A=0.57 X 1000
            JSR      PRN_PPM
END011F: LDD CNT_PR                   ; Cheak for Cu-1
            CPD      CU1MIN
            BLO      END011G
            CPD      CU1MAX
            BHI      END011G
            JSR      CLR_LCD          ; Clear LCD
            MOVB     #1,CHR_FLG
            LDY      #MSG_CHRg        ; Display "Contmin. COPPER (Cu-1) "
            JSR      CHAR_STR
END011G: LDD CNT_PR                   ; Cheak for Cu-2
            CPD      CU2MIN
            BLO      END011H
            CPD      CU2MAX
            BHI      END011H
            JSR      CLR_LCD          ; Clear LCD
            MOVB     #1,CHR_FLG
            LDY      #MSG_CHRh        ; Display "Contmin. COPPER (Cu-2) "
            JSR      CHAR_STR
END011H: LDD CNT_PR                   ; Cheak for Cu-3
            CPD      CU3MIN
            BLO      END011Z
            CPD      CU3MAX
            BHI      END011Z
            JSR      CLR_LCD          ; Clear LCD
            MOVB     #1,CHR_FLG
            LDY      #MSG_CHRi        ; Display "Contmin. COPPER (Cu-3) "
            JSR      CHAR_STR
            LDD      #505             ; A=0.505 X 1000
            JSR      PRN_PPM
END011Z: LDAA CHR_FLG
            CMPA     #0
            BNE      END011ZZ
            JSR      CLR_LCD          ; Clear LCD
            LDY      #MSG_CHRz        ; Display "No recognised "
            JSR      CHAR_STR
END011ZZ:   RTS
****************************************
* Subroutine:  CHAR_STR
* Description: This subroutine prints
*              a character string
****************************************
CHAR_STR:   NOP
TXT_LOOP:   LDAA     0,Y
            CMPA     #$FF
            BEQ      TXT_END1
            JSR      PRNLCD
            INY
            BRA      TXT_LOOP
TXT_END1:   RTS
;***************************************
```

```
;*      SUBRUTINE: PRN_PPM
;*      INFO:       Display PPM
;*      PASS:
;*      RETURNE:
;****************************************
PRN_PPM: LDY      AMPLITUDE              ; In uA X 10;
                  EMUL                   ; A*AMP*10=(Y:D)
                  LDX     #10000
                  EDIV                   ;(Y:D)/10000=Y.D
                  STY     RES_PPM        ;Store results
                  JSR     LINE_LCD       ; Next line
                  LDD     RES_PPM        ; Load variable to print
                  JSR     CONV
                  LDAA    DIGIT3         ; No of digit on LCD 15/20
                  JSR     PRNLCD
                  LDAA    DIGIT2         ; No of digit on LCD 16/20
                  JSR     PRNLCD
                  LDAA    DIGIT1         ; No of digit on LCD 17/20
                  JSR     PRNLCD
                  LDAA    #'             ; No of digit on LCD 20/20
                  JSR     PRNLCD
                  LDAA    #'p            ; No of digit on LCD 18/20
                  JSR     PRNLCD
                  LDAA    #'p            ; No of digit on LCD 19/20
                  JSR     PRNLCD
                  LDAA    #'m            ; No of digit on LCD 20/20
                  JSR     PRNLCD
                  LDAA    #'             ; No of digit on LCD 20/20
                  JSR     PRNLCD
                  JSR     ENT_BTN        ; Read ENTER bout-on
                  RTS
;****************************************
;*      SUBRUTINE: ALGO1
;*      INFO:       Peak detection Algorithm
;*      PASS:
;*      RETURNE:
;****************************************
ALGO1:            NOP
;****************************
;* Four Points moving average
;****************************
                  LDAA    FLAG
                  CMPA    #1
                  BNE     BR_1
                  LDD     SAMPLE_M
                  STD     DATA_1
                  JMP     BR_NXT
BR_1:             LDAA    FLAG
                  CMPA    #2
                  BNE     BR_2
                  LDD     SAMPLE_M
                  STD     DATA_2
                  JMP     BR_NXT
BR_2:             LDAA    FLAG
                  CMPA    #3
                  BNE     BR_3
                  LDD     SAMPLE_M
                  STD     DATA_3
                  JMP     BR_NXT
BR_3:             LDAA    FLAG
                  CMPA    #4
                  LBNE    BR_NXT
                  LDD     SAMPLE_M
                  STD     DATA_4
                  LDD     DATA_1
                  LSRD
                  LSRD
                  STD     ADATA_1
                  LDD     DATA_2
                  LSRD
                  LSRD
                  STD     ADATA_2
                  LDD     DATA_3
                  LSRD
                  LSRD
                  STD     ADATA_3
                  LDD     DATA_4
                  LSRD
                  LSRD
                  STD     ADATA_4
                  LDD     ADATA_1
                  ADDD    ADATA_2
                  ADDD    ADATA_3
                  ADDD    ADATA_4
                  STD     F              ; Four Points moving average variable
;****************************************
;* Process 1 - detection of min and max
;****************************************
                  LDD     CNT_X          ; Check if first point
```

```
            CPD     #1
            BNE     BRN_1
            LDD     F               ; If first point then all variable = F
            STD     OLD_DATA
            STD     MAX
            STD     MIN
            STD     MAX_1
            STD     MIN_1
BRN_1:      LDAA    P               ; Check if P = 0
            CMPA    #1
            BNE     BRN_2
            LDD     OLD_DATA        ; If P = 0 then continue
            CPD     F
            BHI     BRN_3
            LDAA    #1
            STAA    P
            LDD     OLD_DATA
            STD     MAX
BRN_3:      LDD     OLD_DATA
            CPD     F
            BLS     BRN_2
            ldd     MAX
            cpd     MIN
            blo     GOMAN1
            LDD     MAX
            SUBD    MIN
            STD     AMP
            bra     GOMAN2
GOMAN1:     LDD     #0
            STD     AMP
GOMAN2:     LDD     AMP
            CPD     ALG1_THR        ; Threshold 1.0uA
            BLS     BRN_5
            LDAA    #1
            STAA    P_2
            LDD     MAX
            STD     MAX_1
            LDD     CNT_X
            STD     CNT_1
            LDD     MINPOS
            STD     MINPOS_1
            LDD     MIN
            STD     MIN_1
BRN_5:      CLR     P
BRN_2:      LDAA    P               ; Check if P is still 0
            CMPA    #0
            LBNE    BRN_6           ; IF P not 0 leave process (min-max-min)
            LDD     OLD_DATA        ; IF P = 0 continue
            CPD     F
            BLS     BRN_7
            CLR     P
            LDD     OLD_DATA
            STD     MIN
            LDD     CNT_X
            STD     MINPOS
BRN_7:      LDD     OLD_DATA
            CPD     F
            LBHI    BRN_6           ;8
            LDAA    P_2
            CMPA    #1
            LBNE    BRN_9
            ldd     MAX
            cpd     MIN
            blo     GOMAN3
            LDD     MAX
            SUBD    MIN
            STD     DEF
            BRA     GOMAN4
GOMAN3:     LDD     #0
            STD     DEF
GOMAN4:     LDD     MIN_1           ; 1st min point
            ;LSRD                   ; divide by 2
            STD     A_MIN_1         ; store 1st min point
            LDD     MIN             ; 2nd min point
            ;LSRD                   ; divide by 2
            STD     A_MIN           ; store 2nd min point
            LDD     A_MIN_1
            ;ADDD   A_MIN           ; Add 1st and 2nd min points
            STD     AV_MIN          ; Store average min
            ldd     MAX_1
            cpd     AV_MIN
            blo     GOMAN5
            LDD     MAX_1
            SUBD    AV_MIN
            STD     AMP_2
            BRA     GOMAN6
GOMAN5:     ldd     #0
            std     AMP_2
GOMAN6:     LDD     DEF
```

```
                CPD     ALG1_THR        ; Threshold 1.0uA
                BLS     BRN_9           ;10
;***********************************
;* Calculate & convert max potential
;***********************************
                LDD     CNT_1
                LDY     #244            ; Counter x 2.44V x 100
                EMUL                    ; Multiplication: DxY=Y:D
                LDX     #10
                EDIV                    ; 32bit division: Y:D/X=Y.D
                STY     CNT_PR          ; Current counter potential
                LDD     CNT_PR          ; Load COUNTMAX
                CPD     #14000          ; Compare with 1.4V
                BLO     NNNEG           ; If lower then is negative
                SUBD    #14000          ; If not is positive
                STD     POTEN           ; Shift down 1.1V and leave
                MOVB    #$01,SINFLAG    ; Set SIGNFLAG to 1 (positive)
                JMP     EEEND           ; Leave
NNNEG:          LDD     #14000          ; Calculate offset
                SUBD    CNT_PR
                CLR     SINFLAG         ; Set SIGNFLAG to 0 (negative)
                STD     POTEN
EEEND:          LDD     POTEN
                LDX     #10
                IDIV                    ; 16bit division
                STX     POTEN
                LDD     AMP_2           ; Save to PRINT AMP_2 and POTEN
                STD     AMPLITUDE
                LDY     POINTER
                LDAA    SINFLAG
                STAA    0,Y             ;One place (8bit) $0000
                LDD     POTEN
                STD     1,Y             ;Two places (16bits) $0001-$0002
                LDD     AMPLITUDE
                STD     3,Y             ;Two places (16bits) $0003-$0004
                LDD     CNT_PR
                STD     5,Y             ;Two places (16bits) $0005-$0006
                LDD     POINTER
                ADDD    #7
                STD     POINTER
                clr     P_2
BRN_9:          LDD     OLD_DATA
                STD     MAX
                LDAA    #1
                STAA    P
BRN_6:          LDD     F
                STD     OLD_DATA
;***********************************
;* Ready to continue for next sample
;***********************************
                LDD     CNT_X
                ADDD    #1
                STD     CNT_X
                LDD     DATA_2
                STD     DATA_1
                LDD     DATA_3
                STD     DATA_2
                LDD     DATA_4
                STD     DATA_3
                LDAA    #4
                STAA    FLAG
BR_NXT:         LDAA    FLAG
                CMPA    #4
                BHS     NXT
                LDAA    FLAG
                INCA
                STAA    FLAG
NXT:            RTS
;****************************************************
;*      SUBRUTINE: PRDATA
;*      INFO:      Print on LCD max current & potential
;*
;****************************************************
PRDATA:         JSR     CLR_LCD         ; Clear LCD
                LDAA    #'P             ; No of digit on LCD 1/20
                JSR     PRNLCD
                LDAA    #'e             ; No of digit on LCD 2/20
                JSR     PRNLCD
                LDAA    #'a             ; No of digit on LCD 3/20
                JSR     PRNLCD
                LDAA    #'k             ; No of digit on LCD 4/20
                JSR     PRNLCD
                LDAA    #'(             ; No of digit on LCD 5/20
                JSR     PRNLCD
                LDAA    #0
                LDAB    PEAK            ; Load PEAK variable to print
                JSR     CONV
                LDAA    DIGIT2          ; No of digit on LCD 6/20
                JSR     PRNLCD
```

```
                LDAA    DIGIT1          ; No of digit on LCD 7/20
                JSR     PRNLCD
                LDAA    #')             ; No of digit on LCD 8/20
                JSR     PRNLCD
                LDAA    #'              ; No of digit on LCD 9/20
                JSR     PRNLCD
                LDAA    #'I             ; No of digit on LCD 10/20
                JSR     PRNLCD
                LDAA    #'=             ; No of digit on LCD 11/20
                JSR     PRNLCD
                LDD     AMPLITUDE       ; Load MAX variable to print
                JSR     CONV
                LDAA    DIGIT5          ; No of digit on LCD 12/20
                JSR     PRNLCD
                LDAA    DIGIT4          ; No of digit on LCD 13/20
                JSR     PRNLCD
                LDAA    DIGIT3          ; No of digit on LCD 15/20
                JSR     PRNLCD
                LDAA    DIGIT2          ; No of digit on LCD 16/20
                JSR     PRNLCD
                LDAA    #'.             ; No of digit on LCD 14/20
                JSR     PRNLCD
                LDAA    DIGIT1          ; No of digit on LCD 17/20
                JSR     PRNLCD
                LDAA    #'u             ; No of digit on LCD 18/20
                JSR     PRNLCD
                LDAA    #'A             ; No of digit on LCD 19/20
                JSR     PRNLCD
                LDAA    #'              ; No of digit on LCD 20/20
                JSR     PRNLCD
                JSR     LINE_LCD        ; Next line
                LDAA    #'@             ; No of digit on LCD 1/20
                JSR     PRNLCD
                LDAA    #'              ; No of digit on LCD 2/20
                JSR     PRNLCD
                LDD     POTEN
                JSR     CONV
                LDAA    SINFLAG         ; Check sign
                CMPA    #0              ; If 0 then negative
                BNE     BARAS
                LDAA    #'-             ; No of digit on LCD 3/20
                JSR     PRNLCD
                BRA     BARAS2
BARAS:          LDAA    #'+             ; No of digit on LCD 3/20
                JSR     PRNLCD
BARAS2:         LDAA    DIGIT5          ; No of digit on LCD 4/20
                JSR     PRNLCD
                LDAA    DIGIT4          ; No of digit on LCD 5/20
                JSR     PRNLCD
                LDAA    #'.             ; No of digit on LCD 6/20
                JSR     PRNLCD
                LDAA    DIGIT3          ; No of digit on LCD 7/20
                JSR     PRNLCD
                LDAA    DIGIT2          ; No of digit on LCD 8/20
                JSR     PRNLCD
                LDAA    DIGIT1          ; No of digit on LCD 9/20
                JSR     PRNLCD
                LDAA    #'V             ; No of digit on LCD 10/20
                JSR     PRNLCD
                LDAA    #%00010000      ; Finish printing
                JSR     PRNLCD
                RTS
;***************************************
;*              CHARACTERS FOR DISPLAY
;***************************************
MSG_1a          FCC     "Deposition time,"
                FCB     $FF
MSG_1b          FCC     "wait 60 sec "
                FCB     $FF
MSG_2           FCC     "System working! "
                FCB     $FF
MSG_3           FCC     "End of process "
                FCB     $FF
MSG_Ta          FCC     "Wait: "
                FCB     $FF
MSG_Tb          FCC     " sec "
                FCB     $FF
MSG_Wa          FCC     "Volt. Analyser-I "
                FCB     $FF
MSG_Wb          FCC     "R.G.U. 2004. "
                FCB     $FF
MSG_CHRa FCC    "Contmin. LEAD (Pb) "
                FCB     $FF
MSG_CHRb FCC    "Contm. CADMIUM (Cd) "
                FCB     $FF
MSG_CHRc FCC    "Contm. MERCURY (Hg) "
                FCB     $FF
MSG_CHRd FCC    "Contm. ZINK (Zn) "
                FCB     $FF
```

```
MSG_CHRe FCC      "Contm. NICKEL (Ni-1) "
                  FCB      $FF
MSG_CHRf FCC      "Contm. NICKEL (Ni-2) "
                  FCB      $FF
MSG_CHRg FCC      "Contm. COPPER (Cu-1) "
                  FCB      $FF
MSG_CHRh FCC      "Contm. COPPER (Cu-2) "
                  FCB      $FF
MSG_CHRi FCC      "Contm. COPPER (Cu-3) "
                  FCB      $FF
MSG_CHRz FCC      "No recognised "
                  FCB      $FF
MSG_TR1           FCC      "No Match"
                  FCB      $FF
MSG_IA3           FCC      "RETURN "
                  FCB      $FF
MSG_Sam           FCC      "Sample: <> "
                  FCB      $FF
MSG_5a            FCC      "Ready for GPS: "
                  FCB      $FF
MSG_5b            FCC      "Connect GPS module "
                  FCB      $FF
MSG_6a            FCC      "Ready for identif. "
                  FCB      $FF
MSG_6b            FCC      "Press <ENTER> "
                  FCB      $FF
MSG_pha           FCC      "Ready to Measure pH"
                  FCB      $FF
MSG_phb           FCC      "Press <ENTER> "
                  FCB      $FF
MSG_phc           FCC      "Measure Acidity"
                  FCB      $FF
MSG_phd           FCC      "Please wait... "
                  FCB      $FF
MSG_RSa           FCC      "Sensor Resting "
                  FCB      $FF
MSG_RSb           FCC      "Please wait... "
                  FCB      $FF
;****************************
;*                END OF CODE
;****************************
```

Appendix C

Software developed in C language

Serial Communication with the Analyser

```
/*****************************************************************
* Name:     Konstantinos Christidis
* Date:     11-October-2005
* Filename: comp_2.CPP  (working)
*
* Description: Serial Communication
* Note: Compile this program with Test Stack Overflow OFF.
*****************************************************************/
#include <dos.h>
#include <conio.h>
#include <stdio.h>
#include <string.h>
#include "serial.h"
#include <math.h>
#include <graphics.h>
#include <stdlib.h>
#include <iostream.h>
#define VERSION 0x0101
#define FALSE          0
#define TRUE           (!FALSE)
#define NOERROR        0       /* No error               */
#define BUFOVFL        1       /* Buffer overflowed      */
#define ESC            0x1B    /* ASCII Escape character */
#define ASCII          0x007F  /* Mask ASCII characters  */
#define SBUFSIZ        0x4000  /* Serial buffer size     */
int           SError         = NOERROR;
int           portbase       = 0;
void          interrupt(*oldvects[2])(...);
static   char ccbuf[SBUFSIZ];
unsigned int  startbuf       = 0;
unsigned int  endbuf         = 0;

/* Handle communications interrupts and put them in ccbuf */
void interrupt com_int(...)
{
    disable();
    if ((inportb(portbase + IIR) & RX_MASK) == RX_ID)
    {
        if (((endbuf + 1) & SBUFSIZ - 1) == startbuf)
            SError = BUFOVFL;
        ccbuf[endbuf++] = inportb(portbase + RXR);
        endbuf &= SBUFSIZ - 1;
    }
    /* Signal end of hardware interrupt */
    outportb(ICR, EOI);
    enable();
}
/* Output a character to the serial port */
serial& serial::operator<<( char x )
{
    long int          timeout = 0x0000FFFFL;
    outportb(portbase + MCR,  MC_INT | DTR | RTS);
```

```
    /* Wait for Clear To Send from modem */
    while ((inportb(portbase + MSR) & CTS) == 0)
        if (!(--timeout))
                return *this;
    timeout = 0x0000FFFFL;
    /* Wait for transmitter to clear */
    while ((inportb(portbase + LSR) & XMTRDY) == 0)
        if (!(--timeout))
                return *this;
    disable();
    outportb(portbase + TXR, x);
    enable();
        return *this;
}
/* Output a string to the serial port */
serial& serial::operator<<( char *string )
{
        while (*string)
        {
           (*this) << *string;
           string++;
        }
        return *this;
}

/* This routine returns the current value in the buffer */
serial &serial::operator>>( char &ch )
{
        if (endbuf == startbuf)
        {
                ch = -1;
                return *this;
        }
        ch = ccbuf[startbuf];
        startbuf++;
        startbuf %= SBUFSIZ;
        return *this;
}
/* Install our functions to handle communications */
void setvects(void)
{
    oldvects[0] = getvect(0x0B);
    oldvects[1] = getvect(0x0C);
    setvect(0x0B, com_int);
    setvect(0x0C, com_int);
}
/* Uninstall our vectors before exiting the program */
void resvects(void)
{
    setvect(0x0B, oldvects[0]);
    setvect(0x0C, oldvects[1]);
}
/* Turn on communications interrupts */
void i_enable(int pnum)
{
    int     c;
    disable();
    c = inportb(portbase + MCR) | MC_INT;
    outportb(portbase + MCR, c);
    outportb(portbase + IER, RX_INT);
    c = inportb(IMR) & (pnum == COM1 ? IRQ4 : IRQ3);
    outportb(IMR, c);
    enable();
}
/* Turn off communications interrupts */
void i_disable(void)
{
    int     c;
    disable();
    c = inportb(IMR) | ~IRQ3 | ~IRQ4;
    outportb(IMR, c);
    outportb(portbase + IER, 0);
    c = inportb(portbase + MCR) & ~MC_INT;
    outportb(portbase + MCR, c);
    enable();
}

/* Tell modem that we're ready to go */
```

```
void comm_on(void)
{
    int                 c, pnum;
    pnum = (portbase == COM1BASE ? COM1 : COM2);
    i_enable(pnum);
    c = inportb(portbase + MCR) | DTR | RTS;
    outportb(portbase + MCR, c);
}
/* Go off-line */
void serial::comm_off(void)
{
    i_disable();
    outportb(portbase + MCR, 0);
}
void serial::init_serial(void)
{
    endbuf = startbuf = 0;
    setvects();
    comm_on();
}
serial::~serial()
{
    comm_off();
    resvects();
}
/* Set the port number to use */
int serial::SetPort(int Port)
{
    int                 Offset, far *RS232_Addr;
    switch (Port)
    { /* Sort out the base address */
      case COM1 : Offset = 0x0000;
                  break;
      case COM2 : Offset = 0x0002;
                  break;
      default   : return (-1);
    }
       RS232_Addr = (int far *)MK_FP(0x0040, Offset);  /* Find out where the port is. */
    if (*RS232_Addr == NULL) return (-1);/* If NULL then port not used. */
    portbase = *RS232_Addr;              /* Otherwise set portbase      */
    return (0);
}
/* This routine sets the speed; will accept funny baud rates. */
/* Setting the speed requires that the DLAB be set on.        */
int serial::SetSpeed(int Speed)
{
    char        c;
    int         divisor;
    if (Speed == 0)             /* Avoid divide by zero */
        return (-1);
    else
        divisor = (int) (115200L/Speed);
    if (portbase == 0)
        return (-1);
    disable();
    c = inportb(portbase + LCR);
    outportb(portbase + LCR, (c | 0x80)); /* Set DLAB */
    outportb(portbase + DLL, (divisor & 0x00FF));
    outportb(portbase + DLH, ((divisor >> 8) & 0x00FF));
    outportb(portbase + LCR, c);          /* Reset DLAB */
    enable();
    return (0);
}
/* Set other communications parameters */
int serial::SetOthers(int Parity, int Bits, int StopBit)
{
    int                 setting;
    if (portbase == 0)                                   return (-1);
    if (Bits < 5 || Bits > 8)                            return (-1);
    if (StopBit != 1 && StopBit != 2)                    return (-1);
    if (Parity != NO_PARITY && Parity != ODD_PARITY && Parity != EVEN_PARITY)
                                                         return (-1);
    setting  = Bits-5;
    setting |= ((StopBit == 1) ? 0x00 : 0x04);
    setting |= Parity;
    disable();
    outportb(portbase + LCR, setting);
    enable();
```

