DESIGN AND DEVELOPMENT OF AN AUTOMATIC RESIDUAL STRESS MEASURING DEVICE

by

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ABSTRACT

This thesis describes the design and development of prototype automatic devices for the measurement of residual stress in magnetic materials. The device, called an "Automatic Rotation Rig", or ARR for short, uses the principal of magnetic anisotropy to determine the difference in the principal stresses and their direction at the surface of the material. The stress measurement is averaged over an area of approximately 5 mm by 5 mm, to a depth of about 1 mm.

Three such devices have been built in the period from January 1987 to February 1989. These have been designed for the measurement of residual stress in railway wheels and tracks. Railway wheels may fail if the rim becomes sufficiently tensile, hence the device may be used to detect unsafe wheels and allow for their removal from service. Continuous railway tracks are welded together to induce tension along their length. This tension counteracts compression due to heating of the rail. Thus the ARR may be able to be used to determine the "stress free" temperature of the rail. This can be used to find whether or not the welding has induced sufficient tension into the rail, or at what ambient temperature the rail may buckle due to excessive longitudinal compression.

The residual stress measuring device can also be used for other applications where the difference in principle stresses needs to be measured on reasonably flat ferrous materials. The device is portable and reasonably cheap and easy to produce. Prototype ARR's have proven to be reliable in field trials, thus leading to the possibility of their being manufactured commercially.

CONTENTS

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CHAPTER 1

INTRODUCTION

About twenty years ago Mr. Richard Langman was asked by his then employer, British Rail, to design a device that would measure the mechanical stress in railway lines. This was done so that the effect of residual compression in continuously welded rail could be determined. At the time, Mr. Langman was unsuccessful in developing a suitable device, based on magnetic principles, that could measure the residual and/or applied stress in the rails.

Richard Langman continued his investigations in Tasmania from 1976. He was successful in developing a method, using the principle of magnetic anisotropy, that could measure the residual stress in magnetic materials to an accuracy of approximately +/- 20 MPa. The principle of magnetic anisotopy is that the permeability of a magnetic material will increase in the direction of mechanical tension (i.e. it is easier to magnetise the steel parallel to the direction of tension compared to that perpendicular to it). Hence, if we can measure the change in permeability with angular direction, then we can determine the magnitude and direction of the stress in the material. Note that this method only determines the difference in the principal stresses, not their individual values. This limitation of the method is not that great if we assume something about the stress pattern. For example, if we know that one of the principle stresses is either small or constant. This means that we can measure the stress in the other principal direction using magnetic anisotropy.

Richard Langman pursued the development of this method until

1986 at which time a portable device had been built which was small, cheap and reasonably simple and easy to use. This device has a probe about 25mm in diameter that is placed on the surface of the steel sample to be measured. This surface needs to be reasonably flat and free of scale and rust, but other than this no further surface preparation is needed. The probe contains a magnetising coil wound on a "C" core (see Figure 1.1) that is excited with a 68 Hz AC signal, an air-wound pickup coil (SCm) is located between the poles of the "C" core, with its axis at right angles to the direction of the flux between them.

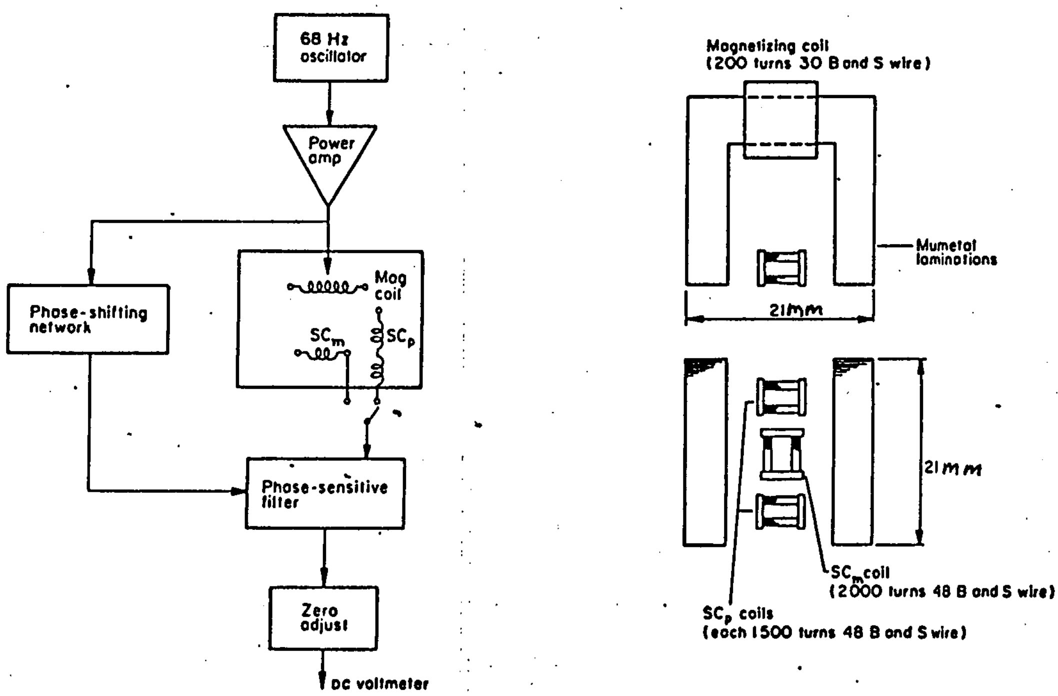


Figure 1.1 Rotation Rig Schematic and Probe Details.
(from Reference 12)

During the production of the probe assembly, the airwound SCm coil is aligned so that in air, the output voltage from it is zero. This means that the axis of the coil is aligned exactly at 90° with the lines of flux between the poles. If we feed the output of the air-wound coil through a phase sensitive filter (that is switched in phase with the excitation signal) then we can filter out most of the noise picked up by the SCm coil. The phase sensitive filter will only allow the fundamental and odd harmonics of the excitation frequency to be passed, all other frequency components being averaged out to zero over the switching period. The signal level from the SCm coil, when the probe is placed on stressed steel is in the order of tens to hundreds of microvolts. This makes the signal susceptable to noise, but in practice the phase sensitive filter works very well in removing this.

If the probe is placed on un-stressed steel then the output from the SCm coil will be zero (i.e. the principle used here is a true "null" method). Placing the probe on a stressed steel surface will give an output voltage from the phase sensitive filter relating to the stress level. This is because the increase in the permeability towards the direction of tension causes a slight (1 to 2 degrees) change between the direction of H (magnetic field strength) and B (magnetic flux density) developed between the poles of the C-core (B and H are normally parallel to each other in unstressed steel). The change in angle between B and H will cause a small voltage to be induced into the SCm coil.

With the output of the low pass filter connected to a digital voltmeter, then the whole instrument becomes a simple, cheap and reasonably accurate tool for measuring residual stress in flat magnetic materials. One of the problems with this instrument, though, is that it requires manual rotation of the probe to enable the maximum values of the voltage from the SCm coil to be recorded. The angular position of these voltage maxima and minima are at 45° to the direction of the principal stresses. From the magnitude of these voltage peaks we can determine the magnitude of the difference between the principal stresses and from the angular location of the peaks, the direction of the principal stresses.

Nothing was done to further enhance the operation of this instrument (called a "rotation rig") until the Railways of Australia Committee ("ROA") funded the development of an automatic instrument based on the rotation rig. The instrument was to be used to measure the residual stress in the flange of railway wheels. This being undertaken to detect potentially unsafe railway wheels and allow for them to be removed from service. The rotation rig was to be made automatic to remove the task of manually rotating the probe of the rotation rig and calculating the stress value.

At present, railway wheels are subjected to heat treatment during the manufacturing process which is intended to leave the rim of the wheel in compression. The purpose of this is to help prevent the propagation of radial cracks from the tread of the rim. Because the brakes of a train bear directly onto the rim of the wheel, then the deliberatly induced compression disappears during the service life of the wheel. Eventually, the rim of the wheel may go into tension. This is a potentially dangerous situation as any cracks that start near the rim, may propagate through the wheel quickly. In extreme cases this may cause the wheel to fail catastrophically, with the possibility of derailing the train: This problem is more noticable on freight trains, where the loads on wagons are higher than on passenger cars. This is further compounded by faulty or ill-adjusted brake sets on freight trains (not normally a problem on passenger trains due to the stricter transport laws governing them).

At present the only way of checking wheels for excessive overheating, and hence the possibility that the wheel has gone into tension, is to paint the wheel with temperature sensitive paint. If the paint becomes discoloured or burnt to a depth of four inches from the rim, then the wheel is considered to be overheated and must be removed from service (due to Federal Transport Laws). The problem with this is that up to 90% of the wheels removed from service for overheating may not have gone into dangerous levels of tension and also that some of the wheels that have not been overheated, may be defective (from Reference 11). This is because it is not only the severity of the overheating that causes the wheel to go into tension, but also the cummulative effect of this overheating. As the discoloured paint method is not adequate in determining whether a wheel has been heat damaged, then railway authorities worldwide have sought a method which will non-destructively measure the residual stress level in railway wheels. If the residual stress in the wheel was found to be excessively tensile, then it would be removed from service, thus eliminating the wasteful scrapping of wheels which are still serviceable.

The automatic version of the rotation rig could only perform this task if the measured difference in the principal stresses could be related to the circumferencial stress in railway wheels. Studies have shown that the radial stresses in railway wheels are either relatively constant or are small compared to the circumferential stress and that the stress measured at the surface of the wheel flange is related to the bulk stress in the rim of the wheel (by Finite Element Analysis). This means that the measured stress difference at the flange of the wheel can be used to determine whether or not the rim is in compression or tension.

After some prelimenary tests carried out in 1986 to determine the validity of the method to measure the stress in ferrous materials, it was decided that a prototype automatic instrument was to be made by the University of Tasmania, with funds provided by the Railways of Australia Committee (ROA). The prototype device was then to be field tested by ROA to determine its ability to seperate "unsafe" tensile wheels from "safe" wheels.

The first prototype ARR-1 (Automatic Rotation Rig number 1) was completed in 1987 and showed that the principle of operation looked promising. There were some shortcomings in the design of ARR-1, the main ones being the suitability of the instrument for portable field use in harsh environments and its speed of operation. Both these problems were solved by changing the chassis layout and the control computer, but the basic principle of operation of the device was not changed. The new field prototype, ARR-2 (Automatic Rotation Rig number 2), was designed to, hopefully, withstand the rigour of field use, but at the same time be reasonably flexible to allow it to be modified to meet the requirements of the ROA, should this arise. This device was completed and dispatched to ROA in early 1988. It has been used in Western Australia by Mt. Newman Mining and Hammersley Iron (in the Pilbara region) and in Queensland, New South Wales and Victoria by their respective state railways. During this testing period it has operated with few problems.

At present the ARR-2 is undergoing comparative tests with the "Trepan-ring" destructive method and the Barkhausen Noise non-destructive method of residual stress measurement to try and verify the instruments suitability to detect suspect wheels. This comparison is being completed at time of writing and at present the results (unpublished, Reference 13) look promising.

Another rotation rig was built for the ROA called ARR-3 (Automatic Rotation Rig number 3). This works on the same principle as the previous two, but was built to measure the residual and applied stresses in continuous welded railway lines. The ROA wish to measure the "stress free temperature" of the line to within an accuracy of 6° C. This has to be done non-destructively and also account for any residual stress that may be present in the rail due to its prior manufacturing and field history. The stress present in the rail needs to be measured before and after the thermo-alumeric welding process. The ARR-3 appears to work well in determining the magnitude of the stress present in the rail, but not to the accuracy required by the railways (approximately +/- 10 MPa). In fact only x-ray or neutron diffraction techniques will give results that approach this accuracy, but the have their own problems such as the expense of the equipment, the need for skilled operators and the potential dangerous nature of the equipment. There is also the need for special surface preparation of the metal under examination (see Reference 14 for more detail on Barkhausen Noise, Trepan-Ring and X-Ray Diffraction measurement techniques).

At this time more research needs to be undertaken before it is known whether or not ARR-3 can be used to successfully measure the stress free temperature of railway tracks to the accuracy required by the ROA.

This thesis describes the development of, equipment used and the testing of all three automatic rotation rigs designed by the author and also includes conclusions on the performance of each and a summary of possible improvements.

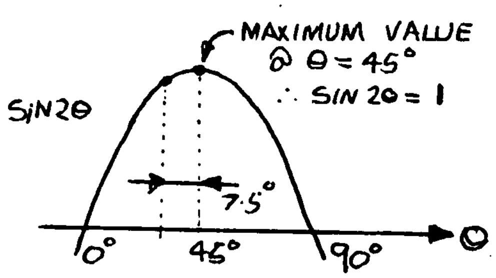
CHAPTER 2

AUTOMATIC ROTATION RIG 1

2.1 Design Development.

The Automatic Rotation Rig Number 1, or ARR-1 for short, was developed around the Hewlett Packard HP-IL system. This system is a serial communication link which allows the use of a simple calculator/computer to control the operation of peripheral devices, such as printers, plotters and scientific instruments. The instrument used in this case was a digital multimeter (HP 3468B) and the controller was a Hewlett Packhard HP 41CV programmable calculator. The calculator was of the hand held variety and the multimeter had its own internal battery supply, thus allowing the complete instrument to be portable. The digital multimeter has an accuracy of +/- 1 microvolt, thus making it suitable to measure the small voltages out of the SCm search coil (tens of microvolts). An interface board (HP82166C) was also incorporated into the design to allow the calculator to control the operation of the motor needed to turn the probe through 360° . This motor was chosen to be a stepper motor with 7.5° steps. It had been found (see Example 2.1) that by taking 24 steps of 15° each that the maximum loss in accuracy in finding the magnitude of the peak voltages out of the search coil (assuming that it has a SIN 2Θ change with rotation angle Θ) would be less than 3.4%. Thus the stepper motor can be stepped twice for each reading of the filtered SCm coil output to be taken with out to much loss in accuracy.

The calculator is programmed to find the maxima and minima SCm voltages as the probe is rotated, calculate the resultant average difference, $\hat{SCm}$, and also from the angular positions of these peaks, calculate the direction of the principal stresses.



EACH STEP = 15°

∴ MAXIMUM ANGLE FROM PEAK SCm VALUE = 7.5°

$$\therefore \text{MAXIMUM ERROR} = \frac{\sin(2\times45) - \sin(2\times37.5)}{\sin(2\times45)}$$

$$= \frac{1 - 0.9659}{1}$$

$$= 0.034 = 3.4\%$$

Example 2.1 Accuracy Using 24 SCm Readings.

The whole instrument was designed to operate off 12 V DC sealed lead-acid batteries that are charged from an internal battery charger that derives its supply from the 240 V AC mains.

To take a stress measurement, the probe (see Figure 2.1) is connected to the main electronics unit, containing the calculator, batteries, battery charger and other electronics, by its flexible cable. The calculator and multimeter are turned on, with the MULTIMETER ARR/NORMAL switch set to ARR. The calculator is switched to "USER". Pressing the $\Sigma+$ key starts the initialisation program. This sets up the HP-IL loop. The main program then starts and rewinds the stepper motor starting position. From here the program steps the probe through 23 15° intervals, giving 24 positions with the probe momentarily stationary.

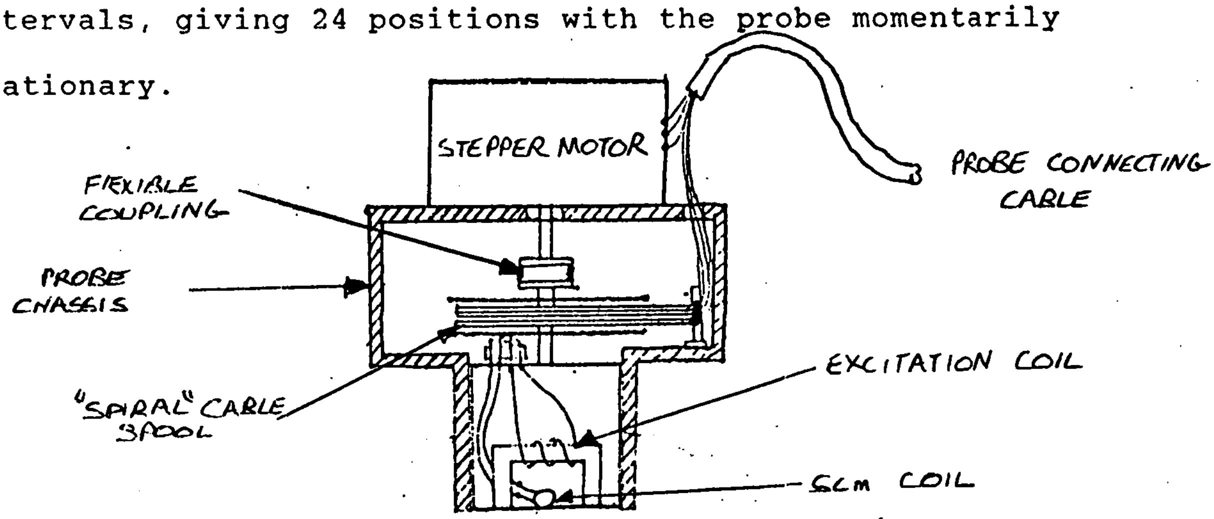
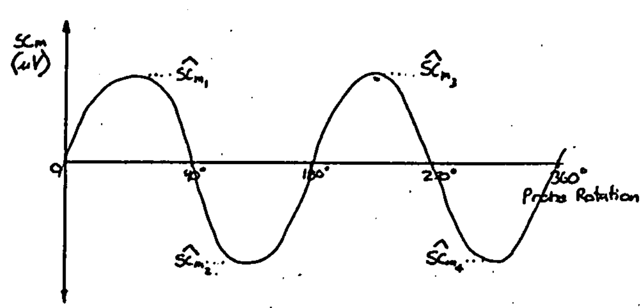


Figure 2.2 Probe Assembly Schematic.

In each of these positions the multimeter reads the SCm voltage, and in four out of the 24 it reads the SCp voltage. These values are digitised by the multimeter and sent via the HP-IL loop to the calculator, where they are stored.

The HP 41CV calculator is programmed to display three values. The first is the quantity SCp. This value will change with the air gap between the end of the probe and the surface of the steel. It is not dependant on the stress level in the steel and can therefore be used to calibrate the sensitivity of the SCm reading. $\hat{SCp}$ can also be used as a guide to whether or not the probe is positioned flatly or correctly onto the steel surface. The value of SCp does not vary much as the probe rotates (about 1%) hence the average of the four readings of SCp, $\hat{SCp}$, is considered accurate enough. These values of SCp are recorded by the calculator when a maxima and minima value of SCm has been found.

The values of SCm have been found to vary almost as SIN 2θ, with angular position θ (see Figure 2.2). There are normally 2 maximum and 2 minimum values of SCm per revolution of the probe when it is on stressed steel. Ideally, the two maximum peaks should be the same value, but in practice, mainly due to the imperfect alignment of the SCm coil in the probe, they differ. Similarily this holds for the two minimum SCm values.



ARR-1 OUTPUT $\hat{SCm} = \frac{\hat{SCm}_1 + \hat{SCm}_3}{2} - \frac{\hat{SCm}_2 + \hat{SCm}_4}{2}$

Figure 2.2 Variation of SCm with rotation of probe.

The calculator program finds the two maximum values, and averages them. It also finds the two minimum values and averages them. The difference between these two average values is taken and this is denoted $\hat{SCm}$. The probe connections are adjusted so that when the probe is aligned with the SCm coil parallel to the direction of tension, then the $\hat{SCm}$ reading is positive. The units of SCm are volt (DC).

When the R/S key is pressed on the calculator, the display will show the direction of tension. This is calculated in the program by taking the angle which is half way between the angular positions of the first maxima and the next minima (see Figure 2.3). In the production of ARR-1, the probe is wired so that this occurs (instead of giving the direction of compression in the sample).

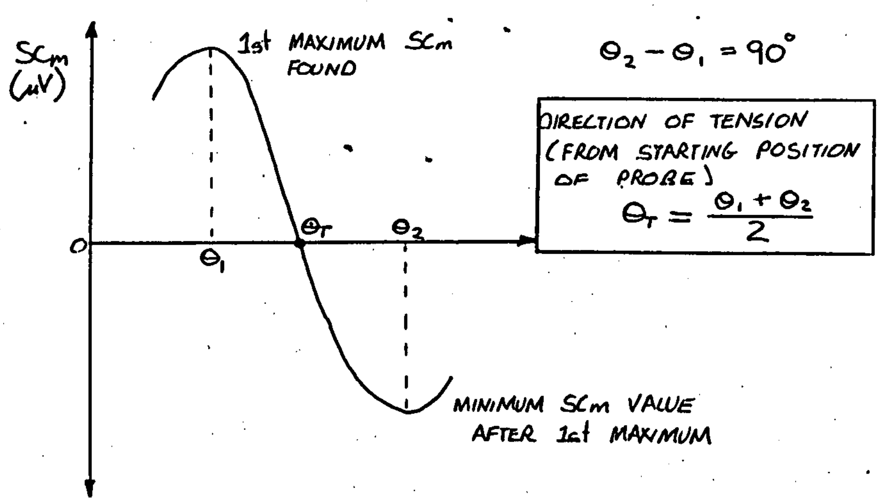


Figure 2.3 Finding the angular position of principal tension.

This stress measuring process can then be repeated by pressing R/S again. Each reading takes about 90 seconds to complete. The stress difference in the sample is then estimated by means of a calibration curve (see Figure 2.4). The calculator was not programmed to display the stress difference directly (in

MPa) because different types of wheel steel give different sensitivities and hence different calibrations. Note the stress hysterisis effect on the calibration curve. The cause of this is not fully understood at present, though some investigations have been started to try and solve this (Reference 20). This effect reduces the accuracy of the technique by about +/- 10 MPa.

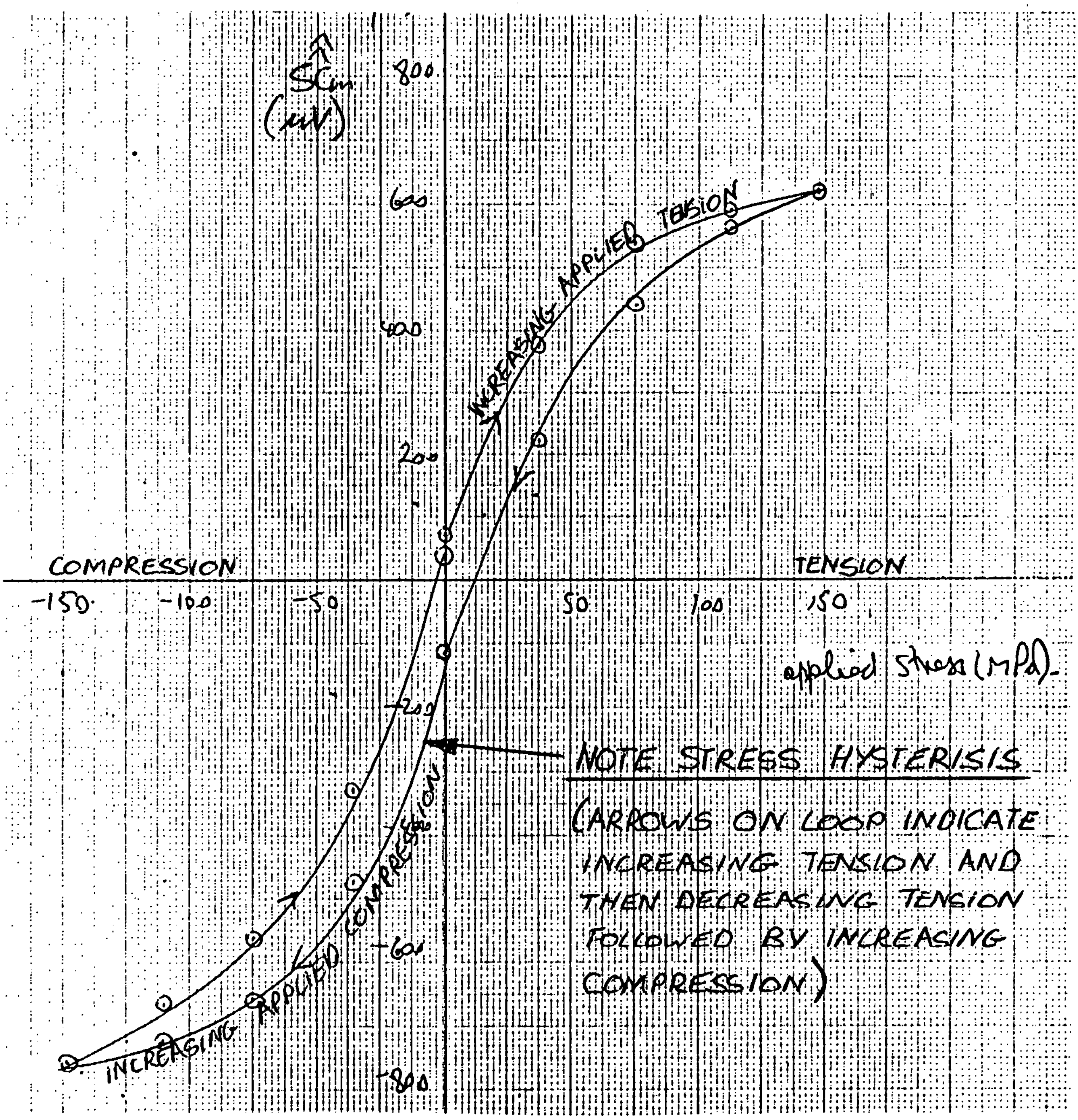


Figure 2.4 Typical calibration curve for ARR-1 (mild steel).

2.2 Electronics Design.

The following descriptions have been made with reference to the circuit diagrams of ARR-1 as shown in Appendix E (a). A block diagram of ARR-1 can be seen in the Provisional Patent Application, Appendix B.

2.2 (a) Oscillator and Filter.

The oscillator used to derive the excitation signal for the probe was sourced from a design that appears in the Motorola Linear Handbook (Reference 1). This oscillator was chosen because it was powered by a single ended supply, was simple and it worked. The use of a single ended supply simplified the battery set up and the battery charger design.

The oscillator (shown in Figure 2.5) was designed to run at 80 Hz, but this frequency is not critical. It was found that the waveform produced was not very sinusoidal, but this did not seem to affect the performance of ARR-1 to any noticeable level. The oscillator is a modified Wien bridge Oscillator. Non linear feedback is used to provide the correct level of feedback needed to maintain oscillation. This is provided by the two back to back diodes D1 and D2. This removes the need for a feedback stabilising device, such as a thermistor.

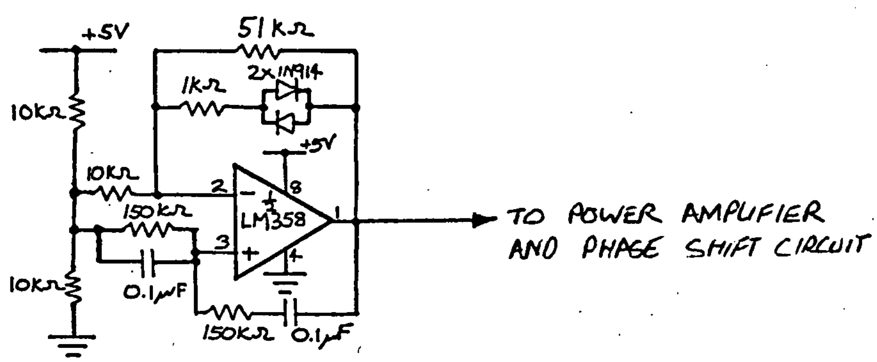


Figure 2.5 80 Hz oscillator circuit.