```
    return (0);
}
/* Set up the port */
serial::serial(int Port, int Speed, int Parity, int Bits, int StopBit)
{
        flag = 0;
        if (SetPort(Port))
          flag = -1;
        if (SetSpeed(Speed))
          flag = -1;
        if (SetOthers(Parity, Bits, StopBit))
          flag = -1;
        if (!flag)
           init_serial();
}
/*  Control-Break interrupt handler */
int c_break(void)
{
    i_disable();
    fprintf(stderr, "\nStill online.\n");
    return(0);
}

void main()
{
    /***************************************
    * Variables declaration: Communication
    ***************************************/
    int         port     = COM1;
    int         speed    = 9600;
    int         parity   = NO_PARITY;
    int         bits     = 8;
    int         stopbits = 1;
    /*************************************************
    * Variables declaration: Graphs and presentation
    *************************************************/
    int            driver, mode;       //Driver and mode variables
    FILE           *outfile;
    /******************************************
    * Variable declaration: Data manipulation
    ******************************************/
    int     i_counter=1, prs_1=1, prs_2=1;
    char              c;              //Input character
    unsigned char     cc;
    unsigned char   array_data[40];
    unsigned int      DT_0,DT_1,DT_2,DT_3,DT_4,DT_5,DT_6,DT_7;
    unsigned int        DT_8, DT_9;
    unsigned long     DT,DTT,DTT1,DTT2,DTT3;
  /*****************************************
    * Variables for grahical output
    ****************************************/
    int     i,selection;
    float   range;
    int     flag_plot=0;
    float   y_point,y1_point, y2_point, y_old_point;
    int     cnt_plot=1;
    int     x_point;
    serial comport(port, speed, parity, bits, stopbits);
    ctrlbrk(c_break);
    outfile=fopen("ncr_data.txt","w");
    if (outfile==NULL)
    {
           printf("Cannot open file");
           exit(0);
    }
    driver = DETECT;
    initgraph(&driver, &mode, "c:\\turboc\\bgi\\");
   /************************
    * Say hello...         *
    ************************/
    cleardevice();
    setbkcolor(15);
    setcolor(4);
    moveto(200, 80);
    outtext("The Robert Gordon University");
    moveto(200, 100);
    outtext("Data Logging-Upload MEM DATA");
    moveto(240, 120);
```

```
outtext("by K. Christidis");
moveto(220, 160);
outtext("Press any Key to start");
getch();
//************************
/************************
* Input range          *
************************/
cleardevice();
setbkcolor(1);
setcolor(4);
for (i=1; i<=17; i++)
{
    printf("\n");
}
printf("                ");
moveto(20, 80);
outtext("Voltage Range Selection");
moveto(20, 95);
outtext("____________________________________");
moveto(20, 125);
outtext("Selection: [1] Range 0 - 500mV");
moveto(20, 145);
outtext("           [2] Range 0 - 1000mV");
moveto(20, 165);
outtext("           [3] Range 0 - 2000mV");
moveto(20, 185);
outtext("           [4] Range 0 - 5000mA");
moveto(20, 226);
outtext("Enter range:");
cin >> selection;
while (selection > 5)
{
    printf("Try again:");
    cin >> selection;
}
cleardevice();
setbkcolor(15);
range = 0.352;          /* Defult range 0-5000mV */
if (selection == 1)
{
    range = 0.352*10; //0.352*0.1;   // 360/1024=0.352
/***** Labeling Y-axis *****/
    setcolor(5);
    moveto(30,260+150-50);
    outtext("71");
    moveto(30,260+150-100);
    outtext("143");
    moveto(30,260+150-150);
    outtext("214");
    moveto(30,260+150-200);
    outtext("286");
    moveto(30,260+150-250);
    outtext("357");
    moveto(30,260+150-300);
    outtext("429");
    moveto(30,260+150-350);
    outtext("500");
    /****************************/
}
if (selection == 2)
{
    range = 0.352*5; //0.352*0.2;   // 360/1024=0.352
/***** Labeling Y-axis *****/
    setcolor(5);
    moveto(30,260+150-50);
    outtext("142");
    moveto(30,260+150-100);
    outtext("286");
    moveto(30,260+150-150);
    outtext("428");
    moveto(30,260+150-200);
    outtext("572");
    moveto(30,260+150-250);
    outtext("714");
    moveto(30,260+150-300);
    outtext("858");
    moveto(30,260+150-350);
```

```
    outtext("1000");
/*****************************/
}

if (selection == 3)
{
range = 0.352*2.5; //0.352*0.4;    //360/1024=0.352
/***** Labeling Y-axis *****/
    setcolor(5);
    moveto(30,260+150-50);
    outtext("284");
    moveto(30,260+150-100);
    outtext("572");
    moveto(30,260+150-150);
    outtext("856");
    moveto(30,260+150-200);
    outtext("1144");
    moveto(30,260+150-250);
    outtext("1428");
    moveto(30,260+150-300);
    outtext("1716");
    moveto(30,260+150-350);
    outtext("2000");
/*****************************/
}
if (selection == 4)
{
range = 0.352;    // 360/1024=0.352
/***** Labeling Y-axis *****/
    setcolor(5);
    moveto(30,260+150-50);
    outtext("710");
    moveto(30,260+150-100);
    outtext("1430");
    moveto(30,260+150-150);
    outtext("2140");
    moveto(30,260+150-200);
    outtext("2860");
    moveto(30,260+150-250);
    outtext("3570");
    moveto(30,260+150-300);
    outtext("4290");
    moveto(30,260+150-350);
    outtext("5000");
 /*****************************/
}
/*************************
* Plot the Axis          *
*************************/
setcolor(1);
setlinestyle(0,0,3);
line (50,260+150,630,260+150);            /* X-axis */
line (630,260+150,630-10,260+150-10); /* X-axis (arror) */
line (630,260+150,630-10,260+150+10); /* X-axis (arror) */
line (70,280+150,70,10);                  /* Y-axis */
line (70,10,70-10,10+10);
line (70,10,70+10,10+10);
moveto(350+100, 280+150);
outtext("Number of Samples");
moveto(10, 30);
outtext("Voltage [mV]");
/***** Labeling X-axis *****/
setcolor(5);
moveto(50+0,265+150);
outtext("0");
moveto(50+100-20,265+150);
outtext("100");
moveto(50+200-20,265+150);
outtext("200");
moveto(50+300-20,265+150);
outtext("300");
moveto(50+400-20,265+150);
outtext("400");
moveto(50+500-20,265+150);
outtext("500");
/*****************************/
setcolor(4);
moveto(220, 30); //310+150);
```

```
outtext("Data Logging Voltage Vs No Samples");
setcolor(4);
line (220,445,430,445);
line (220,460,430,460);
line (220,445,220,460);
line (430,445,430,460);
moveto(230, 450);
outtext("STATUS:");
moveto(300, 450);
outtext("Program Running");
setcolor(5);   /* Colour for data  */
//****************************************
//*********PROCESS - FIRST PART************
//****************************************
//printf("Waiting for Data.....\n");
do{
        comport >> c;

        if(c != -1)
        {
               cc=c;
               DT=c;

       if (DT == 11)     //Start Word
       {
           //printf("Transfering Started.....\n");
           do {
               comport >> c;
                if(c != -1)
                {
                   cc=c;
                   DT=c;
                  if (DT !=12)      //Stop Word
                   {
                       array_data[i_counter]=cc;
                      printf("bit(%d)=%ld \n",i_counter,DT);
                      i_counter=i_counter+1;
                       if (i_counter == 17)             //8+8+(1)
                       {
                            DT_0=array_data[1];
                            DT_1=array_data[2];
                            DT_2=array_data[3];
                            DT_3=array_data[4];
                            DT_4=array_data[5];
                            DT_5=array_data[6];
                            DT_6=array_data[7];
                            DT_7=array_data[8];
                            DTT1=(DT_0*1)+(DT_1*2)+(DT_2*4)+(DT_3*8);
                            DTT2=(DT_4*16)+(DT_5*32)+(DT_6*64)+(DT_7*128);
                            DTT = DTT1 + DTT2;

                          DT_8=array_data[9];
                          DT_9=array_data[10];
                          DTT3=(DT_8*256)+(DT_9*512);
                          DTT = DTT + DTT3;
                            //printf("data=%ld \n",DTT);

                            i_counter = 1;

                          //********************
                            //****Plot Data*******

                           flag_plot=flag_plot+1;
                           y_point=260+150-(DTT*range);

                          if (flag_plot == 1)
                           {
                               y_old_point=y_point;
                           }
                           else if (flag_plot == 2)
                           {
                               x_point=cnt_plot+70;
                               y_point=(y_point+y_old_point)/2;
                               setcolor(5);
                               moveto(x_point,y_point);
                               outtext(".");
                               fprintf(outfile, "%d \n", DTT);
                               cnt_plot=cnt_plot+1;
```

```
                                        flag_plot = 0;
                                    }
                                    //********************
                                    //***End Plot Data****
                               }
                          }
                          else if (c == 12)    // If DATA = 12
                          {
                             prs_1=0;
                              prs_2=0;
                             //printf("Stop Transferring.....");
                              setcolor(15);
                              moveto(300, 450);
                              outtext("Program Running");
                              setcolor(4);
                              moveto(300, 450);
                              outtext("End of Process");
                          }
                     }
                }while(prs_2 != 0);
           }
      }
   }while(prs_1 != 0);
   getchar();
   fclose(outfile);
   closegraph();
}
```

Appendix D

Technical Information

D.1: 12 bit DAC - AD7541A

D.2: Operational Amplifier – OP07

D.3: Program. Ref. Voltage Device – TL431

D.4: 1-to-8 Analogue Multiplexer – 4052B

D.5: 16 bit ADC – LTC1605

D.6: 2 x 20 Alphanumerical Display

D.7: 64 x 128 Graphic Display

D.8: 512 Kbit IC2 Serial EEPROM – 24AA512

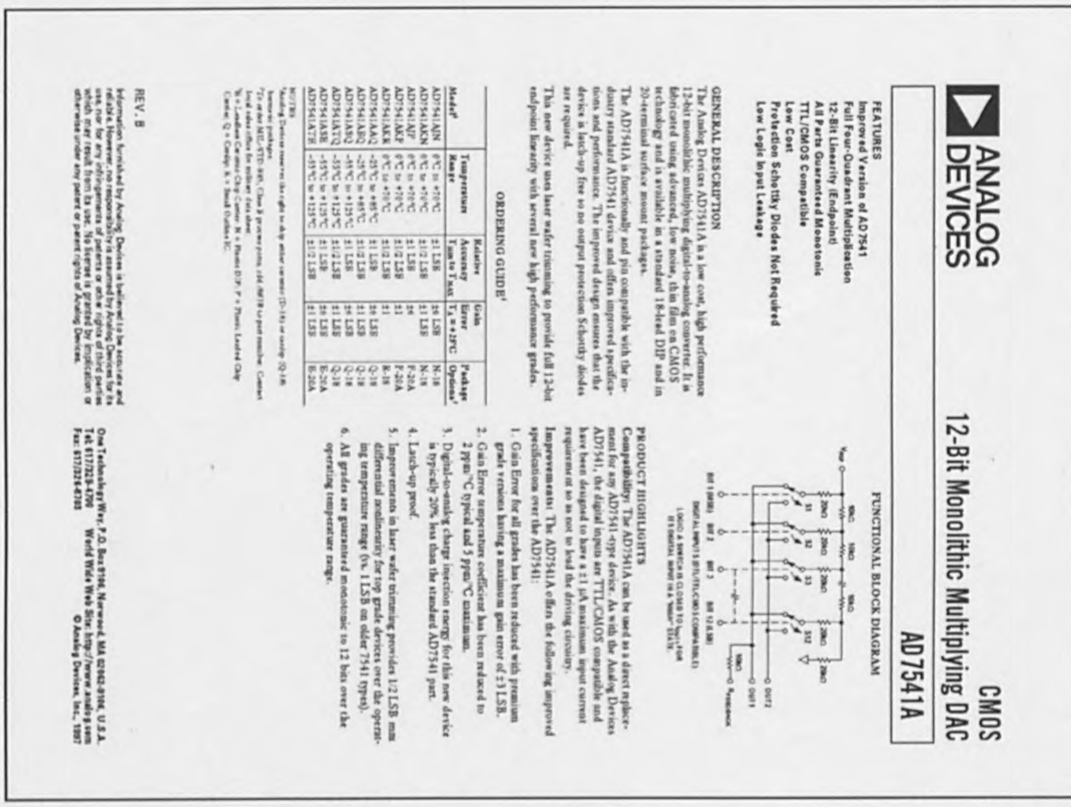
D.9: Voltage Regulator – LM2940

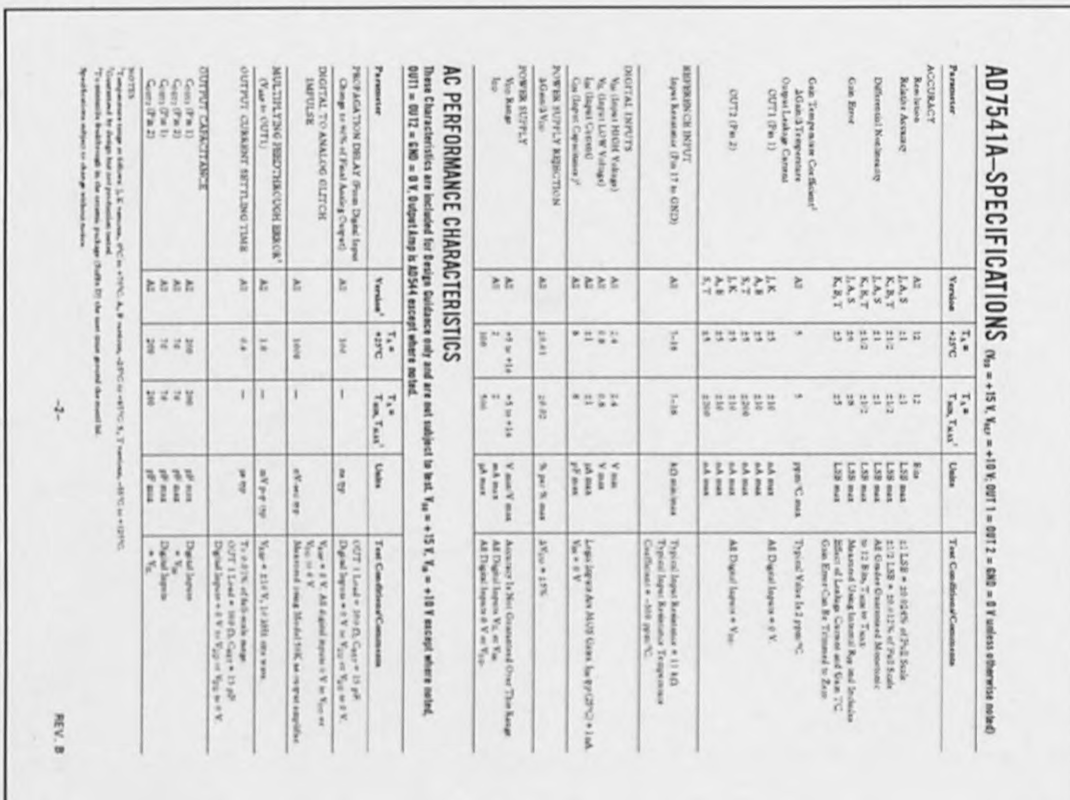
D.10: Voltage Regulator – LM2940

D.11: DC-to-DC Converter – TEN 5-0522

D.12. RS232 driver – MAX323

D.1: 12 bit DAC – AD7541A





AD7541A

ABSOLUTE MAXIMUM RATINGS*
(T_A = +25°C unless otherwise noted)

V_{DD} to GND . . . . +17 V
V_{REF} to GND . . . . ±25 V
V_{RFB} to GND . . . . ±25 V
Digital Input Voltage to GND . . . . −0.3 V, V_{DD} + 0.3 V
OUT 1, OUT 2 to GND . . . . −0.3 V, V_{DD} + 0.3 V
Power Dissipation (Any Package)
To +75°C . . . . 450 mW
Derates above +75°C . . . . 6 mW/°C

Operating Temperature Range
Commercial (J, K Versions) . . . . 0°C to +70°C
Industrial (A, B Versions) . . . . −25°C to +85°C
Extended (S, T Versions) . . . . −55°C to +125°C
Storage Temperature . . . . −65°C to +150°C
Lead Temperature (Soldering, 10 secs) . . . . +300°C

*Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational sections of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

CAUTION

ESD (electrostatic discharge) sensitive device. Electrostatic charges as high as 4000 V readily accumulate on the human body and test equipment and can discharge without detection. Although the AD7541A features proprietary ESD protection circuitry, permanent damage may occur on devices subjected to high energy electrostatic discharges. Therefore, proper ESD precautions are recommended to avoid performance degradation or loss of functionality.

WARNING!
ESD SENSITIVE DEVICE

TERMINOLOGY

RELATIVE ACCURACY
Relative accuracy or endpoint nonlinearity is a measure of the maximum deviation from a straight line passing through the endpoints of the DAC transfer function. It is measured after adjusting for zero and full scale and is expressed in % of full-scale range or (sub)multiples of 1 LSB.

DIFFERENTIAL NONLINEARITY
Differential nonlinearity is the difference between the *measured* change and the *ideal* 1 LSB change between any two adjacent codes. A specified differential nonlinearity of ±1 LSB max over the operating temperature range insures monotonicity.

GAIN ERROR
Gain error is a measure of the output error between an ideal DAC and the actual device output. For the AD7541A, ideal maximum output is

$$-\left(\frac{4095}{4096}\right)(V_{REF}).$$

Gain error is adjustable to zero using external trims as shown in Figures 4, 5 and 6.

OUTPUT LEAKAGE CURRENT
Current which appears at OUT1 with the DAC loaded to all 0s or at OUT2 with the DAC loaded to all 1s.

MULTIPLYING FEEDTHROUGH ERROR
AC error due to capacitive feedthrough from V_{REF} terminal to OUT1 with DAC loaded to all 0s.

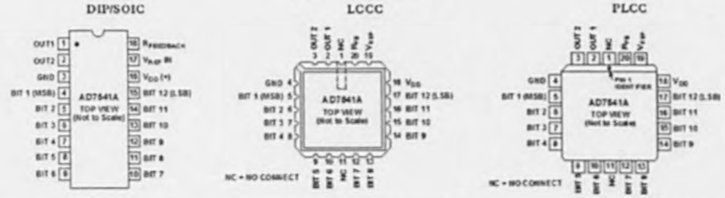
OUTPUT CURRENT SETTLING TIME
Time required for the output function of the DAC to settle to within 1/2 LSB for a given digital input stimulus, i.e., 0 to full scale.

PROPAGATION DELAY
This is a measure of the internal delay of the circuit and is measured from the time a digital input changes to the point at which the analog output at OUT1 reaches 90% of its final value.

DIGITAL-TO-ANALOG CHARGE INJECTION (QDA)
This is a measure of the amount of charge injected from the digital inputs to the analog outputs when the inputs change state. It is usually specified as the area of the glitch in nV secs and is measured with V_{REF} = GND and a Model 50K as the output op amp, C1 (phase compensation) = 0 pF.

PIN CONFIGURATIONS

DIP/SOIC LCCC PLCC



AD7541A

GENERAL CIRCUIT INFORMATION

The simplified D/A circuit is shown in Figure 1. An inverted R-2R ladder structure is used—that is, the binarily weighted currents are switched between the OUT1 and OUT2 bus lines, thus maintaining a constant current in each ladder leg independent of the switch state.

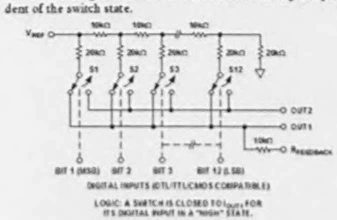


Figure 1. Functional Diagram (Inputs HIGH)

The input resistance at V_{REF} (Figure 1) is always equal to R_{LDR} (R_{LDR} is the R/2R ladder characteristic resistance and is equal to value "R"). Since R_{IN} at the V_{REF} pin is constant, the reference terminal can be driven by a reference voltage or a reference current, ac or dc, of positive or negative polarity. (If a current source is used, a low temperature coefficient external R_{FB} is recommended to define scale factor.)

EQUIVALENT CIRCUIT ANALYSIS
The equivalent circuits for all digital inputs LOW and all digital inputs HIGH are shown in Figures 2 and 3. In Figure 2 with all digital inputs LOW, the reference current is switched to OUT2. The current source $I_{LEAKAGE}$ is composed of surface and junction leakages to the substrate, while the I_{ON} current source represents a constant 1-bit current drain through the termination resistor on the R-2R ladder. The ON capacitance of the output N-channel switch is 200 pF, as shown on the OUT2 terminal. The OFF switch capacitance is 70 pF, as shown on the OUT1 terminal. Analysis of the circuit for all digital inputs HIGH, as shown in Figure 3 is similar to Figure 2; however, the ON switches are now on terminal OUT1, hence the 200 pF at that terminal.

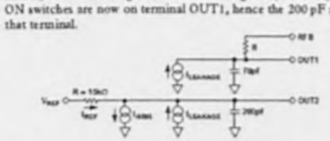


Figure 2. DAC Equivalent Circuit All Digital Inputs LOW

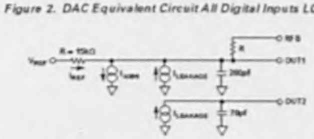


Figure 3. DAC Equivalent Circuit All Digital Inputs HIGH

APPLICATIONS

UNIPOLAR BINARY OPERATION (2-QUADRANT MULTIPLICATION)
Figure 4 shows the analog circuit connections required for unipolar binary (2-quadrant multiplication) operation. With a dc reference voltage or current (positive or negative polarity) applied at Pin 17, the circuit is a unipolar D/A converter. With an ac reference voltage or current, the circuit provides 2-quadrant multiplication (digitally controlled attenuation). The input/output relationship is shown in Table II.

R1 provides full-scale trim capability [i.e., load the DAC register to 1111 1111 1111, adjust R1 for V_{OUT} = $-V_{REF}$ (4095/4096)]. Alternatively, Full Scale can be adjusted by omitting R1 and R2 and trimming the reference voltage magnitude.

C1 phase compensation (10 pF to 25 pF) may be required for stability when using high speed amplifiers. (C1 is used to cancel the pole formed by the DAC internal feedback resistance and output capacitance at OUT1).

Amplifier A1 should be selected or trimmed to provide V_{OS} ≤ 10% of the voltage resolution at V_{OUT}. Additionally, the amplifier should exhibit a bias current which is low over the temperature range of interest (bias current causes output offset at V_{OUT} equal to I_B times the DAC feedback resistance, nominally 11 kΩ). The AD544L is a high speed implanted FET input op amp with low factory-trimmed V_{OS}.

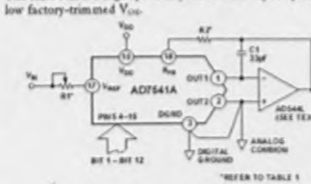


Figure 4. Unipolar Binary Operation

Table I. Recommended Trim Resistor Values vs. Grades

Trim Resistor	JN/AQ/SD	KN/BQ/TD
R1	100 Ω	100 Ω
R2	47 Ω	33 Ω

Table II. Unipolar Binary Code Table for Circuit of Figure 4

Binary Number in DAC MSB		LSB	Analog Output, V_{OUT}
1111	1111	1111	$-V_{IN}\left(\frac{4095}{4096}\right)$
1000	0000	0000	$-V_{IN}\left(\frac{2048}{4096}\right) = -1/2\ V_{IN}$
0000	0000	0001	$-V_{IN}\left(\frac{1}{4096}\right)$
0000	0000	0000	0 Volts

BIPOLAR OPERATION (4-QUADRANT MULTIPLICATION)

Figure 5 and Table III illustrate the circuitry and code relationship for bipolar operation. With a dc reference (positive or negative polarity) the circuit provides offset binary operation. With an ac reference the circuit provides full 4-quadrant multiplication.

With the DAC loaded to 1000 0000 0000, adjust R1 for V_{OUT} = 0 V (alternatively, one can omit R1 and R2 and adjust the ratio of R3 to R4 for V_{OUT} = 0 V). Full-scale trimming can be accomplished by adjusting the amplitude of V_{REF} or by varying the value of R5.

As in unipolar operation, A1 must be chosen for low V_{OS} and low I_B. R3, R4 and R5 must be selected for matching and tracking. Mismatch of 2R3 to R4 causes both offset and full-scale error. Mismatch of R5 to R4 or 2R3 causes full-scale error. C1 phase compensation (10 pF to 50 pF) may be required for stability, depending on amplifier used.

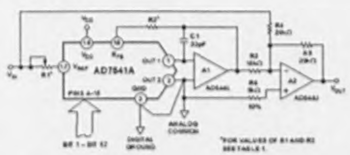


Figure 5. Bipolar Operation (4-Quadrant Multiplication)

Table III. Bipolar Code Table for Offset Binary Circuit of Figure 5

Binary Number in DAC MSB		LSB	Analog Output, V_{OUT}
1111	1111	1111	$+V_{IN}\left(\frac{2047}{2048}\right)$
1000	0000	0001	$+V_{IN}\left(\frac{1}{2048}\right)$
1000	0000	0000	0 Volts
0111	1111	1111	$-V_{IN}\left(\frac{1}{2048}\right)$
0000	0000	0000	$-V_{IN}\left(\frac{2048}{2048}\right)$

Figure 6 and Table IV show an alternative method of achieving bipolar output. The circuit operates with sign plus magnitude code and has the advantage of giving 12-bit resolution in each quadrant, compared with 11-bit resolution per quadrant for the circuit of Figure 5. The AD7592 is a fully protected CMOS changeover switch with data latches. R4 and R5 should match each other to 0.01% to maintain the accuracy of the D/A converter. Mismatch between R4 and R5 introduces a gain error.

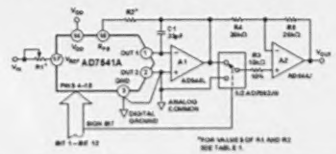


Figure 6. 12-Bit Plus Sign Magnitude Operation

Table IV. 12-Bit Plus Sign Magnitude Code Table for Circuit of Figure 6

Sign Bit	Binary Number in DAC MSB		LSB	Analog Output, V_{OUT}
0	1111	1111	1111	$+V_{IN}\times\left(\frac{4095}{4096}\right)$
0	0000	0000	0000	0 Volts
1	0000	0000	0000	0 Volts
1	1111	1111	1111	$-V_{IN}\times\left(\frac{4095}{4096}\right)$

Note: Sign bit of "0" connects R3 to GND.

APPLICATIONS HINTS

Output Offset: CMOS D/A converters exhibit a code-dependent output resistance which in turn can cause a code-dependent error voltage at the output of the amplifier. The maximum amplitude of this offset, which adds to the D/A converter nonlinearity, is 0.67 V_{OS} where V_{OS} is the amplifier input offset voltage. To maintain monotonic operation it is recommended that V_{OS} be no greater than (25 × 10^{-6}) (V_{REF}) over the temperature range of operation. Suitable op amps are AD517L and AD544L. The AD517L is best suited for fixed reference applications with low bandwidth requirements: it has extremely low offset (50 μV) and in most applications will not require an offset trim. The AD544L has a much wider bandwidth and higher slew rate and is recommended for multiplying and other applications requiring fast settling. An offset trim on the AD544L may be necessary in some circuits.

Digital Glitches: One cause of digital glitches is capacitive coupling from the digital lines to the OUT1 and OUT2 terminals. This should be minimized by screening the analog pins of the AD7541A (Pins 1, 2, 17, 18) from the digital pins by a ground track run between Pins 2 and 3 and between Pins 16 and 17 of the AD7541A. Note how the analog pins are at one end of the package and separated from the digital pins by V_{DD} and GND to aid screening at the board level. On-chip capacitive coupling can also give rise to crosstalk from the digital-to-analog sections of the AD7541A, particularly in circuits with high currents and fast rise and fall times.

Temperature Coefficients: The gain temperature coefficient of the AD7541A has a maximum value of 5 ppm/°C and a typical value of 2 ppm/°C. This corresponds to worst case gain shifts of 2 LSBs and 0.8 LSBs, respectively, over a 100°C temperature range. When trim resistors R1 and R2 are used to adjust full-scale range, the temperature coefficient of R1 and R2 should also be taken into account. The reader is referred to Analog Devices Application Note "Gain Error and Gain Temperature Coefficient of CMOS Multiplying DACs," Publication Number E630c-5-3/86.

SINGLE SUPPLY OPERATION

Figure 7 shows the AD7541A connected in a voltage switching mode. OUT1 is connected to the reference voltage and OUT2 is connected to GND. The D/A converter output voltage is available at the V_{REF} pin (Pin 17) and has a constant output impedance equal to R_{LDR}. The feedback resistor R_{FB} is not used in this circuit.

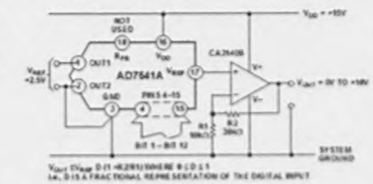


Figure 7. Single Supply Operation Using Voltage Switching Mode

The reference voltage must always be positive. If OUT1 goes more than 0.3 V less than GND, an internal diode will be turned on and a heavy current may flow causing device damage (the AD7541A is, however, protected from the SCR latch-up phenomenon prevalent in many CMOS devices). Suitable references include the AD580 and AD584.