The output from the LM358 Wien Bridge Oscillator is fed through a potential divider, a potentiometer to ground, in order to set the input level to the power amplifier. This amplifier is a LM380, used in the standard way (see Figure 2.6). It provides an adequate amount of power to the excitation probe. The signal from the oscillator is capacitively coupled to the amplifier via the 0.1 μF capacitor. The LM380 is bypassed in the usual way to prevent it becoming unstable and oscillating. The output from the power amplifier is fed, via a 1000μF capacitor and a 1:2 autotransformer to the excitation coil. The capacitor value was chosen because it has a low impedance at 80 Hz. The auto-transformer is used for impedance matching the excitation coil to the nominal output impedance of the amplifier. This was done because the excitation coil used in this instrument was originally designed for use with an LM380 operating off a higher supply voltage. Thus, to obtain enough excitation power in the probe with the use of a 12V supply, the autotransformer was included to provide a four to one impedance transformation. This increased the excitation current in the coil to an acceptable level.

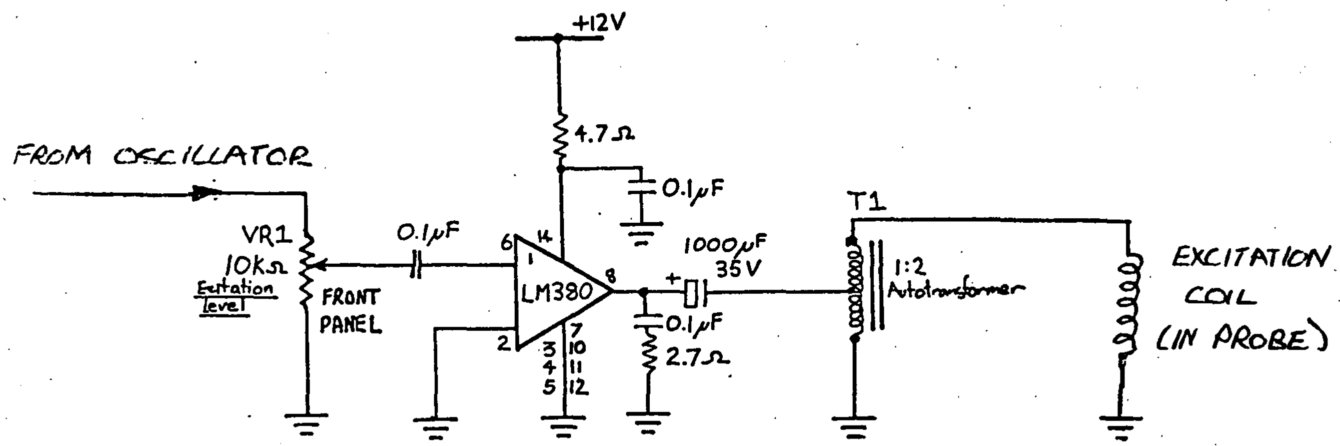


Figure 2.6 Power Amplifier Circuit.

In order to filter the signals picked up by the SCp and SCm coils, two phase sensitive filters are provided (see Figure 2.7). These are switched in phase from reference signals, ϕ and $\overline{\phi}$ derived from the oscillator.

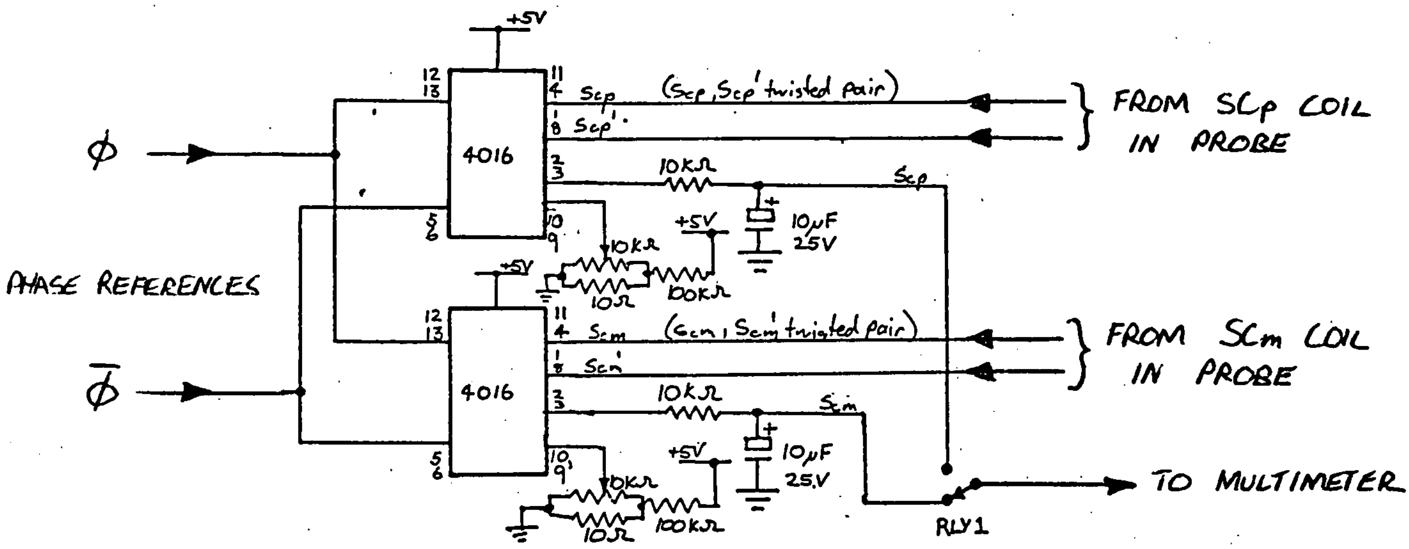


Figure 2.7 Phase sensitive filter circuits.

Because there is a phase shift between the excitation signal and the detected SCm and SCp signals, due to the transformer action of the probe, then a phase shift must be allowed, between the oscillator and the phase reference, for the phase sensitive filter. This was achieved by using a variable low pass filter with its knee frequency set near to the oscillator frequency (see Figure 2.8). Thus, VR2 can adjust the phase of the reference signal with respect to the oscillator signal. Because the output of the oscillator has a DC offset of 2.5 V then the "ground" end of the phase shift network is set at 2.5 V DC from the 2.5 V DC offset point on the Wein bridge oscillator. This is filtered by a 220 μF electrolytic capacitor to ground.

In order to switch the 4016 quad CMOS switch, the phase shifted reference signal is fed through two LM358 operational amplifiers acting as comparators. This gives complementary 5V amplitude squarewaves, ϕ and $\overline{\phi}$, phase shifted from the original excitation frequency. Each of the 4016 Quad CMOS switches is fed from the search coils via twisted pair. In order to filter the signals, in turn, and in phase with the oscillator reference signal, one of the leads from the search coil in connected to the output low pass filter and then to a DC offset circuit. The other lead is connected to the same points but 180° out of phase with the other lead (see Figure 2.9). This effectively full wave rectifies the signal detected in the probe. The resultant output consists of the fundamental and odd harmonic frequency components of the signals from the search coils. These are further filtered into a DC signal by a single pole low pass filter, consisting of a 10 kΩ resistor and 10 μF electrolytic capacitor to ground. This DC signal is proportional to the level of excitation signal that is detected by the pick up coils and hence, in the case of the SCm coil, is related to the level of stress in the steel surface under investigation.

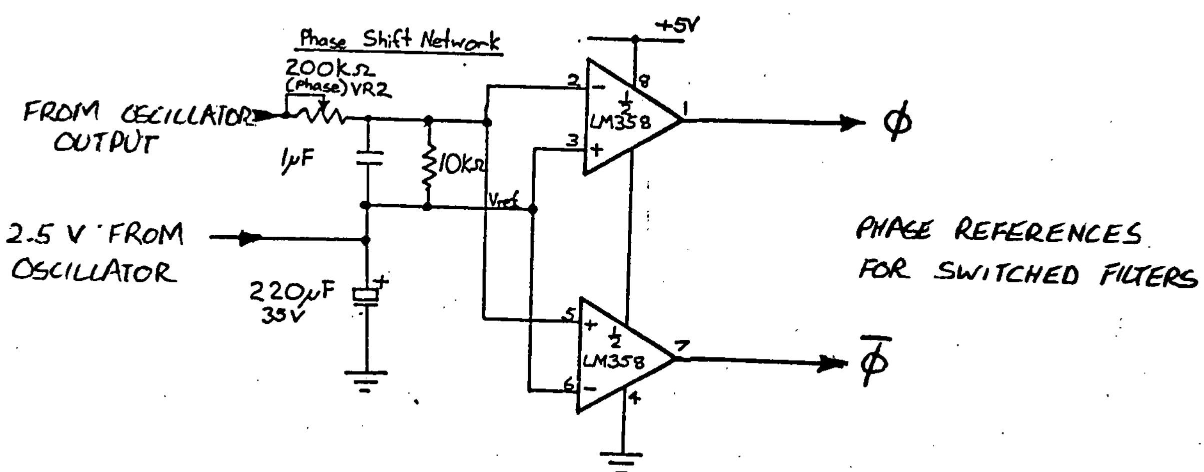


Figure 2.8 Phase Reference Circuit.

Because there may be an offset signal present on a stress free sample, when the probe is placed on it, due imperfections in the probe, then a correction DC is given by the following circuit (see Figure 2.10).

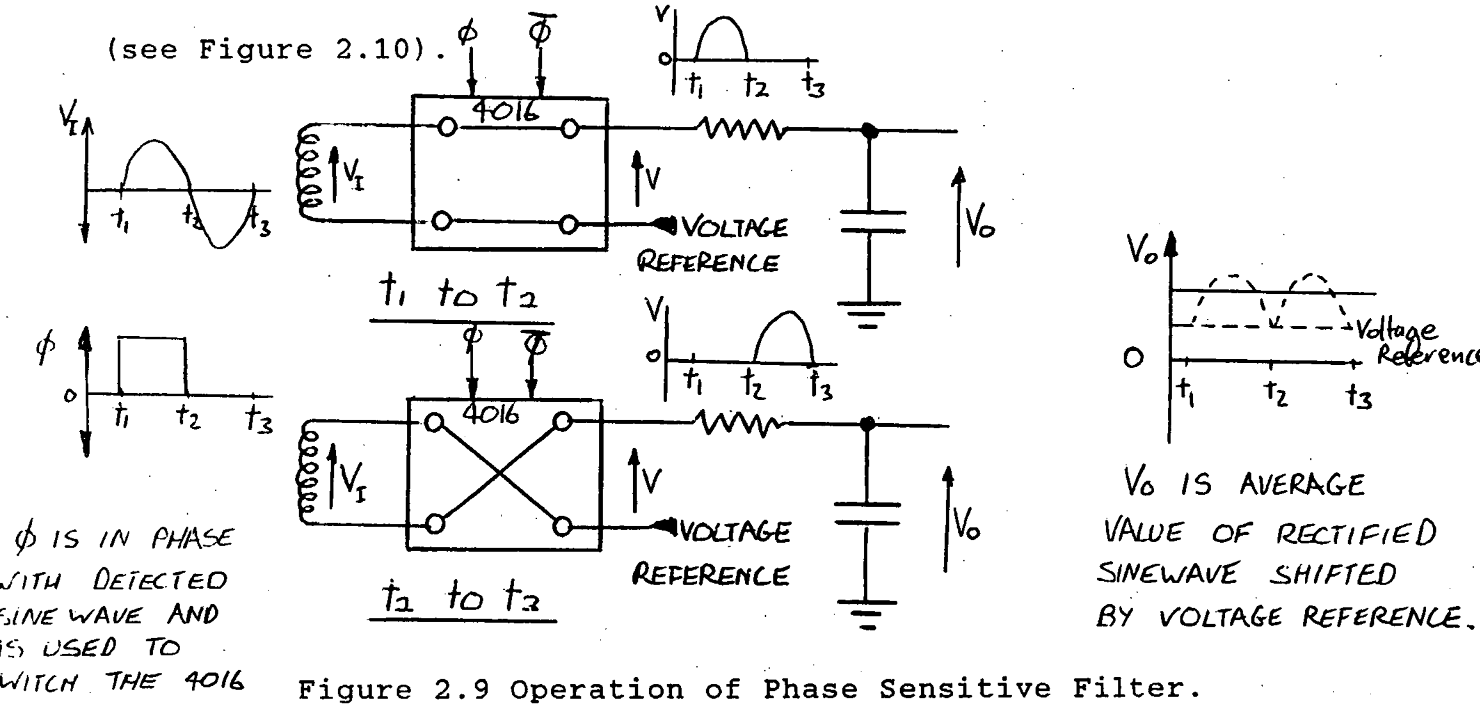


Figure 2.9 Operation of Phase Sensitive Filter.

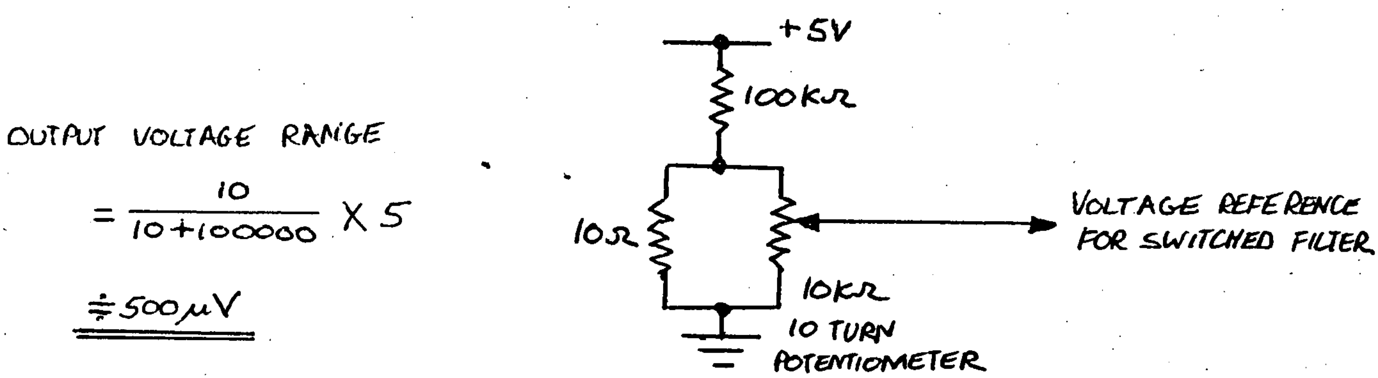


Figure 2.10 DC offset correction circuit.

This allows very fine ajustment of the DC offset. The range of adjustment given is approximatly 500 μV DC. This adjustment is usually set so that $\hat{\hat{SCm}}$ is zero for the probe on a stress free steel surface.

To allow the single input multimeter to read the two outputs SCp and SCm, a relay, RLY 1, is provided to switch them. This is controlled by the calculator via the HP-IL interface board and a simple relay driver (see Figure 2.11).

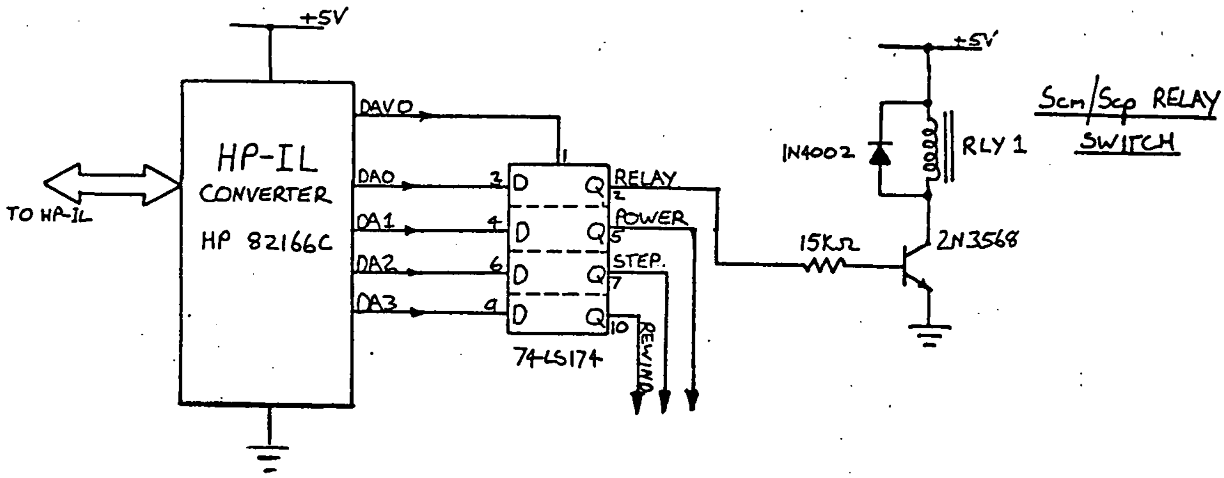


Figure 2.11 SCm/SCp relay driver circuit.

The signal from the HP-IL interface kit, HP 82166C, is latched using one flip flop from a 74LS174 HEX D-type flip flop. This is latched from the "DAVO" line from the HP-IL interface kit. This line goes low when there is data available on the output lines DA0 to DA7. The latched relay control "power" is amplified by the 2N3568 NPN transistor. In order to prevent damage to this transistor from switching the inductive load of the relay then a flywheel diode (1N4002) is placed in parallel with the relay armature. Therefore, writing a "1" to the DA0 line will cause the SCm line to be connected to the multimeter input.

2.2 (b) Stepper Motor Control.

The control of the stepper motor has two modes of operation. Firstly the motor is stepped in the forward direction, two steps at a time, under the control of the HP 41CV calculator. When it has reached the end of its rotation (after 23 double steps of the motor) the calculator is informed that the correct number of steps have been done. The calculator then makes the stepper motor rewind back to the starting position, under the contol of some logic circuitry.

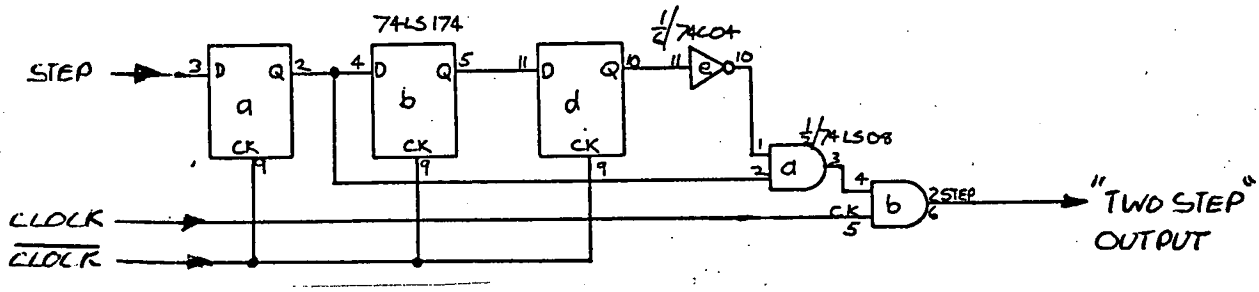


Figure 2.12 (a) "Two Step" circuit.

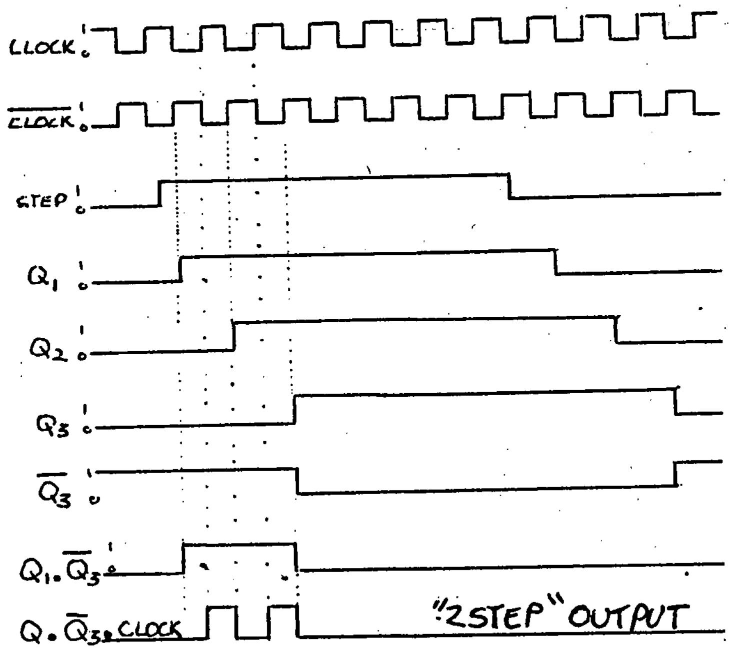


Figure 2.12 (b) "Two Step" circuit timing diagram.

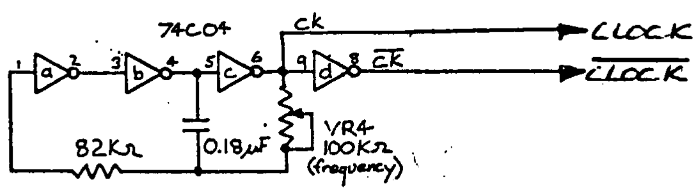


Figure 2.13 Clock circuit

In order to make the stepper motor step twice under command, a "Two Step" circuit was devised (see Figures 2.12 (a) and (b)) to give two pulses to the stepper motor driver integrated circuit. This circuit gives two pulses at the clock frequency when the "STEP" line from the HP-IL interface goes high (the clock circuit is a typical "three cmos inverter" circuit and is shown in Figure 2.13). The "STEP" line is latched in the same manner as that for the SCm/SCp relay as described previously. When this line goes high, the output of the first D type flip flop goes high after the next rising clock pulse. After the second clock pulse the second flip flop output, Q_2, goes high and after the third clock pulse rise, the output of the third flip flop goes high. If we combine the outputs of the first flip flop and the inverted output of the third flip flop, with an AND gate, then we get a signal which goes high for two clock pulses in duration. If we now AND this with an inverted clock signal we get two clock pulses at the "2STEP" output. The timing diagram (Figure 2.12 (b)) shows the timing of this operation. The cicuit will only give two pulses out while the STEP input remains high. It will only give another "TWO STEP" output when the STEP input goes low and then goes high again.

The clock for the stepper motor is provided by a simple CMOS clock circuit (see Figure 2.13). VR4 was set by experiment to give the maximum stepping rate for the stepper motor that does not cause it to miss steps under the inertial load of the probe assembly. The frequency of the clock was set to approximately 100 Hz.

The direction of rotation of the stepper motor is controlled by the Hall effect limit switches which are mounted at the rotational limits of the probe. The magnet which switches them is mounted on the probe, with the switches themselves mounted on the probe chassis. In order to obtain the correct logic for the rest of the circuit, the outputs of both the switches are inverted (see Figure 2.14). To inform the calculator that the limit of rotation of the probe has been reached (in either the forward or reverse direction) the MSRQ (message request) line on the HP-IL board is pulled low if either of the outputs from the inverters goes low. This is achieved by an OR gate and then an inverter. This whole circuit thus has the effect of a NOR gate, but since this would require the use of an extra integrated circuit, the circuit was designed to use the gate out of a quad OR gate (as other elements of this were needed elsewhere in the circuit).

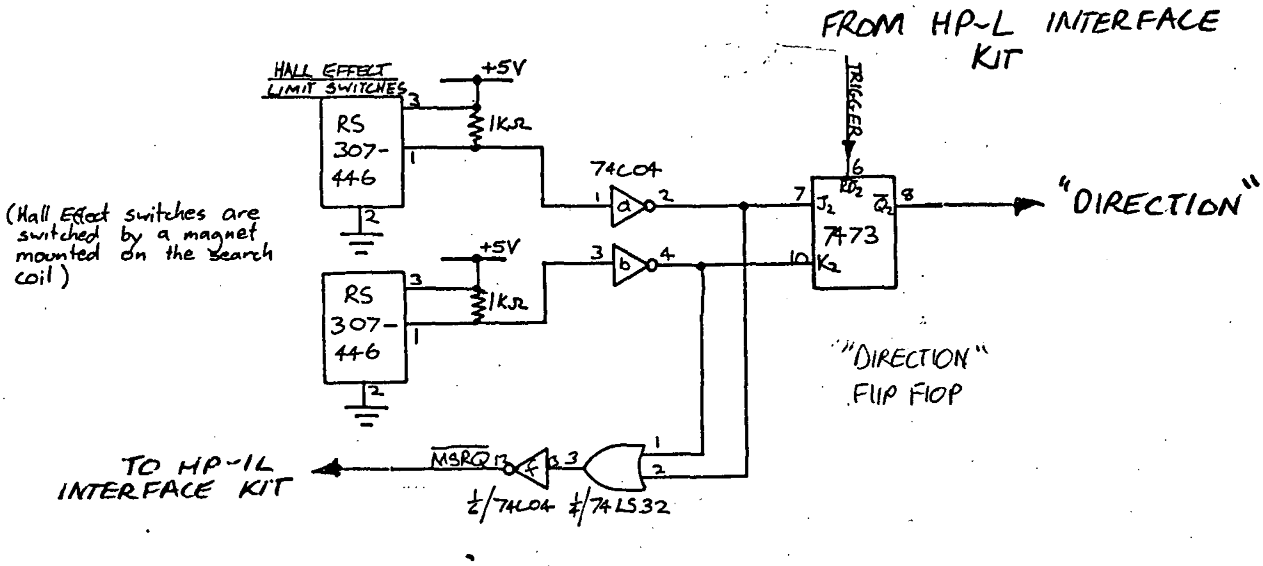


Figure 2.14 Stepper motor direction control.

In order to give a direction signal for the stepper motor, the two signals from the limit switches are fed into a JK flip flop. The flip flop can be reset with the TRIGGER line from the HP-IL interface. This allows the direction of rotation to be set to the rewind direction at any time, under control of the HP 41 CV calculator. Hence if the equipment is turned on and it is detected from the limit switches, via the MSRQ line, that the probe is not in the rewound position, then it can be rewound to its starting position under the control of the calculator. The direction signal is fed to the SAA 1027 stepper motor driver IC via a 5V logic to 12 V logic convertor. This is an opto isolator which effectively converts the voltage and also provides isolation of the electronics supplies from that of the stepper motor, thus helping to reduce interference to the filter cicuit.

In order to allow the stepper motor to step using the "Two Step" circuit in the forward direction and to use just the clock pulses in the reverse direction, the following logic circuit was used (see Figure 2.15). This allows the clock pulses to be fed to the motor when the direction is correct (i.e. after the probe is at the end of its travel and has set the "direction" flip flop). This is controlled also by the calculator, which sets the REWIND line high via DA3 from the HP-IL interface board. In order to allow clock pulses to be fed to the stepper motor drive IC they are AND'ed with the DIRECTION line as well as the REWIND line. The output of this is OR'd with the output of the "Two Step" circuit (these being mutually exclusive events).

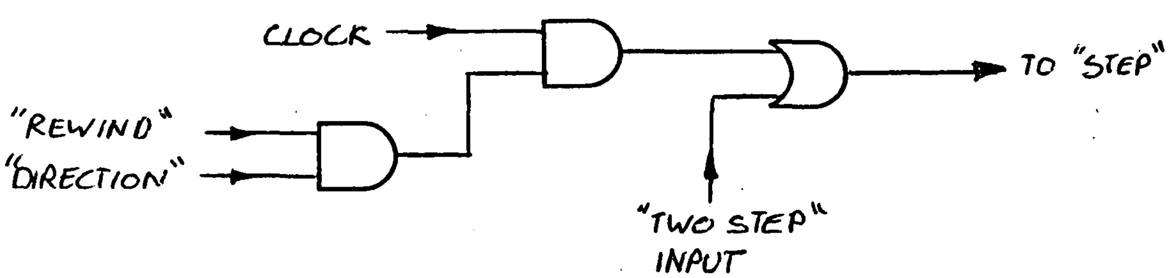


Figure 2.15 Stepper motor logic circuit.

The stepper motor drive circuit is a SAA 1027. This only requires a few additional components, a signal for the direction of stepping and a step clock signal. The components used are as per the data sheet for this IC (see Reference 15 and Figure 2.16). The reset line is always high in this application. In order to protect the switching transitors from switching off an inductive load, flywheel diodes are placed across each of the four poles of the stepper motor. These were chosen to be 1N4002's.

The power to the stepper motor is turned off when it is not being used in order to conserve the battery power. This is done under control from the HP 41CV calculator, via the DA1 port of the HP-IL interface board. This signal is latched by one flip flop in the 74LS174 and amplified by a 2N3568 NPN transitor in order to drive the BD140 power transistor, which is used to switch the 12 V supply to the stepper motor off and on (see Figure 2.16).

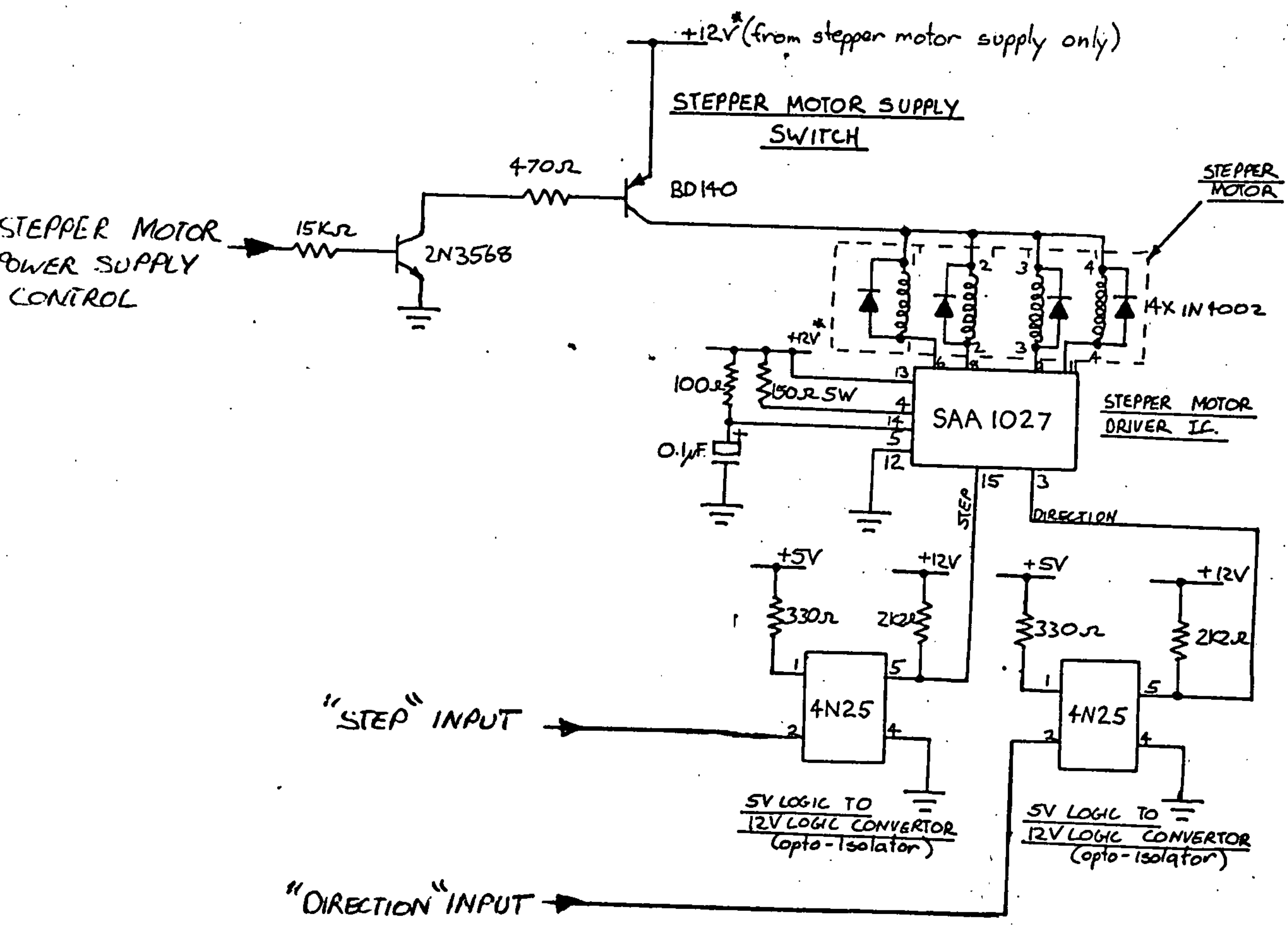


Figure 2.16 Stepper motor drive circuit.

2.2 (c) Battery Charger Design.

The battery charger uses constant voltage charging for the 4 lead calcium batteries (see Sheet 2, Appendix E (a)). These batteries are sealed and can be mounted and charged in any position. The particular size of 1.9 AH was chosen to give the instrument sufficient battery life when operating in the field and also because they were a convienient size for mounting in the chassis. They are charged at a constant voltage of 14.4 V. This is not the highest voltage that these batteries can be charged at. This means that the charge rate is not very high, but the batteries can still be charged overnight quite easily.

The constant voltage charging supply is provided by a 240 V to 18 V 60 VA transformer which is rectified by a 10 A full wave rectifier bridge and filtered by a 470 μF capacitor. The voltage is regulated by a LM350 voltage regulator, which, using a typical circuit, is adjusted to give an output voltage of 14.4 V DC. This provides a 1.5 A maximum, constant voltage supply to charge the batteries. If the batteries are flat then they may have a terminal voltage of 9 V DC or so. In order to prevent this condition causing excessive current being drawn from the regulator, two series current limiting resistors are provided.

The batteries are arranged in order to seperate the stepper motor supply from the supply for the electronics, thus helping to reduce interference to the small SCm voltages from the stepper motor drive.

To simplify the switching arrangement for the batteries to be charged, a double throw double pole 2 A switch is used to switch the output from the current limiting resistors to the batteries. This switch is also used to connect the batteries to the rest of the equipment when it is turned on. In order to calculate the resistor values for the current limiting resistors the following method was used:

Assume that the battery terminal voltage is 9 V when it is flat

The output of the voltage regulator of the battery charger is set to 14.4 V DC.

This means that there must be a 5.4 V drop between the voltage regulator and the batteries, when they are flat.

The maximum charging current for these batteries is 0.47 A. As there are four batteries, with each current limiting resistor in series with two batteries in parallel then the maximum current through each resistor is 0.94 A.

Therefore each resistor needs to be 5.4/0.94 = $\underline{5.7\,\Omega}$.

Thus choose 6.8 Ω resistors to be on the safe side.

Check power dissipation in each resistor

$$P = 5.4*5.4/6.8 = \underline{4.2\ W}$$

Therefore use 5 W resistors.

To protect against damage to the wiring by shorting the batteries to ground, fuses are placed in the supply lines to the ON/OFF switch.

A 5V DC supply is provided for the electronics via a 5V regulator, a 7805. This provides a 0.5 A supply. The circuit used is as per the Motorola Linear Handbook (see Reference 1).

2.2 (d) HP-IL Interface Board.

The HP-IL Interface Board was taken from the circuit diagrams from the HP 82166C Interface Kit Technical Guide (see Reference 7). This kit provides a link between the HP 41CV calculator and the "outside world" via the HP-IL serial communications loop. The kit provides all the neccessary components and technical information needed to build the interface, with the exception of the printed circuit board. A circuit board was designed by the author for this application. The board also contains all the logic for the stepper motor control. The circuit board layout is not included in this thesis as ARR-1 was a laboratory prototype and a similar rotation rig is unlikely to be built again.

2.3 HP-IL Programming.

The program for ARR-1 is written in the "language" used by the HP 41CV calculator. This language uses the normal instruction set (see Reference 6) for the calculator along with some special instructions that are used with the HP-IL serial interface loop and the other devices connected to it. A flowchart showing the operation of the control program, as well as the program listing is shown in Appendix C (a). These can used as aids to the following program description. In this listing note that the comments to the program have been added in and are not included in the HP 41CV memory.

In order for the program to run correctly the HP-IL module must be plugged into the calculator and connected in the correct manner to the HP 3468B multimeter and the HP 82166C interface kit. The HP 000041-15043 HP-IL Development Module must also be plugged into the HP 41CV calculator.

The program "STRESS" is assigned to the Σ+ key on the HP 41CV , this means that if the calculator is in the "USER" mode then pressing this key will run the stress measuring program. The first thing that the calculator does when running is to set up the HP-IL loop. This is done in the sub-program "INIT". This program first uses the HP-IL development module program "CF 33" to prevent the HP-IL module from searching for a printer. This program clears flag 33 in the HP 41CV. This flag cannot be set or cleared by the user of the calculator with the normal clear flag (CF) and set flag (SF) keystrokes (this flag is not cleared when the calculator is turned on). As the HP-IL loop will not operate if this flag is set, then it must be cleared. This can only be done conveniently by the module program "CF 33" (the other method is to remove the calculator batteries to give a memory lost condition, which is inconvenient).

The HP-IL loop is then set up for automatic loop operation by the "AUTOIO" command. This assigns device numbers to each peripheral device connected to the loop. These need to be used when "talking" to them from the loop controller (the calculator in this case). Hence their loop numbers are obtained by finding their assigned identification numbers. This is done by using the "FINDID" function of the HP-IL module. These identification numbers are stored for future reference.

The multimeter is then selected for communication and then set for remote operation. This means that the front panel of the multimeter is made inoperable to prevent tampering (which may affect the operation of ARR-1). The serial data to be sent to the multimeter is set for normal end of line characters to suit the multimeter operation. The multimeter is set up for manual range, no autozero, internal trigger and 5 1/2 digits. This is done by sending the code "F1R1Z1N5T1" to the multimeter (see Figure 2.17). Manual ranging means that the multimeter will remain on the set range and not change to suit itself. This means that time will not be wasted whilst the multimeter decides which range it is supposed to be on. The Autozero function of the multimeter means that an accurate measurement is taken over a period of time. If this function was turned off then the readings taken by the multimeter would be quicker, but there would be a loss in accuracy in the readings. The multimeter is set for internal trigger. This means that it is continuously taking readings. If a reading is to be sent to the controller via the HP-IL then it will be sent when the multimeter has a new reading and not when the calculator tells the multimeter it can take a reading. This may speed up the operation by a slight amount. Because of the accuracy required for the SCm signals, then the 5 1/2 digit mode is selected. This is the slowest range, with 1.7 readings being taken each second.

Function	Code	Range Codes R1	R2	R3	R4	R5	R6	RA Autorange
DC Volts	F1	.3V	3V	30V	300V	•	•	
AC Volts	F2	.3V	3V	30V	300V	•	•	
2-Wire Ohms	F3	300Ω	3KΩ	30KΩ	300KΩ	3MΩ	30MΩ	
4-Wire Ohms	F4	300Ω	3KΩ	30KΩ	300KΩ	3MΩ	30MΩ	
DC Amps	F5	3A	•	•	•	•	•	
AC Amps	F6	300mA	3A	•	•	•	•	
Extended Ohms	F7	(default range) 10MΩ//Rx	•	•	•	•	•	

• Indicates an invalid combination of Function and Range codes.

Other Program Codes:

Function	Qualifier	Description	Example
N	3,4,5	Selects the number of digits of display.	N3 selects the 3 1/2 digit display mode.
T	1,2	Trigger Mode: Internal, Single.	T1 selects internal trigger, T2 selects single.
Z	0,1	Autozero mode: off,on	Z0 turns Autozero off.
C		Calibrate (see 3468A Service Manual).	
D	1,2	Display mode: Normal Text.	D2text displays the message "text" on the 3468A/B display.

Figure 2.17 Set-up table for the HP 3468B Multimeter. (from HP 3468B operators manual see Reference 8)

The correct hand shake for the HP-IL interface board is set up using a special program from Hewlett Packard (from Reference 9) called "WGPIO". This program allows the control registers of the ILB3-0003 HP-IL integrated circuit to be altered. The handshake is set to negative logic and a DAVO (data available for output) pulse time unit is set to 5μS. The total number of time units is set to 255. This means that the total DAVO pulse length is 13mS. All other handshake functions are as per the default values (see Reference 7). The program to set up these registers is described following. The statistical registers are set to begin at register 20 and the initialisation program returns to the main program.

The main program now continues with a program label, called "SET" which allows the operator to start at the beginning of the program, but without needing to go through the time consuming initialisation procedure if it has already been done. This function can be seen as a "reset" one, i.e. a new set of readings can be taken, after terminating the operation of ARR-1. This program label can be allocated to the keyboard of the HP 41CV calculator, so that it can be run under the "user" mode.

The next label on line 04 is the main loop label 06. This is where the program returns to take a new set of readings. Directly after this, the stepper motor is directed to rewind the probe to its starting position. This is done by the sub-program "REWIND".

The rewind program first sets up a loop counter. This is used to detect if the stepper motor does not rewind the probe correctly after five attempts. The HP-IL interface is selected on the HP-IL loop. The HP-IL module is then set to send normal end of line characters by clearing flag 17 (line 07). The direction flip flop (see Figure 2.13) is then reset so that the stepper motor will rotate in the proper (rewind) direction. This is done by making the TRIGGER line go low on the HP-IL interface board using the "TRIGGER" command. The rewind signal is then given to the motor control logic by sending the letter J to the output port of the HP-IL interface. This has the ASCII value of 74_{10} or

01001010_2. This allows the correct logic signal to be sent to the quad latch circuit connected to the output port of the HP-IL interface. The end of line characters must be supressed so that the ASCII value of "J" is stored and not that of the end of line character. This is done by setting flag 17. The "OUTA" command sends the control character to the HP-IL interface.

The program then pauses in order to allow the stepper motor time to rewind. The error counter is checked to see if it has exceeded five. If it hasn't then the program goes to line 16 where the status register of the HP-IL interface is checked to see if the MSRQ has been set. If it has, flag 00 has been set, if it hasn't, then the program returns to line 04 and repeats the process. If the MSRQ has been set, then the probe has been rewound, so the program returns to the main program. The program will only try to rewind the motor five times. If the probe has not been rewound after these attemps then it is assumed that something is wrong, Hence a message "NO REWIND" is displayed on the calculator screen. The program then stops. If the operator wishes, the main program can be run again by pressing R/S on the calculator keyboard.

With the probe successfully rewound to its starting point ,the main program, starting at line 06, starts taking readings from the probe. The main loop counter is set on line 06 so that 24 readings are taken at 24 different angular positions. Storage register 01 keeps the loop counter value. Lines 08 to 14 clear the various registers used to store the minimum and maximum SCm values and the average SCp values.

The main program then branches to a sub-program called "READING". This subroutine takes a SCm reading. This first reading is taken in the rewound position. The "READING" program will now be described.

The SCm reading program first recalls the identification number of the HP 3468B multimeter from storage register 3, sets normal end of line character, and then selects the multimeter as the device which the calculator wishes to communicate with. On line 05 the multimeter is triggered, which means that it will trigger the multimeter to take a voltage reading. The IND command on line 06 tells the multimeter to send the voltage reading as a serial data stream on the HP-IL. This is recorded by the calculator. The reading program then returns to the main program.

The SCm voltage obtained is stored in two storage registers, one is used as a temporary storage register (05) and the other (18) is used to compare the reading obtained from this first position with that obtained later for the last stepped position of the probe. The main program now steps the stepper motor to move the probe to the first of the twenty three angular positions remaining.

The "STEP" program is another sub-program. Firstly this program selects the HP-IL interface board (lines 01 to 03). The normal end of line characters are deleted by the use of SF 17 on line 04. This is done, as in the rewind program, so that the stored data for the stepper motor drive circuit is the correct control command and not the end of line character. The correct command for the stepping of the motor is "F". This will turn on the power to the stepper motor and allow the "two step" circuit to send two step pulses to the stepper motor drive integrated circuit (SAA 1027). These two step pulses will then move the motor two 7.5° steps and hence the probe will be rotated 15°. The power to the motor is then switched off so that the batteries are preserved. This is done by lines 06 and 07. The step program then returns to the main program.

The main program now clears the flags used by the program. Flag 08 is set when the first maximum is found, flag 09 is set when the first minimum has been found and flag 10 is set when two maximums and two minimums have been found. This is done because if the stress reading is taken under normal conditions, we would expect there to be two maximums and two minimums in the 24 SCm readings. If this occurs, we know, to some extent, that the stress reading has been taken correctly (unfortunately, further work has shown that this may not be the case for all stressed steel samples, hence the program used in future ARR's was modified to tackle the problem of getting SCm values using a different algorithm).

The main program now enters the main reading loop at line 22. In order for the signal levels at the output of the filters to settle to a steady value, as the stepper motor to comes to a complete stop, the program pauses for 1 second at line 23. The program then takes another SCm reading from the multimeter using the "READING" sub-program as described before. This reading is stored in the temporary storage register 12 and then the program checks how many readings have been taken. If 24 SCm readings have been taken then the program will jump to the output stage of the program. If more SCm readings need to be taken, then the program will continue to get these and more SCp readings as well.

If there are still readings to be taken, the program goes to program label 27 on line 29. The probe is rotated again to a new position and it is checked by the program whether or not there has been two maximums and two minimums found. If there has, then the program goes to the "EXIT" routine which calculates the results. If the two maximums and minimums have not been found then the program proceeds to find more SCm readings. At this stage (lines 33 to 36) the program checks the SCm results taken so far, to see which is bigger. The value that was stored in the temporary storage location 12 is stored in location 05 for use later in the program. The trend of these results will show whether or not the readings are increasing to a maximum or decreasing to a minimum. Here the program splits into one of two paths depending whether or not the readings are increasing or decreasing in value.

If the SCm readings are increasing then the program branches to label 10 on line 73, otherwise the program keeps going to label 12 on line 38. In both of these paths another SCm reading is taken (the probe already being rotated to a new position previously). This allows a time delay to allow the probe to stop rotating and for the filters outputs to settle to their new values. This reading is stored in register 12. The previous SCm value from storage register 05 is compared to this new value. If this new value is greater than the previous one, then we have found a minimum SCm value. The program goes to line 52, or label 13 and checks to see if this is the first or second minimum found by checking if flag 09 has been set. If it is not set, then the first minimum SCm value is stored in register 06. Flag 09 is then set in order to indicate that the first minimum has been found.

If the first maximum has been found (indicated by flag 08 being set) then on line 58, the program will test to see if the sequence first SCm maximum then next SCm minimum has occured. This is used to get the angular direction of the principal tension direction. The probe is set up so that this occurs at an angle half way between the position of the first maximum and next minimum. Thus if flag 08 has been set, then we have the correct sequence and we need to store the angular position of the probe (obtained from the loop counter). This is done from line 66, or label 26. To correct this value, 1 is subtracted from the loop counter and this is stored in register 10. Flag 10 is set to indicate that the angular position of the principal stress has been found. Note that flag 08 is cleared when it is checked on line 58. This prevents the process of finding the angular position of the principal stresses from being repeated if we find another sequence of SCm maximum followed by a SCm minimum.

If the minimum we have just found is not the first one then we go to label 14 on line 61 and store this SCm value in storage register 07. Flag 09 is cleared to indicate that we have found two minimums.

If the program has not found a minimum, then it stores the last SCm value in storage register 05, increments the loop counter and if the total number of readings have not been taken, steps the motor (line 50) and then returns to line 38 to get another reading. If 24 SCm readings have been taken then the program goes to line 125 to check the last SCm value with the first SCm value obtained.

The program for finding the positions and magnitudes of the maximum SCm values works in the same manner except that the flags and storage registers are different (and it finds maximums instead of minimums). This program starts at line 73 and ends at line 100. Because the voltage input to the multimeter has only one line, there is a relay connected to it to muliplex it between the SCm filter output and the SCm filter output. A reading of SCp is taken after each maximum or minimum SCm value is taken. The part of the program to do this starts at line 101 or label 03. Firstly the HP-IL interface board is selected and then the character "A" is sent to it to control the position of the relay. The relay connects the SCp signal to the multimeter. The program then instructs the multimeter to get a reading on line 107, using the sub-program "READING". Thus the SCp reading is stored in register 04. Note that the store instruction used here, is a "add and store" instruction "ST+". Thus register 04 contains an accumlative value for SCp. Later in the program, in order to calculate the true $\widehat{SCp}$ value, the stored value is divided by four. This means that the displayed value for $\widehat{SCp}$ is an average one. In order to check that four readings of SCp are taken as expected (we assume that there should be two maximums and two minimums SCm values found) the number of SCp values taken is stored in register 13. The program then checks to see if we have completed the required number of readings. If we have, then the program goes to the output routine. If not, then the stepper motor is stepped again to a new position and the program returns to the start of the main loop again after the "old" value of SCm is stored in register 05 (so that it can be compared with the new SCm value about to be taken). The above process is repeated until all the 24 SCm and 4 SCp values have been taken.

If a maximum or minimum value of SCm happens to be either the last or first value taken then the previously described algorithm will not detect this. The section of the program written to solve this problem starts at line 125, or label 25. The first SCm value taken (which was stored in register 18), is compared to the last SCm value taken (stored in register 12). If either of them are the second maximum or second minimum then they are stored in the relavent storage registers. This is 07 for the second minimum and 09 is the second maximum SCm value. If either the second maximum has been found, or the second minimum, then the program goes and gets the fourth value of SCp at label 25 (at line 146). This program is a repeat of the program used previously to get the SCp values by switching the relay at the input to the multimeter.

If all the readings have been taken then the program has reached the output stage. This starts at label 08, which is on line 156. The program first checks that the probe has reached the end of its travel, and has made 24 SCm readings at 24 different angular positions. This is done by selecting the HP-IL interface and reading the status register using the "INSTAT" function. If Flag 00 has not been set then the MSRQ line is not low. This means that the stepper motor has not reached the mechanical stop at the end of its travel. Hence a "stepping error" has taken place and the results are not valid. In order to warn the operator of this error, the message "STEP ERROR" is placed on the screen of the calculator using the PROMPT command (see lines 165 to 166). In order to give a audible warning to the operator of this condition, the TONE command is used. This beeps the internal piezo buzzer in the HP 41CV calculator. This is done on line 164. The tone frequency is set by the number following the TONE command. The value of TONE 5 was chosen so as to distiguish the warning of a step error from the other audible beeps used in the rest of the program. If there has not been a step error then the calculator proceeds with the rest of the calculations.

It is then checked that four SCp readings has been taken. This is done on line 170, where the contents of register 13 are compared with the number four. If there have not been four SCp readings taken. then the calculator will display a warning to the operator. This is done from lines 231 to 234, in a similar manner to that used to warn the operator of a step error. The warning to the operator in this case is "SMALL SCM". This warning should ideally be "SUSPECT SCM", as the usual condition for other than four SCp values, or more accuratly two maximum and two minimum SCm values, is when there is little stress in the sample being measured. This condition gives an almost constant SCm output near to zero. Hence it is difficult for the program to accuratly determine the peaks of the signal as the probe is rotated. If the operator wishes to continue after this warning the R/S button is pressed and the program goes to the start again (line 04).

If the correct number of SCp readings have been taken then the program calculates the average SCp value by dividing the contents of register 04 by the contents of register 13 (which equals four). The display is then set to give four decimal places (by using the FIX 4 command on line 175) and the average SCp value is displayed on line 175. In order to mix the numerical SCp data will the prompt "SCP=" then command "+ is used along with the command "ARCL X" (alpha recall X register). This combines the alphabetical string with the numerical data stored in the x register of the calculator (the SCp value) into an alpha-numeric message. The calculator then beeps to indicate that a reading has successfully been taken and stops on line 181, awaiting further command from the operator with the SCp value dispayed on the LCD calculator screen.

The next piece of information to be given to the operator is the SCm value. In order to run the routine to calculate this, after the SCp value has been displayed, the operator presses the

R/S button on the calculator keyboard. This starts the program running again from line 182. Between lines 183 and 193 the calculator gets the average of the two minimums, stored in registers 06 and 07, and subtracts this from the average of the two maximums stored in registers 08 and 09. This difference in the $\widehat{SCm}$ values is related to the stress in the steel. The averages of the extreme values are taken to enhance the accuracy of the measurement method. The $\widehat{SCm}$ value is stored in register 14 for display later on. The next algorithm, from line 195 calculates the direction of principal stress. This is done by finding the angular position half way beween the first maximum and the next minimum. As the step position of the first maximum and the next minimum are stored in registers 11 and 10 respectively, then the angle half way between them can be found by averaging the two step positions and then multiplying this value by 15. This is done because each "STEP" routine rotates the probe 15°. On line 235 the calculated angle of the direction of principal stress is checked to see if it is less than or greater than 135°. If it is less than 135° then the $\widehat{SCm}$ value is deemed to be tensile and hence is given a negative sign. If the angle is greater that 135°, then the $\widehat{SCm}$ value is considered to be compressive and its sign remains unchanged. The angle value is stored in register 15 on line 203 and the correctly signed $\widehat{SCm}$ value is combined with the message "SCM=" on lines 212 to 214. The $\widehat{SCm}$ value is displayed on the calculator screen on line 215 as an alphanumeric display and the program stops. In order for the operator to know the angular direction of the principal stresses the R/S button is pressed.

The calculator then proceeds from line 217. The calculator recalls the angle from register 15 and adds it to the message "

=". This is done between lines 218 and 221. The display is set from 6 decimal places as used in the SCm display (on line 182) to no decimal places for the angle display. Hence the angle displayed is in degrees. The program now selects the interface board and sends the command "A" to the control register. This controls the relay to switch the multimeter to display the SCp value continuously on its display. This is done so that the probe can be checked that it is correctly positioned on the steel and also so that the level control on the front panel of ARR-1 can be reset, if needed, to the correct SCp value of 80 mV (this may have drifted with time and temperature). The program then stops and awaits command from the operator. The readings may be retaken by pressing the R/S button, this returns the program to label 06 and the whole process is repeated.