The loading on the reference voltage source is code-dependent and the response time of the circuit is often determined by the behavior of the reference voltage with changing load conditions. To maintain linearity, the voltage at OUT1 should remain within 2.5 V of GND, for a V_{DD} of 15 V. If V_{DD} is reduced from 15 V or the reference voltage at OUT1 increased to more than 2.5 V, the differential nonlinearity of the DAC will increase and the linearity of the DAC will be degraded.

SUPPLEMENTAL APPLICATION MATERIAL

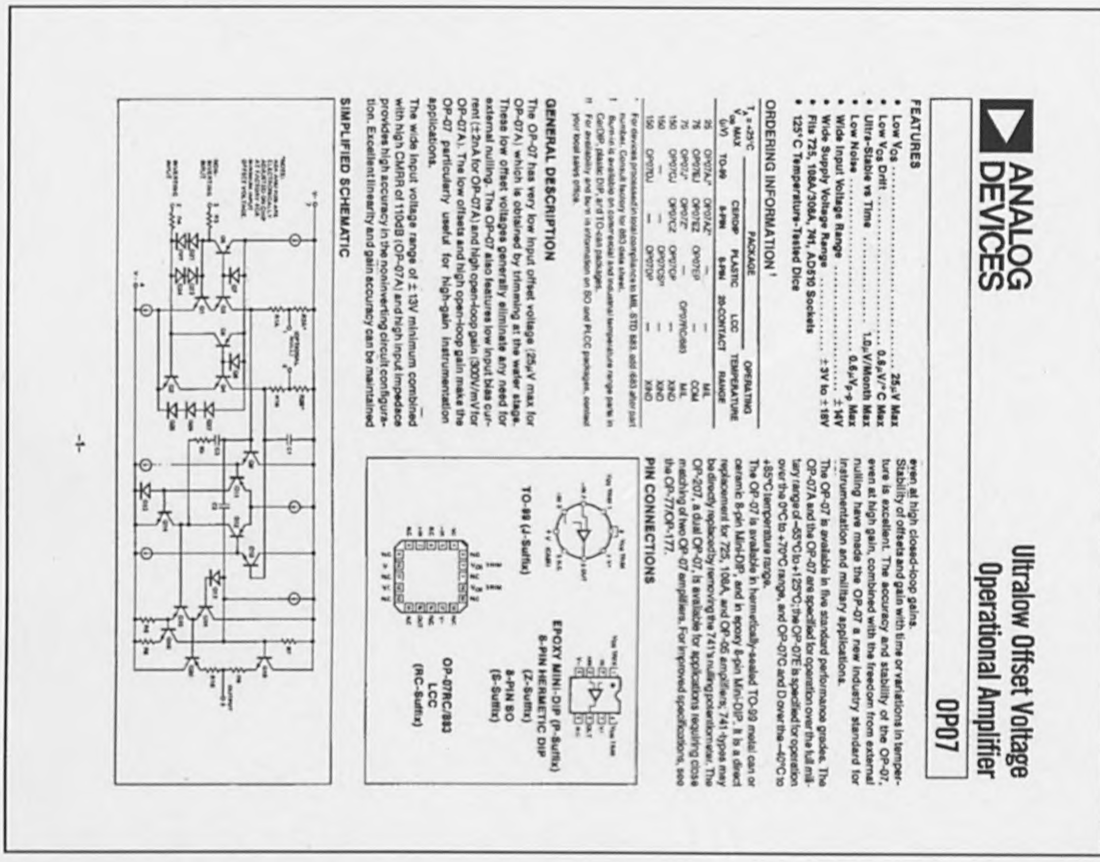
For further information on CMOS multiplying D/A converters, the reader is referred to the following texts:

CMOS DAC Application Guide, Publication Number G872b-8-1/89 available from Analog Devices.

Gain Error and Gain Temperature Coefficient of CMOS Multiplying DACs Application Note, Publication Number E630c-5-3/86 available from Analog Devices.

Analog-Digital Conversion Handbook—available from Analog Devices.

D.2: Operational Amplifier - OP07



ANALOG DEVICES

Ultralow Offset Voltage Operational Amplifier

OP07

FEATURES

- Low V_{OS} .... 25µV Max
- Low V_{OS} Drift .... 0.6µV/°C Max
- Ultra-Stable vs Time .... 1.0µV/Month Max
- Low Noise .... 0.6µV_{p-p} Max
- Wide Input Voltage Range .... ±14V
- Wide Supply Voltage Range .... ±3V to ±18V
- Fits 725, 108A/308A, 741, AD510 Sockets
- 125°C Temperature-Tested Dice

ORDERING INFORMATION †

T_A = +25°C V_{OS} MAX (µV)	TO-99	CERDIP 8-PIN	PLASTIC 8-PIN	LCC 20-CONTACT	OPERATING TEMPERATURE RANGE
25	OP07AJ*	OP07AZ*	—	—	MIL
75	OP07EJ	OP07EZ	OP07EP	—	COM
75	OP07J*	OP07Z*	—	OP07RC/883	MIL
150	OP07CJ	OP07CZ	OP07CP	—	XIND
150	—	—	OP07CS††	—	XIND
150	OP07DJ	—	OP07DP	—	XIND

* For devices processed in total compliance to MIL-STD 883, add /883 after part number. Consult factory for 883 data sheet.

† Burn-in is available on commercial and industrial temperature range parts in CerDIP, plastic DIP, and TO-can packages.

†† For availability and burn-in information on SO and PLCC packages, contact your local sales office.

GENERAL DESCRIPTION

The OP-07 has very low input offset voltage (25µV max for OP-07A) which is obtained by trimming at the wafer stage. These low offset voltages generally eliminate any need for external nulling. The OP-07 also features low input bias current (±2nA for OP-07A) and high open-loop gain (300V/mV for OP-07A). The low offsets and high open-loop gain make the OP-07 particularly useful for high-gain instrumentation applications.

The wide input voltage range of ±13V minimum combined with high CMRR of 110dB (OP-07A) and high input impedace provides high accuracy in the noninverting circuit configuration. Excellent linearity and gain accuracy can be maintained even at high closed-loop gains.

Stability of offsets and gain with time or variations in temperature is excellent. The accuracy and stability of the OP-07, even at high gain, combined with the freedom from external nulling have made the OP-07 a new industry standard for instrumentation and military applications.

The OP-07 is available in five standard performance grades. The OP-07A and the OP-07 are specified for operation over the full military range of −55°C to +125°C; the OP-07E is specified for operation over the 0°C to +70°C range, and OP-07C and D over the −40°C to +85°C temperature range.

The OP-07 is available in hermetically-sealed TO-99 metal can or ceramic 8-pin Mini-DIP, and in epoxy 8-pin Mini-DIP. It is a direct replacement for 725, 108A, and OP-05 amplifiers; 741-types may be directly replaced by removing the 741's nulling potentiometer. The OP-207, a dual OP-07, is available for applications requiring close matching of two OP-07 amplifiers. For improved specifications, see the OP-77/OP-177.

PIN CONNECTIONS

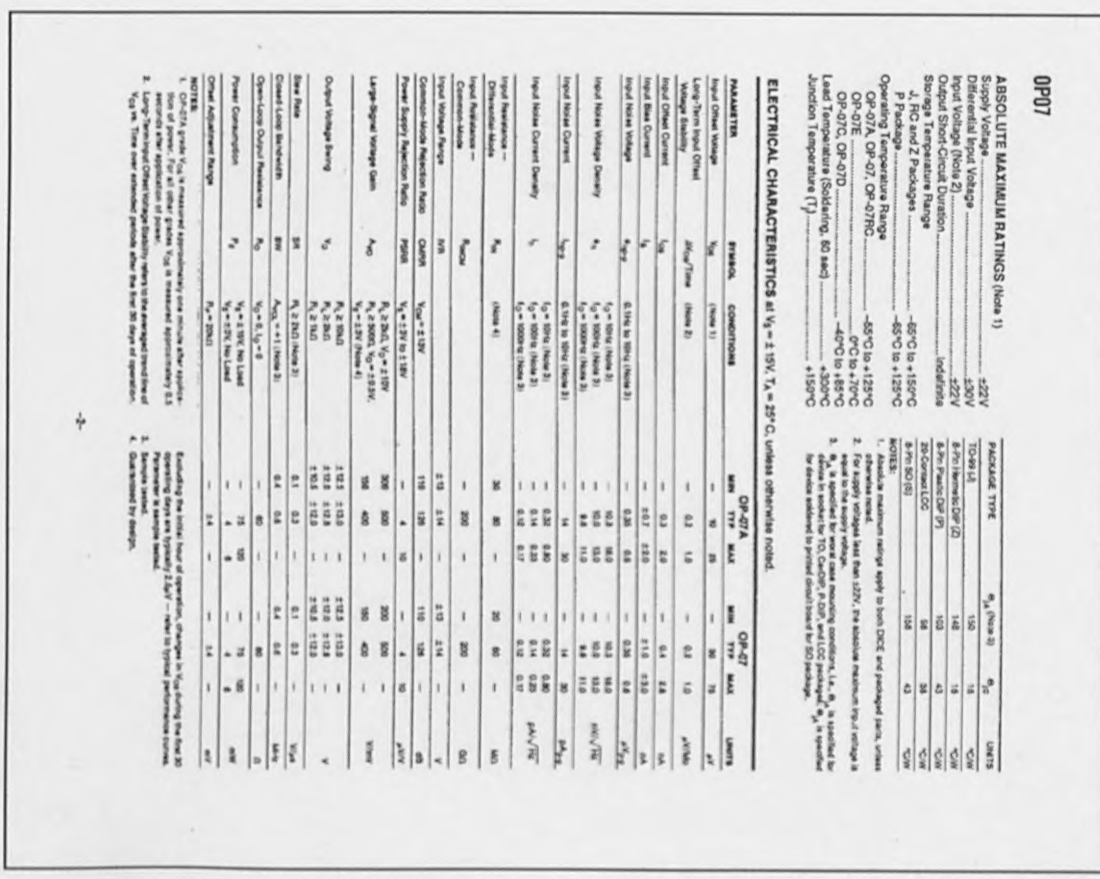
TO-99 (J-Suffix)

EPOXY MINI-DIP (P-Suffix)
8-PIN HERMETIC DIP (Z-Suffix)
8-PIN SO (S-Suffix)

OP-07RC/883 LCC (RC-Suffix)

SIMPLIFIED SCHEMATIC

-1-



OP07

ABSOLUTE MAXIMUM RATINGS (Note 1)

Supply Voltage .... ±22V
Differential Input Voltage .... ±30V
Input Voltage (Note 2) .... ±22V
Output Short-Circuit Duration .... Indefinite
Storage Temperature Range
J, RC and Z Packages .... −65°C to +150°C
P Package .... −65°C to +125°C
Operating Temperature Range
OP-07A, OP-07, OP-07RC .... −55°C to +125°C
OP-07E .... 0°C to +70°C
OP-07C, OP-07D .... −40°C to +85°C
Lead Temperature (Soldering, 60 sec) .... +300°C
Junction Temperature (T_j) .... +150°C

PACKAGE TYPE	θ_{jA} (Note 3)	θ_{jC}	UNITS
TO-99 (J)	150	18	°C/W
8-Pin Hermetic DIP (Z)	148	16	°C/W
8-Pin Plastic DIP (P)	103	43	°C/W
20-Contact LCC	98	38	°C/W
8-Pin SO (S)	158	43	°C/W

NOTES:
1. Absolute maximum ratings apply to both DICE and packaged parts, unless otherwise noted.
2. For supply voltages less than ±22V, the absolute maximum input voltage is equal to the supply voltage.
3. θ_{jA} is specified for worst case mounting conditions, i.e., θ_{jA} is specified for device in socket for TO, CerDIP, P-DIP, and LCC packages; θ_{jA} is specified for device soldered to printed circuit board for SO package.

ELECTRICAL CHARACTERISTICS at V_S = ±15V, T_A = 25°C, unless otherwise noted.

PARAMETER	SYMBOL	CONDITIONS	OP-07A MIN	OP-07A TYP	OP-07A MAX	OP-07 MIN	OP-07 TYP	OP-07 MAX	UNITS
Input Offset Voltage	V_{OS}	(Note 1)	—	10	25	—	30	75	µV
Long-Term Input Offset Voltage Stability	ΔV_{OS}/Time	(Note 2)	—	0.2	1.0	—	0.2	1.0	µV/Mo
Input Offset Current	I_{OS}		—	0.3	2.0	—	0.4	2.8	nA
Input Bias Current	I_B		—	±0.7	±2.0	—	±1.0	±3.0	nA
Input Noise Voltage	e_{np-p}	0.1Hz to 10Hz (Note 3)	—	0.35	0.6	—	0.35	0.6	μV_{p-p}
Input Noise Voltage Density	e_n	f_O = 10Hz (Note 3)	—	10.3	18.0	—	10.3	18.0	nV/$\sqrt{Hz}$
		f_O = 100Hz (Note 3)	—	10.0	13.0	—	10.0	13.0	
		f_O = 1000Hz (Note 3)	—	9.6	11.0	—	9.6	11.0	
Input Noise Current	i_{np-p}	0.1Hz to 10Hz (Note 3)	—	14	30	—	14	30	pA_{p-p}
Input Noise Current Density	i_n	f_O = 10Hz (Note 3)	—	0.32	0.80	—	0.32	0.80	pA/$\sqrt{Hz}$
		f_O = 100Hz (Note 3)	—	0.14	0.23	—	0.14	0.23	
		f_O = 1000Hz (Note 3)	—	0.12	0.17	—	0.12	0.17	
Input Resistance — Differential-Mode	R_{IN}	(Note 4)	30	80	—	20	60	—	MΩ
Input Resistance — Common-Mode	R_{INCM}		—	200	—	—	200	—	GΩ
Input Voltage Range	IVR		±13	±14	—	±13	±14	—	V
Common-Mode Rejection Ratio	CMRR	V_{CM} = ±13V	110	126	—	110	126	—	dB
Power Supply Rejection Ratio	PSRR	V_S = ±3V to ±18V	—	4	10	—	4	10	µV/V
Large-Signal Voltage Gain	A_{VO}	R_L ≥ 2kΩ, V_O = ±10V	300	500	—	200	500	—	V/mV
		R_L ≥ 500Ω, V_O = ±0.5V, V_S = ±3V (Note 4)	150	400	—	150	400	—	
Output Voltage Swing	V_O	R_L ≥ 10kΩ	±12.5	±13.0	—	±12.5	±13.0	—	V
		R_L ≥ 2kΩ	±12.0	±12.8	—	±12.0	±12.8	—	
		R_L ≥ 1kΩ	±10.5	±12.0	—	±10.5	±12.0	—	
Slew Rate	SR	R_L ≥ 2kΩ (Note 3)	0.1	0.3	—	0.1	0.3	—	V/µs
Closed-Loop Bandwidth	BW	A_{VCL} = +1 (Note 3)	0.4	0.6	—	0.4	0.6	—	MHz
Open-Loop Output Resistance	R_O	V_O = 0, I_O = 0	—	60	—	—	60	—	Ω
Power Consumption	P_d	V_S = ±15V, No Load	—	75	120	—	75	120	mW
		V_S = ±3V, No Load	—	4	6	—	4	6	
Offset Adjustment Range		R_P = 20kΩ	—	±4	—	—	±4	—	mV

NOTES:
1. OP-07A grade V_{OS} is measured approximately one minute after application of power. For all other grades V_{OS} is measured approximately 0.5 seconds after application of power.
2. Long-Term Input Offset Voltage Stability refers to the averaged trend line of V_{OS} vs. Time over extended periods after the first 30 days of operation. Excluding the initial hour of operation, changes in V_{OS} during the first 30 operating days are typically 2.5µV — refer to typical performance curves. Parameter is sample tested.
3. Sample tested.
4. Guaranteed by design.

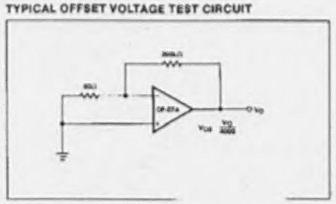
-2-

ELECTRICAL CHARACTERISTICS at $V_S = \pm 15V$, $-55°C \le T_A \le +125°C$, unless otherwise noted.

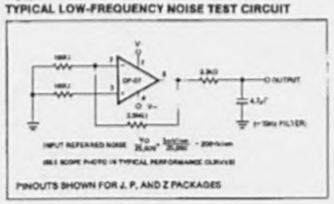
PARAMETER	SYMBOL	CONDITIONS	OP-07A MIN	OP-07A TYP	OP-07A MAX	OP-07 MIN	OP-07 TYP	OP-07 MAX	UNITS
Input Offset Voltage	V_{OS}	(Note 1)	—	25	60	—	60	200	μV
Average Input Offset Voltage Drift Without External Trim	TCV_{OS}	(Note 2)	—	0.2	0.6	—	0.3	1.3	μV/°C
With External Trim	TCV_{OSn}	$R_P = 20k\Omega$ (Note 3)	—	0.2	0.6	—	0.3	1.3	μV/°C
Input Offset Current	I_{OS}		—	0.8	4	—	1.2	5.6	nA
Average Input Offset Current Drift	TCI_{OS}	(Note 2)	—	5	25	—	8	50	pA/°C
Input Bias Current	I_B		—	±1	±4	—	±2	±6	nA
Average Input Bias Current Drift	TCI_B	(Note 2)	—	8	25	—	13	50	pA/°C
Input Voltage Range	IVR		±13	±13.5	—	±13	±13.5	—	V
Common-Mode Rejection Ratio	CMRR	$V_{CM} = \pm 13V$	106	123	—	106	123	—	dB
Power Supply Rejection Ratio	PSRR	$V_S = \pm 3V$ to $\pm 18V$	—	5	20	—	5	20	μV/V
Large-Signal Voltage Gain	A_{VO}	$R_L \ge 2k\Omega$, $V_O = \pm 10V$	200	400	—	150	400	—	V/mV
Output Voltage Swing	V_O	$R_L \ge 2k\Omega$	±12	±12.6	—	±12	±12.6	—	V

NOTES:
1. OP-07A grade V_{OS} is measured approximately one minute after application of power. For all other grades V_{OS} is measured approximately 0.5 seconds after application of power.
2. Sample tested.
3. Guaranteed by design.

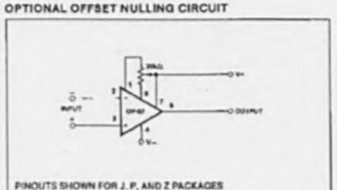
TYPICAL OFFSET VOLTAGE TEST CIRCUIT



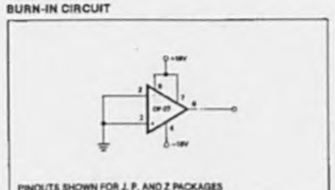
TYPICAL LOW-FREQUENCY NOISE TEST CIRCUIT



OPTIONAL OFFSET NULLING CIRCUIT



BURN-IN CIRCUIT



ELECTRICAL CHARACTERISTICS at $V_S = \pm 15V$, $T_A = 25°C$, unless otherwise noted.

PARAMETER	SYMBOL	CONDITIONS	OP-07E MIN	OP-07E TYP	OP-07E MAX	OP-07C MIN	OP-07C TYP	OP-07C MAX	OP-07D MIN	OP-07D TYP	OP-07D MAX	UNITS
Input Offset Voltage	V_{OS}	(Note 1)	—	30	75	—	60	150	—	60	150	μV
Long-Term V_{OS} Stability	V_{OS}/Time	(Note 2)	—	0.3	1.5	—	0.4	2.0	—	0.5	3.0	μV/Mo
Input Offset Current	I_{OS}		—	0.5	3.8	—	0.8	6.0	—	0.8	6.0	nA
Input Bias Current	I_B		—	±1.2	±4.0	—	±1.8	±7.0	—	±2.0	±12	nA
Input Noise Voltage	e_{np-p}	0.1Hz to 10Hz (Note 3)	—	0.35	0.6	—	0.38	0.65	—	0.38	0.65	μV_{p-p}
Input Noise Voltage Density	e_n	$f_O = 10Hz$	—	10.3	18.0	—	10.5	20.0	—	10.5	20.0	$nV/\sqrt{Hz}$
		$f_O = 100Hz$ (Note 3)	—	10.0	13.0	—	10.2	13.5	—	10.3	13.5	
		$f_O = 1000Hz$	—	9.6	11.0	—	9.8	11.5	—	9.8	11.5	
Input Noise Current	i_{np-p}	0.1Hz to 10Hz (Note 3)	—	14	30	—	15	35	—	15	35	pA_{p-p}
Input Noise Current Density	i_n	$f_O = 10Hz$	—	0.32	0.80	—	0.35	0.90	—	0.35	0.90	$pA/\sqrt{Hz}$
		$f_O = 100Hz$ (Note 3)	—	0.14	0.23	—	0.15	0.27	—	0.15	0.27	
		$f_O = 1000Hz$	—	0.12	0.17	—	0.13	0.18	—	0.13	0.18	
Input Resistance — Differential-Mode	R_{IN}	(Note 4)	15	50	—	8	33	—	7	31	—	MΩ
Input Resistance — Common-Mode	R_{INCM}		—	160	—	—	120	—	—	120	—	GΩ
Input Voltage Range	IVR		±13	±14	—	±13	±14	—	±13	±14	—	V
Common-Mode Rejection Ratio	CMRR	$V_{CM} = \pm 13V$	106	123	—	100	120	—	94	110	—	dB
Power Supply Rejection Ratio	PSRR	$V_S = \pm 3V$ to $\pm 18V$	—	5	20	—	7	32	—	7	32	μV/V
Large-Signal Voltage Gain	A_{VO}	$R_L \ge 2k\Omega$, $V_O = \pm 10V$	200	500	—	120	400	—	120	400	—	V/mV
		$R_L \ge 500\Omega$, $V_O = \pm 0.5V$, $V_S = \pm 3V$ (Note 4)	150	400	—	100	400	—	—	400	—	
Output Voltage Swing	V_O	$R_L \ge 10k\Omega$	±12.5	±13.0	—	±12.0	±13.0	—	±12.0	±13.0	—	V
		$R_L \ge 2k\Omega$	±12.0	±12.8	—	±11.5	±12.8	—	±11.5	±12.8	—	
		$R_L \ge 1k\Omega$	±10.5	±12.0	—	—	±12.0	—	—	±12.0	—	
Slew Rate	SR	$R_L \ge 2k\Omega$ (Note 3)	0.1	0.3	—	0.1	0.3	—	0.1	0.3	—	V/μs
Closed-Loop Bandwidth	BW	$A_{VCL} = +1$ (Note 5)	0.4	0.6	—	0.4	0.6	—	0.4	0.6	—	MHz
Open-Loop Output Resistance	R_O	$V_O = 0$, $I_O = 0$	—	60	—	—	60	—	—	60	—	Ω
Power Consumption	P_d	$V_S = \pm 15V$, No Load	—	75	120	—	80	150	—	80	150	mW
		$V_S = \pm 3V$, No Load	—	4	6	—	4	8	—	4	8	
Offset Adjustment Range		$R_P = 20k\Omega$	—	±4	—	—	±4	—	—	±4	—	mV

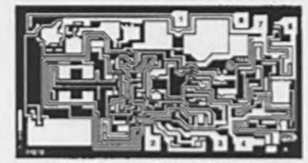
NOTES:
1. Input Offset Voltage measurements are performed by automated test equipment approximately 0.5 seconds after application of power.
2. Long-Term Input Offset Voltage Stability refers to the averaged trend line of V_{OS} vs. Time over extended periods after the first 30 days of operation. Excluding the initial hour of operation, changes in V_{OS} during the first 30 operating days are typically 2.5μV — refer to typical performance curves. Parameter is sample tested.
3. Sample tested.
4. Guaranteed by design.
5. Guaranteed but not tested.

ELECTRICAL CHARACTERISTICS at V_S = ±15V, 0°C ≤ T_A ≤ +70°C for OP-07E, and −40°C ≤ T_A ≤ +85°C for OP-07C/D, unless otherwise noted.

PARAMETER	SYMBOL	CONDITIONS	OP-07E MIN	OP-07E TYP	OP-07E MAX	OP-07C MIN	OP-07C TYP	OP-07C MAX	OP-07D MIN	OP-07D TYP	OP-07D MAX	UNITS
Input Offset Voltage	V_{OS}	(Note 1)	—	45	130	—	85	250	—	85	250	µV
Average Input Offset Voltage Drift Without External Trim	TCV_{OS}	(Note 3)	—	0.3	1.3	—	0.5	1.8	—	0.7	2.5	µV/°C
With External Trim	TCV_{OSn}	R_P = 20kΩ (Note 3)	—	0.3	1.3	—	0.4	1.6	—	0.7	2.5	µV/°C
Input Offset Current	I_{OS}		—	0.8	5.3	—	1.6	8.0	—	1.6	8.0	nA
Average Input Offset Current Drift	TCI_{OS}	(Note 2)	—	8	35	—	12	50	—	12	50	pA/°C
Input Bias Current	I_B		—	±1.5	±5.5	—	±2.2	±9.0	—	±3.0	±14	nA
Average Input Bias Current Drift	TCI_B	(Note 2)	—	13	35	—	18	50	—	18	50	pA/°C
Input Voltage Range	IVR		±13.0	±13.5	—	±13.0	±13.5	—	±13.0	±13.5	—	V
Common-Mode Rejection Ratio	CMRR	V_{CM} = ±13V	103	123	—	97	120	—	94	106	—	dB
Power Supply Rejection Ratio	PSRR	V_S = ±3V to ±18V	—	7	32	—	10	51	—	10	51	µV/V
Large-Signal Voltage Gain	A_{VO}	R_L ≥ 2kΩ, V_O = ±10V	180	450	—	100	400	—	100	400	—	V/mV
Output Voltage Swing	V_O	R_L ≥ 2kΩ	±12	±12.6	—	±11	±12.6	—	±11	±12.6	—	V

NOTES:
1. Input offset voltage measurements are performed by automated test equipment approximately 0.5 seconds after application of power.
2. Sample tested.
3. Guaranteed by design.

DICE CHARACTERISTICS (125°C TESTED DICE AVAILABLE)



DIE SIZE 0.100 × 0.055 inch, 5500 sq. mils