The programs "WGPIO" and "RGPIO" were obtained from the HP-IL Development Module Manual (see Reference 9). These programs allow the programmer to write and read any of the control registers of the HP-IL intergrated circuit. Thus the handshaking etc. can be set up at will. Some of the commands used by this program are from the HP-IL development and as such will not work if the module is not plugged into the calculator. These commands are a manual way of excecuting HP-IL commands that are normally carried out automatically about the loop. Note that there is an error in the WGPIO program in the manual. After the 0 DDL sequence there should be the commands "0 PT=". Also note that the programs used in this application finds the required device identification from storage register 02 and not by searching all the loop devices as the program does in the HP-IL Development Module Manual.

2.4 ARR-1 Performance Summary.

In general the equipment worked well, but there were a few problems which needed to be solved before it would be useful in the field. The first problem was that the equipment was far too slow in obtaining a set of readings. This was due to a combination of factors. Firstly the HP-IL is slow in communicating the messages between the calculator and the other devices on the loop. The calculator is slow in itself because it is not dedicated to the task in hand. The method used by the program in getting the $\widehat{SCm}$ value is slow (i.e. finding the two minimums and two maximums, then the difference between them) and the frequency used by the oscillator is low, hence the time constants used in the filters was long (these were also conservatively designed). This led to a time taken between readings of around 90 seconds. This was considered to be too long.

Another problem with ARR-1 was that the direction of principal stress was given relative to the probe starting position, and the sign of SCm was changed to say whether or not it was tensile or compressive. This method was very confusing to use. Also the assumption that a correct stress measurement should have two maximum and two minimum SCm values was not found to hold for all stress measurements. Thus a different approach to getting $\widehat{SCm}$ was needed.

Other minor problems encountered were; the probe design did not allow for easy manufacture, the equipment was bulky and expensive (due to the use of commercial equipment in the design) and the excitation oscillator did not have a very stable amplitude. These problems were eliminated by redesigning the equipment and the control program into a field prototype called ARR-2.

CHAPTER 3

AUTOMATIC ROTATION RIG 2

3.1 Introduction to ARR-2.

ARR-2 (Automatic Rotation Rig number 2) was designed to solve some of the problems with ARR-1 (as described previously) and make it more suitable for field operation. The electronics design was changed (see Figure 3.1) by using a JED STD 800 CMOS computer board as the controller. This allowed the slow HP-IL loop to be removed, along with the digital multimeter (this being replaced by amplifiers for SCm and SCp and the A to D convertor on the JED STD 800). The results from each stress reading are displayed to the user of ARR-2 by a LCD display (JED STD 860) and information from the user is fed to the JED STD 800 via a keypad mounted on the front panel (see Figure 5.1).

The stepper motor is driven in a similar manner to that used on ARR-1, using a SAA 1027 stepper motor driver. The probe layout is similar to that used in ARR-1, but it is more refined (this is described in more detail in Chapter 5). The electronic circuits were redesigned to complement the JED STD 800. One of the major changes from ARR-1 is the excitation oscillator circuit.

The main problem with the excitation oscillator used in ARR-1 was that it did not produce a very stable in amplitude sinewave. This was due to the diodes in the feedback network varying their forward voltage drop with temperature. A stable amplitude sinewave is needed so that the voltages detected by the SCm and SCp coils only reflect the stress value in the steel and the airgap between the probe and metal surface respectively. A search was undertaken to try and find a circuit that had a stable amplitude. It was found that all the circuits investigated were designed to be stable in frequency but not in amplitude. The oscillator for this device does not need to be particularily stable in frequency because this only effects the depth of penetration of the excitation flux into the steel. This will not affect the SCm readings to any great extent.

In order to have an oscillator that was stable in amplitude, the following circuit was developed. A sinewave was converted into 8 bit binary words with each word representing the value of the sine function at a particular angle. These words were stored in a 2K EPROM (a 2716). Thus each value represents the sine value at 360/2048 degree increments. Each of these values is fed in turn to a D to A convertor. The whole 360° being stepped through continuously by a 12 bit counter. The counter is clocked by a "3 CMOS inverter" clock circuit.

The frequency of oscillation of the excitation oscillator was increased to 144 Hz. This frequency is not critical as long as it is not a harmonic of 50 HZ (this would be 60 Hz in the case where this is the mains supply frequency) as this may make the signal processing of ARR-2 susceptable to noise from the mains.

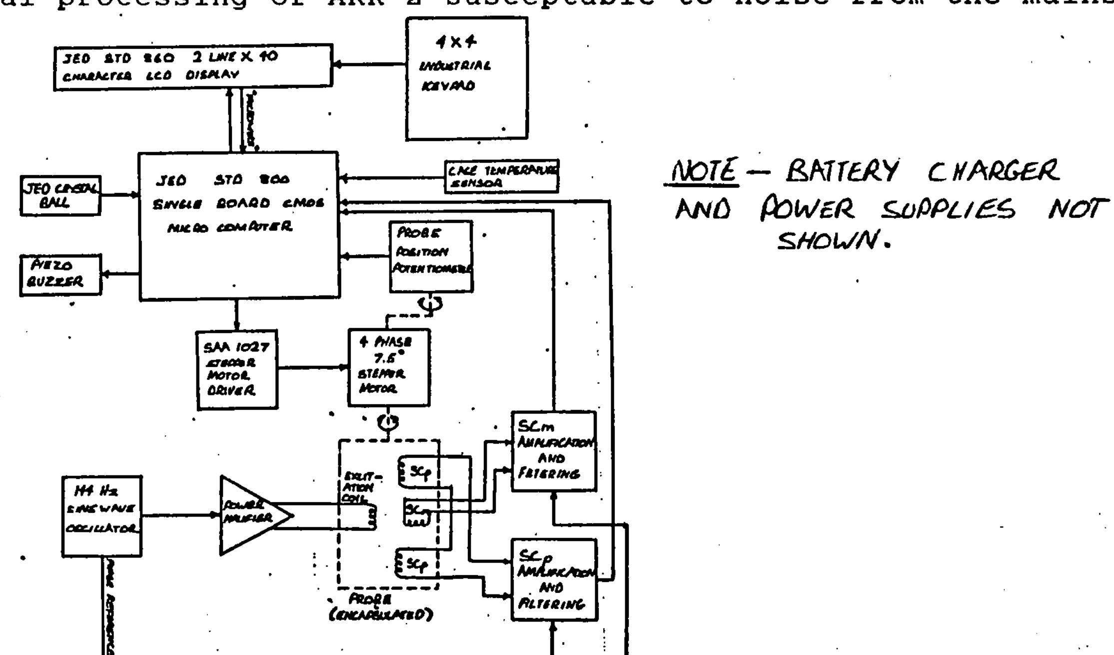


Figure 3.1 ARR-2 Schematic.

The reason for the frequency increase was to allow for shorter time constant low pass filters in the signal processing. This allows ARR-2 to measure the stress in the steel faster.

3.2 Electronics Design.

The complete circuit diagrams for ARR-2 are shown in Appendix E (b). In order to simplify the description of the circuit used for ARR-2, it has been seperated into sections. These are described following:

3.2 (a) Oscillator Circuit.

The complete circuit for the oscillator is shown on drawing 1 sheet 3 (Appendix E (b)). To aid the description of this circuit it has been seperated into further "building blocks". Each of these will be described along with a corresponding circuit.

The circuit used for the clock to derive the counting signal for the EPROM is a simple "three CMOS inverter" clock circuit as shown in Figure 3.2. The capacitor and 180Ω resistor values were obtained by experiment to give the correct output frequency of 144 Hz from the sinewave oscillator. The 82 kΩ resistor is a standard design value for this circuit. In order to aid the frequency stabillity of the circuit, although this is not that critical in this application, metal oxide resistors and a polyester capacitor were selected. The output of the clock is buffered by three CMOS inverter gates in parallel to give the required fan-out conditions for driving the following TTL gates.

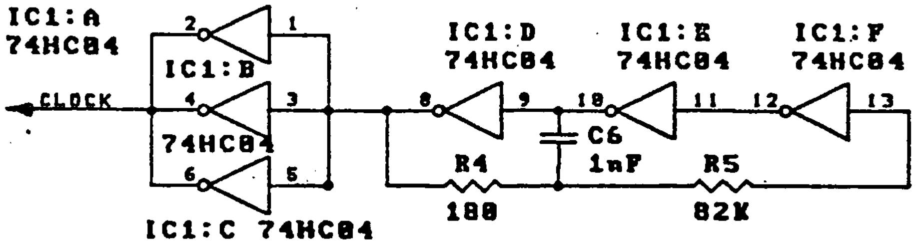


Figure 3.2 CMOS clock circuit.

In order to address all the memory of the 2716 EPROM (2K) then an eleven bit address word is needed. To give continuously changing consecutive address words, then the output of three cascaded 4 bit synchronous counters are fed into the address lines of the EPROM. The counters run continuously and count from 000_{16} to FFF_{16} without resets. They are wired to count up. The circuit used is as per the Signetics Logic Data Book (see Figure 3.3 and Reference 2).

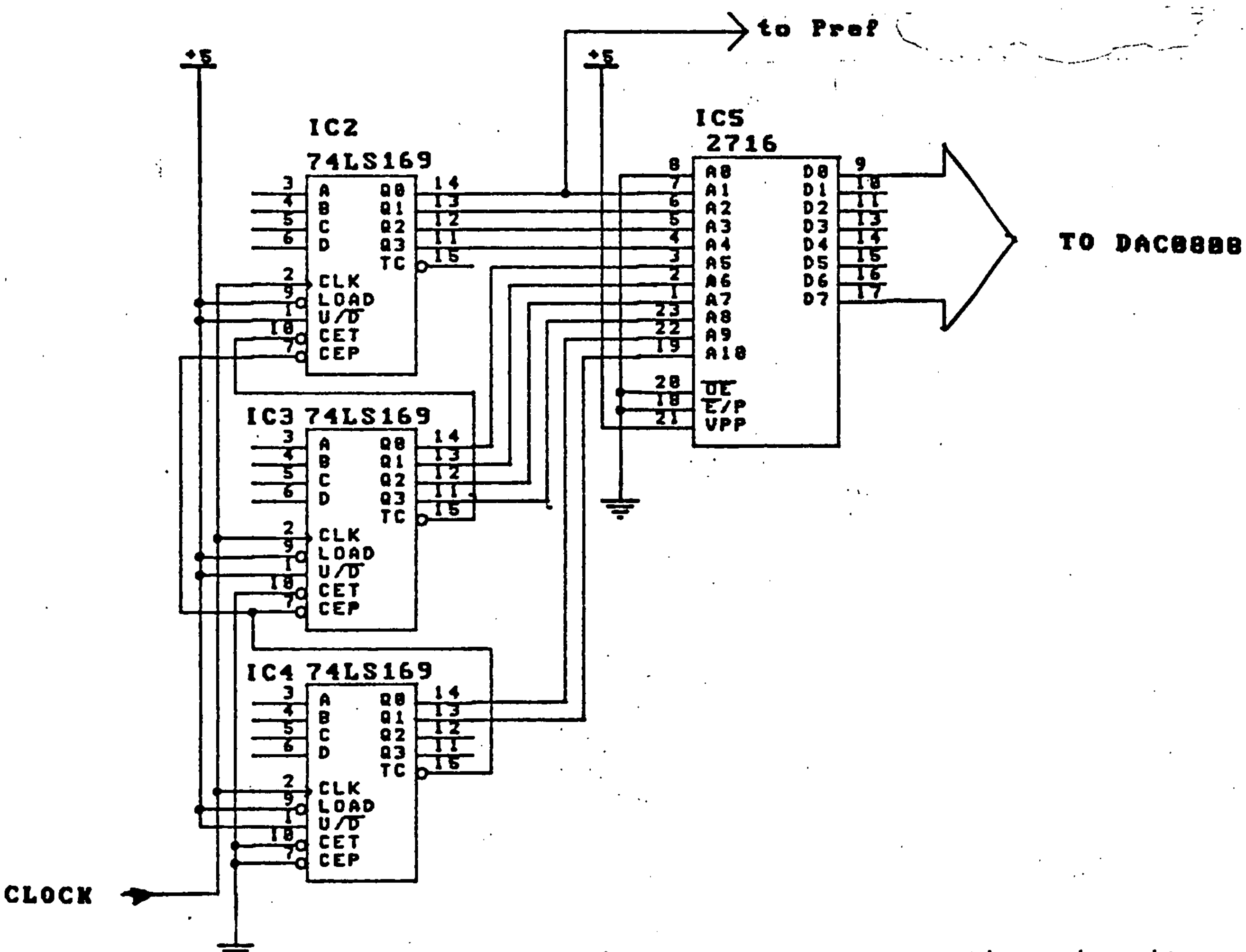


Figure 3.3 EPROM counting circuit.

Because the original oscillator was going to be operating at 80 Hz, but was later changed to 144 Hz (after the EPROM had been programmed), then the addressing for the EPROM was changed so that only every second memory content is addressed (by connecting A0 to ground). This was done so that the access time of the EPROM was sufficient to allow correct operation of the oscillator at the higher output frequency. This means that the counter circuit needs only 10 bits instead of eleven. Hence if three, 4 bit synchronous counters are cascaded, then no reset circuitry is needed when the counters reach a terminal count. This simplifies the circuit and allows the counters to run continuously.

Because there are only ten address lines needed for the EPROM and there are twelve output lines from the counter circuit, only the ten least significant bits are connected to the EPROM. When the counter counts past $3FF_{16}$. the counter output, as far as the EPROM is concerned, returns to 000_{16}. This cycle is repeated three more times before the counter actually returns to 000_{16}. This has no effect on the addressing of the EPROM.

The EPROM is programmed with the binary equivalent of a sinewave with an amplitude of FF hex. (see Appendix E for the EPROM hex dump). Thus -1 and 1 equate to 00000000_2 and 11111111_2 respectively. One wavelength of the sinewave occupies 2048 bytes. The contents of the EPROM are "phase shifted", i.e. the zero crossing of the sinewave does not start at address 000_{16}. This has been done to counteract the effect of the phase shift caused by the probe. When the probe is placed onto a metal surface, there is a phase shift between the excitation signal and the detected SCp and SCm signals. Because the phase sensitive filters derive their timing from the oscillator circuit, then some allowance must be made for this phase shift, in order to obtain the maximum signal output from the filters.

The timing, or phase reference signal, is obtained from the oscillator circuit via the A_{10} address line from the counter circuit. This signal has the same period as the 144 Hz oscillator output and as such makes an excellent phase reference for the filter circuit. By shifting the addresses of the contents of the EPROM, there will be a phase shift between the phase reference signal and the excitation signal. The amount of phase shift neccesary was determined by placing the probe on a steel surface with an "un-phase-shifted" EPROM in the oscillator circuit and looking at the resultant signals detected from SCp coil on an oscilloscope. The phase shift was noted and then transfered to the EPROM contents by noting that 360° is equal to 2048 bytes of memory.

The digitised sinewave output from the EPROM is fed into a DAC 808 Digital to Analogue (D to A) convertor. This is connected in the usual manner (see Reference 16) and has a buffer amplifier connected to its output (see Figure 3.4). The reference voltage for the D to A converter is set to 5 V DC. This gives an analogue sinewave output between +5 and -5 V DC. The buffer amplifier is a FET input operational amplifier.

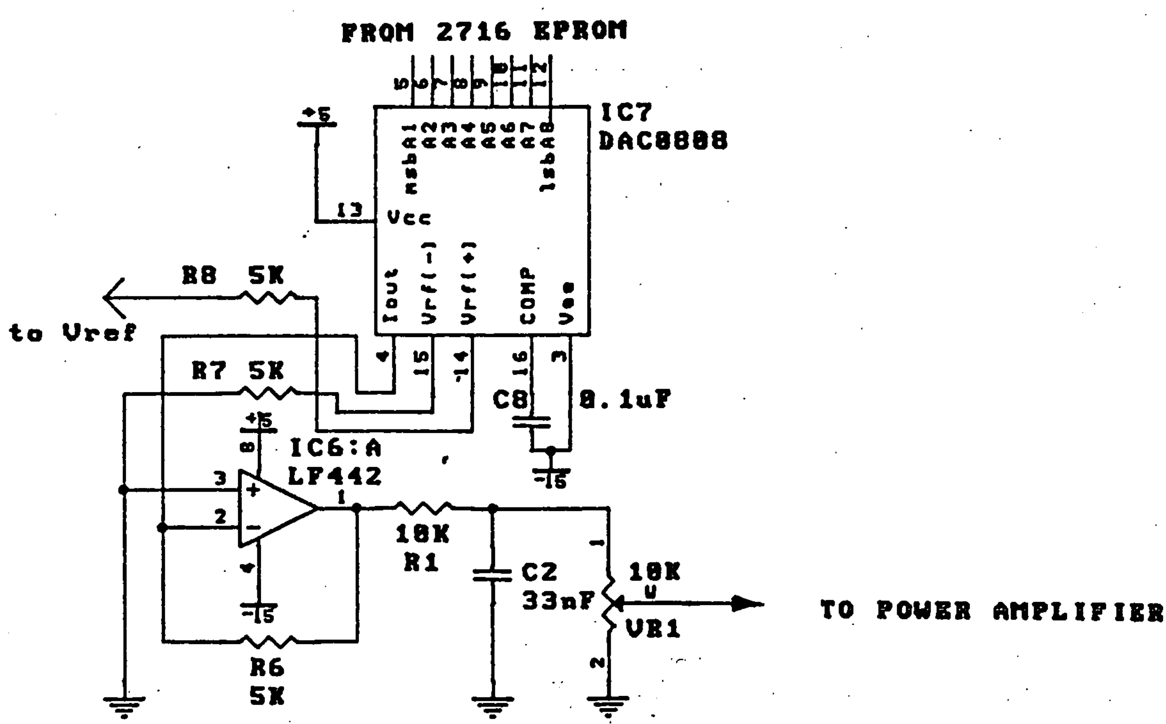


Figure 3.4 D to A Convertor Circuit.

The output of the amplifier is filtered (to remove the quantised steps on the D to A output) using a single stage low pass filter. The choice of cut off frequency for this filter is not critical since the sinewave is made up of 1024 steps. This means that to filter out these steps the cut off must be somewhere above the fundamental of 144 Hz, but less than the frequency of the CMOS clock. Hence a value of 500 Hz was chosen. This filter is realised by a 10 kΩ resistor and a 33nF capacitor.

The power amplifier used to drive the excitation coil in the probe is a simple single ended supply circuit using a commonly available 1/2 watt audio amplifier, the LM380 (see Figure 3.5). The bypassing is needed to stop the amplifier oscillating at around 1 MHz. The power supply is decoupled by a 4.7Ω resistor in series with the 12 V DC supply and a 0.1 μF capacitor to ground. The 4.7Ω resistor also acts as a current limiting resistor if the output becomes short circuit. The power amplifier is capacitivly coupled to the oscillator output via a 0.1μF capacitor.

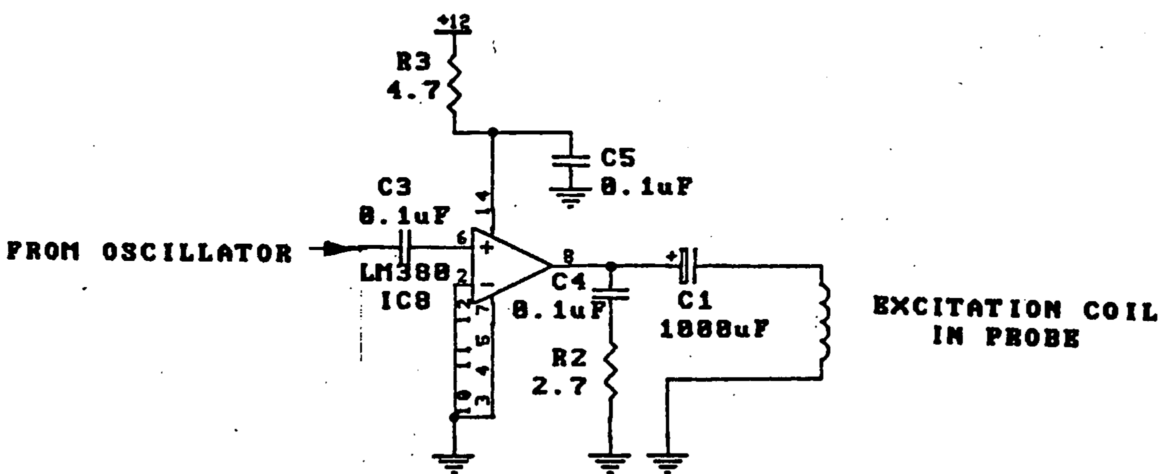


Figure 3.5 Power Amplifier Circuit.

To prevent the output of the oscillator from saturating the amplifier, a level setting potentiometer is connected as shown (see Figure 3.4). The level is set so that the point of saturation of the output of the power amplifier is not quite reached.

The excitation coil in the probe was designed (by Richard Langman) so that its impedance at 144 Hz is close to the output impedance of the LM380 amplifier. This is approximately 8Ω. The excitation coil is fed by twisted pair.

3.2 (b) SCm Preamplifier.

The SCm signal preamplifier was designed to amplify the small voltages that are induced in the SCm coil due to the magnetic anisotropy of the steel sample under examination. These voltages are of the order of 10's to 100's of microvolts.

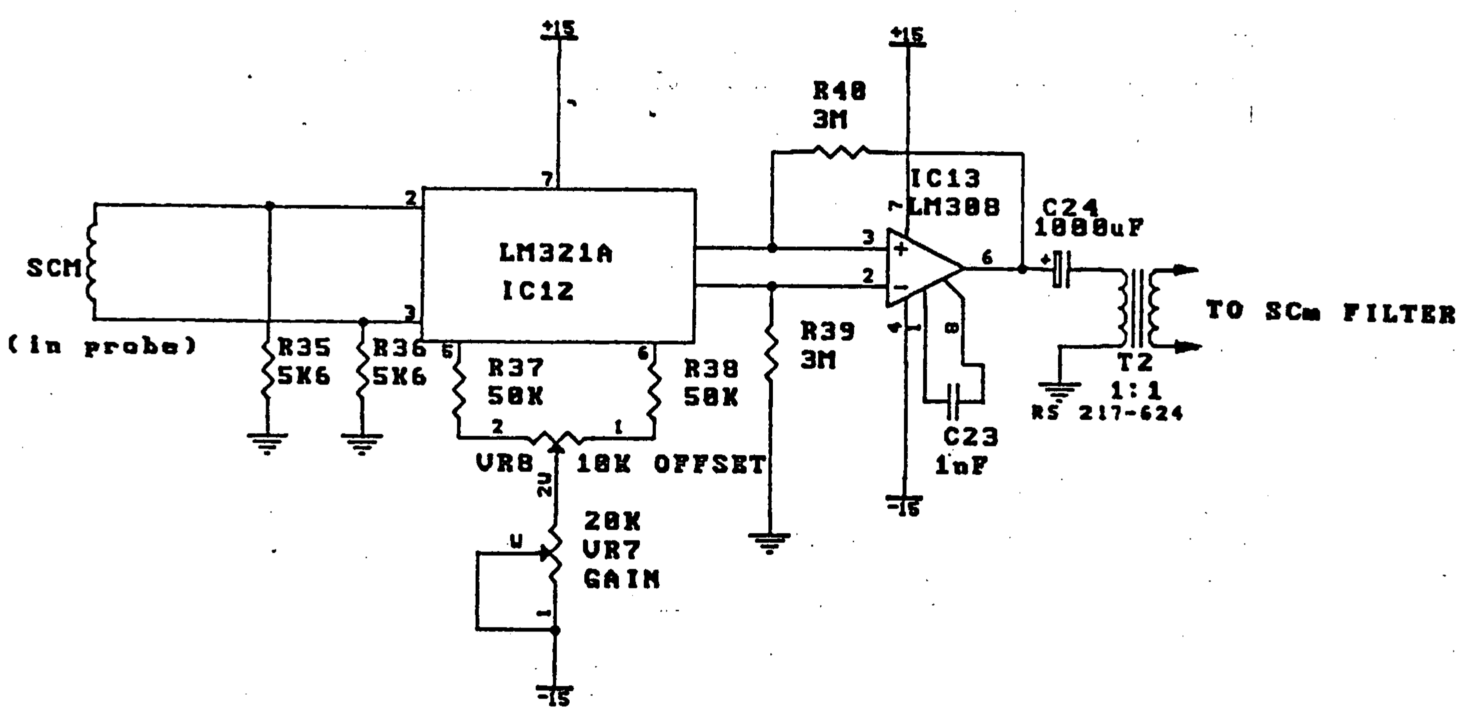


Figure 3.6 SCm Preamplifier Circuit.

The SCm signal preamplifier circuit uses a LM321 differential current amplifier, coupled to a LM308 operational amplifier (see Figure 3.6). The gain of this instrumentation amplifier is 1000 (this amplifier design is based on the instrumentation amplifier in application note AN79, Reference 19). The differential input from the SCm coil is shunted to ground by two 5.6 kΩ resistors. These were included in the circuit in order to give a reasonable load for the SCm coil to "look into". These values were chosen by experimentation by looking at the noise level at the output of the LM308. The actual values of the resistors were not found to be critical, but the noise output for the amplifier was generally better for resistor values that were several times larger than the impedance of the SCm coil (approximately 1 kΩ).

The LM321 can be adjusted by trimmer 10 turn potentiometers for gain and DC offset. The gain of the amplifier was set to its maximum value (1000 times amplification). The offset adjustment does not really do any thing because the amplifier is AC coupled to the following stage, but when there are large signals present at the input of the amplifier, then the offset adjustment can be used to allow an equal amount of clipping at the output. This means that large amplitude input signals may be able to be amplified without any clipping at all. The 3MΩ resistors, used in the amplifier to set the gain, need to be 1% tolerance and have good temperature stability. These resistors were purchased as voltmeter shunts. In order to help the temperature stability and the resistance to interference of the amplifier, it was enclosed in its own seperate aluminium box.

In order to make the single ended output of the instrumentation amplifier a differential one, for the phase sensitive filter that follows, the output was fed through the 1000μF capacitor to AC couple it to a 1:1 audio transformer. The output of this transformer is thus a differential signal.

3.2 (c) SCm Filter.

In order to seperate the low level SCm signal from the noise, it is filtered using a phase sensitive filter. This filter actually full wave rectifies the SCm signal at the same frequency and phase as the excitation signal. This rectification is achieved by alternately switching each of the differential lines to a voltage reference and connecting the other one to the output low pass filter. The switching is done by a 4016 quad CMOS switch (see Figure 3.7). This method of filtering is very effective because it will only pass the fundamental (144 Hz) and odd harmonic frequency components of the oscillator, in the detected SCm signal. All other signals being averaged to a zero voltage signal over the switching period of the filter. The output of the phase sensitive filter is further filtered by a single stage low pass filter. The time constant of this was chosen to be a compromise between the ability to smooth the fundamental frequency component of 144 Hz and rate of change of the SCm value as the probe is rotated whilst on a stressed steel surface. This allows the filtered SCm output to settle to its true value before it is read by the JED computer board (via the onboard A to D convertor). Thus the time constant of the low pass filter was chosen to be 0.01 S.

The filtered SCm voltage can be positive or negative depending on its phase relative to the phase reference signal. In order for it to be converted to digital word by the A to D convertor it needs to be between 0 and 5 V. The 2.5 V DC reference line on the JED board (used as a reference for the A to D convertor) was used as the voltage reference for the phase sensitive filter. Thus positive SCm voltages are above 2.5 V and negative ones are below 2.5 V. As the A to D converter uses 10 bits then the voltage of 2.5 volts relates to a decimal value of 512 (i.e 0 V = 0 and 5 V = 1024)

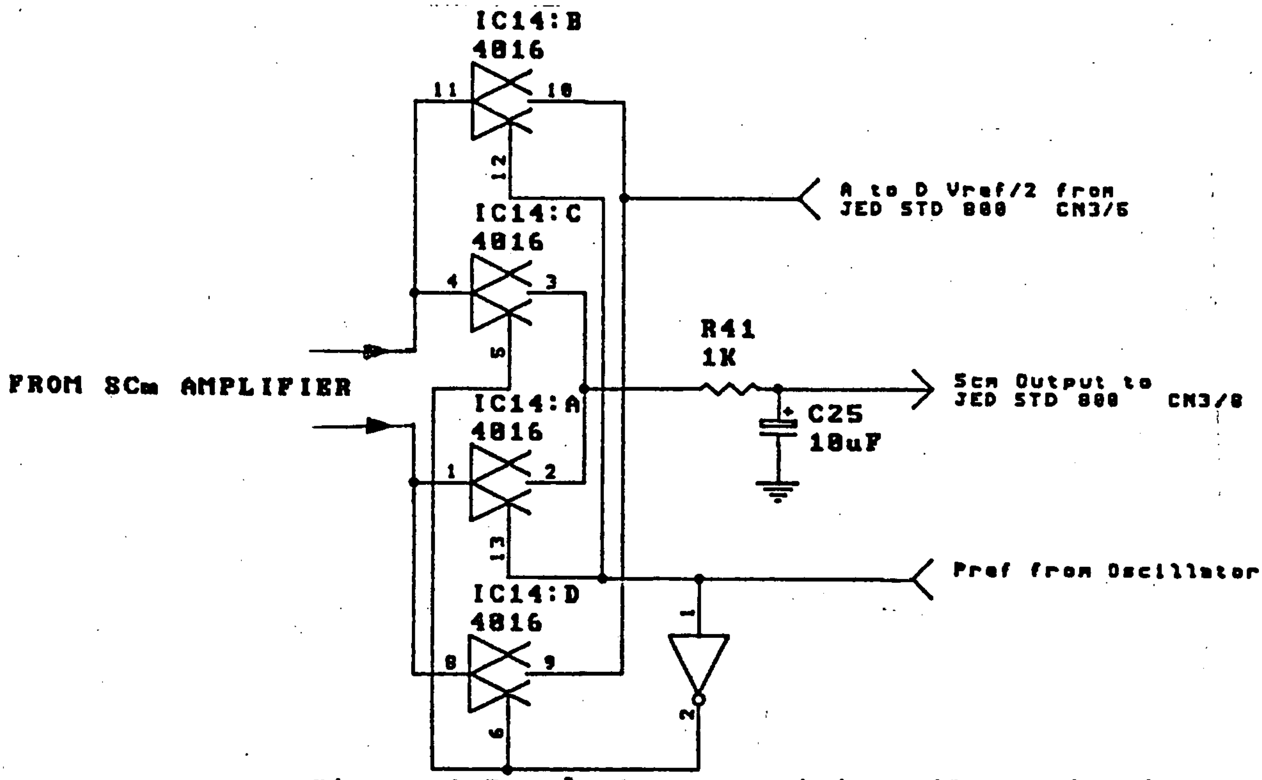


Figure 3.7 SCm Phase Sensitive Filter Circuit.

3.2 (d) SCp Amplifier.

The method used for amplifying the SCp signal is similar to that used for the SCm signal. Because the level of the SCp signal is greater than that of the SCm signal, not as great a level of amplification is needed. The required amplification was achieved by using a MC1733 differential amplifier (see Figure 3.8). This allows the differential, amplified signal to be fed directly to the phase sensitive filter.

The differential inputs from the SCp coils are shunted to ground by two 1 kΩ resistors. This is done to help reduce the noise input to the amplifier. The value of these resistors are not critical. They were chosen because they are several times greater than the impedance of the SCp coils (which are connected in series). As the input impedance of the MC1733 varies with temperature (see data sheet in Reference 1), then the 1 kΩ resistors also give a reasonably constant input impedance for the SCp coils to look into. The gain of the differential amplifier was set to the maximum value before clipping. This was achieved by the use of a 110-Ω resistor connected as per the data sheet.

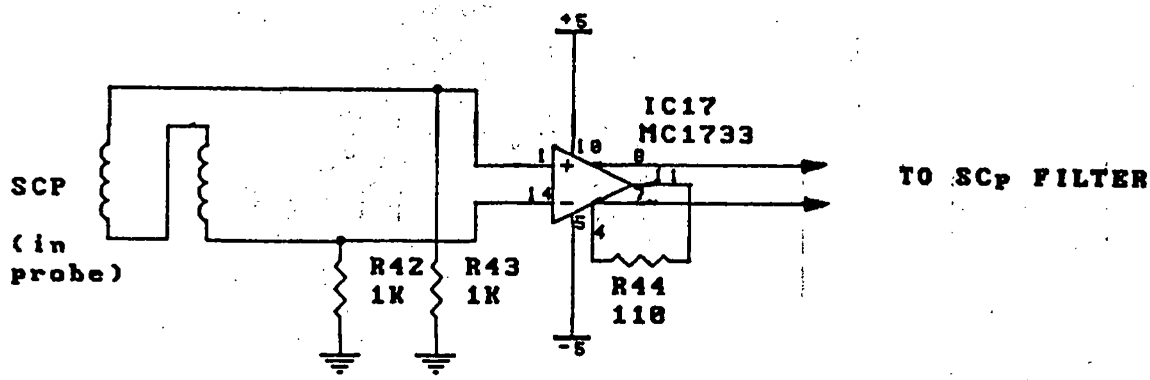


Figure 3.8 SCp amplifier circuit.

The amplifier circuit worked perfectly on the bench, but in the completed instrument it worked, but not up to expectations. There was a reasonably large change in the SCp signal as the probe was placed from air to a steel surface, but the output of the differential amplifier did not show the same amount a change. The only explanation for this is that the signal contained some common mode components which were not amplified by the MC1733. The source of this effect is not known. The resultant variation of SCp between air and steel was just acceptable with a resolution of 0.1 mm (approximately normal paper thickness) between the end of the probe and the surface of the steel being measurable. More resolution in the SCp signal would be benificial.

3.2 (e) SCp Filter.

The SCp amplified signal is filtered in the same manner as the SCm signal, using a 4016 quad CMOS switch which is switched by a phase reference signal from the excitation oscillator (see Figure 3.9). The SCp signal is arranged during the wiring up of the probe so that the output from the filter is always positive. This allows the voltage reference for the filter to be connected to the electrical ground. Thus the signal fed to the A to D convertor on the JED board is an arbitrary voltage related to the distance (airgap) between the end of the probe and the surface of the steel. The signal was calibrated during the setting up of ARR-2 using paper spacers under the end of the probe. The SCp signal can then be used to correct for the loss in sensitivity of the SCm signal as the airgap is increased, due to such effects as paint, grease or corrosion on the steel surface.

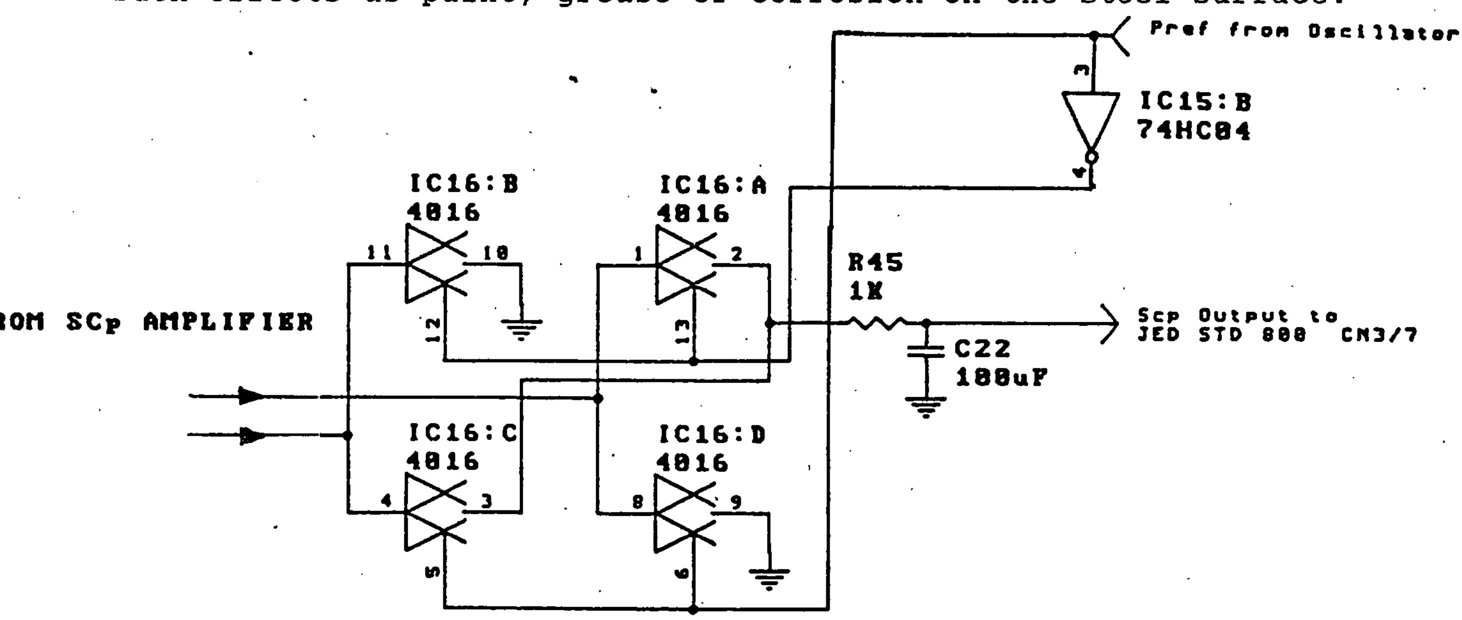


Figure 3.9 SCp filter circuit.

Because the SCp signal does not vary very much as the probe is rotated, then a slower time constant (0.1 S) was chosen for the low pass filter on the output of the phase sensitive filter. This means that the time constant is much longer than the period of the 144 Hz excitation signal. Thus the ripple on the SCp signal fed to the A to D convertor is small.

3.2 (f) A to D Scaling.

Th ARR-2 control program needs to know the angular position of the probe, so that it can control it properly. To do this a 10 kΩ 360° rotation servo potentiometer is attached to the shaft of the stepper motor. This potentiometer is designed for use in servo-mechanisms and has very good linearity (better than 1%). 5V DC has been placed across the potentiometer and the wiper voltage is scaled for use by the A to D converter by a 10 turn potentiometer to ground. This gives a voltage for the A to D convertor which is less than 5V, and is proportional to the angular position of the stepper motor (see Sheet 2, Appendix E (b)). The 10 turn potentiometer is set so that when the probe is at its maximum rotational travel then the A to D convertor output is a numerical value of 1000.

So that the battery voltages can be read by the A to D convertor they need to be scaled to a voltage below 5 V DC. This was achieved by a voltage divider network as shown in Figure 3.10. The potentiometer is adjusted so that the output number from the A to D convertor is half the actual voltage of the batteries (between 11 and 14 volts). This is done because the JED XTBasic language (see Reference 3) only allows the use of integers. To be able to display the battery voltage for the user, the A to D output will only need to be multiplied by 2. The battery voltages are also used by the control program to warn the user of ARR-2 of flat batteries, as this condition may adversly affect the operation of ARR-2.

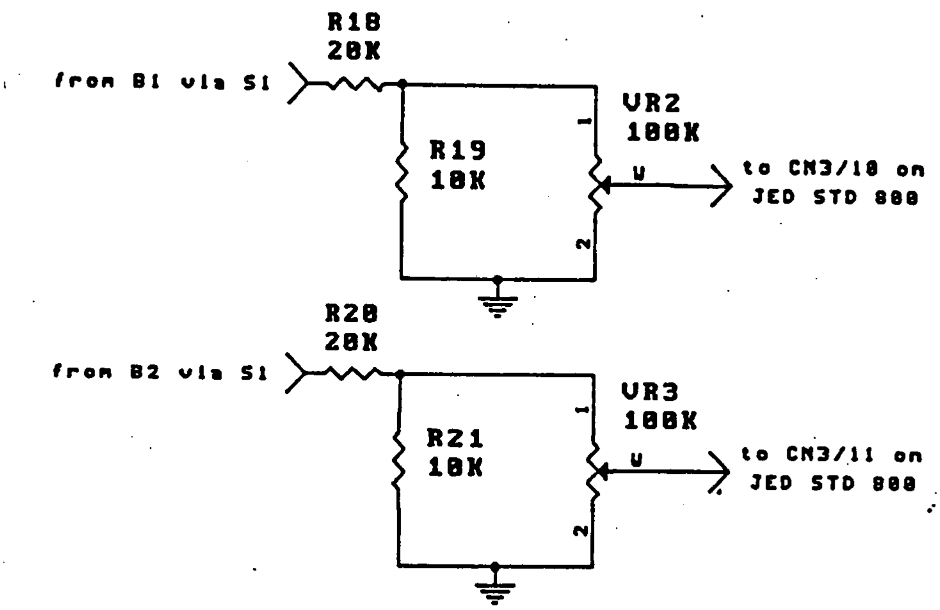


Figure 3.10 Battery Voltage Scaling.

3.2 (g) Piezo Audio Warning Device.

To warn the operator of ARR-2 of incorrect operation, flat batteries or if readings have been taken, then an audible warning is given. This is a simple piezo-electric buzzer which is turned on and off by a transistor switch driven by a square wave from the JED board (see Figure 3.11). The frequency of the squarewave sets the audio frequency eminating from the buzzer. The piezo buzzer is supplied by 12 V D C and has a 10 kΩ resistor connected across it, to help the transistor turn on. This is because the piezo does not draw enough current initially to allow the transistor to turn on effectively. To protect the buzzer, it was mounted inside the case. This reduced the sound level considerably, but it was found to be still audible in most normal situations.

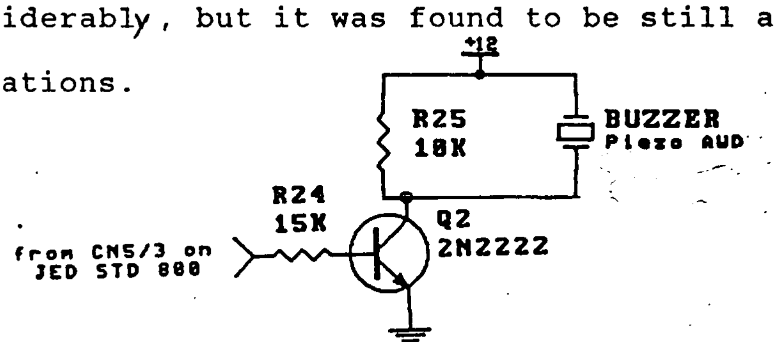


Figure 3.11 Piezo Buzzer circuit

3.2 (h) Temperature Probe.

During the development of ARR-2 it was discovered that the effective operating range of the device was from about 0° C to 70° C. Temperatures outside this range tend to affect the calibration by more than 3%, which was deemed to be unacceptable. In order for the operator of the device to check if the temperature of the device is outside this range, a temperature probe was incorperated into the chassis, to enable the control program to read the temperature. This was achieved by using a RS 590h temperature probe (see Reference 5) which passes 1μA of current for every degree Kelvin of temperature. Thus if the probe is fed with 12 V and is in series with a 10 kΩ resistor (see Sheet 2, Appendix E (b)) to ground, then the resultant output voltage at a temperature of 25° is 2.982 V. This voltage output across the 10 kΩ resistor is read by the A to D convertor. The A to D convertor output was calibrated by measuring the ambient temperature at two different values and noting the A to D outputs at these temperatures.

It was found in practice that the probe did not seem very reliable in giving the correct temperature (this was noted by the ROA after ARR-2 was used in the field). The reason for this is not known. The enclosed case does have a long thermal time constant and can also be heated by external sources such as the Sun if it is outside (the colour of ARR-2 being matt grey and green not helping this effect) and internal sources such as the battery charger (could be up to 20 W) and the electronics (10 W).

3.2 (i) Battery Charger.

The battery charger circuit was originally from a National Semiconductor Data Sheet (see Reference 17). It has been modified to allow for the charging of two lead acid sealed batteries (the original design being for a single battery with a much lower capacity). The battery charger circuit can be seen on Sheet 1, Appendix E(b). The batteries for ARR-2 were chosen to be 12 V 6 A-h Lead Acid "gel" cells. These are sealed and can be charged and operated in any position. The capacity of 6 A-h was chosen to give a continuous operating time of ARR-2 of 8 hours (see the graph of battery voltage versus operating time in the ARR-2 operators manual, Appendix A). The batteries are arranged so that one battery supplies the stepper motor and the other supplies the JED computer board and the rest of the electronics. This was done to minimise interference to the electronics from the stepper motor, when it is stepped. This interference is most prevalent as voltage spikes on the output of the filters. The noise transfer via the supplies is eliminated by using the seperate battery arrangement. In order to allow the batteries to be charged from a single battery charger supply, but not be allowed to discharge back through the battery charger or to the other battery, two diodes have been connected in series between each battery and the battery charger output. In order to prevent excessive current being passed into the batteries when they are flat, two current limiting resistors are also connected in series with the diodes. These prevent damage to the batteries or the battery charger if the batteries have a terminal voltage of less than 10 V. Their values were calculated by the following method:

Flat battery terminal voltage = 10 V
Maximum charging voltage = 15 V

Therefore voltage drop across resistors = 5 V

Maximum charging current = 1.5 A

Therefore resistor value = 5/1.5 = $\underline{3.3\,\Omega}$

To be on the safe side choose 5.6Ω resistors.

Check power rating of resistor,

$$P = 5*5/5.6 = \underline{4.46\ W}$$

Therefore use 5 W resistor.

In order to prevent any damage that may occur if the battery supplies are shorted to ground, the positive terminals have 3A in line fuses, mounted as close as practical to the batteries.

The battery charger is of the "constant voltage" type which is the method recommended for sealed lead acid batteries. It incorperates two charging levels, "float" charging and "boost" charging. The charging rate is automatically set by the battery charger. If the batteries are flat then the charger detects the large current flowing into the batteries and sets the charging voltage to the high value. As the batteries are charged, at constant voltage, the current into them drops. When this current drops below a certain value, the batteries are deemed "charged" and the output voltage of the battery charger drops to allow the batteries to be trickle charged.

The difference between the battery terminal voltage and the battery charger output voltage sets the charging current for the battery. The output voltage was set at 15 V for boost charging (the maximum recommended charging voltage for this capacity battery). Hence the output voltage from the battery charger needs to be 15.8 V for the boost charge mode (to allow for the voltage drop across the diodes). In trickle charge mode, in order to maintain the charge in the battery, the output from the charger needs to be 14.4 V. Hence the output voltage from the voltage regulator needs to be 15.2 V.

In order to switch automatically from boost charge to trickle charge, the following circuit is used (see Figure 3.12)

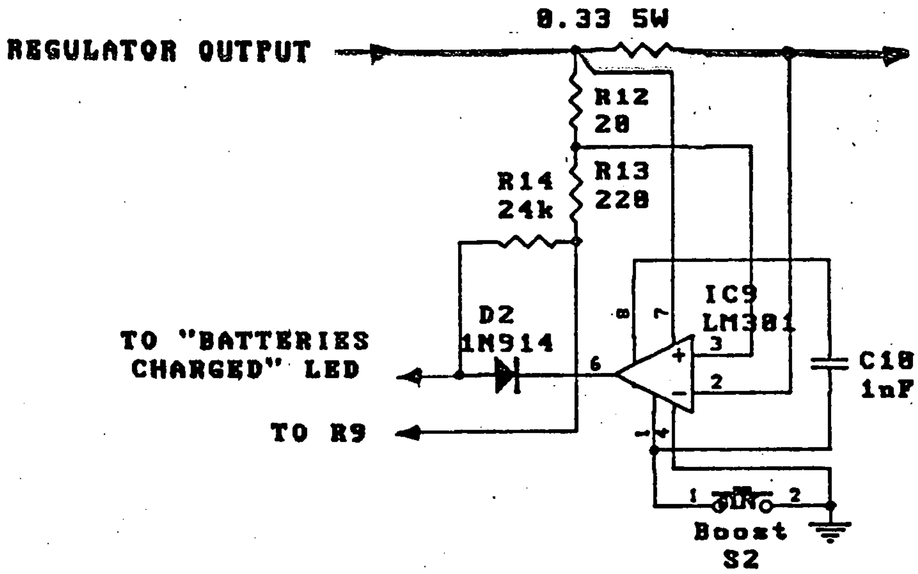


Figure 3.12 Charge rate switching circuit.

The operational amplifier detects the voltage drop across the 20Ω and 0.33Ω resistors and hence measures the current drawn by the batteries. The voltage drop across the 0.33Ω resistor providing the current information and the 20Ω resistor giving some hysterisis to the op-amp and also making the input to the op-amp less than its supply voltage. The supply to the op-amp is derived from the output of the LM 317 voltage regulator. The output of the op-amp is used to change the voltage output of the regulator and also to switch a PNP transistor which is used to turn on a LED indicator mounted on the front panel of ARR-2. This indicates whether or not the batteries have been charged sufficiently and are being trickle charged. The voltage regulator output voltage is controlled by the circuit shown in Figure 3.13.

When the output of the voltage regulator is high, the output of the voltage regulator is set by the 2.7 kΩ and 100Ω resistors in series to ground. This gives, in the usual manner as described by the data sheets for the regulator (see Reference 1) an output from the regulator of 15.8 V.

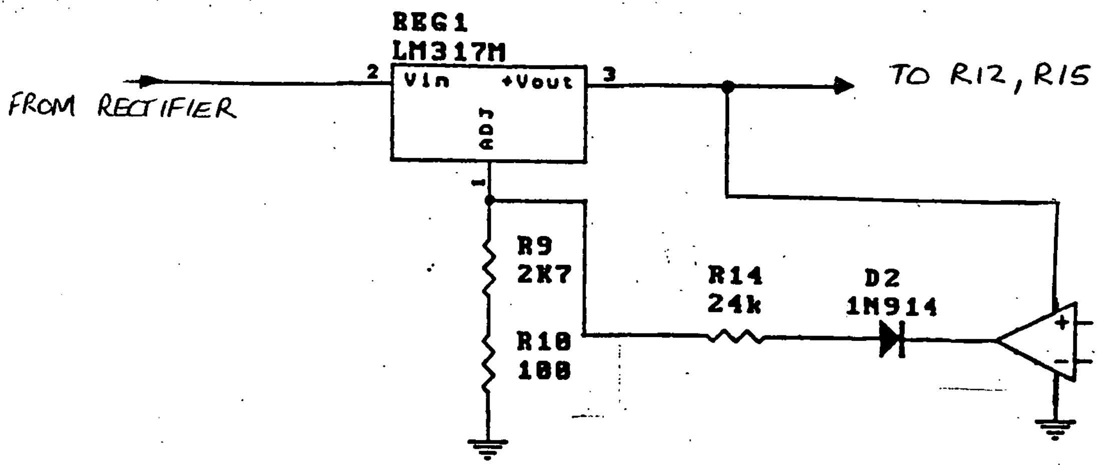


Figure 3.13 Regulator voltage control circuit.

When the output of the op-amp is low then the 24 kΩ resistor is connected in parrallel with the 2.8 kΩ resistor (made from the 2.7 kΩ and 100Ω resistors in series). The 24 kΩ resistor was chosen by experiment to give the required output voltage from the regulator when in trickle charge mode. The 1N914 diode prevents current flow through the 24 kΩ resistor when the output of the op-amp is high.

If the batteries are nearly fully charged, and ARR-2 is turned off and connected to the mains, then due to the hysteresis in the battery charger circuit and the small current being drawn by the batteries, the charge rate selected may be the "trickle" charge rate. Because it may be desired to "top-up" the batteries (so that a complete working day of operation may be extracted from ARR-2), a "boost charge" pushbutton switch is mounted on the front panel of ARR-2. This allows the operator to manually select the boost charge rate. If the batteries are indeed charged then the battery charger will automatically revert back to trickle charging the batteries.

The input and output of the voltage regulator are filtered in the usual manner. The supply for the battery charger is derived from the 240 V AC mains in the same manner as that used in ARR-

1.

In order to provide a 5 V DC supply for the JED STD 800 computer board and the logic circuits used in the Oscillator /Filter sections, a 7805, 1.5A, 5 V DC voltage regulator is connected in the usual manner (see Sheet 4, Appendix E (b)). To prevent an excessive voltage drop across the 5 V regulator, and hence cause excessive heat dissipation, a 4.7Ω 5W resistor is connected in series with the voltage regulator and the 12 V DC supply from the battery. Thus heat is dissipated in the resistor and not in the voltage regulator. This prevents the thermal protection in the voltage regulator from shutting down the regulator at elevated ambient temperatures. The filtering of the regulator is as recommended in the data sheets (see Reference 1).

In order to allow correct shutdown of the JED STD 800 board when ARR-2 is turned off, a 10000μF capacitor is connected between the 5 V supply and ground. This holds the supply up long enough for the JED monitor program to run through the correct shutdown sequence (as initiated by the "crystal ball", see Reference 3).

To give a +/- 15 V supply for the SCm amplifier and a -15 V supply for the D to A convertor used in the excitation sine wave oscillator, a 5V DC to +/-15V D.C. convertor is used (see Figure 3.14). This was chosen to be a RS 591-304 from Reference 5. Additional filtering of the converter was incorperated as the output voltages were found to contain large amounts of noise, generated by the convertor itself. The commponent values for the L-C filtering on both the input and output rails were determined by Mr. John Grace, through experimentation. These values were found to suitable for this application. So that the positive supply draws enough current to keep the convertor stable a 1kΩ resistor is connected from it to ground. This means that 15 mA is always drawn from this supply.

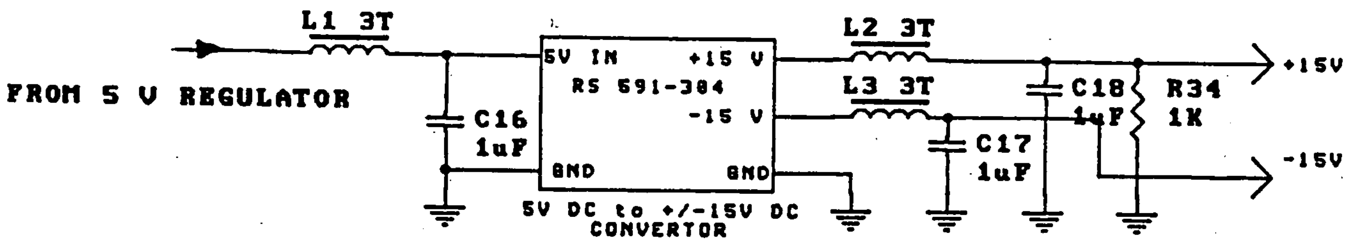


Figure 3.14 +/- 15 V supply circuit.