(2.54 × 1.40 mm, 3.56 sq. mm)

1. BALANCE
2. INVERTING INPUT
3. NONINVERTING INPUT
4. V−
6. OUTPUT
7. V+
8. BALANCE

WAFER TEST LIMITS at V_S = ±15V, T_A = 25°C for OP-07N, OP-07G and OP-07GR devices; T_A = 125°C for OP-07NT and OP-07GT devices, unless otherwise noted.

PARAMETER	SYMBOL	CONDITIONS	OP-07NT LIMIT	OP-07N LIMIT	OP-07GT LIMIT	OP-07G LIMIT	OP-07GR LIMIT	UNITS
Input Offset Voltage	V_{OS}		140	60	210	80	150	µV MAX
Input Offset Current	I_{OS}		4.0	2.0	5.6	2.8	6.0	nA MAX
Input Bias Current	I_B		±4	±2	±6	±3	±7	nA MAX
Input Resistance Differential-Mode	R_{IN}	(Note 2)	—	20	—	20	8	MΩ MIN
Input Voltage Range	IVR		±13	±13	±13	±13	±13	V MIN
Common-Mode Rejection Ratio	CMRR	V_{CM} = ±13V	100	110	100	110	100	dB MIN
Power Supply Rejection Ratio	PSRR	V_S = ±3V to ±18V	20	10	20	10	30	µV/V MAX
Output Voltage Swing	V_O	R_L = 10kΩ R_L = 2kΩ R_L = 1kΩ	— ±12.0 —	±12.5 ±12.0 ±10.5	— ±12.0 —	±12.0 ±11.5 ±10.5	±12.0 ±11.5 —	V MIN
Large-Signal Voltage Gain	A_{VO}	R_L = 2kΩ, V_O = ±10V	200	200	150	120	120	V/mV MIN
Differential Input Voltage			±30	±30	±30	±30	±30	V MAX
Power Consumption	P_d	V_{OUT} = 0V	—	120	—	120	150	mW MAX

NOTES:
1. For 25°C characteristics of OP-07NT and OP-07GT, see OP-07N and OP-07G characteristics, respectively.
2. Guaranteed by design.

Electrical tests are performed at wafer probe to the limits shown. Due to variations in assembly methods and normal yield loss, yield after packaging is not guaranteed for standard product dice. Consult factory to negotiate specifications based on dice lot qualification through sample lot assembly and testing.

TYPICAL ELECTRICAL CHARACTERISTICS at V_S = ±15V, T_A = +25°C, unless otherwise noted.

PARAMETER	SYMBOL	CONDITIONS	OP-07NT TYPICAL	OP-07N TYPICAL	OP-07GT TYPICAL	OP-07G TYPICAL	OP-07GR TYPICAL	UNITS
Average Input Offset Voltage Drift	TCV_{OS}	R_S = 50Ω	0.2	0.2	0.3	0.3	0.7	µV/°C
Nulled Input Offset Voltage Drift	TCV_{OSn}	R_S = 50Ω, R_P = 20kΩ	0.2	0.2	0.3	0.3	0.7	µV/°C
Average Input Offset Current Drift	TCI_{OS}		5	5	8	8	12	pA/°C
Slew Rate	SR	R_L ≥ 2kΩ	0.3	0.3	0.3	0.3	0.3	V/µs
Closed-Loop Bandwidth	BW	A_{VCL} = +1	0.6	0.6	0.6	0.6	0.6	MHz

D.3: Program. Ref. Voltage Device – TL431

MOTOROLA

Order this document by TL431/D

TL431, A, B Series

PROGRAMMABLE PRECISION REFERENCES

SEMICONDUCTOR TECHNICAL DATA

Programmable Precision References

The TL431, A, B integrated circuits are three–terminal programmable shunt regulator diodes. These monolithic IC voltage references operate as a low temperature coefficient zener which is programmable from V_{ref} to 36 V with two external resistors. These devices exhibit a wide operating current range of 1.0 mA to 100 mA with a typical dynamic impedance of 0.22 Ω. The characteristics of these references make them excellent replacements for zener diodes in many applications such as digital voltmeters, power supplies, and op amp circuitry. The 2.5 V reference makes it convenient to obtain a stable reference from 5.0 V logic supplies, and since the TL431, A, B operates as a shunt regulator, it can be used as either a positive or negative voltage reference.

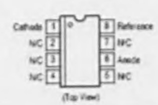
- Programmable Output Voltage to 36 V
- Voltage Reference Tolerance: ±0.4%, Typ @ 25°C (TL431B)
- Low Dynamic Output Impedance, 0.22 Ω Typical
- Sink Current Capability of 1.0 mA to 100 mA
- Equivalent Full–Range Temperature Coefficient of 50 ppm/°C Typical
- Temperature Compensated for Operation over Full Rated Operating Temperature Range
- Low Output Noise Voltage

LP SUFFIX
PLASTIC PACKAGE
CASE 29
(TO–92)

Pin 1. Reference
2. Anode
3. Cathode

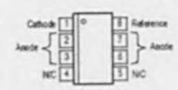
P SUFFIX
PLASTIC PACKAGE
CASE 626

DM SUFFIX
PLASTIC PACKAGE
CASE 846A
(Micro–8)



(Top View)

D SUFFIX
PLASTIC PACKAGE
CASE 751
(SOP–8)



(Top View)

SOP–8 is an internally modified SO–8 package. Pins 2, 3, 6 and 7 are electrically common to the die attach flag. This internal lead frame modification decreases power dissipation capability when appropriately mounted on a printed circuit board. SOP–8 conforms to all external dimensions of the standard SO–8 package.

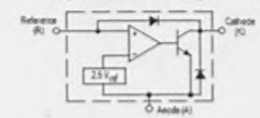
ORDERING INFORMATION

Device	Operating Temperature Range	Package
TL431CLP, ACLP, BCLP	T_A = 0° to +70°C	TO–92
TL431CP, ACP, BCP		Plastic
TL431CDM, ACDM, BCDM		Micro–8
TL431CD, ACD, BCD		SOP–8
TL431ILP, AILP, BILP	T_A = –40° to +85°C	TO–92
TL431IP, AIP, BIP		Plastic
TL431IDM, AIDM, BIDM		Micro–8
TL431ID, AID, BID		SOP–8

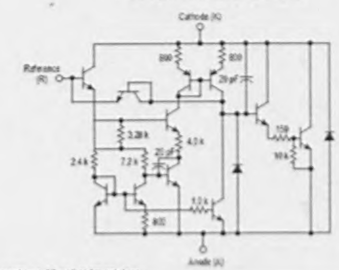
 Rev 6

Symbol

Representative Block Diagram



Representative Schematic Diagram
Component values are nominal



This device contains 12 active transistors.

MAXIMUM RATINGS (Full operating ambient temperature range applies, unless otherwise noted.)

Rating	Symbol	Value	Unit
Cathode to Anode Voltage	V_{KA}	37	V
Cathode Current Range, Continuous	I_K	–100 to +150	mA
Reference Input Current Range, Continuous	I_{ref}	–0.05 to +10	mA
Operating Junction Temperature	T_J	150	°C
Operating Ambient Temperature Range TL431I, TL431AI, TL431BI TL431C, TL431AC, TL431BC	T_A	 –40 to +85 0 to +70	°C
Storage Temperature Range	T_{stg}	–65 to +150	°C
Total Power Dissipation @ T_A = 25°C Derate above 25°C Ambient Temperature D, LP Suffix Plastic Package P Suffix Plastic Package DM Suffix Plastic Package	P_D	 0.70 1.10 0.52	W
Total Power Dissipation @ T_C = 25°C Derate above 25°C Case Temperature D, LP Suffix Plastic Package P Suffix Plastic Package	P_D	 1.5 3.0	W

NOTE: ESD data available upon request.

RECOMMENDED OPERATING CONDITIONS

Condition	Symbol	Min	Max	Unit
Cathode to Anode Voltage	V_{KA}	V_{ref}	36	V
Cathode Current	I_K	1.0	100	mA

THERMAL CHARACTERISTICS

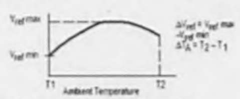
Characteristic	Symbol	D, LP Suffix Package	P Suffix Package	DM Suffix Package	Unit
Thermal Resistance, Junction–to–Ambient	$R_{\theta JA}$	178	114	240	°C/W
Thermal Resistance, Junction–to–Case	$R_{\theta JC}$	83	41	–	°C/W

ELECTRICAL CHARACTERISTICS (T_A = 25°C, unless otherwise noted.)

Characteristic	Symbol	TL431I Min	TL431I Typ	TL431I Max	TL431C Min	TL431C Typ	TL431C Max	Unit
Reference Input Voltage (Figure 1) $V_{KA} = V_{ref}$, I_K = 10 mA T_A = 25°C $T_A = T_{low}$ to T_{high} (Note 1)	V_{ref}	 2.44 2.41	 2.495 –	 2.55 2.58	 2.44 2.423	 2.495 –	 2.55 2.567	V
Reference Input Voltage Deviation Over Temperature Range (Figure 1, Notes 1, 2) $V_{KA} = V_{ref}$, I_K = 10 mA	ΔV_{ref}	–	7.0	–	–	3.0	–	mV
Ratio of Change in Reference Input Voltage to Change in Cathode to Anode Voltage I_K = 10 mA (Figure 2), ΔV_{KA} = 10 V to V_{ref} ΔV_{KA} = 36 V to 10 V	$\frac{\Delta V_{ref}}{\Delta V_{KA}}$	 – –	 –1.4 –1.0	 –2.7 –2.0	 – –	 –1.4 –1.0	 –2.7 –2.0	mV/V
Reference Input Current (Figure 2) I_K = 10 mA, R1 = 10 k, R2 = ∞ T_A = 25°C $T_A = T_{low}$ to T_{high} (Note 1)	I_{ref}	 – –	 1.8 –	 4.0 6.5	 – –	 1.8 –	 4.0 5.2	µA
Reference Input Current Deviation Over Temperature Range (Figure 2, Note 1, 4) I_K = 10 mA, R1 = 10 k, R2 = ∞	ΔI_{ref}	–	0.8	2.5	–	0.4	1.2	µA
Minimum Cathode Current For Regulation $V_{KA} = V_{ref}$ (Figure 1)	I_{min}	–	0.5	1.0	–	0.5	1.0	mA
Off–State Cathode Current (Figure 3) V_{KA} = 36 V, V_{ref} = 0 V	I_{off}	–	260	1000	–	2.6	1000	nA
Dynamic Impedance (Figure 1, Note 3) $V_{KA} = V_{ref}$, ΔI_K = 1.0 mA to 100 mA f ≤ 1.0 kHz	$\|Z_{KA}\|$	–	0.22	0.5	–	0.22	0.5	Ω

NOTES: 1. T_{low} = –40°C for TL431AIP, TL431AILP, TL431IP, TL431ILP, TL431BID, TL431BIP, TL431BILP, TL431AIDM, TL431IDM, TL431BIDM
= 0°C for TL431ACP, TL431ACLP, TL431CP, TL431CLP, TL431CD, TL431ACD, TL431BCD, TL431BCP, TL431BCLP, TL431CDM, TL431ACDM, TL431BCDM
T_{high} = +85°C for TL431AIP, TL431AILP, TL431IP, TL431ILP, TL431BID, TL431BIP, TL431BILP, TL431IDM, TL431AIDM, TL431BIDM
= +70°C for TL431ACP, TL431ACLP, TL431CP, TL431ACD, TL431BCD, TL431BCP, TL431BCLP, TL431CDM, TL431ACDM, TL431BCDM

2. The deviation parameter ΔV_{ref} is defined as the difference between the maximum and minimum values obtained over the full operating ambient temperature range that applies.



The average temperature coefficient of the reference input voltage, αV_{ref} is defined as:

$$V_{ref}\ \frac{ppm}{°C} = \frac{\left(\frac{\Delta V_{ref}}{V_{ref}\ @\ 25°C}\right) X\ 10^6}{\Delta T_A} = \frac{\Delta V_{ref} \times 10^6}{\Delta T_A\ (V_{ref}\ @\ 25°C)}$$

αV_{ref} can be positive or negative depending on whether V_{ref} Min or V_{ref} Max occurs at the lower ambient temperature. (Refer to Figure 6.)

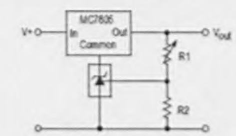
Example: ΔV_{ref} = 8.0 mV and slope is positive,

V_{ref} @ 25°C = 2.495 V, ΔT_A = 70°C $\alpha V_{ref} = \frac{0.008 \times 10^6}{70\ (2.495)} = 45.8$ ppm/°C

3. The dynamic impedance Z_{KA} is defined as $|Z_{KA}| = \frac{\Delta V_{KA}}{\Delta I_K}$

When the device is programmed with two external resistors, R1 and R2, (refer to Figure 2) the total dynamic impedance of the circuit is defined as:

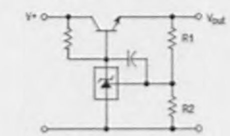
$$|Z_{KA}'| = |Z_{KA}| \left(1 + \frac{R1}{R2}\right)$$



$V_{out} = \left(1 + \frac{R1}{R2}\right) V_{ref}$

$V_{out}\ min = V_{ref} + 5.0V$

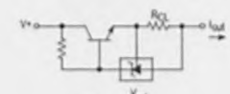
Figure 20. Output Control for a Three–Terminal Fixed Regulator



$V_{out} = \left(1 + \frac{R1}{R2}\right) V_{ref}$

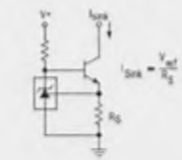
$V_{out}\ min = V_{ref} + V_{be}$

Figure 21. Series Pass Regulator



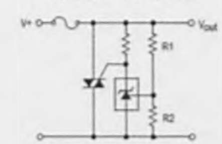
$I_{out} = \frac{V_{ref}}{R_{CL}}$

Figure 22. Constant Current Source



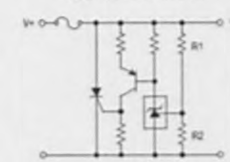
$I_{sink} = \frac{V_{ref}}{R_S}$

Figure 23. Constant Current Sink



$V_{out(trip)} = \left(1 + \frac{R1}{R2}\right) V_{ref}$

Figure 24. TRIAC Crowbar



$V_{out(trip)} = \left(1 + \frac{R1}{R2}\right) V_{ref}$

Figure 25. SRC Crowbar

D.4: 1-8 Analogue Multiplexer - 4052B

Dual 4-channel analogue multiplexer/demultiplexer — HEF4052B MSI

DESCRIPTION

The HEF4052B is a dual 4-channel analogue multiplexer/demultiplexer with common channel select logic. Each multiplexer/demultiplexer has four independent inputs/outputs (Y_0 to Y_3) and a common input/output (Z). The common channel select logic includes two address inputs (A_0 and A_1) and an active LOW enable input ($\overline{E}$).

Both multiplexers/demultiplexers contain four bidirectional analogue switches, each with one side connected to an independent input/output (Y_0 to Y_3) and the other side connected to a common input/output (Z).

With $\overline{E}$ LOW, one of the four switches is selected (low impedance ON-state) by A_0 and A_1. With $\overline{E}$ HIGH, all switches are in the high impedance OFF-state, independent of A_0 and A_1.

V_{DD} and V_{SS} are the supply voltage connections for the digital control inputs (A_0, A_1 and $\overline{E}$). The V_{DD} to V_{SS} range is 3 to 15 V. The analogue inputs/outputs (Y_0 to Y_3, and Z) can swing between V_{DD} as a positive limit and V_{EE} as a negative limit. $V_{DD} - V_{EE}$ may not exceed 15 V.

For operation as a digital multiplexer/demultiplexer, V_{EE} is connected to V_{SS} (typically ground).

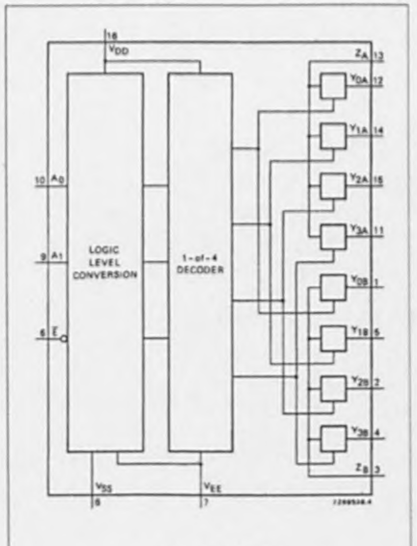


Fig.1 Functional diagram.

PINNING

Y_{0A} to Y_{3A}	independent inputs/outputs
Y_{0B} to Y_{3B}	independent inputs/outputs
A_0, A_1	address inputs
$\overline{E}$	enable input (active LOW)
Z_A, Z_B	common inputs/outputs

FAMILY DATA, I_{DD} LIMITS category MSI

See Family Specifications

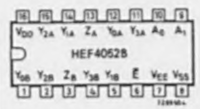


Fig.2 Pinning diagram.

HEF4052BP(N): 16-lead DIL; plastic (SOT38-1)

HEF4052BD(F): 16-lead DIL; ceramic (cerdip) (SOT74)

HEF4052BT(D): 16-lead SO; plastic (SOT109-1)

( ): Package Designator North America

Dual 4-channel analogue multiplexer/demultiplexer — HEF4052B MSI

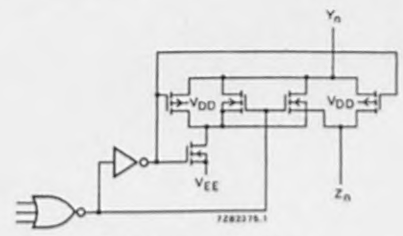


Fig.3 Schematic diagram (one switch).

FUNCTION TABLE

INPUTS			CHANNEL ON
$\overline{E}$	A_1	A_0	
L	L	L	$Y_{0A}-Z_A$; $Y_{0B}-Z_B$
L	L	H	$Y_{1A}-Z_A$; $Y_{1B}-Z_B$
L	H	L	$Y_{2A}-Z_A$; $Y_{2B}-Z_B$
L	H	H	$Y_{3A}-Z_A$; $Y_{3B}-Z_B$
H	X	X	none

Notes

1. H = HIGH state (the more positive voltage)
   L = LOW state (the less positive voltage)
   X = state is immaterial

RATINGS

Limiting values in accordance with the Absolute Maximum System (IEC 134)

Supply voltage (with reference to V_{DD})	V_{EE}	-18 to + 0,5 V

Note

1. To avoid drawing V_{DD} current out of terminal Z, when switch current flows into terminals Y, the voltage drop across the bidirectional switch must not exceed 0,4 V. If the switch current flows into terminal Z, no V_{DD} current will flow out of terminals Y, in this case there is no limit for the voltage drop across the switch, but the voltages at Y and Z may not exceed V_{DD} or V_{EE}.

Dual 4-channel analogue multiplexer/demultiplexer — HEF4052B MSI

AC CHARACTERISTICS

$V_{EE} = V_{SS} = 0$ V; $T_{amb} = 25$ °C; input transition times ≤ 20 ns

	V_{DD} V	TYPICAL FORMULA FOR P (μW)	
Dynamic power dissipation per package (P)	5	$1\,300\ f_i + \Sigma(f_oC_L) \times V_{DD}^2$	where
	10	$6\,100\ f_i + \Sigma(f_oC_L) \times V_{DD}^2$	f_i = input freq. (MHz)
	15	$15\,600\ f_i + \Sigma(f_oC_L) \times V_{DD}^2$	f_o = output freq. (MHz)
			C_L = load capacitance (pF)
			$\Sigma(f_oC_L)$ = sum of outputs
			V_{DD} = supply voltage (V)

AC CHARACTERISTICS

$V_{EE} = V_{SS} = 0$ V; $T_{amb} = 25$ °C; input transition times ≤ 20 ns

	V_{DD} V	SYMBOL	TYP.	MAX.		
Propagation delays						
$V_{is} \to V_{os}$	5		10	20	ns	
HIGH to LOW	10	t_{PHL}	5	10	ns	note 1
	15		5	10	ns	
	5		10	20	ns	
LOW to HIGH	10	t_{PLH}	5	10	ns	note 1
	15		5	10	ns	
$A_n \to V_{os}$	5		150	305	ns	
HIGH to LOW	10	t_{PHL}	65	135	ns	note 2
	15		50	100	ns	
	5		150	300	ns	
LOW to HIGH	10	t_{PLH}	75	150	ns	note 2