To give a -5V DC supply for the MC1733 differential amplifier for the SCp signal, a -5 V D C regulator (79L05) is connected to the -15 V output from the RS 591-304 DC to DC convertor. The positive supply for the MC1733 derived from a 78L05 connected to the 12 V battery supply. This supply is also used as the reference voltage for the D to A convertor used in the excitation oscillator. This was kept seperate from the main +5 V DC regulator in order to help reduce interference. The reference voltage for the D to A convertor is set using a 10 turn, 10 kΩ potentiometer to ground (see Sheet 4, Appendix E(b)).

3.2 (j) Stepper Motor Drive.

The stepper motor driver (see Figure 3.15) is the same as that used for ARR-1, except for the following changes; (a) the reset line is not connected to the positive 12 V DC supply, but can be controlled by the JED STD 800 computer board, (b) all the logic control lines are driven from the FET output port on the JED board and as such only require pull-up resistors to enable conversion between 5 V logic and 12 V logic, (c) the flywheel diodes across each of the stepper motor phases have been replaced with a single flywheel diode across the BD140 power transistor used to switch the stepper motor supply on and off (this being done to help save the battery supply).

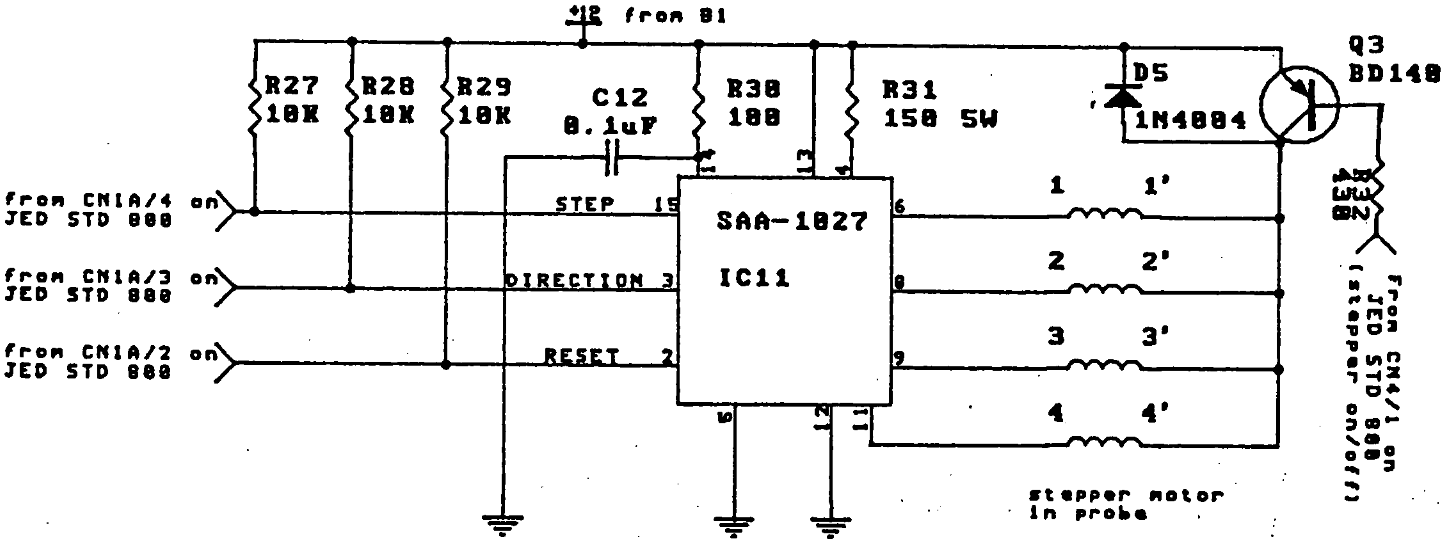


Figure 3.15 Stepper Motor drive circuit

3.3 Probe Cable Design.

The cable connecting the probe to the main chassis of ARR-2 is about 2 m in length. It was specially constructed at the Department of Electrical Engineering and Computer Science, University of Tasmania to reduce the interference between the stepper motor phase supplies and the SCm and SCp pick up wires. The SCp and SCm filters are fed by twisted wire pair from their respective pick up coils in the probe. The twisted pair arrangement was chosen as this reduces the effect of noise picked up on the connecting cable. Any such noise would appear as common mode voltages at the amplifier input. Thus the effect of the noise will be reduced compared to the differential SCm or SCp signal as the amplifiers used have high common mode rejection ratio's.

The excitation signal is fed to the excitation coil via twisted pair. This signal is of reasonably low level and does not interfere with the signals detected by the SCm and SCp coils. Therefore, the three twisted pairs of the SCm, SCp and excitation lines are all enclosed in a continuous, earthed,copper braid sheath. This was obtained by using the copper sheath removed from RG8U coaxial cable.

The five supply lines for the stepper motor, the common line and the four phase lines, are also enclosed in a similar copper sheath. This effectively prevents any inductive coupling between the stepper motor drive lines and the SCp and SCm signal lines. The other wires connecting the probe to the main chassis are for the probe position potentiometer (3 wires, in a twisted trio) and for the "probe connected" resistor. The latter was originally intended to be a temperature probe, but the components for this were not supplied in time for the delivery of ARR-2 to the ROA. Thus the resistor was incorporated instead,as a check to see if the probe is connected to the main chassis via its multipin connector, CN1A. These lines are not affected by the stepper motor drive and as such are not enclosed in a copper braid sheath.

All the wires and sheaths are covered by a flexible PVC outer sheath. The PVC cover was obtained by stripping some large 3 core cable. The lead to the probe was considered to be a weak spot in the design as it is hard to predict the "flex" life of the cable in the field. Up to time of writing the cable has not given any trouble. For a schematic diagram of the cable see Appendix G.

3.4 JED computer Board Connections.

The JED STD 800 computer board was connected to "the outside world" by a 100 way STD connector (see Appendix F) and various "speed block" or IDC connecters. The inter-board wiring schematic is shown in Appendix G. The A to D inputs are fed directly into the multiplexer at port C. The piezo electric buzzer is driven off the counter output at port B. The driver for the software Centronics Printer interface and the other outputs needing FET drivers (i.e. for the stepper motor drive) are connected to port A. The drivers for the stepper motor were chosen to be in the upper part of the 8 bit word from this port so as to avoid cross talk between it and the centronics printer output. Note that the centronics printer option was only included because at the time of construction, the ROA did not know the exact purpose that the device was going to perform. For example, whether or not the device was going to be used to log the data it obtained from specific wheels. This would entail the use of a printer to allow a hard copy of these results to be obtained. In the end, the ROA decided that the project was far too immature to allow use of the device in this manner. This means that this facility is not used, but the ability for it to be used still remains.

The STD 860 LCD display is connected to the JED STD 800 board by the supplied 10-way cable, as per the instruction manual (see Reference 4). The display board also contains the keyboard encoder and this is connected to an industrial keyboard. This keyboard is sealed to IP65 to prevent dirt and water from getting into the switch mechanism and the ARR-2 chassis (the keyboard is a RS 336-630, see Reference 5, for "IP" international protection numbers, see Reference 18).

3.5 Modifications to the JED Board.

For the JED STD 800 computer board to operate correctly it must be connected to, and modified with the use of jumpers. The location of these is shown in Drawing 2, Appendix F. The baud rate of the software RS232 interface is set to 9600 baud. For further information refer to the JED STD 800 operators manual (Reference 3).

Because the JED board may have been used for data logging it is furnished with a memory backup. The probe position potentiometer readings are also stored in RAM. In order to prevent the computer from loosing this information it must be shut down correctly when ARR-2 is turned off. This is done with the use of a "crystal Ball", supplied by JED (see drawing 3, sheet 1, Appendix F). This device looks at the +12 V supply to the electronics, and if this drops below a preset value, it tells the monitor program about the impending event and thus gives it time to store the stack used in the CPU, in the correct manner. This prevents the loss of memory stored in RAM.

3.6 ARR-2 Program Description.

The JED STD 800 computer board has a monitor program known as JMON. It also uses a program language similar to BASIC. This is a simplified form of this language and is called "eXtended Tiny BASIC" or XTBASIC for short. This is not intended for string or full arithmetic handling, but is suitable for control applications. This means that it cannot handle floating point arithmetic, but integer numbers can be printed with decimal points in any position. XTBASIC is easy to program and reasonably fast in operation.

The first thing that the user program does (see appendix C,

(b) for the program listing), is set the strings for the battery warning displays. These are to be displayed on the 20 character by 2 line LCD display mounted on the front panel of ARR-2. On line 10 and 15 we see that the locations for these strings in memory are set to locations %C0A0 and %C0B0. These locations are in RAM and they are HEX locations (the % sign indicates that they are in hexadecimal). The strings E$ and D$ are both set to the same display. This is because later in the program, if the batteries become flat, then one (D$) will be changed to indicate this condition, and the other one (E$) will be cleared. Because the display alternatly displays D$ and E$, then if one is cleared, the display will change from a continuous one to a flashing one.

Line 20 sets up the counters used for the buzzer and the input and output ports. The counter on the JED board is a NSC 810 RAM-I/O-Timer. This device has 1024 bits of static RAM, 22 programable input/output bits arranged in three ports and two independant programmable 16 bit counters, each with 6 modes of operation. These modes are selected by writing the relavent codes to addresses assigned to this device. The mode of operation for this was square wave output mode and was programmed as per the JED STD 800 operators manual (see Reference 3).

The LCD display and keyboard encoder communicates with the JED STD 800 via a 10-way ribbon cable. This is connected to the CN2 connector on the JED STD 800, known as the "microwire" I/O port. This port sends and receives serial data clocked by the CPU. This I/O operates seperatly from the onboard RS 232 interface. The JED JMON monitor version C2 is used for ARR-2 and contains the relavent software needed to drive the LCD display and the keyboard encoder. The following set ups are stored in RAM for use by the control program.

POKE %DFD4,%C5 sets the monitor so that it is communicating with a 2 line by 40 character display. The next command on line 80, POKE %DF4E,%A8 sets the cursor address of the LCD display to the next line after a carrage return or \ (backslash). The final command on this line sets the cursor mode. The data %E sets the cursor on only (the other modes being no cursor and flashing cursor).

As a data storage array is to be used later in the program, it must be allocated a position in RAM. This has been selected to start from location %C000 and finish at location %C0FF. This command, using XTBASIC, is shown on line 110. So that all print commands used in the program will be directed towards the microwire port, and hence the LCD display, the print vector of the monitor must be set to do this. This is set by the command "PV=PUTM" (i.e. PrintVector = PutMicrowire).

The next part of the program, from lines 130 to 190, sets up the LCD display control registers. This program was obtained from the JED manual (see Reference 4) on the STD 860 Liquid Crystal Display and Keyboard Interface. The sequence of the commands, and the delay, was chosen by JED Microprocessors Pty. Ltd.. The display control registers are accessed by sending the data after the data byte %FE has been sent to the LCD display. This is done by the "PRINT" command. Since we need to send the ASCII value of the data then the "ASC" command is used in conjunction with the print command. Thus the command PRINTASC(%FE),ASC(%38) will send the data %38 to the control register of the display. This command sets it up for 8 bit interface, 2 line with 5 by 7 dot matrix characters. Sending the command %1 to the display will clear it, while sending %6 will give an incremental cursor with new data (as opposed to a shifting display). The final command on line 190, %E, turns the cursor on.

The next task for the program is to set up the keyboard interface. This interface is included as part of the JED STD 860 LCD display. The keyboard is arranged as a 8 by 8 matrix. To enable each of the keys to be given a particular ASCII value, a data matrix is stored in RAM starting from location %DA00. The XTBASIC assembler knows to look for the data from this address by the command on line 200. The pointer for the data is stored in location %DF49. Then on lines 210 to 240, the relavent ASCII characters corresponding to the keys are stored in memory. Thus if a key is pressed on the keyboard, the assembler matches it with the relavent ASCII character in the RAM look-up table. So that all data that is inputted during the running of this program comes from the keyboard, the data collection vector, or "GET" vector, GV, is set to the keyboard. This is done by the command GV = GETK (i.e. GetVector = GetKeyboard). Thus if the INPUT command is used in the program, then the assembler will expect an input from the keyboard. The other command on this line is used to set the interupt vector, IV, to the keyboard interrupt line. This means that the monitor program will know if a key has been pressed. It is recommended in the JED STD 800 handbook (see Reference 3) that these two vectors are set on the same line (the comma seperates the commands).

After the display and keyboard has been set up then the program checks to see if the the probe is connected to the main chassis by its multipin connector, CN1A. This is done on line 255. The A to D convertor is checked to see if one of its inputs, ADC10(5), is less than 100. If it is, then the probe is not connected (there is a resistor connected between the ADC10(5) input and 12 V DC in the probe, thus if the probe is not connected then the voltage at the A to D convertor is zero). If the probe is not connected, then the program branches to line 9000 where a warning is given to the operator of ARR-2.

At line 9000 the LCD display is cleared by the command PRINTASC(%FE),ASC(1) and then the message "NO PROBE SIGNALS!!!,<0> = Try Again" is displayed on the first line of the display. On the second line of the display the message "\Is the Probe Connected ?" is printed. Note that the backslash, \, is recognised by the STD 860 LCD display as a carriage return, and thus prints all following ASCII characters on the next line. On line 9025 the program then goes to the subroutine, starting on line 10000, to sound the buzzer in order to give an audible warning to the operator. Lines 9030 and 9040 form a loop which waits for the operator to press a key on the keyboard. When the correct key is pressed it will return to the main program. In this case the warning display will remain until the operator presses the "0" key.

The buzzer subroutine starts on line 10000 and is used by different parts of the main program. The program beeps the piezo electric buzzer three times. This is done by having a "FOR" loop from line 10000 to line 10080. Firstly the counter in the NSC 810 on the JED STD 800 is set running by writing any data to the %F5 address. This starts the counter, which has previously been set to give a contiuous squarewave output. This square wave drives a transistor which turns the piezo electric buzzer on and off at the required audio frequency. The program then has a delay loop at line 10030. This was set by experimentation and sets the time that the buzzer is on. The buzzer is then turned off by writing to address %F4. Any data can be sent to this address. There is another delay at line 10060 and this sets the delay between the beeps. After doing the above process three times the subroutine returns to the main program.

If the "0" button is pressed while the program is in the "probe not connected" section, then the program returns to line 255 to see if the probe has been connected, if it hasn't then the warning is given again, and so on. If the probe is connected, then the program continues by giving a single beep. This indicates to the operator that ARR-2 is ready to take stress measurements. The single beep is given by lines 290 to 296. The buzzer counter is turned on by writing to %F5 at line 290. There is a delay at line 295 and the buzzer is turned off at line 296 by writing to address %F4.

The program now clears the display and prints the device identification. This is left on for a few seconds by the wait loop on line 320. The main program now goes off to the subroutine that checks the condition of the batteries. This begins at line 8000. This subroutine will now be described.

The battery check subroutine was incorporated into the program so that a visual warning could be given to the operator of ARR-2. Because the correct and accurate operation of ARR-2 is threatened if the battery voltages fall below 11.0 volts, then it is imperative that the operator is aware of this condition. If the batteries become too flat then the operation of ARR-2 will be suspended until the batteries are recharged.

The battery voltages are detected by a voltage divider network connected to the ADC10(3) and ADC10(4) inputs of the 10 bit A to D convertor on the JED STD 800 board. The voltage divider networks are adjusted so that the number outputted by the A to D convertor is half the actual battery voltage in volts. Thus on lines 7010 and 7020 the battery data is obtained from the A to D convertor and multiplied by two to get the actual batttery voltage.

On lines 7030 to 7050 the program checks to see which voltage range the batteries lie in, and branches to the relavent part of the program for the appropriate action to be taken. Thus, if either of the batteries are less than 11.00 V DC then the program branches to line 7300 and a message that the batteries are dead flat is given to the operator. Because it was chosen that this voltage was the lowest battery voltage which would support correct operation of the device, then the operation of ARR-2 is stopped at this point. On line 7300 the LCD display is cleared and the message "BATTERIES DEAD FLAT!!!!" printed on the first line of the display. The buzzer is then sounded to warn the operator by going to the subroutine on line 10000 (as previously described). The message "No More Readings, Recharge NOW...." is then displayed on the second line of the display. The program then stops. ARR-2 can be operated again by turning it off and then on again, but as the batteries are checked again they will be found to still be flat and stress readings will not be able to be taken by the operator.

If the batteries are between 11.00 and 11.3 V DC they are deemed to be nearly flat. The program jumps to line 7200 where the battery condition annunciators are changed from "BATTERIES OK" to "BATTERIES FLAT" and a blank. The reason for blanking one of the displays (E$) will be made more clear later in this program description, but it is used to get a flashing warning display for the operator. Because the program repeatedly checks the condition of the battery, the buzzer is sounded at this point (from lines 7240 to 7244). This means that the buzzer will beep continuously while ARR-2 is in the idle state waiting to take a stress reading. The reason for these warnings is that from the time that the flat battery warning starts (for continuous operation of ARR-2) about 20 minutes will elapse before the batteries will be deemed to be flat. Thus it is up to the operator to decide to take some more readings or to recharge the batteries at this stage.

If the batteries are between 11.30 and 11.50 V DC the are considered to be low. Hence on line 7100 the battery condition annunciators are changed to "BATTERIES LOW" and a blank. This gives a flashing low battery warning for the operator. If the batteries are above 11.50 V DC then they are considered to be still in reasonable condition. From the time the batteries go into the "BATTERIES LOW" condition, there will be about 1 hour of continuous operation of ARR-2 left. If the battery condition is good then the annunciators are set to the "BATTERIES OK" condition, in a non-flashing mode. After all the above battery conditions, with the exception of the the batteries flat condition, the battery checking subroutine goes back to the main program.

With the battery condition checked the main program now displays the "Main Menu". This is the starting point for the ARR-2 to take a stress measurements.

The main program now displays the "Main Menu" on the LCD display after clearing it (see chart in ARR-2 Operators Manual, APPENDIX A). The display asks the user to press the green button on the keyboard if they wish to take a stress reading, the amber button to stop the stress reading during a run and the red button to go to the support menu (which allows the user to look at the battery voltages or the case temperature). The second line of the display (on line 410) also prints out the battery condition annunciator, D$. The batteries are then checked again by going to the battery checking subroutine starting at line 7000. This is done so that the audible warning will beep in sequence with the flashing display. On line 412 there is a delay used to set the flashing rate of the display if a flashing battery warning annunciator is needed. The next line prints out the second line of the display again, but this time with the E$ battery warning annunciator, and this is followed on line 417 with another delay. Both the D$ and the E$ annunciators start out with the same message - "BATTERIES OK" - with charged batteries. When the batteries discharge enough, the D$ annunciator changes to the battery condition, and the E$ annunciator is cleared. Thus if the display alternatly displays D$ and E$ on the same part of the LCD display then the battery condition annunciator will appear to flash on and off.

To get the operators response to the Main Menu, the keyboard is checked by the "IFKEY" command. If the "R", "A", "G" or "1" keys are pressed then the program will branch to the relavent section of the main program. The "G" key was given a green button, the "A" key has an amber button, the red key was assigned as the "R" key and the "1" key has a button with 1 on it. If none of the keys are pressed then the program loops back to line 410 to display the Main Menu again (thus giving the flashing display effect). Note that the "1" key is not included in the Main Menu as displayed on the LCD screen. This key is used to access the program used to calibrate the stepper motor potentiometer and should not be normally available to the operator. If this is incorrectly used, it will make ARR-2 inoperable. This part of the program will now be described.

Pushing the "1" button when ARR-2 is in the "Main Menu" mode will send the program to line 5000. Here the user will be asked to type in, using the keyboard, a code to enable the program to continue. This is needed for security reasons as the probe has to be in the rewound position before the potentiometer readings are taken. This requires the cover to be taken off the probe in order to check the probe position. On line 5000 the display is cleared and the question "CODE?" asked. This is a prompt for the user to input the code. If this equals the security code, "4803" in this case, then the program proceeds to store the readings from the probe position potentiometer, as the probe rotates, into RAM. These values will be used to check to see if the probe rotates correctly during the taking of stress measurements. If the code is not correct, then the program returns to the Main Menu. If the code is correct then the program continues. On line 5010 the stepper motor driver is reset and then turned on by writing the relavent data to the output port %E1. This controls the gates of the output FET's on the JED STD 800 board. These in turn control the stepper motor driver integrated circuit. The program then gets the reading from the ADC10(2) line. This is connected to the wiper of the probe position potentiometer and reflects the angular position of the probe. To make this more accurate, twenty position potentiometer readings are obtained in the loop on line 5040. These are then averaged to eliminate the small amount of scatter on signal. The average position potentiometer reading is then stored into the array (starting at array value @(25)) on line 5070.

The stepper motor is then stepped by sending %90 to port C by writing to address %E1. This turns the power on to the stepper motor and sends a signal to the stepper motor driver to step the motor. There is then a loop on line 5100 to wait for the probe to be stepped to its new position. Another position potentiometer reading is then taken, by taking twenty ADC10(2) readings and averaging them. This is stored in the relavent location in the array. This process is repeated until all 48 (7.5°) step positions have been recorded. Note that although only 24 of these positions are used under normal operating conditions (i.e. every 15°) all the step positions are recorded so that ARR- 2 will know the position of the probe to within one step position if the probe is moved between stress measurements (including when ARR-2 is turned off). On line 5200 the program jumps to the probe rewind subroutine after completing all 48 position potentiometer readings. Note that the probe position potentiometer calibration only needs to be done when ARR-2 is first completed, the probe is dismantled or the Lithium backup battery on the JED STD 800 board fails, as the potentiometer readings will normally be permanently stored in RAM.

The REWIND subroutine is used to rewind the stepper motor to the starting position, after the position potentiometer readings or a stress measurement has been taken, or if ARR-2 is turned on with the probe in some other position than the rewound one. This subroutine starts at line 6000 and sets up an "error loop" to check if the probe has tried to be rewound three times. If this number is exceeded then a warning is displayed for the operator. Nestled within this loop the probe will also try to rewind the probe three times without a warning to the operator. If the probe is not rewound after these nine attempts it is assumed that there is something faulty with the equipment and operation of ARR-2 will be suspended.

To allow for any movement of the probe to subside from previous operations of ARR-2, a wait loop is given at line 6020. The A to D convertor output ADC10(2) is then read to get the probe angular position. This is then compared to the array containing the 48 posible probe positions, to pick the one that is closest to the actual probe position. This part of the program is in a loop, so the loop count, I, is the step position of the probe, when the correct position has been found and the program jumps out of the loop and goes to line 6100. The conditional check for the position of the probe has a spread, so that if the probe is not on an exact step position, the nearest one will be picked. If a position is not chosen then the step position is selected to be 2. This means that the probe will only step back one position. Hence, if the probe is within one step of the first position it will only step back one step, thus preventing the probe gaining a lot of momentum and crashing into the mechanical return stop. This will not damage the probe at all, but should be avoided if possible.

If the loop counter (used to find the step position of the probe) is equal to one then the probe is at the start of its travel and does not need to be rewound. Thus on line 6100, if I=1 the program will go to the "RETURN" command to return to the main program. Note that the power to the stepper motor is turned off here, is case it has been left on (if there was a step error during a reading at position one).

If the probe is not found to be at the rewound position, then the stepper motor needs to be stepped the required number of times, in the reverse direction, to rewind it. This is done in the "FOR" loop on line 6110. The step input for the stepper motor driver is turned off and on, with a suitable delay between lines 6120 and 6160, to step the probe back to its starting position. The program then goes back to the start of the rewind subroutine to check if the probe has indeed returned to the rewound position. If it has, then the power to the stepper motor is turned off and the subroutine returns to the main program. If the probe has not been rewound, the program tries to rewind it again. If this is not successful after three attemps then an audio-visual warning is given to the operator of this condition. This is given on line 7300.

To warn that the probe has not been rewound after three attempts the LCD screen is cleared and the message "INCORRECT REWIND!!!" is given to the operator. The stepper motor is turned off and the user is prompted to press the "0" button on the keyboard to attempt further rewinds. If the probe still does not rewind, then the operator is told that there is no probe rewind and that technical repairs are needed to ARR-2. The program is then stopped. Further operation can recommence by turning ARR-2 off and then on again, but correct operation of the device will only occur if the probe can be rewound. For the above warnings the buzzer is sounded by going to the buzzer subroutine on line 10000.

If the probe has been successfully been rewound, then ARR-2 can be used to take stress measurements. This is started by the operator pressing the green key while in the "Main Menu". The stress reading part of the main program starts at line 4000. At this point the program checks that the probe has been rewound by going to the rewind subroutine at line 6000 and on the next line checks that the batteries are in a suitable condition for stress measurements to be taken. On line 4012 the ADC10(5) line is checked to see if the probe is connected. If it isn't then the program goes to line 9000 to warn the operator of this condition. If the probe is rewound, the batteries in a suitable and the probe connected, then SCm and SCp readings can be taken.

On line 4015 the user is given the message that ARR-2 is running and that the user can abort the stress measurement by pressing the amber button on the keyboard. This is included to save time if the reading is not wanted, for example if it is realised that the probe is in the wrong position on the railway wheel. The program then takes 20 SCp readings, averages them and stores the value in S. The SCp coil is read by looking at ADC10(0). Likewise, from line 4070 to line 4110 twenty SCm readings are taken, averaged and stored in the array element @(1). Successive values of SCm will be stored in incremental elements of this array. The stepper motor integrated circuit is then reset and it is checked if the abort button has been pressed (on line 4123) , if it has, then the program jumps to line 3000 and stops the running of the program. The loop counter for the forward stepping of the stepper motor, I , has been set to 1 so that the display to the user, indicating that the run has been aborted, shows the correct step position of the aborted run. If the button has not been pressed, then the program continues taking the readings. The main loop now begins to step the stepper motor 23 times (two steps for each position) so that all 24 step positions are covered, with SCm and SCp readings taken at each one. Between lines 4130 and 4190 the stepper motor is stepped twice by toggling the stepper motor driver IC step input twice. There is a delay on line 4203 to wait for the stepper motor to stop moving and then the position of the probe is checked, by comparing the output from the position potentiometer, ADC10(2) to the expected value stored in RAM. If this is incorrect, then the program branches to line 8000 to warn the operator of this error condition.

At line 8000, if there has been a step error, the message "STEP ERROR AT POSITION" is displayed for the operator. The loop counter value is added after this display to give the number of steps that had been done (this does not really perform any useful function, but may be handy in trouble shooting problems with the probe). The user is then prompted to press the "0" button on the keyboard. The above display will remain until this button is pressed and then the program will return to the Main Menu. If the problem of step errors occur often, then the operator of ARR-2 is advised, in the operators manual (see Appendix A), that ARR-2 should be repaired.

If there has not been a step error, then twenty SCp values are taken on line 4210. The average value of these are then added to the accumulative SCp value stored in S. When 24 average SCp values have been taken, S will be divided by 24 to give an average SCp value (an average of 24*20 SCp values).

The program then gets another average SCm value from twenty readings and stores this in the appropriate array position (line 4290). The program again checks to see if the abort button has been pressed. If it has, then the program goes to line 8000 and stops, otherwise it continues to get more SCp and SCm values. If all 24 readings have been taken then the program continues to get the average SCp, SCm and angular direction of tension values.

ARR-2 differs from ARR-1 in the way it gets the SCm value. In ARR-1, the two minimum SCm values were averaged and then subtracted from the average of the two maximum SCm values to give the value for $\hat{SCm}$. In ARR-2 the integral of the SCm values is used as $\hat{SCm}$. Thus the average SCm value is needed. This is calculated by lines 4310 to 4350, with the average SCm value being stored in T. The next part of the program calculates the integral of the SCm values by adding up the differences between each of the 24 SCm values and the average value, T. The values of these differences need to be unsigned, hence the absolute values of these differences are taken on line 4395. Note that the difference is also calculated for the next SCm value. This is done so that the position of the first positive to negative "zero" crossing of the SCm waveform to the average SCm value, T, can be found. So that all twenty four SCm readings are taken into consideration, R, is used as the offset value. It is initially set to "1". This means that the difference between the SCm value and the average SCm value, T, is compared to the next difference calculated. When the 24th SCm difference is compared, then the R value is set to -23, so the last SCm difference value is compared to the first. The "step" position of this first negative slope crossing gives the direction, from the starting position of the probe, to the angular position of tension. If the program does not locate the zero crossing then it goes back to compare another pair of readings. If it does locate one, then the program goes on to calculate the angular position of tension.

If the SCm difference is larger than some arbitrary value (218) then it is assumed that something is wrong with the results. Thus the user is informed that there is something wrong by setting W to a value greater than 2 (3 in this case). The value of W indicates the number of negative slope zero crossings that are detected through the complete probe rotation. If the probe is on stressed steel then this value should be 2. If less or more than two crossings are detected, then the user is informed, later on, that the reading is suspect. This does not prevent the user from getting the results though. Hence by setting W to 3 we will produce a suspect SCm reading warning.

On line 4444 the W value is incremented every time there is a negative slope zero crossing detected. If this is not the first such zero crossing (W not equal to one) then the program goes to line 4500 to complete the calculation of the integral of SCm. If this is the first zero crossing then the angle, B, from the starting position of the probe to the direction of tension is calculated. This is done on line 4460. The value of B calculated here is ten times the actual value. It is divided by ten on the next line. The equation is derived from the fact that every measurement position of the probe is 15° apart and the zero crossing position is approximately proportional to the crossing point of the line between the SCm value above the average value, T, and the SCm value below it (see Figure 3.16).

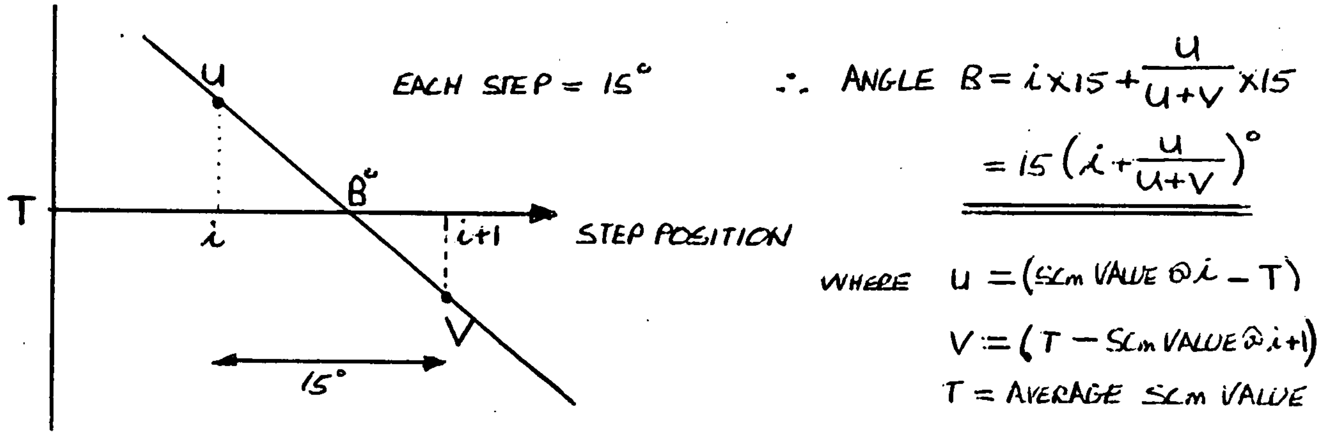


Figure 3.16 SCm Negative Slope "Zero" Crossing.

The method of assembly of the probe means that the starting point of the probe may not line up with the direction of tension. To counteract this an experimentally derived correction factor is included. This is the "(I-5)" part of the equation. I is the step position and the correction in this case is 5 step positions, or 75°. The calculated value of this is deliberatly set ten times too big to counteract the loss of accuracy due to the use of integers. On line 4470, if the calculated value of angle is less than zero, 180° is added to it so that it is always positive.

The calculation of all the main parameters of $\hat{SCm}$, SCp and direction of tension have now been completed, so the probe is rewound and the buzzer sounded to inform the operator that the readings have been taken.

The average SCp value is calculated by dividing the accumulated SCp value by 24 on line 4595. the program then checks the number of negative slope zero crossings of SCm. This has been stored in W and should be equal to two, for readings taken on stressed steel. If it is not equal to two then the user is warned of this condition, on line 4596, by the caption "SUSPECT Scm READING!!!". The buzzer is sounded and the user has to press the "0" button on the keyboard in order to continue to get the results of $\hat{SCm}$, SCp and direction of principal tension. The results will still be given to the operator, but they must be considered suspect. For very low stess conditions the result may be legitimate as there may have been less than two negative slope zero crossings in the SCm readings.

If there was the required number of zero crossings or the operator has pressed the "0" button after a "Suspect SCm" condition, then the program scales the $\hat{SCm}$ reading by dividing it by 10. This does not have any noticeable effect on the accuracy of the $\widehat{SCm}$ value due to roundoff error. This is because the scatter on the SCm values is of the order of the least significant digit on the SCm value.

On line 4610 the results of $\widehat{SCm}$, SCp and angle of tension are printed out for the user. Another menu is also given to the user. This menu has two options, the stress measurement can be taken again or the user can select the support menu. Thus, if the green button is pressed, the program will go back to line 4000 and new results for $\widehat{SCm}$, SCp and angle will be obtained again. If the red button is pressed then the program will go to the support menu on line 2000.

The support menu allows the user to look at the temperature of the case or the battery voltages. In an earlier version of this program, the support menu also had the option to print out stored stress measurements, but this feature was not included in the final version as it was not to be used by the Railways of Australia Committee (ROA). Hence from lines 2000 to 2060 the user is asked to choose whether to look at the battery voltages (by pressing the "B" button), the temperature (by pressing the "1" button) or returning to the main menu (by pressing the "0" button). If the "B" button is pressed, then the program branches to line 2100 and the battery voltages are displayed by multiplying the ADC10(3) and ADC10(4) readings by two. These are displayed until the user presses the "0" button, causing the program to return to the support menu. The battery voltages are used to predict the remaining operating time of the rotation rig. A chart is included in the instruction manual for ARR-2 showing the operating time remaining versus battery voltage (see Appendix A).

If the case temperature is selected, then the temperature is calculated by a simple equation that was determined experimentally. It turned out in practice that this function did not prove to be very useful, as users of ARR-2 tended to disbelieve the case temperature displayed. The "accuracy" of the temperature is effected by the long thermal time constant of the case. For example, if the batteries have been charged then the heat from the charger may hold the internal temperature of the case at a reasonably high temperature for some time. Thus the operator may read a case temperature which is 5 or 10 degrees celsius higher than the ambient temperature and thus discard it as being errorous. The actual use of the temperature reading was to check that the case temperature did not exceed 70° C as this will effect the accuracy of the instrument. It was assumed that if ARR-2 was in the Sun and there were high ambient temperatures, this condition could be exceeded in the field.

Although the support menu functions did give accurate and useful information, they were considered by the ROA to be of limited use.

3.7 ARR-2 Performance Summary.

It was decided by ROA that there had not been enough development of the equipment and field use to warrent the device to be used for data logging. This means that the keyboard (to input the wheel numbers etc.) and the printer output would not be needed. This means that the front panel could be simplified (see Figure 5.1). If the menu operation of the control program is also removed then the front panel need only contain three switches, for the On/Off, battery charger boost and "RUN" switches, (see front panel layout of ARR-3, Figure 5.5). It was decided that the piezo electric buzzer contained within the case is not loud enough for some field conditions. This could be improved by moving it to the front panel.

The ROA also thought that the LCD display was not very visible from some angles. This is due to the design of the STD 860 LCD display from JED Microprocessors Pty. Ltd. and can only be altered by turning a trim potentiometer on the display board itself (this being preset during manufacture). This trimmer changes the "display angle" of the display. If desired, this potentiometer could be moved to the front panel where its setting could be altered by the operator. At the time of manufacture of ARR-2, backlighting of the LCD display was not available. It is thought that this option would be a benificial one, especially as the light level under trains in a work shop is not very high. The backlighting could be turned on and off by a switch on the front panel.

The case design of ARR-2 was designed by Mr. Steve Avery in order to be simple to make (discussed in more detail in Chapter 5). It was thought by the ROA that it was not suffciently weatherproof for extended operation in wet or dusty field conditions, typical of railway operations. Thus, any future ARR's should have an enclosure that is sealed to at least IP55 (see Reference 18).

Another problem found with ARR-2 is the use of a multipin connector for the lead between the probe and chassis. This was originally included to make it more convienient to store and carry the equipment. In practice though, even using a reasonably expensive connector, some problems were encountered in reconnection reliability. The problem was fixed using gold plated connector pins (the pins in the connectors are removable) but this leads to the question of long term reliabilty of the connections in general. This problem could be totally eliminated by having the probe connected permanently to the chassis via cable glands. This would, of course, lead to some inconvenience.

CHAPTER 4

AUTOMATIC ROTATION RIG 3

4.1 Introduction to ARR-3.

ARR-3 (Automatic Rotation Rig number 3) was designed for measuring the stress in railway lines before and after they have been welded together to form a continuous track. A problem with continuously welded track, is that at high ambient temperatures, the track may have enough internal compression (due to expansion of the rails) to buckle. ROA wished to measure the "stress free temperature" of the railway track. That is, the ambient temperature at which the rail is neither in tension nor compression. The welding process for the rails is designed so that it will stretch the rail and thus induce some tension into it. This will counteract any compression, caused by heating of the rail, up to the stress free temperature. If the stress in the rail can be measured after the welding process then, with reference to the stress free temperature of the rail, it can be determined whether or not the rail has been tensioned enough to prevent buckling at elevated ambient temperatures. As the manufacturing process of the rail (rolling) and the straightening process which follows, both induce residual stresses into the rail, then a non destructive method is needed to measure the total stress (induced and residual) in the rail after welding.

ARR-3 was also designed to overcome some of the problems that were found with ARR-2 after field trials. The principle of operation is essentially the same as that of ARR-2, but the clamping method for the probe was changed to allow the probe to be held onto the rail. The probe on ARR-3 is held to the rail by a mechanical toggle clamp, instead of magnets as per the wheel stress measuring device ARR-2. The probe for ARR-3 was also designed to fit all of the Australian standard size railway lines (as per AS 1085, Reference 10). A later modification to the probe made it easier to locate on the rail. This made the probe unsuitable for placement onto the smallest railway line. This was not considered to be a big problem as this weight of rail (37 Kg/m) is not used often. Some modification to the probe (see chapter 5), would again make the probe suitable for all weights of railway track.

The electronics design of ARR-3 is quite similar to ARR-2, except for the SCp signal amplification and some rationalisation of the operating procedure and simplification of the front panel layout. The keyboard and printer output of ARR-2 have been removed, leaving only the ON/OFF, boost charge and RUN switches. This was done because it was assumed that ARR-3 and all following automatic rotation rigs are not going to be used for data logging. As the keyboard has been removed from the front panel then the menu system of operation of ARR-2 has been simplified to a "run only" type of operation. All user information, such as low battery warnings etc. are displayed on the LCD screen if needed.

4.2 ARR-3 Electronics Design

The following circuit descriptions are made with reference to the complete circuit diagrams for ARR-3 as shown in Appendix E (c). Only the major differences between ARR-2 and ARR-3 have been described. One of the minor changes was the use of "HC" TTL intergrated circuits, instead of "LS". These did not require any changes to the oscillator circuit, where they were used, but because they draw less current than the "LS" type, the series resistor to the +5 V regulator could be removed (as described in Chapter 3). The EPROM was also changed to a CMOS type, again with further power savings. The current drawn from the +5 V supply was reduced sufficiently to allow the use of only one regulator for the +5 V supply to the electronics. The regulator has a small heatsink bolted to it. Another difference between ARR-2 and ARR-3 is the wiring to the STD connector used for the printed circuit board for the excitation oscillator, SCp and SCm filters and the stepper motor drive. This was changed to allow for the slightly different printed circuit board used for ARR-3. The STD connector wiring is shown on Sheet 2, Appendix F. All other aspects of ARR-3 are as per ARR-2.

4.2 (a) SCp amplifier.

The SCp amplifier used on ARR-2 was only marginally satisfactory. The change in SCp voltage with the airgap between the end of the probe and the steel surface gave a resolution of only 0.1 mm. To enable a better resolution to be obtained, the MC 1733 differential amplifier was replaced with a normal operational amplifier, with a single ended output (see Figure 4.1). This was converted to a differential signal, in a similar fashion to that used on ARR-2, for SCm, by capacitivly coupling the output of the operational amplifier to the primary side of a 1 to 1 audio transformer. Hence the secondary of the transformer will give a differential signal for use by the SCp phase sensitive filter.

The amplifier chosen was a LM 308. This was connected in the usual manner. A voltage gain of 13 was used in order to give a reasonably large change in SCp, with the airgap between the end of the probe and the surface of the steel surface under examination. This gain figure is not critical within certain limits as the Automatic Rotation Rig must be calibrated, after it has been manufactured, with non magnetic spacers under the probe, to give calibration curves of SCm versus stress versus SCp. Setting the gain of the amplifier as high as possible, before clipping, is to give as much change in the SCp value with airgap as possible.

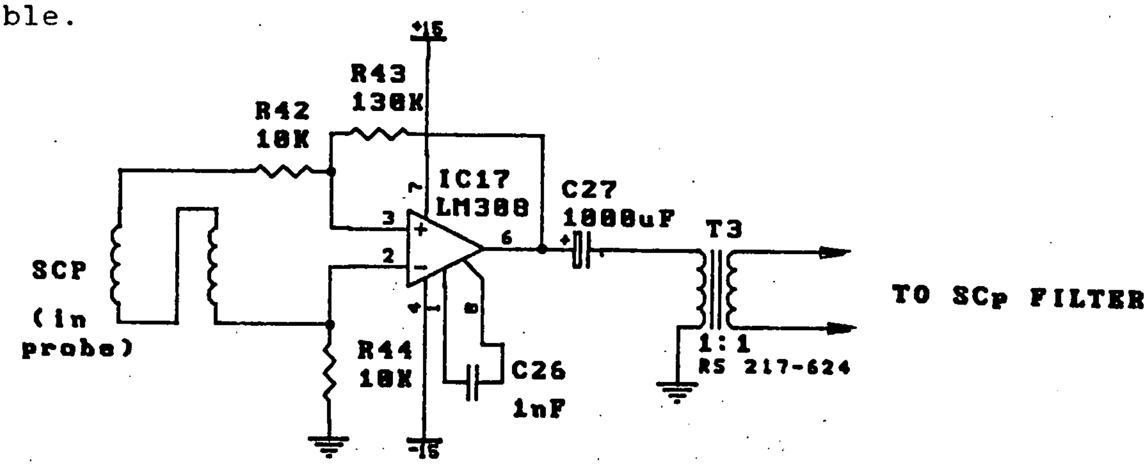
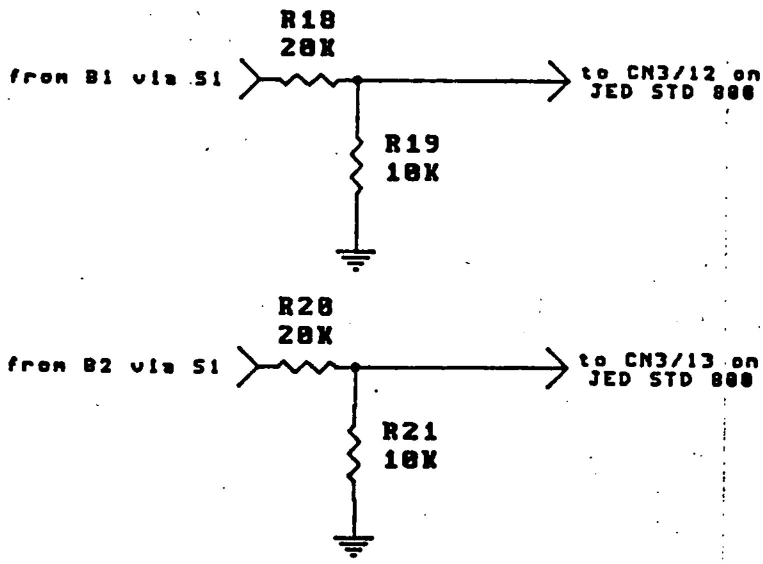


Figure 4.1 SCp Amplifier Circuit.

The SCp amplifier used in ARR-3 operates off +/- 15 V instead of +/- 5 V as in ARR-2. This supply is derived from the 5 v to +/- 15 V convertor used to supply the DAC 808 and the SCm preamplifier.

4.2 (b) A to D Convertor Changes.

Because the battery voltages are no longer required to be displayed for the operator, then they do not need to be scaled for ease of conversion by the control program. This means that they only need to be set to some value between 0 and 5 V (so that they fall in the input range of the A to D convertor on the JED board). To achieve this, the nominal 12 V DC battery voltage is reduced by a voltage divider as shown in Figure 4.2. The resistors used for the dividers are of the metal oxide type, so that they are reasonably stable with temperature. Battery condition warnings are given to the operator on the liquid crystal display. The battery levels are monitored by the control program by comparing the numerical A to D convertor output with a look up table of known battery conditions.



B1 AN B2 12V
6A-h SEALED
LEAD ACID BATTERIES

Figure 4.2 A to D Scaling Circuits.

The probe angular position potentiometer voltage is not scaled as in ARR-2, instead, its 0 to 5 V wiper output is fed straight to the A to D convertor.

4.2 (c) Probe Temperature Sensor.

Because it was thought that variations in probe temperature (i.e. the rail temperature) may affect the calibration of the instrument, then a temperature probe was encapsulated in the probe assembly along with the excitation, SCp and SCm coils. The circuit used for this is the same as that used for the ARR-2 case temperature probe.

It was found in practice that the temperature probe could only be used as an indication. This is because the probe assembly has a very long time constant and as such would have to be placed against the rail for a long time before the (possibly elevated) temperature of the rail heated the probe, adversely affecting the accuracy of the readings. Thus the temperature readout should only be used if it appears that the internal probe temperature exceeds 70 ° C. It must be noted that the probe temperature may be elevated from the ambient temperature by a few degrees normally, due to the heating effect of the excitation coil.

As the SCm readings can be calibrated for differences in temperature using the Δ SCp technique (see the ARR-2 instruction manual, Appendix A) then the temperature sensor in the probe may be superfluous. This may not be this case, though, if the probe is not to be removed from the rail between stress readings as this will not allow accurate use of the Δ SCp technique. This problem may be overcome, though, by taking the in air SCp reading before the probe is connected to the rail. Then the "on steel" SCp reading is taken, along with the stress readings, with the probe on the rail. After the welding of the rail has been completed, the stress readings can be taken again, the probe removed and the SCp reading in air taken again. Because of the long thermal time constant of the probe. this should lead to little error in the two Δ SCp values taken.

4.2 (d) Piezo Audible Warning Device.

It was found that the audible buzzer in ARR-2 was not loud enough for some field environments (such as in railway yard workshops). To solve this problem a panel mounting two tone piezo electric buzzer was mounted on the front panel of ARR-3 (see Figure 4.3 for the circuit used). Because this device has no protection from dust and water a small piece of foam was inserted into the sound emitting hole (the device itself will not allow moisture or dust to enter the case of ARR-3, but the vibrating element of the piezo-electric buzzer is exposed). This did not quieten the buzzer by any appreciable ammount. The buzzer chosen is a "two tone" one from Radio Spares Pty. Ltd. (part number RS 249-429, Reference 5).

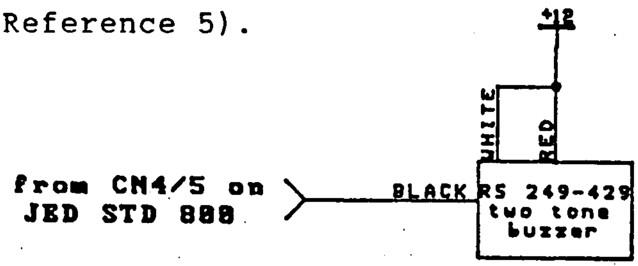


Figure 4.3 Piezo Buzzer Circuit.

Only one of the two possible tones of the buzzer was used (the other, a "high tone" did not sound very good). As the buzzer contains its own electronic oscillator, then only the supply voltage to the buzzer needs to be switched. This was controlled by the JED board from one of the FET output transistors on port B by switching the negative lead of the buzzer to ground.

4.2 (e) Probe to Chassis Connecting Cable.

Because of the problems experienced with the cable connector on ARR-2 in the field, it was decided to do away with the connecter altogether (see Sheet 2, Appendix G). The cable is permanently connected to the probe and the chassis by waterproof 20 mm cable glands. This causes some inconvenience in the manufacturing of the device, but did not seem to cause any problems during the operation of ARR-3 in the field.

4.3 Program Changes for ARR-3.

In order to allow for the simplification of the operation of ARR-2, the program needed to be modified for ARR-3. The program listing for ARR-3 is shown in Appendix C (c). The keyboard of ARR-2 was replaced with a single "RUN" button. This meant that the operation of the program could not be menu driven. Because of this the Main Menu and Support Menu were deleted (their overall usefullness being limited anyway). As the time taken for ARR-3 to get a stress reading is short (about 15 seconds), then it was decided to remove the "RUN ABORT" feature. If the operator of the rotation rig does not require the stress reading, then there is not a long time to wait before another stress measurement can be taken.

There were problems with the reliability of the connector used to couple the main electronics to the chassis as described previously. This was eliminated by joining the two permanently together with the connecting cable (see Sheet 2, Appendix G). This meant that the program had to be modified to check for signals in the connecting wires, rather than whether or not the probe was connected to the chassis. This is done on line 402 by checking ADC10(0), the SCp input, and ADC10(7), the probe temperature input, to see if they are less than 100 in value. The other inputs could not be checked as they normally can have any value. Thus, if these two lines are less than 100 it is assumed that something is wrong. The program will go to a warning section at line 9000 to tell the operator that probe signals are not being detected. The other main aspects of the program were not modified.

In order to identify where the program has been changed for ARR-3, the following short description is given:

The program for ARR-3 is essentially the same as for ARR-2 until line 405. Here, instead of the Main Menu, the operator is asked to press the green button if a reading is to be taken. The only other information given to the operator is the condition of the batteries. The battery condition display can be flashing, as for ARR-2.

Because there is no way to access the program subroutine for storing the position potentiometer readings then the access routine was deleted. In order to run this part of the program, a terminal must be connected to the JED board via the RS232 port. The program can then be run by accessing the BASIC line by line compiler (as per the JED STD instruction manual, see Reference 3) by typing "GOTO 5000".

The process for obtaining of the results for SCm, SCp and the angle is the same as ARR-2. These are displayed along with the probe temperature. This was included as ARR-3 was intended for use on railway lines. These may have temperatures in excess of the ambient temperature. Because of the long thermal time constant of the probe, if it is left on the rail for a long period of time, it may heat up. If the temperature becomes excessive it may alter the accuracy of the results, due to the resistance of the excitation coil increasing and reducing the excitation current of the coil. This will in turn be reflected as a reduction in the detected signals SCp and SCm. This can be reduced to some extent by the "Delta SCp" method (see Appendix A) but an indication of the heating effect might be useful. As ARR-3 has not been used in the field by ROA, it is difficult to gauge the usefulness of this feature.

As the accuracy of the temperature probe in the case of ARR-2 was questioned, the method of calculating the temperature of the probe was revised. This was also checked against experimental results obtained by placing the probe in a heated closet and checking the probe temperature against the ambient temperature in the closet. It was found by experiment that the probe had a thermal time constant of about 1 hour. The calculation for getting the temperature of the probe is on line 4607.

Because the voltage divider networks for the batteries were changed on ARR-3, the setpoints for the various battery warning conditions needed to be changed. These were checked by measuring the terminal voltage of the batteries and comparing these with the A to D converter outputs ADC10(5) and ADC10(6) and are shown between lines 7030 to 7050.

The REWIND, STEP ERROR, PROBE POSITION and WARNING BUZZER subroutines of ARR-2 have been retained in ARR-3. Note in the program for ARR-3, the piezo-electric buzzer is turned on and off by writing to location %E1 and not by turning the counter on and off as in ARR-2.

4.4 Performance Summary for ARR-3.

ARR-3 performed as expected, but the problem of hysterisis associated with the use of magnetic anisotopy to measure residual stress (see Figure 2.4, Chapter 2) reduced the accuracy of the method too much. The ROA required a measurement tolerance of +/- 8 MPa. It is difficult to approach this kind of accuracy with any known stress measurement method, whether destructive or not. X-Ray and neutron diffraction techniques have this order of accuracy but the equipment is expensive, potentially dangerous and needs skilled operators. The use of any type of destructive testing has to be ruled out because it would damage the rail and this may possibly lead to breakage of the track. If the problem of stress hysteisis can be eliminated, by using demagnitisation techniques (see Reference 20), then ARR-3 may be able to measure the stress free temperature of the rail to the required accuracy.

If ARR-3 is going to be manufactured, there are several developments which would simplify or aid its production. These are mainly to do with the probe assembly of the device, but some rationalisation of the electronics would be benificial.

In practice, although the probe design works, and in ARR-3 has not given problems with "step error" (as occurred occasionally with ARR-2), it is not simple to manufacture due to the amount of machining needed. Also because it is heavy, it is prone to damage from being dropped. The problem of machining during manufacture may be helped by rearranging the probe as described in the conclusion of Chapter 5. The heavy mass of the probe assembly could be reduced by the use of lighter materials, such as aluminium, instead of the brass and stainless steel (non magnetic) as used for ARR-2 and ARR-3.