	15		50	100	ns	
Output disable times						
$\overline{E} \to V_{os}$	5		95	190	ns	
HIGH	10	t_{PHZ}	90	180	ns	note 3
	15		90	180	ns	
	5		100	205	ns	
LOW	10	t_{PLZ}	90	180	ns	note 3
	15		90	180	ns	
Output enable times						
$\overline{E} \to V_{os}$	5		130	260	ns	
HIGH	10	t_{PZH}	55	115	ns	note 3
	15		45	85	ns	
	5		120	240	ns	
LOW	10	t_{PZL}	50	100	ns	note 3
	15		35	75	ns	

Dual 4-channel analogue multiplexer/demultiplexer — HEF4052B MSI

	V_{DD} V	SYMBOL	TYP.	MAX.		
Distortion, sine-wave	5		0,25		%	
response	10		0,04		%	note 4
	15		0,04		%	
Crosstalk between	5		-		MHz	
any two channels	10		1		MHz	note 5
	15		-		MHz	
Crosstalk; enable	5		-		mV	
or address input	10		50		mV	note 6
to output	15		-		mV	
OFF-state	5		-		MHz	
feed-through	10		1		MHz	note 7
	15		-		MHz	
ON-state frequency	5		13		MHz	
response	10		40		MHz	note 8
	15		70		MHz	

Notes

V_{is} is the input voltage at a Y or Z terminal, whichever is assigned as input.

V_{os} is the output voltage at a Y or Z terminal, whichever is assigned as output.

1. $R_L = 10$ kΩ to V_{EE}; $C_L = 50$ pF to V_{EE}; $\overline{E} = V_{SS}$; $V_{is} = V_{DD}$ (square-wave); see Fig.8.
2. $R_L = 10$ kΩ; $C_L = 50$ pF to V_{EE}; $\overline{E} = V_{SS}$; $A_n = V_{DD}$ (square-wave); $V_{is} = V_{DD}$ and R_L to V_{EE} for t_{PLH}; $V_{is} = V_{EE}$ and R_L to V_{DD} for t_{PHL}; see Fig.8.
3. $R_L = 10$ kΩ; $C_L = 50$ pF to V_{EE}; $\overline{E} = V_{DD}$ (square-wave);
   $V_{is} = V_{DD}$ and R_L to V_{EE} for t_{PHZ} and t_{PZH};
   $V_{is} = V_{EE}$ and R_L to V_{DD} for t_{PLZ} and t_{PZL}; see Fig.8.
4. $R_L = 10$ kΩ; $C_L = 15$ pF; channel ON; $V_{is} = \frac{1}{2} V_{DD\,(p-p)}$ (sine-wave, symmetrical about $\frac{1}{2} V_{DD}$);
   $f_{is} = 1$ kHz; see Fig.9.
5. $R_L = 1$ kΩ; $V_{is} = \frac{1}{2} V_{DD\,(p-p)}$ (sine-wave, symmetrical about $\frac{1}{2} V_{DD}$):
   $$20 \log \frac{V_{os}}{V_{is}} = -50 \text{ dB; see Fig. 10.}$$
6. $R_L = 10$ kΩ to V_{EE}; $C_L = 15$ pF to V_{EE}; $\overline{E}$ or $A_n = V_{DD}$ (square-wave); crosstalk is $|V_{os}|$ (peak value); see Fig.8.
7. $R_L = 1$ kΩ; $C_L = 5$ pF; channel OFF; $V_{is} = \frac{1}{2} V_{DD\,(p-p)}$ (sine-wave, symmetrical about $\frac{1}{2} V_{DD}$):
   $$20 \log \frac{V_{os}}{V_{is}} = -50 \text{ dB; see Fig. 9.}$$
8. $R_L = 1$ kΩ; $C_L = 5$ pF; channel ON; $V_{is} = \frac{1}{2} V_{DD\,(p-p)}$ (sine-wave, symmetrical about $\frac{1}{2} V_{DD}$):
   $$20 \log \frac{V_{os}}{V_{is}} = -3 \text{ dB; see Fig. 9.}$$

D.5: 16 bit ADC – LTC1605

16-Bit, 100ksps, Sampling ADC

FEATURES

- Sample Rate: 100ksps
- **Single 5V Supply**
- **Bipolar Input Range: ±10V**
- **Power Dissipation: 55mW Typ**
- Integral Nonlinearity: ±2.0LSB Max
- **Guaranteed No Missing Codes**
- Signal-to-Noise Ratio: 86dB Typ
- Operates with Internal or External Reference
- Internal Synchronized Clock
- 28-Pin 0.3" PDIP, SSOP and SW Packages
- Improved 2nd Source to ADS7805 and AD976

APPLICATIONS

- Industrial Process Control
- Multiplexed Data Acquisition Systems
- High Speed Data Acquisition for PCs
- Digital Signal Processing

DESCRIPTION

The LTC®1605 is a 100ksps, sampling 16-bit A/D converter that draws only 55mW (typical) from a single 5V supply. This easy-to-use device includes sample-and-hold, precision reference, switched capacitor successive approximation A/D and trimmed internal clock.

The LTC1605's input range is an industry standard ±10V. Maximum DC specs include ±2.0LSB INL and 16-bits no missing codes over temperature. An external reference can be used if greater accuracy over temperature is needed.

The ADC has a microprocessor compatible, 16-bit or two byte parallel output port. A convert start input and a data ready signal (BUSY) ease connections to FIFOs, DSPs and microprocessors.

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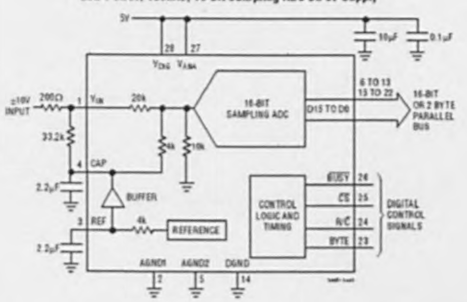
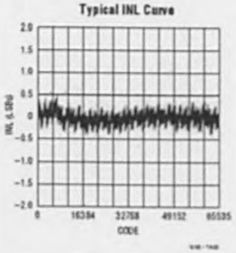
TYPICAL APPLICATION

Low Power, 100kHz, 16-Bit Sampling ADC on 5V Supply



Typical INL Curve



ANALOG INPUT (Note 5)

SYMBOL	PARAMETER	CONDITIONS	LTC1605/LTC1605A MIN	TYP	MAX	UNITS
V_{IN}	Analog Input Range (Note 9)	$4.75V \le V_{ANA} \le 5.25V$, $4.75V \le V_{DIG} \le 5.25V$		±10		V
I_{IN}	Analog Input Leakage Current	CS = High			±1	µA
C_{IN}	Analog Input Capacitance			10		pF
R_{IN}	Analog Input Impedance			20		kΩ

DYNAMIC ACCURACY (Notes 5, 14)

SYMBOL	PARAMETER	CONDITIONS	LTC1605/LTC1605A MIN	TYP	MAX	UNITS
S/(N + D)	Signal-to-(Noise + Distortion) Ratio	1kHz Input Signal (Note 14)		87.5		dB
		10kHz Input Signal		87		dB
		20kHz, −60dB Input Signal		30		dB
THD	Total Harmonic Distortion	1kHz Input Signal, First 5 Harmonics		−102		dB
		10kHz Input Signal, First 5 Harmonics		−94		dB
	Peak Harmonic or Spurious Noise	1kHz Input Signal		−102		dB
		10kHz Input Signal		−94		dB
	Full-Power Bandwidth	(Note 15)		275		kHz
	Aperture Delay			40		ns
	Aperture Jitter			Sufficient to Meet AC Specs		
	Transient Response	Full-Scale Step (Note 9)			2	µs
	Overvoltage Recovery	(Note 16)		150		ns

INTERNAL REFERENCE CHARACTERISTICS (Note 5)

PARAMETER	CONDITIONS	LTC1605/LTC1605A MIN	TYP	MAX	UNITS
V_{REF} Output Voltage	$I_{OUT} = 0$	2.470	2.500	2.520	V
V_{REF} Output Tempco	$I_{OUT} = 0$		±5		ppm/°C
Internal Reference Source Current			1		µA
External Reference Voltage for Specified Linearity	(Notes 9, 10)	2.30	2.50	2.70	V
External Reference Current Drain	Ext. Reference = 2.5V (Note 9)			100	µA
CAP Output Voltage	$I_{OUT} = 0$		2.50		V

DIGITAL INPUTS AND DIGITAL OUTPUTS (Note 5)

SYMBOL	PARAMETER	CONDITIONS		LTC1605/LTC1605A MIN	TYP	MAX	UNITS
V_{IH}	High Level Input Voltage	$V_{DD} = 5.25V$		2.4			V
V_{IL}	Low Level Input Voltage	$V_{DD} = 4.75V$				0.8	V
I_{IN}	Digital Input Current	$V_{IN} = 0V$ to V_{DD}				±10	µA
C_{IN}	Digital Input Capacitance				5		pF
V_{OH}	High Level Output Voltage	$V_{DD} = 4.75V$	$I_O = -10µA$		4.5		V
			$I_O = -200µA$	4.0			V
V_{OL}	Low Level Output Voltage	$V_{DD} = 4.75V$	$I_O = 160µA$		0.05		V
			$I_O = 1.6mA$		0.10	0.4	V

ANALOG INPUT (Note 5)

SYMBOL	PARAMETER	CONDITIONS	LTC1605/LTC1605A MIN	TYP	MAX	UNITS
V_{IN}	Analog Input Range (Note 9)	$4.75V \le V_{ANA} \le 5.25V$, $4.75V \le V_{DIG} \le 5.25V$		±10		V
I_{IN}	Analog Input Leakage Current	$\overline{CS}$ = High			±1	µA
C_{IN}	Analog Input Capacitance			10		pF
R_{IN}	Analog Input Impedance			20		kΩ

DYNAMIC ACCURACY (Notes 5, 14)

SYMBOL	PARAMETER	CONDITIONS	LTC1605/LTC1605A MIN	TYP	MAX	UNITS
S/(N + D)	Signal-to-(Noise + Distortion) Ratio	1kHz Input Signal (Note 14) 10kHz Input Signal 20kHz, –60dB Input Signal		87.5 87 30		dB dB dB
THD	Total Harmonic Distortion	1kHz Input Signal, First 5 Harmonics 10kHz Input Signal, First 5 Harmonics		–102 –94		dB dB
	Peak Harmonic or Spurious Noise	1kHz Input Signal 10kHz Input Signal		–102 –94		dB dB
	Full-Power Bandwidth	(Note 15)		275		kHz
	Aperture Delay			40		ns
	Aperture Jitter			Sufficient to Meet AC Specs		
	Transient Response	Full-Scale Step (Note 9)			2	µs
	Overvoltage Recovery	(Note 16)		150		ns

INTERNAL REFERENCE CHARACTERISTICS (Note 5)

PARAMETER	CONDITIONS	LTC1605/LTC1605A MIN	TYP	MAX	UNITS
V_{REF} Output Voltage	$I_{OUT} = 0$	2.470	2.500	2.520	V
V_{REF} Output Tempco	$I_{OUT} = 0$		±5		ppm/°C
Internal Reference Source Current			1		µA
External Reference Voltage for Specified Linearity	(Notes 9, 10)	2.30	2.50	2.70	V
External Reference Current Drain	Ext. Reference = 2.5V (Note 9)			100	µA
CAP Output Voltage	$I_{OUT} = 0$		2.50		V

DIGITAL INPUTS AND DIGITAL OUTPUTS (Note 5)

SYMBOL	PARAMETER	CONDITIONS		LTC1605/LTC1605A MIN	TYP	MAX	UNITS
V_{IH}	High Level Input Voltage	$V_{DD} = 5.25V$		2.4			V
V_{IL}	Low Level Input Voltage	$V_{DD} = 4.75V$				0.8	V
I_{IN}	Digital Input Current	V_{IN} = 0V to V_{DD}				±10	µA
C_{IN}	Digital Input Capacitance				5		pF
V_{OH}	High Level Output Voltage	$V_{DD} = 4.75V$	$I_O = -10µA$		4.5		V
			$I_O = -200µA$	4.0			V
V_{OL}	Low Level Output Voltage	$V_{DD} = 4.75V$	$I_O = 160µA$		0.05		V
			$I_O = 1.6mA$		0.10	0.4	V

DIGITAL INPUTS AND DIGITAL OUTPUTS (Note 5)

SYMBOL	PARAMETER	CONDITIONS	LTC1605/LTC1605A MIN	TYP	MAX	UNITS
I_{OZ}	Hi-Z Output Leakage D15 to D0	V_{OUT} = 0V to V_{DD}, $\overline{CS}$ High			±10	µA
C_{OZ}	Hi-Z Output Capacitance D15 to D0	$\overline{CS}$ High (Note 9)			15	pF
I_{SOURCE}	Output Source Current	V_{OUT} = 0V		–10		mA
I_{SINK}	Output Sink Current	$V_{OUT} = V_{DD}$		10		mA

TIMING CHARACTERISTICS (Note 5)

SYMBOL	PARAMETER	CONDITIONS	LTC1605/LTC1605A MIN	TYP	MAX	UNITS
$f_{SAMPLE(MAX)}$	Maximum Sampling Frequency		100			kHz
t_{CONV}	Conversion Time				8	µs
t_{ACQ}	Acquisition Time				2	µs
t_1	Convert Pulse Width	(Note 11)	40			ns
t_2	Data Valid Delay After R/$\overline{C}$↓	(Note 9)			8	µs
t_3	$\overline{BUSY}$ Delay from R/$\overline{C}$↓	C_L = 50pF			65	ns
t_4	$\overline{BUSY}$ Low				8	µs
t_5	$\overline{BUSY}$ Delay After End of Conversion			220		ns
t_6	Aperture Delay			40		ns
t_7	Bus Relinquish Time		10	35	83	ns
t_8	$\overline{BUSY}$ Delay After Data Valid		50	200		ns
t_9	Previous Data Valid After R/$\overline{C}$↓			7.4		µs
t_{10}	R/$\overline{C}$ to $\overline{CS}$ Setup Time	(Notes 9, 10)	10			ns
t_{11}	Time Between Conversions		10			µs
t_{12}	Bus Access and Byte Delay	(Notes 9, 10)	10		83	ns

POWER REQUIREMENTS (Note 5)

SYMBOL	PARAMETER	CONDITIONS	LTC1605/LTC1605A MIN	TYP	MAX	UNITS
V_{DD}	Positive Supply Voltage	(Notes 9, 10)	4.75		5.25	V
I_{DD}	Positive Supply Current			11	16	mA
P_{DIS}	Power Dissipation			55	80	mW

The indicates specifications which apply over the full operating temperature range; all other limits and typicals $T_A = 25°C$.

Note 1: Absolute Maximum Ratings are those values beyond which the life of a device may be impaired.

Note 2: All voltage values are with respect to ground with DGND, AGND1 and AGND2 wired together (unless otherwise noted).

Note 3: When these pin voltages are taken below ground or above $V_{ANA} = V_{DIG} = V_{DD}$, they will be clamped by internal diodes. This product can handle input currents of greater than 100mA below ground or above V_{DD} without latch-up.

Note 4: When these pin voltages are taken below ground, they will be clamped by internal diodes. This product can handle input currents of 90mA below ground without latchup. These pins are not clamped to V_{DD}.

Note 5: V_{DD} = 5V, f_{SAMPLE} = 100kHz, $t_r = t_f$ = 5ns unless otherwise specified.

Note 6: Linearity, offset and full-scale specifications apply for a V_{IN} input with respect to ground.

Note 7: Integral nonlinearity is defined as the deviation of a code from a straight line passing through the actual end points of the transfer curve. The deviation is measured from the center of the quantization band.

Note 8: Bipolar offset is the offset voltage measured from –0.5 LSB when the output code flickers between 0000 0000 0000 0000 and 1111 1111 1111 1111.

Note 9: Guaranteed by design, not subject to test.

Note 10: Recommended operating conditions.

APPLICATIONS INFORMATION

Internal Voltage Reference

The LTC1605 has an on-chip, temperature compensated, curvature corrected, bandgap reference, which is factory trimmed to 2.50V. The full-scale range of the ADC is equal to ($\pm 4 \bullet V_{REF}$) or nominally $\pm 10V$. The output of the reference is connected to the input of a unity-gain buffer through a 4k resistor (see Figure 3). The input to the buffer or the output of the reference is available at REF (Pin 3). The internal reference can be overdriven with an external reference if more accuracy is needed. The buffer output drives the internal DAC and is available at CAP (Pin 4). The CAP pin can be used to drive a steady DC load of less than 2mA. Driving an AC load is not recommended because it can cause the performance of the converter to degrade.

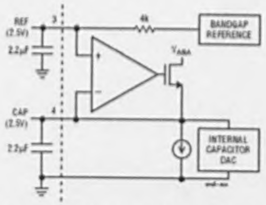


Figure 3. Internal or External Reference Source

For minimum code transition noise the REF pin and the CAP pin should each be decoupled with a capacitor to filter wideband noise from the reference and the buffer (2.2µF tantalum).

Offset and Gain Adjustments

The LTC1605 offset and full-scale errors have been trimmed at the factory with the external resistors shown in Figure 4. This allows for external adjustment of offset and full scale in applications where absolute accuracy is important. See Figure 5 for the offset and gain trim circuit. First adjust the offset to zero by adjusting resistor R3. Apply an input voltage of –152.6mV (–0.5LSB) and adjust R3 so the code is changing between 1111 1111 1111 1111 and 0000 0000 0000 0000. The gain error is trimmed by adjusting resistor R4. An input voltage of 9.999542V (+FS – 1.5LSB) is applied to V_{IN} and R4 is adjusted until the output code is changing between 0111 1111 1111 1110 and 0111 1111 1111 1111. Figure 6 shows the bipolar transfer characteristic of the LTC1605.

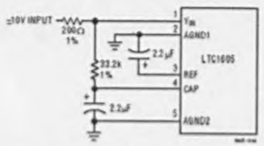


Figure 4. ±10V Input Without Trim

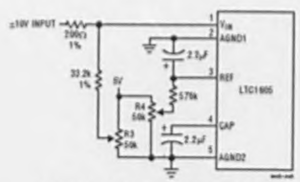


Figure 5. ±10V Input with Offset and Gain Trim

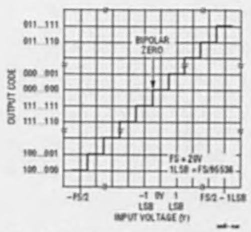


Figure 6. LTC1605 Bipolar Transfer Characteristics

DC Performance

One way of measuring the transition noise associated with a high resolution ADC is to use a technique where a DC

APPLICATIONS INFORMATION

signal is applied to the input of the ADC and the resulting output codes are collected over a large number of conversions. For example in Figure 7 the distribution of output code is shown for a DC input that has been digitized 10000 times. The distribution is Gaussian and the RMS code transition is about 1LSB.

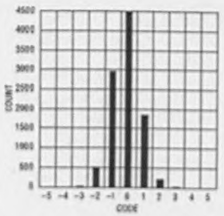


Figure 7. Histogram for 10000 Conversions

DIGITAL INTERFACE

Internal Clock

The ADC has an internal clock that is trimmed to achieve a typical conversion time of 7µs. No external adjustments are required and, with the typical acquisition time of 1µs, throughput performance of 100ksps is assured.

Timing and Control

Conversion start and data read are controlled by two digital inputs: $\overline{CS}$ and R/$\overline{C}$. To start a conversion and put the sample-and-hold into the hold mode bring $\overline{CS}$ and R/$\overline{C}$ low for no less than 40ns. Once initiated it cannot be restarted until the conversion is complete. Converter status is indicated by the $\overline{BUSY}$ output and this is low while the conversion is in progress.

There are two modes of operation. The first mode is shown in Figure 8. The digital input R/$\overline{C}$ is used to control the start of conversion. $\overline{CS}$ is tied low. When R/$\overline{C}$ goes low the sample-and-hold goes into the hold mode and a conversion is started. $\overline{BUSY}$ goes low and stays low during the conversion and will go back high after the conversion has been completed and the internal output shift registers have been updated. R/$\overline{C}$ should remain low for no less than 40ns. During the time R/$\overline{C}$ is low the digital outputs are in a Hi-Z state. R/$\overline{C}$ should be brought back high within 3µs after the start of the conversion to ensure that no errors occur in the digitized result. The second mode shown in Figure 9, uses the $\overline{CS}$ signal to control the start of a conversion and the reading of the digital output. In this mode the R/$\overline{C}$ input signal should be brought low no less than 10ns before the falling edge of $\overline{CS}$. The minimum pulse width for $\overline{CS}$ is 40ns. When $\overline{CS}$ falls, $\overline{BUSY}$ goes low and will stay low until the end of the conversion. $\overline{BUSY}$ will go high after the conversion has been completed. The new data is valid when $\overline{CS}$ is brought back low again to initiate

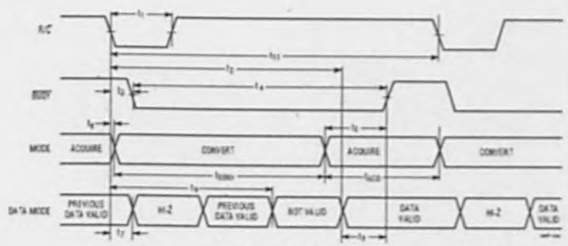
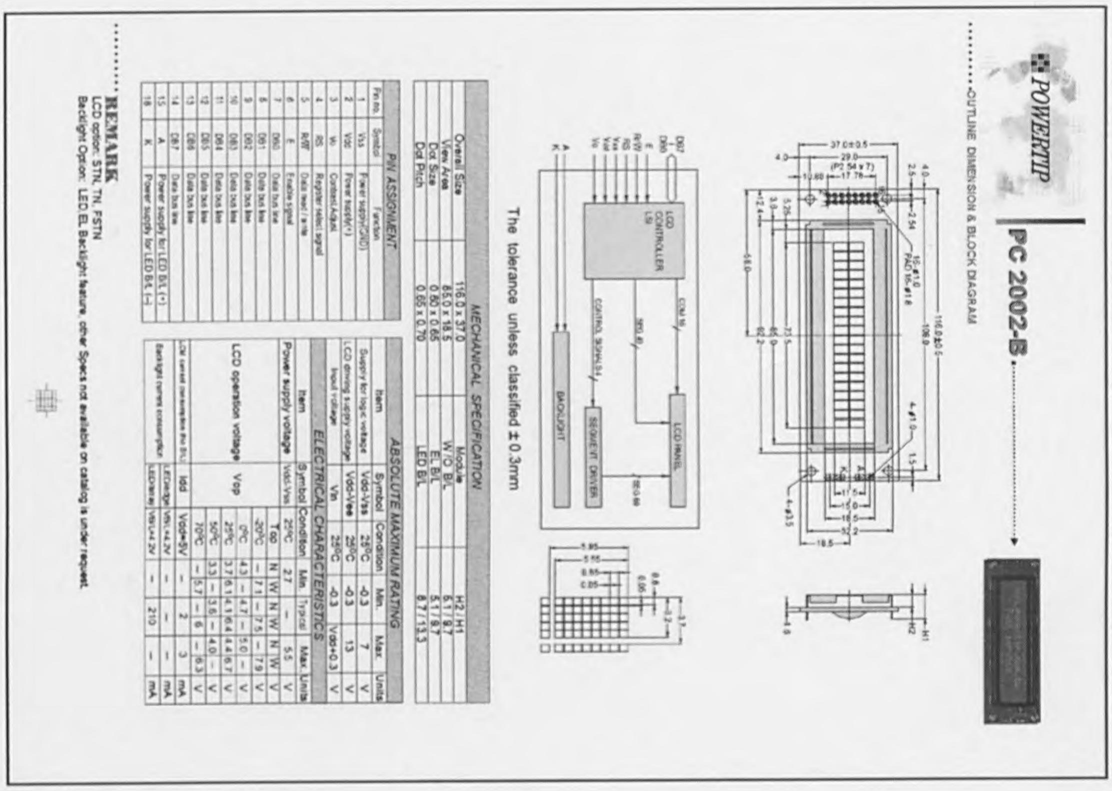


Figure 8. Conversion Timing with Outputs Enabled After Conversion ($\overline{CS}$ Tied Low)

D.6: 2 x 20 Alphanumerical Display



POWERTIP | PC 2002-B

OUTLINE DIMENSION & BLOCK DIAGRAM

The tolerance unless classified ± 0.3mm

MECHANICAL SPECIFICATION			
Overall Size	116.0 x 37.0	Module	H2 / H1
View Area	85.0 x 18.5	W/O B/L	5.1 / 9.7
Dot Size	0.60 x 0.65	EL B/L	5.1 / 9.7
Dot Pitch	0.65 x 0.70	LED B/L	8.7 / 13.3

PIN ASSIGNMENT

Pin no.	Symbol	Function
1	Vss	Power supply(GND)
2	Vdd	Power supply(+)
3	Vo	Contrast Adjust
4	RS	Register select signal
5	R/W	Data read / write
6	E	Enable signal
7	DB0	Data bus line
8	DB1	Data bus line
9	DB2	Data bus line
10	DB3	Data bus line
11	DB4	Data bus line
12	DB5	Data bus line
13	DB6	Data bus line
14	DB7	Data bus line
15	A	Power supply for LED B/L (+)
16	K	Power supply for LED B/L (–)

ABSOLUTE MAXIMUM RATING

Item	Symbol	Condition	Min.	Max.	Units
Supply for logic voltage	Vdd-Vss	25°C	-0.3	7	V
LCD driving supply voltage	Vdd-Vee	25°C	-0.3	13	V
Input voltage	Vin	25°C	-0.3	Vdd+0.3	V

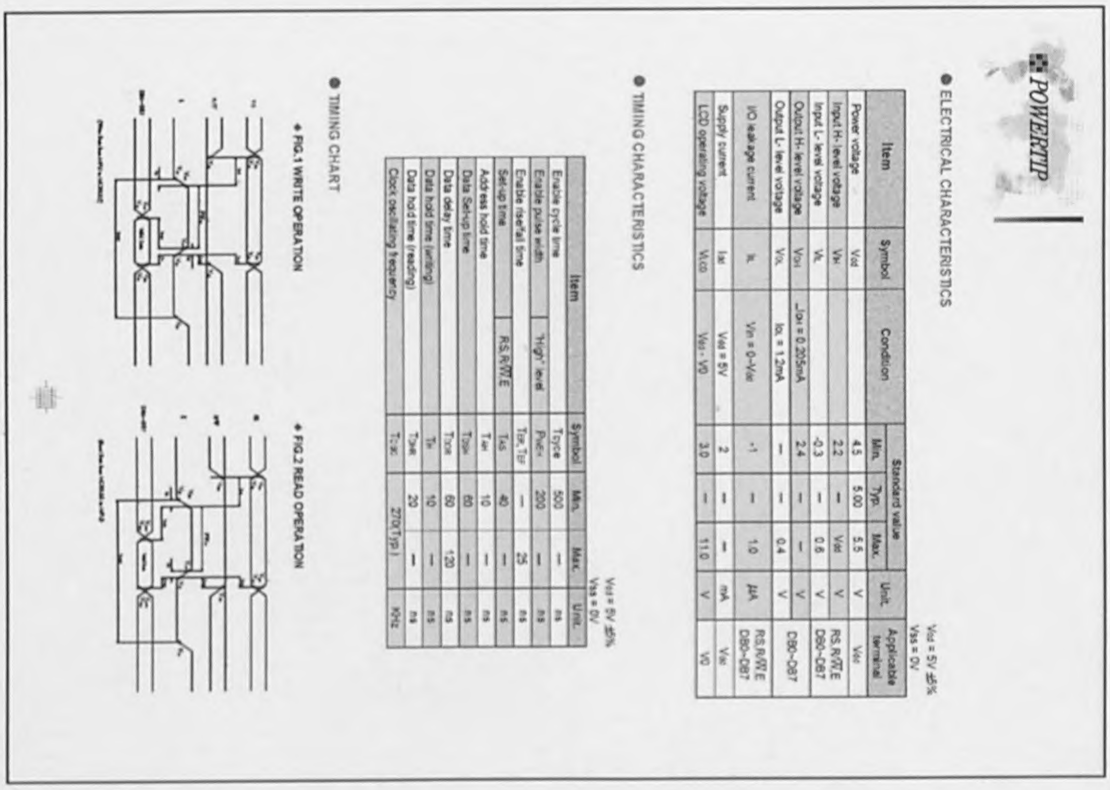
ELECTRICAL CHARACTERISTICS

Item	Symbol	Condition	Min.		Typical		Max.		Units
Power supply voltage	Vdd-Vss	25°C	2.7		–		5.5		V
LCD operation voltage	Vop	Top	N	W	N	W	N	W	V
		-20°C	–	7.1	–	7.5	–	7.9	V
		0°C	4.3	–	4.7	–	5.0	–	V
		25°C	3.7	6.1	4.1	6.4	4.4	6.7	V
		50°C	3.3	–	3.6	–	4.0	–	V
		70°C	–	5.7	–	6	–	6.3	V
LCM current consumption (No B/L)	Idd	Vdd=5V	–		2		3		mA
Backlight current consumption	LED/edge	VB/L=4.2V	–		–		–		mA
	LED/array	VB/L=4.2V	–		210		–		mA

REMARK

LCD option: STN, TN, FSTN

Backlight Option: LED,EL Backlight feature, other Specs not available on catalog is under request.



POWERTIP

● ELECTRICAL CHARACTERISTICS

Vdd = 5V ±5%
Vss = 0V

Item	Symbol	Condition	Standard value Min.	Typ.	Max.	Unit.	Applicable terminal
Power voltage	Vdd		4.5	5.00	5.5	V	Vdd
Input H- level voltage	VIH		2.2	–	Vdd	V	RS,R/W,E DB0~DB7
Input L- level voltage	VIL		-0.3	–	0.6	V	
Output H- level voltage	VOH	-IOH = 0.205mA	2.4	–	–	V	DB0~DB7
Output L- level voltage	VOL	IOL = 1.2mA	–	–	0.4	V	
I/O leakage current	IL	Vin = 0~Vdd	-1	–	1.0	μA	RS,R/W,E DB0~DB7
Supply current	Idd	Vdd = 5V	2	–	–	mA	Vdd
LCD operating voltage	VLCD	Vdd - V0	3.0	–	11.0	V	V0

● TIMING CHARACTERISTICS

Vdd = 5V ±5%
Vss = 0V

Item		Symbol	Min.	Max.	Unit.
Enable cycle time		Tcyce	500	–	ns
Enable pulse width	"High" level	PWEH	200	–	ns
Enable rise/fall time		TER,TEF	–	25	ns
Set-up time	RS,R/W,E	TAS	40	–	ns
Address hold time		TAH	10	–	ns
Data Set-up time		TDSW	60	–	ns
Data delay time		TDDR	60	120	ns
Data hold time (writing)		TH	10	–	ns
Data hold time (reading)		TDHR	20	–	ns
Clock oscillating frequency		TOSC	270(Typ.)		KHz

● TIMING CHART

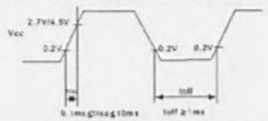
* FIG.1 WRITE OPERATION

* FIG.2 READ OPERATION

POWERTIP

● POWER SUPPLY RESET

The internal reset circuit will be operating properly when the foll owing power supply conditions are satisfied. If it isnot operated properly, please perform the initial setting along with the instruction.



Item	Symbol	Measuring Condition	Standard Value			Unit
			Min.	Typ.	Max.	
Power Supply RISE Time	trcc	—	0.1	—	10	mS
Power Supply OFF Time	toff	—	1	—	—	mS

Reset Function

◆ Initialization Mode by Internal Reset Circuit

The controller automatically initializes (resets) when power is supplied (built-in internal reset circuit). The following instructions are executed during initialization. The busy flag (BF) is kept in busy state until initialization ends (BF=1). The busy state is 10ms after Vdd reaches 4.5V.

(1) Display clear

(2) Function set

- DL=1:8 bit long interface data
- DL=0:4 bit F=0:5 x 7 dots character font
- N=1:2 lines
- N=0:1 line

(3) Display ON/OFF control

- D=0:Display OFF
- C=0:Cursor OFF
- B=0:Blink OFF

(4) Entry mode set

- 1 / D = 1: + 1 (increment)
- S = 0: No shift

Note: When using internal reset circuit is not satisfied in power supply conditions, the internal reset circuit will not function properly and initialization will not be performed. Please initialize using the MPU along with the instrcutuion set.

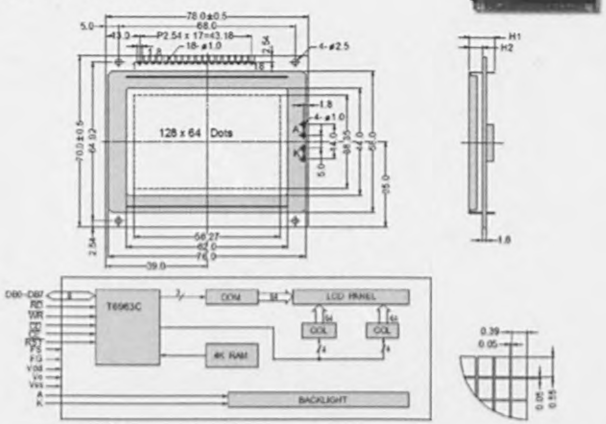
◆ Initialization along with Instruction

If power supply conditions are not satisfied, which for proper operation of internal rest circuit, it is required to make initialzation along with instruction.
Please make following procedures.

D.7: 64 x 128 Graphic Display

POWERTIP | PG 12864-F

OUTLINE DIMENSION & BLOCK DIAGRAM



The tolerance unless classified ±0.3mm

MECHANICAL SPECIFICATION			
Overall Size	78.0 x 70.0	Module	H2 / H1
View Area	62.0 x 44.0	W/O B/L	5.1 / 9.7
Dot Size	0.39 x 0.55	EL B/L	5.1 / 5.7
Dot Pitch	0.44 x 0.60	LED B/L	9.2 / 13.8

PIN ASSIGNMENT		
Pin no.	Symbol	Function
1	FG	Frame ground
2	Vss	Power supply(GND)
3	Vdd	Power supply(+)
4	Vo	Contrast Adjust
5	WR	Data write
6	RD	Data read
7	CE	Chip enable
8	CD	Command / data select
9	RST	Reset
10-17	DB0-DB7	Data bus line
18	FS	Font select

ABSOLUTE MAXIMUM RATING					
Item	Symbol	Condition	Min.	Max.	Units
Supply for logic voltage	Vdd-Vss	25°C	-0.3	7.0	V
LCD driving supply voltage	Vdd-Vee	25°C	0	22.0	V
Input voltage	Vin	25°C	-0.3	Vdd+0.3	V

ELECTRICAL CHARACTERISTICS									
Item	Symbol	Condition	Min.		Typical		Max.		Units
Power supply voltage	Vdd-Vss	25°C	4.5		–		5.5		V
LCD operation voltage	Vop	Top	N	W	N	W	N	W	V
		-20°C	–	8.6	–	9	–	9.5	V
		0°C	8.5	–	8.9	–	9.3	–	V
		25°C	8	8.6	8.4	9	8.8	9.5	V
		50°C	7.6	–	8	–	8.4	–	V
		70°C	–	8	–	8.4	–	7.8	V
LCD current consumption (no BL)	Idd	Vdd=5V	–		6.5		–		mA
Backlight current consumption	LEDedge	VB/L=4.2V	–		–		–		mA
	LEDarray	VB/L=4.2V	–		350		–		mA

REMARK

LCD option: STN, TN, FSTN

Backlight Option: LED,EL Backlight feature, other Specs not available on catalog is under request.

TOSHIBA T6963C

COMMAND DEFINITIONS

COMMAND	CODE	D1	D2	FUNCTION
REGISTERS SETTING	00100001	X address	Y address	Set Cursor Pointer
	00100010	Data	00H	Set Offset Register
	00100100	Low address	High address	Set Address Pointer
SET CONTROL WORD	01000000	Low address	High address	Set Text Home Address
	01000001	Columns	00H	Set Text Area
	01000010	Low address	High address	Set Graphic Home Address
	01000011	Columns	00H	Set Graphic Area
MODE SET	1000X000	—	—	OR mode
	1000X001	—	—	EXOR mode
	1000X011	—	—	AND mode
	1000X100	—	—	Text Attribute mode
	10000XXX	—	—	Internal CG ROM mode
	10001XXX	—	—	External CG RAM mode
DISPLAY MODE	10010000	—	—	Display off
	1001XX10	—	—	Cursor on, blink off
	1001XX11	—	—	Cursor on, blink on
	100101XX	—	—	Text on, graphic off
	100110XX	—	—	Text off, graphic on
	100111XX	—	—	Text on, graphic on
CURSOR PATTERN SELECT	10100000	—	—	1-line cursor
	10100001	—	—	2-line cursor
	10100010	—	—	3-line cursor
	10100011	—	—	4-line cursor
	10100100	—	—	5-line cursor
	10100101	—	—	6-line cursor
	10100110	—	—	7-line cursor
	10100111	—	—	8-line cursor
DATA AUTO READ / WRITE	10110000	—	—	Set Data Auto Write
	10110001	—	—	Set Data Auto Read
	10110010	—	—	Auto Reset
DATA READ / WRITE	11000000	Data	—	Data Write and Increment ADP
	11000001	—	—	Data Read and Increment ADP
	11000010	Data	—	Data Write and Decrement ADP
	11000011	—	—	Data Read and Decrement ADP
	11000100	Data	—	Data Write and Nonvariable ADP
	11000101	—	—	Data Read and Nonvariable ADP
SCREEN PEEK	11100000	—	—	Screen Peek
SCREEN COPY	11101000			Screen Copy

X : invalid

1997-04-07 11/46

CG ROM TYPE 0201

MSB \ LSB	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0		!	"	#	$	%	&	'	(	)	*	+	,	-	.	/
1	0	1	2	3	4	5	6	7	8	9	:	;	<	=	>	?
2	@	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
3	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	_
4	千	万	円	→	←	■	ヲ	ァ	ィ	ゥ	ェ	ォ	ャ	ュ	ョ	ッ
5	ー	ア	イ	ウ	エ	オ	カ	キ	ク	ケ	コ	サ	シ	ス	セ	ソ
6	タ	チ	ツ	テ	ト	ナ	ニ	ヌ	ネ	ノ	ハ	ヒ	フ	ヘ	ホ	マ
7	ミ	ム	メ	モ	ヤ	ユ	ヨ	ラ	リ	ル	レ	ロ	ワ	ン	゛	゜

ABSOLUTE MAXIMUM RATINGS (Ta = 25°C)

ITEM	SYMBOL	RATING	UNIT
Supply Voltage	V_{DD} (Note)	−0.3 to 7.0	V
Input Voltage	V_{IN} (Note)	−0.3 to V_{DD} + 0.3	V
Operating Temperature	T_{opr}	−20 to 70	°C
Storage Temperature	T_{stg}	−55 to 125	°C

(Note) Referenced to V_{SS} = 0V.

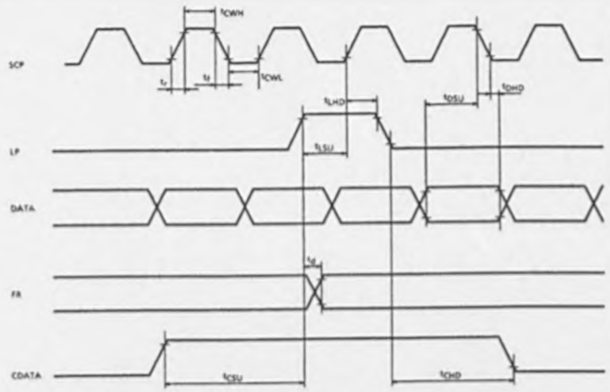
ELECTRICAL CHARACTERISTICS
DC CHARACTERISTICS
TEST CONDITIONS (Unless otherwise noted, V_{SS} = 0V, V_{DD} = 5.0V ± 10%, Ta = −20 to 75°C)

ITEM		SYMBOL	TEST CIR-CUIT	TEST CONDITIONS	MIN	TYP.	MAX	UNIT	PIN NAME
Operating Voltage		V_{DD}	—	—	4.5	5.0	5.5	V	V_{DD}
Input	H Level	V_{IH}	—	—	V_{DD} − 2.2	—	V_{DD}	V	Input pins
	L Level	V_{IL}	—	—	0	—	0.8	V	Input pins
Output Voltage	H Level	V_{OH}	—	—	V_{DD} − 0.3	—	V_{DD}	V	Output pins
	L Level	V_{OL}	—	—	0	—	0.3	V	Output pins
Output Resistance	H Level	R_{OH}	—	V_{OUT} = V_{DD} − 0.5V	—	—	400	Ω	Output pins
	L Level	R_{OL}	—	V_{OUT} = 0.5V	—	—	400	Ω	Output pins
Input Pull-up Resistance		RPU	—	—	50	100	200	kΩ	(Note 1)
Operating Frequency		f_{OSC}	—	—	0.4	—	5.5	MHz	
Current Consumption (Operating)		I_{DD} (1)	—	V_{DD} = 5.0V (Note 2) f_{OSC} = 3.0MHz	—	3.3	6	mA	V_{DD}
Current Consumption (Halt)		I_{DD} (2)	—	V_{DD} = 5.0V	—	—	3	μA	V_{DD}

(Note 1) Applied $\overline{T1}$, $\overline{T2}$, $\overline{RESET}$
(Note 2) MDS = L, MD0 = L, MD1 = L, MD2 = H, MD3 = H, FS0 = L, FS1 = L, $\overline{SDSEL}$ = L, $\overline{DUAL}$ = H, D7 to D0 = LHLHLHLH

AC CHARACTERISTICS

- Switching Characteristics (1)

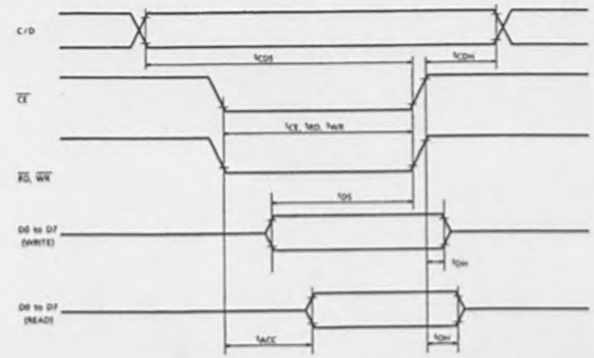


TEST CONDITIONS (Unless otherwise noted, V_{DD} = 5.0V ± 10%, V_{SS} = 0V, Ta = −20 to 70°C)

ITEM	SYMBOL	TEST CONDITIONS	MIN	MAX	UNIT
Operating Frequency	f_{scp}	Ta = −10~70°C	—	2.75	MHz
SCP Pulse Width	t_{CWH}, t_{CWL}	—	150	—	ns
SCP Rise / Fall Time	t_r, t_f	—	—	30	ns
LP Set-up Time	t_{LSU}	—	150	290	ns
LP Hold Time	t_{LHD}	—	5	40	ns
Data Set-up Time	t_{DSU}	—	170	—	ns
Data Hold Time	t_{DHD}	—	80	—	ns
FR Delay Time	t_d	—	0	90	ns
CDATA Set-up Time	t_{CSU}	—	450	850	ns
CDATA Hold Time	t_{CHD}	—	450	950	ns

- Switching Characteristics (2)

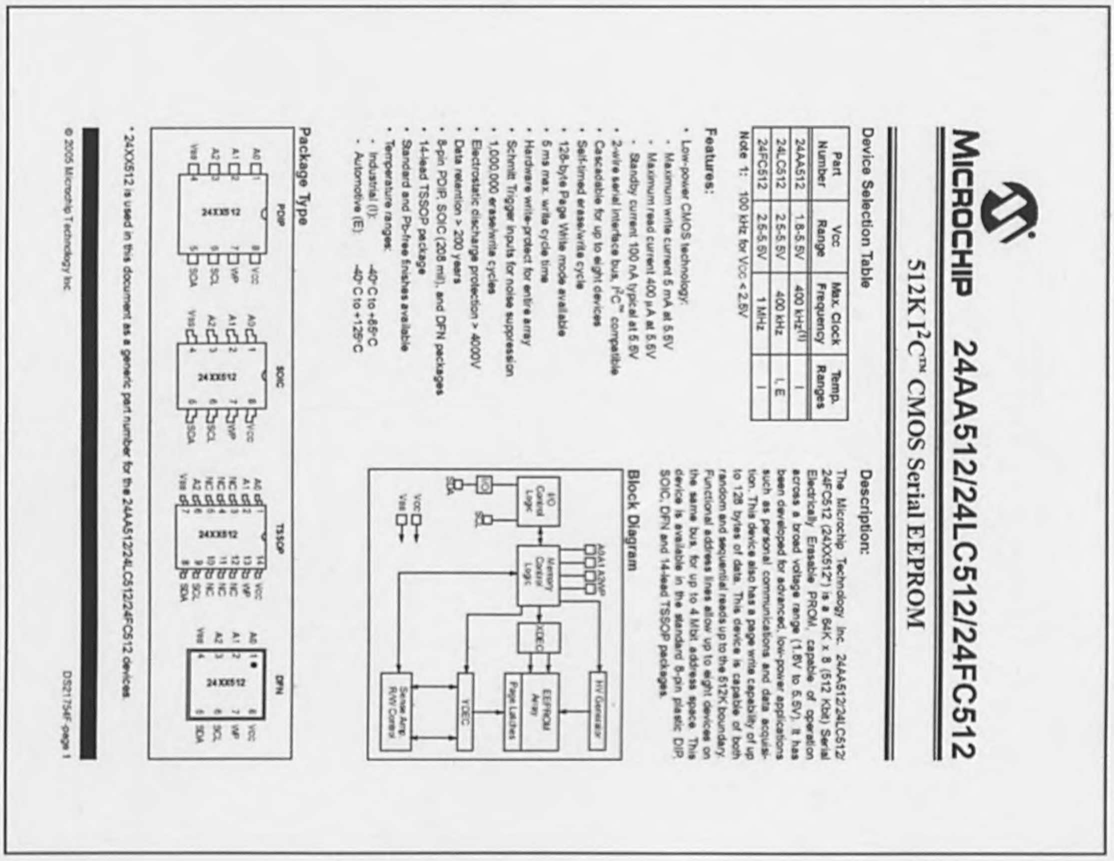
Bus Timing



TEST CONDITIONS (Unless otherwise noted, V_{DD} = 5.0V ± 10%, V_{SS} = 0V, Ta = −20 to 75°C)

ITEM	SYMBOL	TEST CONDITIONS	MIN	MAX	UNIT
C/D Set-up Time	t_{CDS}	—	100	—	ns
C/D Hold Time	t_{CDH}	—	10	—	ns
$\overline{CE}$, $\overline{RD}$, $\overline{WR}$ Pulse Width	t_{CE}, t_{RD}, t_{WR}	—	80	—	ns
Data Set-up Time	t_{DS}	—	80	—	ns
Data Hold Time	t_{DH}	—	40	—	ns
Access Time	t_{ACC}	—	—	150	ns
Output Hold Time	t_{OH}	—	10	50	ns

D.8: 512 Kbit IC2 Serial EEPROM – 24AA512



MICROCHIP 24AA512/24LC512/24FC512

512K I²C™ CMOS Serial EEPROM

Device Selection Table

Part Number	Vcc Range	Max. Clock Frequency	Temp. Ranges
24AA512	1.8-5.5V	400 kHz[(1)]	I
24LC512	2.5-5.5V	400 kHz	I, E
24FC512	2.5-5.5V	1 MHz	I

Note 1: 100 kHz for V_{CC} < 2.5V

Features:

- Low-power CMOS technology:
  - Maximum write current 5 mA at 5.5V
  - Maximum read current 400 µA at 5.5V
  - Standby current 100 nA typical at 5.5V
- 2-wire serial interface bus, I²C™ compatible
- Cascadable for up to eight devices
- Self-timed erase/write cycle
- 128-byte Page Write mode available
- 5 ms max. write cycle time
- Hardware write-protect for entire array
- Schmitt Trigger inputs for noise suppression
- 1,000,000 erase/write cycles
- Electrostatic discharge protection > 4000V
- Data retention > 200 years
- 8-pin PDIP, SOIC (208 mil), and DFN packages
- 14-lead TSSOP package
- Standard and Pb-free finishes available
- Temperature ranges:
  - Industrial (I): -40°C to +85°C
  - Automotive (E): -40°C to +125°C

Description:

The Microchip Technology Inc. 24AA512/24LC512/24FC512 (24XX512*) is a 64K x 8 (512 Kbit) Serial Electrically Erasable PROM, capable of operation across a broad voltage range (1.8V to 5.5V). It has been developed for advanced, low-power applications such as personal communications and data acquisition. This device also has a page write capability of up to 128 bytes of data. This device is capable of both random and sequential reads up to the 512K boundary. Functional address lines allow up to eight devices on the same bus, for up to 4 Mbit address space. This device is available in the standard 8-pin plastic DIP, SOIC, DFN and 14-lead TSSOP packages.

Block Diagram

Package Type

* 24XX512 is used in this document as a generic part number for the 24AA512/24LC512/24FC512 devices.

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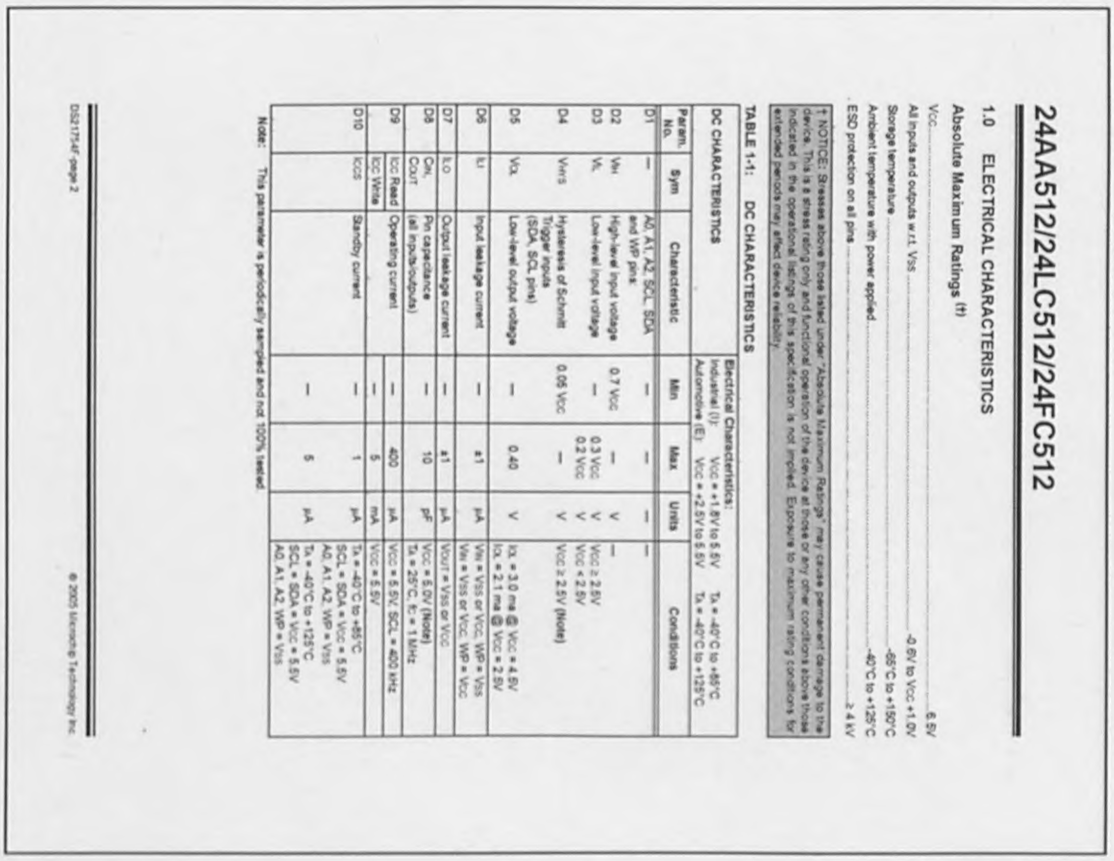

24AA512/24LC512/24FC512

1.0 ELECTRICAL CHARACTERISTICS

Absolute Maximum Ratings (†)

V_{CC} 6.5V
All inputs and outputs w.r.t. V_{SS} .... -0.6V to V_{CC} +1.0V
Storage temperature .... -65°C to +150°C
Ambient temperature with power applied .... -40°C to +125°C
ESD protection on all pins .... ≥ 4 kV

† NOTICE: Stresses above those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. This is a stress rating only and functional operation of the device at those or any other conditions above those indicated in the operational listings of this specification is not implied. Exposure to maximum rating conditions for extended periods may affect device reliability.

TABLE 1-1: DC CHARACTERISTICS

DC CHARACTERISTICS			Electrical Characteristics: Industrial (I): V_{CC} = +1.8V to 5.5V, T_A = -40°C to +85°C; Automotive (E): V_{CC} = +2.5V to 5.5V, T_A = -40°C to +125°C			
Param. No.	Sym	Characteristic	Min	Max	Units	Conditions
D1	—	A0, A1, A2, SCL, SDA and WP pins:	—	—	—	—
D2	V_{IH}	High-level input voltage	0.7 V_{CC}	—	V	—
D3	V_{IL}	Low-level input voltage	—	0.3 V_{CC} 0.2 V_{CC}	V V	V_{CC} ≥ 2.5V V_{CC} < 2.5V
D4	V_{HYS}	Hysteresis of Schmitt Trigger inputs (SDA, SCL pins)	0.05 V_{CC}	—	V	V_{CC} ≥ 2.5V (Note)
D5	V_{OL}	Low-level output voltage	—	0.40	V	I_{OL} = 3.0 ma @ V_{CC} = 4.5V I_{OL} = 2.1 ma @ V_{CC} = 2.5V
D6	I_{LI}	Input leakage current	—	±1	µA	V_{IN} = V_{SS} or V_{CC}, WP = V_{SS} V_{IN} = V_{SS} or V_{CC}, WP = V_{CC}
D7	I_{LO}	Output leakage current	—	±1	µA	V_{OUT} = V_{SS} or V_{CC}
D8	C_{IN}, C_{OUT}	Pin capacitance (all inputs/outputs)	—	10	pF	V_{CC} = 5.0V (Note) T_A = 25°C, f_C = 1 MHz
D9	I_{CC} Read	Operating current	—	400	µA	V_{CC} = 5.5V, SCL = 400 kHz
	I_{CC} Write		—	5	mA	V_{CC} = 5.5V
D10	I_{CCS}	Standby current	—	1	µA	T_A = -40°C to +85°C SCL = SDA = V_{CC} = 5.5V A0, A1, A2, WP = V_{SS}
			—	5	µA	T_A = -40°C to +125°C SCL = SDA = V_{CC} = 5.5V A0, A1, A2, WP = V_{SS}

Note: This parameter is periodically sampled and not 100% tested.

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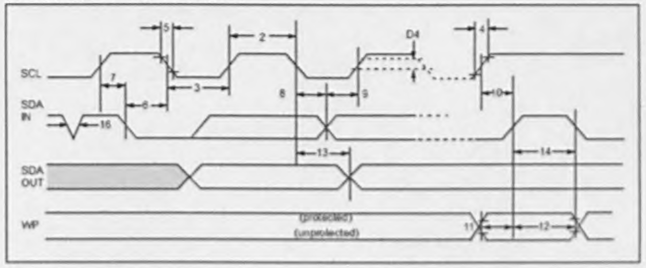
TABLE 1-2: AC CHARACTERISTICS

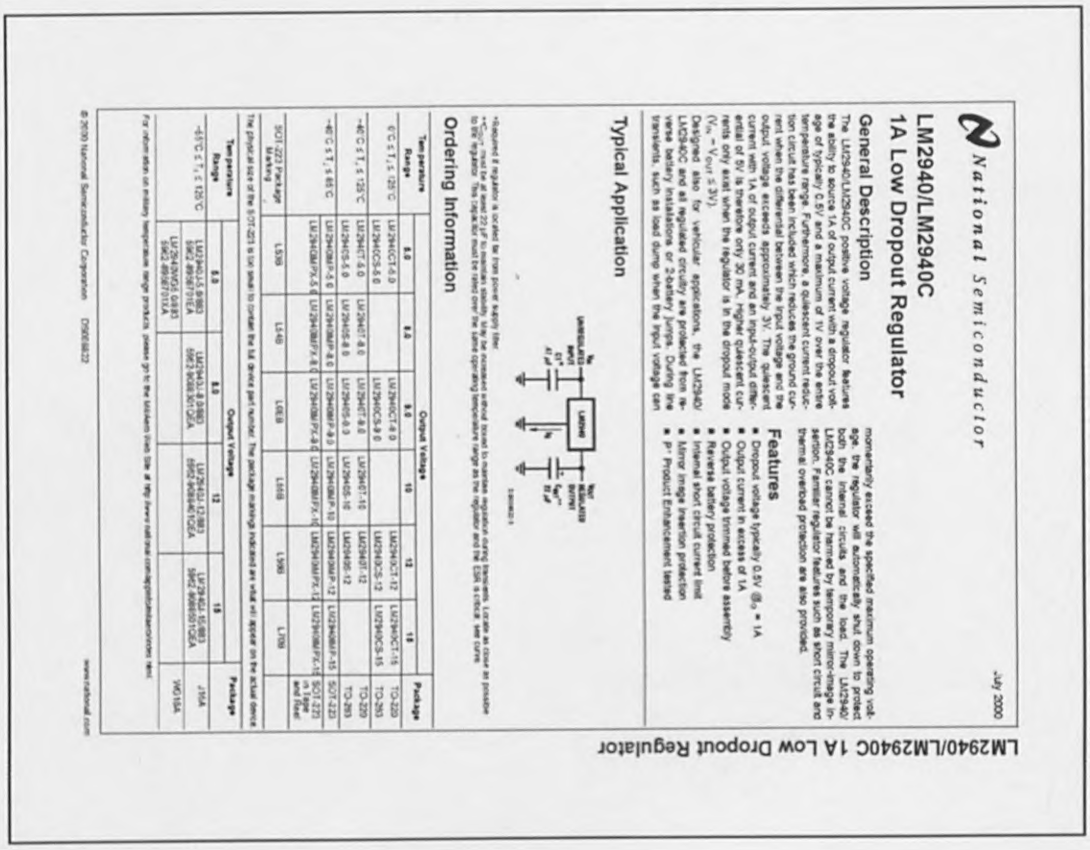
AC CHARACTERISTICS			Electrical Characteristics: Industrial (I): Vcc = +1.8V to 5.5V TA = -40°C to +85°C; Automotive (E): Vcc = +2.5V to 5.5V TA = -40°C to +125°C			
Param. No.	Sym	Characteristic	Min	Max	Units	Conditions
1	FCLK	Clock frequency	— — —	100 400 1000	kHz	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
2	THIGH	Clock high time	4000 600 500	— — —	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
3	TLOW	Clock low time	4700 1300 500	— — —	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
4	TR	SDA and SCL rise time **(Note 1)**	— — —	1000 300 300	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
5	TF	SDA and SCL fall time **(Note 1)**	— —	300 100	ns	All except, 24FC512 2.5V ≤ Vcc ≤ 5.5V 24FC512
6	THD:STA	Start condition hold time	4000 600 250	— — —	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
7	TSU:STA	Start condition setup time	4700 600 250	— — —	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
8	THD:DAT	Data input hold time	0	—	ns	**(Note 2)**
9	TSU:DAT	Data input setup time	250 100 100	— — —	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
10	TSU:STO	Stop condition setup time	4000 600 250	— — —	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
11	TSU:WP	WP setup time	4000 600 600	— — —	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
12	THD:WP	WP hold time	4700 1300 1300	— — —	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
13	TAA	Output valid from clock **(Note 2)**	— — —	3500 900 400	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
14	TBUF	Bus free time: Time the bus must be free before a new transmission can start	4700 1300 500	— — —	ns	1.8V ≤ Vcc < 2.5V 2.5V ≤ Vcc ≤ 5.5V 2.5V ≤ Vcc ≤ 5.5V 24FC512
16	TSP	Input filter spike suppression (SDA and SCL pins)	—	50	ns	All except, 24FC512 **(Notes 1 and 3)**
17	TWC	Write cycle time (byte or page)	—	5	ms	—
18	—	Endurance	1,000,000	—	cycles	25°C **(Note 4)**

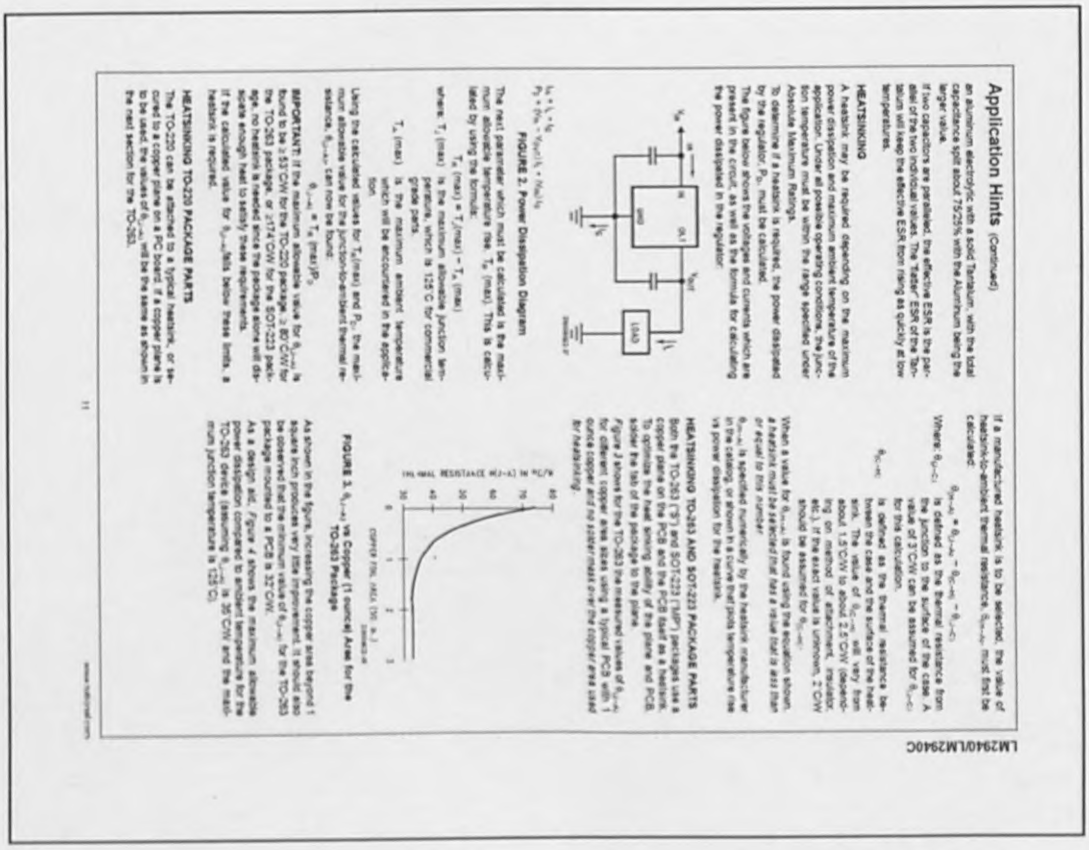
Note 1: Not 100% tested. CB = total capacitance of one bus line in pF.
2: As a transmitter, the device must provide an internal minimum delay time to bridge the undefined region (minimum 300 ns) of the falling edge of SCL to avoid unintended generation of Start or Stop conditions.
3: The combined TSP and VHYS specifications are due to new Schmitt Trigger inputs which provide improved noise spike suppression. This eliminates the need for a TI specification for standard operation.
4: This parameter is not tested but ensured by characterization. For endurance estimates in a specific application, please consult the Total Endurance™ Model which can be obtained from Microchip's web site: www.microchip.com.

FIGURE 1-1: BUS TIMING DATA

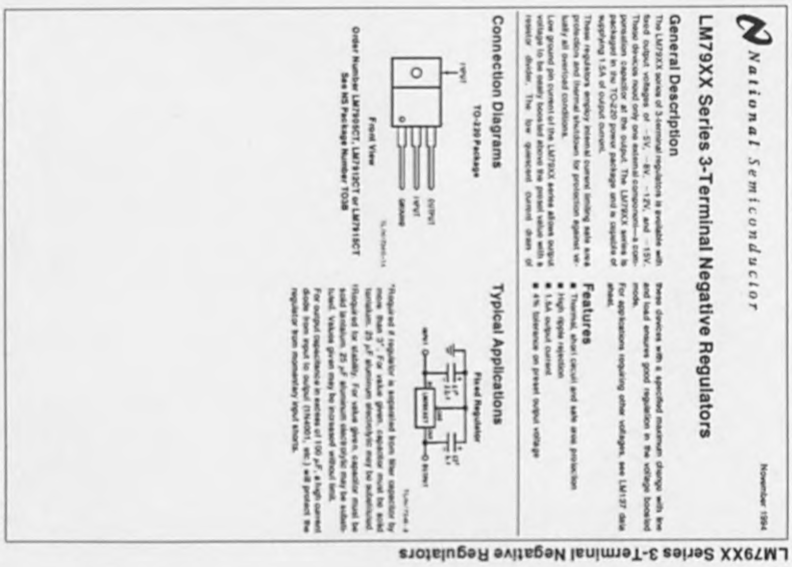


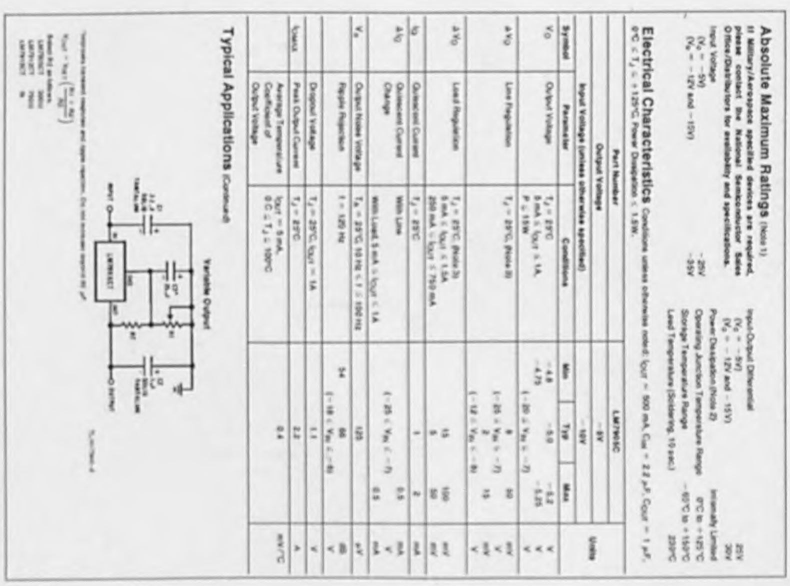
D.9: Voltage Regulator – LM2940





D.10: Voltage Regulator – 79LM05





D.11: DC-to-DC Converter – TEN 5-0522

TRACO POWER® — DC/ DC Converter

TEL 3 Series — 3 Watt

Features

- Wide 2:1/ 3:1 Input Ranges
- High Efficiency up to 81%
- Full SMD-Design
- Indefinite Short-Circuit Protection
- 24-pin DIP Plastic Package
- Pin-compatible with TEM-3 / TED
- 2 Year Product Warranty

NEW Models

With 10 – 30 VDC input

The TEL 3 series is a range of isolated 3 W converter in DIL24 package offering wide 2:1 input voltage range. Further features are high efficiency which allows operation temperature up to 75°C without derating and low output noise.
This product series provides an economical solution for many cost critical applications in industrial and consumer electronics.

Models

Ordercode	Input voltage range	Output voltage	Output current max.	Efficiency typ.
TEL 3-0511	4.5 – 9.0 VDC	5 VDC	600 mA	70 %
TEL 3-0512		12 VDC	250 mA	74 %
TEL 3-0513		15 VDC	200 mA	74 %
TEL 3-0522		±12 VDC	±125 mA	74 %
TEL 3-0523		±15 VDC	±100 mA	74 %
TEL 3-1211	9 – 18 VDC	5 VDC	600 mA	76 %
TEL 3-1212		12 VDC	250 mA	80 %
TEL 3-1213		15 VDC	200 mA	80 %
TEL 3-1222		±12 VDC	±125 mA	80 %
TEL 3-1223		±15 VDC	±100 mA	80 %
TEL 3-2011	10 – 30 VDC	5 VDC	600 mA	76 %
TEL 3-2012		12 VDC	250 mA	80 %
TEL 3-2013		15 VDC	200 mA	80 %
TEL 3-2022		±12 VDC	±125 mA	80 %
TEL 3-2023		±15 VDC	±100 mA	80 %
TEL 3-2411	18 – 36 VDC	5 VDC	600 mA	77 %
TEL 3-2412		12 VDC	250 mA	81 %
TEL 3-2413		15 VDC	200 mA	81 %
TEL 3-2422		±12 VDC	±125 mA	81 %
TEL 3-2423		±15 VDC	±100 mA	81 %
TEL 3-4811	36 – 75 VDC	5 VDC	600 mA	77 %
TEL 3-4812		12 VDC	250 mA	81 %
TEL 3-4813		15 VDC	200 mA	81 %
TEL 3-4822		±12 VDC	±125 mA	81 %
TEL 3-4823		±15 VDC	±100 mA	81 %

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TRACO POWER® — DC/ DC Converter

TEL 3 Series — 3 Watt

Input Specifications

Input current (no load)	5 Vin models	40 mA typ.
	12 Vin models	20 mA typ.
	20 Vin models	15 mA typ.
	24 Vin models	5 mA typ.
	48 Vin models	3 mA typ.
Input current (full load)	5 Vin models	820 mA typ.
	12 Vin models	320 mA typ.
	20 Vin models	190 mA typ.
	24 Vin models	155 mA typ.
	48 Vin models	80 mA typ.
Surge voltage (1 sec. max.)	5 Vin models	11 VDC
	12 Vin models	25 VDC
	20 Vin models	50 VDC
	24 Vin models	50 VDC
	48 Vin models	100 VDC
Reverse voltage protection		1.0 A max.

Output Specifications

Voltage set accuracy		±1 %
Regulation	– Input variation Vin min. to Vin max.	0.5 % max.
	– Load variation 5 – 100 %	
	– single output models	0.5 % max.
	– dual output models balanced load	1.0 % max.
	– dual output models unbalanced load	2.0 % max.
Ripple and noise (20 MHz Bandwidth)		60 mVpk-pk typ.
Temperature coefficient		±0.02 % / °C
Output current limitation		> 110% Iout max., constant current
Short circuit protection		Hiccup mode, indefinite (automatic recovery)
Capacitive load	single output models	2000 µF max.
	dual output models	1000 µF max.

General Specifications

Temperature ranges	– Operating	–25 °C ... +75 °C
	– Case	+95 °C max.
	– Storage	–40 °C ... +125 °C
Humidity (non condensing)		95 % rel H max.
Reliability, calculated MTBF (MIL-HDBK-217 E)		>1 Mio. h @ +25 °C
Isolation voltage	Input/ Output/ Case	1000 VDC
Isolation capacity	Input/ Output	500 pF typ.
Isolation resistance	Input/ Output (500 VDC)	> 1'000 M Ohm
Switching frequency		300 kHz typ. (Pulse frequency modulation PFM)
Safety standards		UL 1950, EN 60950, IEC 60950 Compliance up to 60 VDC input voltage (SELV limit)
Safety approvals		UL/ cUL File E188913

All specifications valid at nominal input voltage, full load and +25°C after warm-up time unless otherwise stated.

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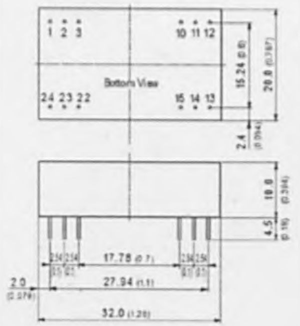
Physical Specifications

Case material	non conductive black plastic
Potting material	silicon rubber (UL94V-0 rated)
Weight	12 g (0.42 oz)
Soldering temperature	max. 250 °C / 10 sec.

Outline Dimensions mm (inches)



Pin	Single	Dual
1	+Vin (Vcc)	+Vin (Vcc)
2	No function	–Vout
3	No function	Common
10	–Vout	Common
11	+Vout	+Vout
12	–Vin (GND)	–Vin (GND)
13	–Vin (GND)	–Vin (GND)
14	+Vout	+Vout
15	–Vout	Common
22	No function	Common
23	No function	–Vout
24	+Vin (Vcc)	+Vin (Vcc)

Pin diameter ø 0.5 ±0.05 (0.02) ±0.002
Tolerances ±0.5 (0.02)

Specifications can be changed without notice

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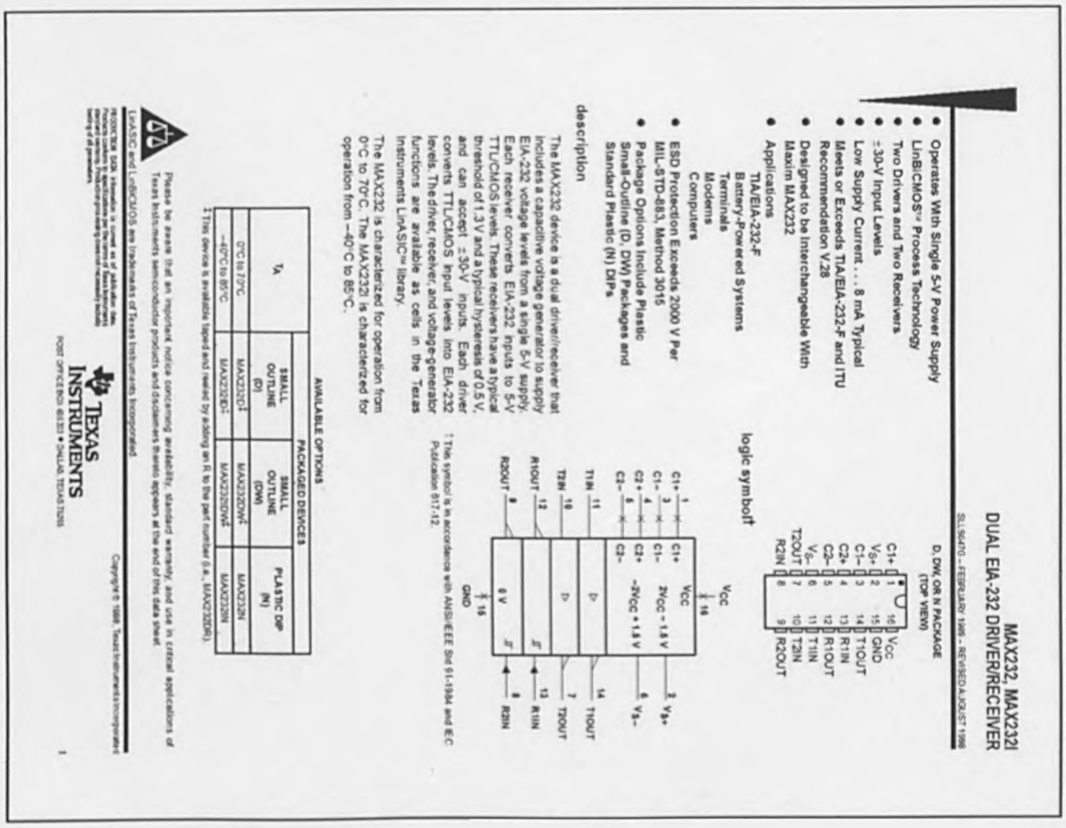
D.12: RS232 Driver – MAX232



MAX232, MAX232I
DUAL EIA-232 DRIVER/RECEIVER
SLLS047G – FEBRUARY 1989 – REVISED AUGUST 1998

- Operates With Single 5-V Power Supply
- LinBiCMOS™ Process Technology
- Two Drivers and Two Receivers
- ±30-V Input Levels
- Low Supply Current . . . 8 mA Typical
- Meets or Exceeds TIA/EIA-232-F and ITU Recommendation V.28
- Designed to be Interchangeable With Maxim MAX232
- Applications
  - TIA/EIA-232-F
  - Battery-Powered Systems
  - Terminals
  - Modems
  - Computers
- ESD Protection Exceeds 2000 V Per MIL-STD-883, Method 3015
- Package Options Include Plastic Small-Outline (D, DW) Packages and Standard Plastic (N) DIPs

D, DW, OR N PACKAGE
(TOP VIEW)

logic symbol†

† This symbol is in accordance with ANSI/IEEE Std 91-1984 and IEC Publication 617-12.

description

The MAX232 device is a dual driver/receiver that includes a capacitive voltage generator to supply EIA-232 voltage levels from a single 5-V supply. Each receiver converts EIA-232 inputs to 5-V TTL/CMOS levels. These receivers have a typical threshold of 1.3 V and a typical hysteresis of 0.5 V, and can accept ±30-V inputs. Each driver converts TTL/CMOS input levels into EIA-232 levels. The driver, receiver, and voltage-generator functions are available as cells in the Texas Instruments LinASIC™ library.

The MAX232 is characterized for operation from 0°C to 70°C. The MAX232I is characterized for operation from –40°C to 85°C.

AVAILABLE OPTIONS

T_A	PACKAGED DEVICES: SMALL OUTLINE (D)	SMALL OUTLINE (DW)	PLASTIC DIP (N)
0°C to 70°C	MAX232D‡	MAX232DW‡	MAX232N
–40°C to 85°C	MAX232ID‡	MAX232IDW‡	MAX232IN

‡ This device is available taped and reeled by adding an R to the part number (i.e., MAX232DR).

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

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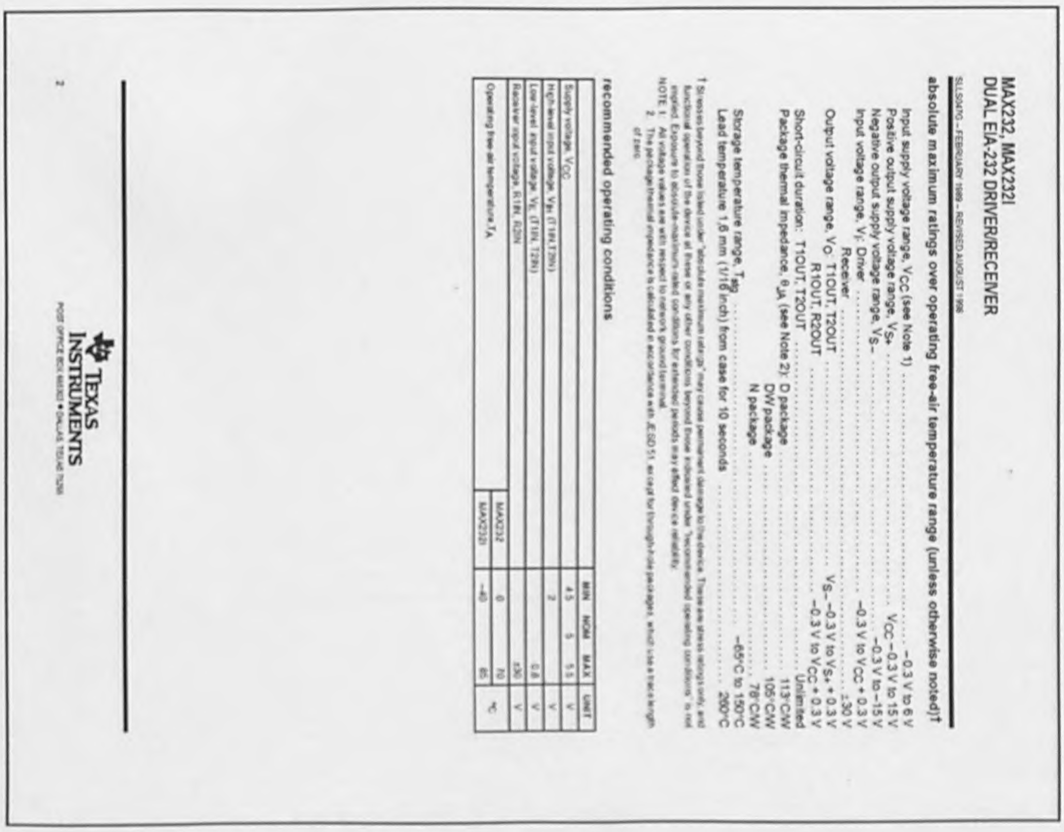

MAX232, MAX232I
DUAL EIA-232 DRIVER/RECEIVER
SLLS047G – FEBRUARY 1989 – REVISED AUGUST 1998

absolute maximum ratings over operating free-air temperature range (unless otherwise noted)†

Input supply voltage range, V_{CC} (see Note 1) . . . . . –0.3 V to 6 V
Positive output supply voltage range, V_{S+} . . . . . V_{CC} –0.3 V to 15 V
Negative output supply voltage range, V_{S-} . . . . . –0.3 V to –15 V
Input voltage range, V_I: Driver . . . . . –0.3 V to V_{CC} + 0.3 V
Receiver . . . . . ±30 V
Output voltage range, V_O: T1OUT, T2OUT . . . . . V_{S-} –0.3 V to V_{S+} + 0.3 V
R1OUT, R2OUT . . . . . –0.3 V to V_{CC} + 0.3 V
Short-circuit duration: T1OUT, T2OUT . . . . . Unlimited
Package thermal impedance, θ_{JA} (see Note 2): D package . . . . . 113°C/W
DW package . . . . . 105°C/W
N package . . . . . 78°C/W
Storage temperature range, T_{stg} . . . . . –65°C to 150°C
Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds . . . . . 260°C

† Stresses beyond those listed under "absolute maximum ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under "recommended operating conditions" is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

NOTES: 1. All voltage values are with respect to network ground terminal.
2. The package thermal impedance is calculated in accordance with JESD 51, except for through-hole packages, which use a trace length of zero.

recommended operating conditions

		MIN	NOM	MAX	UNIT
Supply voltage, V_{CC}		4.5	5	5.5	V
High-level input voltage, V_{IH} (T1IN, T2IN)		2			V
Low-level input voltage, V_{IL} (T1IN, T2IN)				0.8	V
Receiver input voltage, R1IN, R2IN				±30	V
Operating free-air temperature, T_A	MAX232	0		70	°C
	MAX232I	–40		85	°C

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