The JED board set up should be retained for limited production runs. Although the JED board has many more functions that are needed for ARR-3, the cost of designing a dedicated microprocessor control would not be cost effective (except for very large production runs). The JED STD 800 could be simplified from the set up used in ARR-3 , by storing the position potentiometer readings in ROM (they are at present stored in RAM). This would require the position potentiometer to be set up during manufacture instead of being calibrated by the program, but would eliminate the "crystal ball" and the lithium backup battery. These were originally included in the design to allow for the storage of data in RAM, if ARR-2 was used for data logging. This feature is no longer considered necessary.

The "spiral wound cable" and the connecting lead between the probe and the chassis have not given any trouble with wire breakages, but it is difficult to predict the life of these cables. They were made up from ribbon cable (the most flexible available) and some scrap multicore cable respectively. The possibility of using specially designed cable for this application should be considered in order to improve its service life.

By changing the "boost chage" push button switch to a transitor acting as a switch and "bootstrapping" this to the battery charger supply, the boost charge switch could be removed from the front panel. This would mean that the battery charger would be switched to boost charge mode as soon as the battery charger is connected to the mains, it would only return to the trickle charge mode when the batteries are charged.

The removal of this pushbutton, the crystal ball and the lithium battery would save approximately $70 from the materials cost of ARR-3 and lead also to some reduction in the manufacturing cost and time. During the building of ARR-3, some problems with the interboard connectors was experienced. In furture ARR's these should be removed and replaced with soldered joints wherever possible. Although no problems have been encountered with these connectors in the field, having permanent joints in the wiring can only help the reliability of the equipment. Some more feedback from the use of ARR-3 by ROA may also bring about some more rationalisation of the design.

At present it appears that ARR-3 may not be able to be used for the measurement of the stress free temperature in rails. This is not because the device does not work, but because the resolution required for the stress free temperature is +/- 3° C (+/- 8 MPa) as required by the ROA is not achievable by the magnetic anisotropy method. At present the only non-destructive stress measurement method that approaches this accuracy is X-ray or Neutron diffraction. This has a repeatable resolution of about +/- 10 MPa. With more work on the rotation rig, especially into the problem of stress hysteresis (see Chapter 1), then the magnetic anisotropy method may become useful. At present the reliable accuracy of the rotation rig is only +/- 20 MPa at best. This may be adequate for stress measurement on railway wheels, but it is not good enough for the measurement of the stress free temperature in railway tracks to the required resolution.

If more rotation rigs are to be built for the measurement of stress railway wheels, then they should use ARR-3 electronics and probe along with the magnetic clamp from ARR-2.

CHAPTER 5

PROBE AND CHASSIS DETAILS FOR ARR 1, ARR 2 AND ARR 3.

5.1 Probe Details.

All three probes were based on a similar layout (see Figure 5.11), with all detail design and construction being carried out by Mr. Steve Avery at the Department of Electrical Engineering and Computer Science, University of Tasmania. As one of the main design criteria was to make the probe assemblies impervious to the ingress of water and dust, they are completely enclosed. Dust and water must be prevented from entering the probe mechanism as they may cause it to jam and cause stepping errors.

The probe built for ARR-1 was not totally successful as the plastic tube used to enclose the probe was not very practical to manufacture. It could not be machined accurately enough to allow reliable rotation of the encapsulated excitation and pick up coils. This caused "step errors" to occur.

Another cause of step errors in ARR-1 was the use of hall effect limit switches. These control the logic used for rewinding and stepping the stepper motor. They were difficult to set up and did not retain their set positions during extended use. Some problems were also experienced with the switching magnet that was attached to the rotating part of the probe. This appeared to loose some of its magnetism after some time. The reason for this is not known, but it did alter the switching positions of the limit switches. Because of this they needed periodic adjustment.

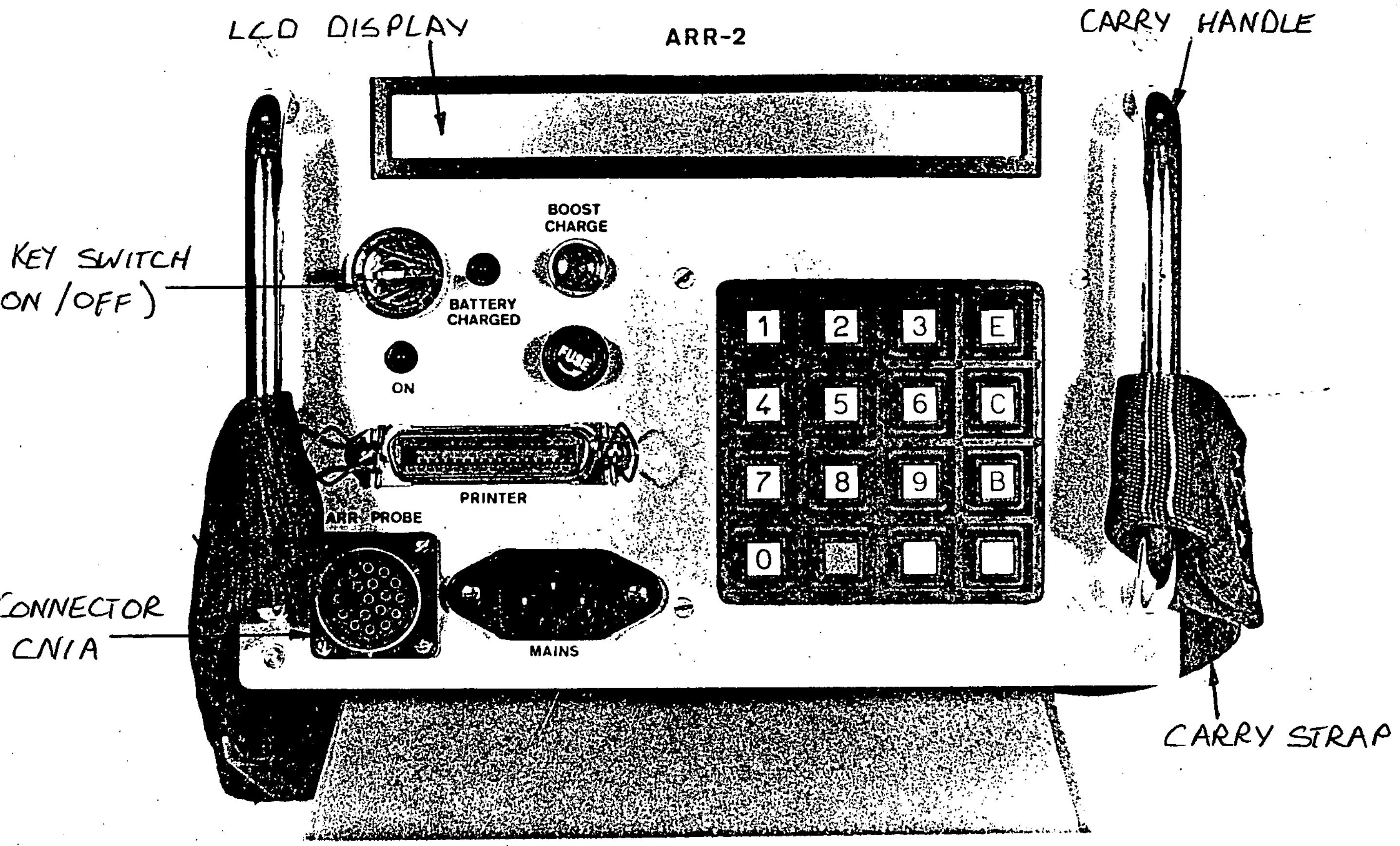


Figure 5.1 ARR-2 Front Panel Layout.

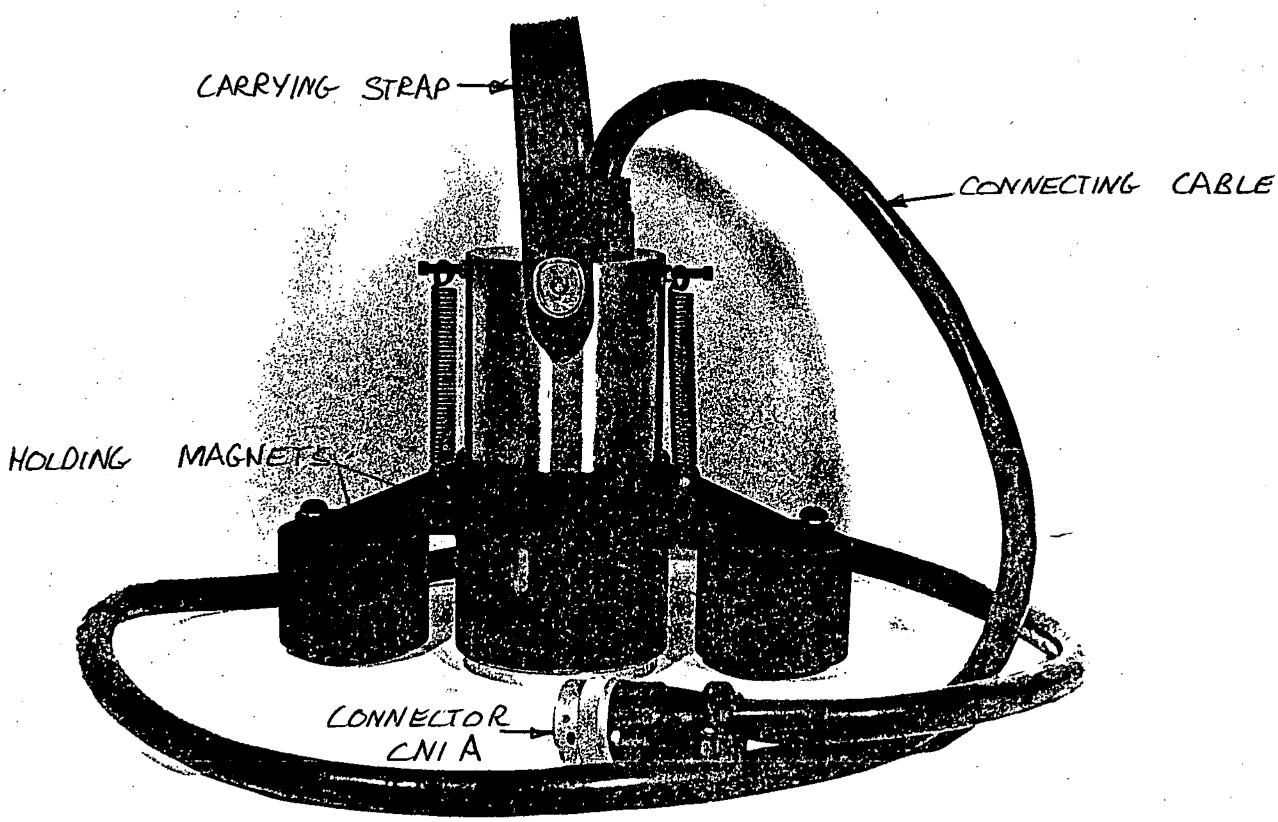


Figure 5.2 ARR-2 Probe Side View.

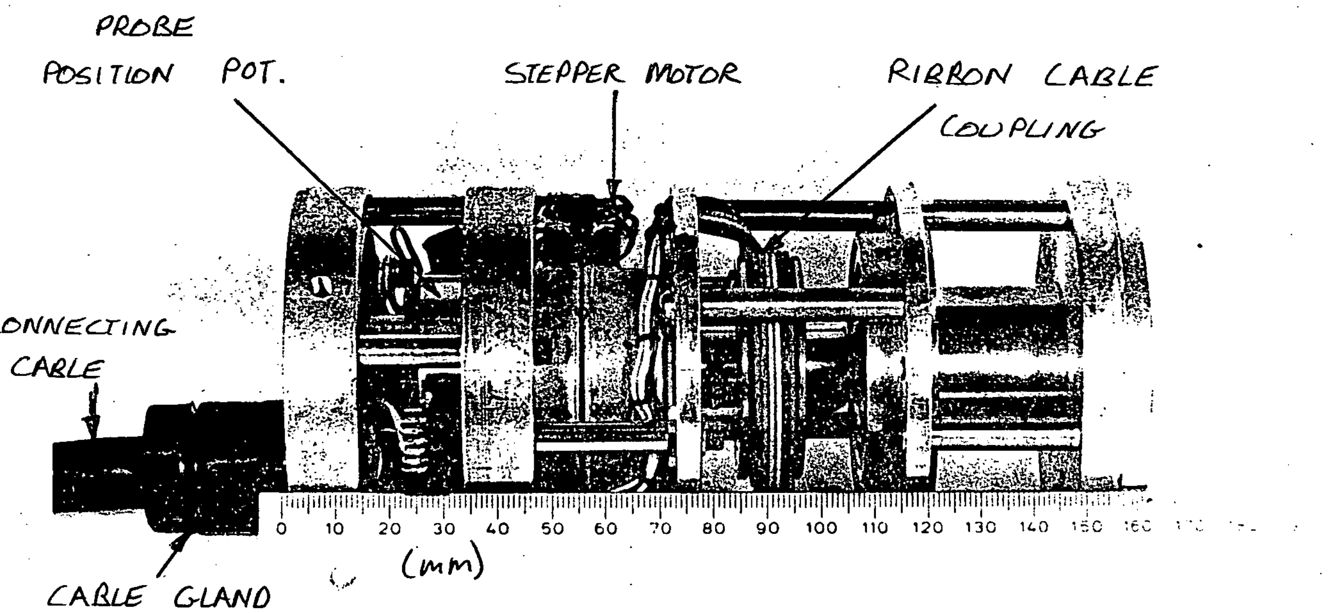


Figure 5.3 ARR-2 Probe (with cover removed).

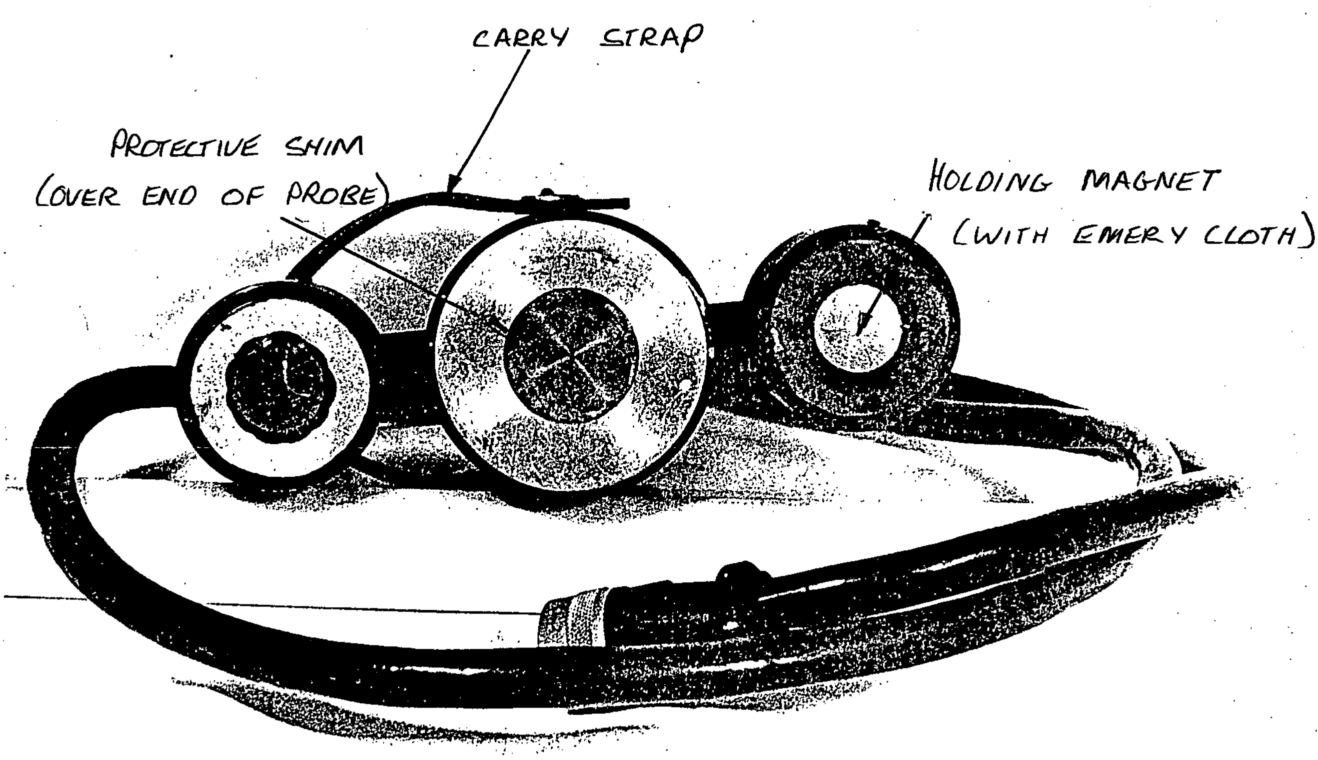


Figure 5.4 ARR-2 Probe End View.

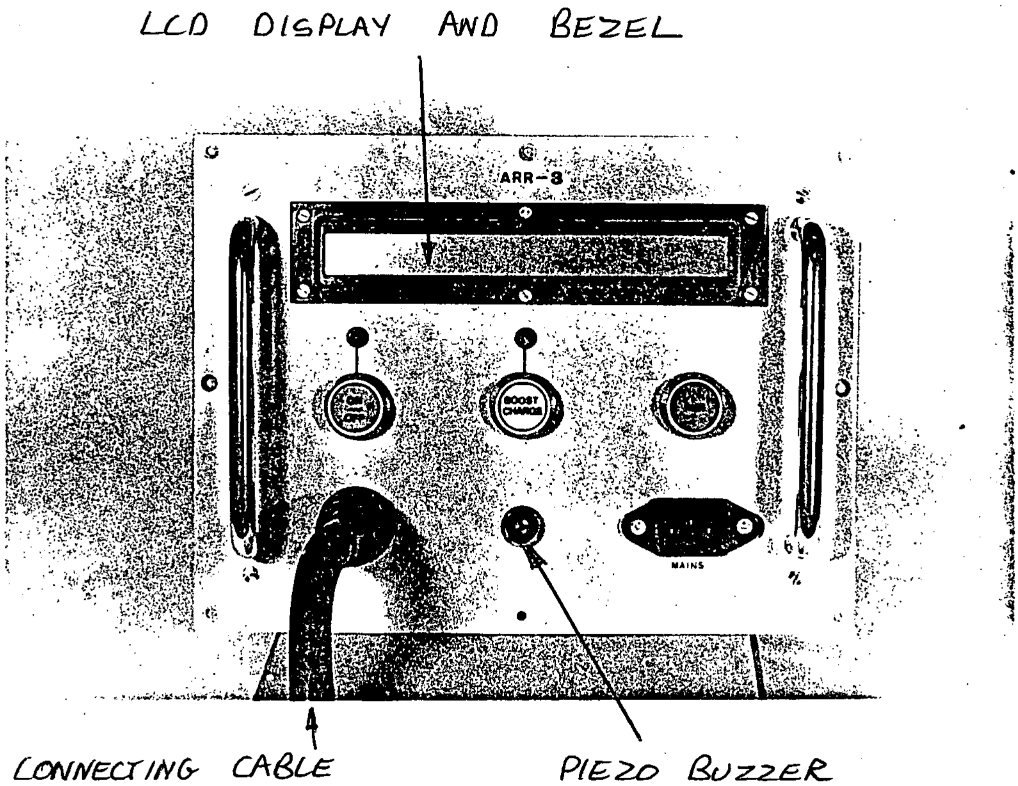


Figure 5.5 ARR-3 Front Panel Layout.

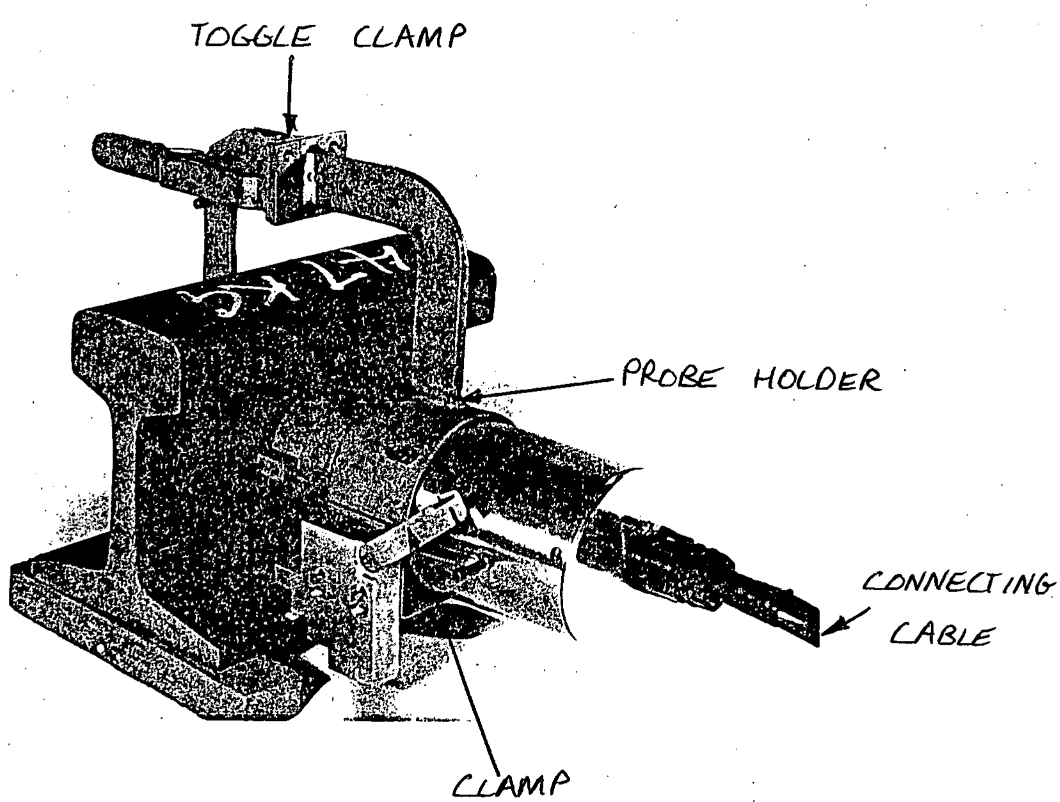


Figure 5.6 ARR-3 Probe (clamped onto a 47 Kg/m rail).

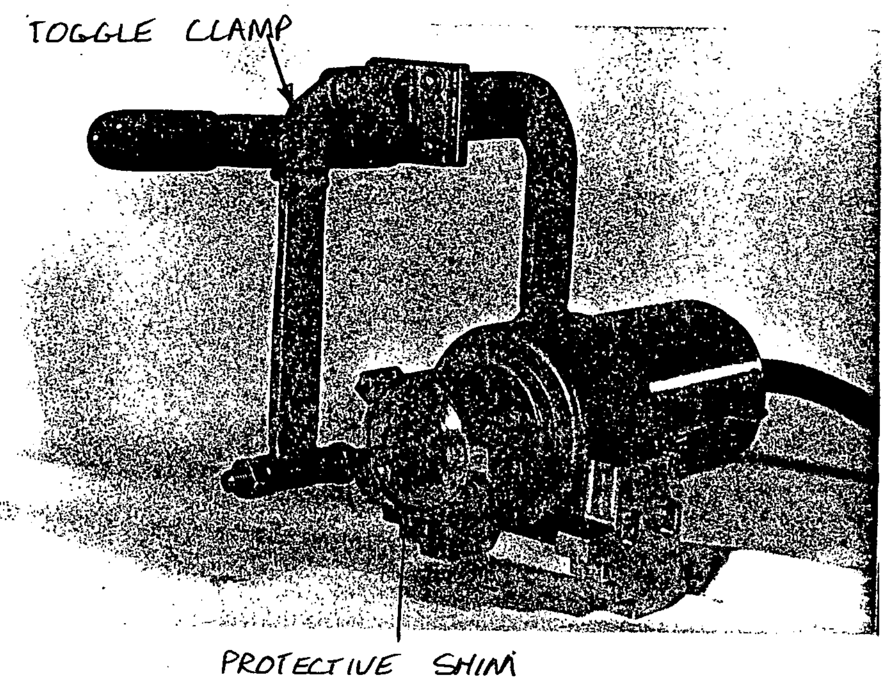


Figure 5.7 ARR-3 Probe and Toggle Clamp.

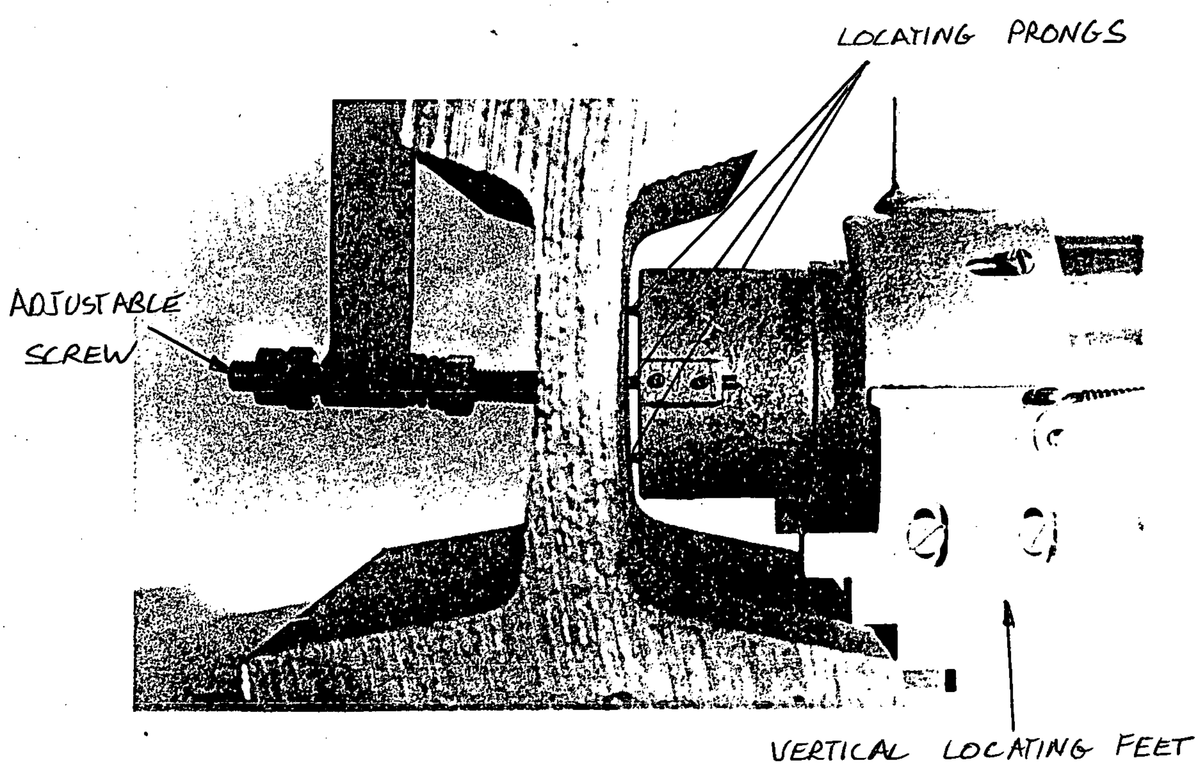


Figure 5.8 ARR-3 Probe (located onto 47 Kg/m rail sample).

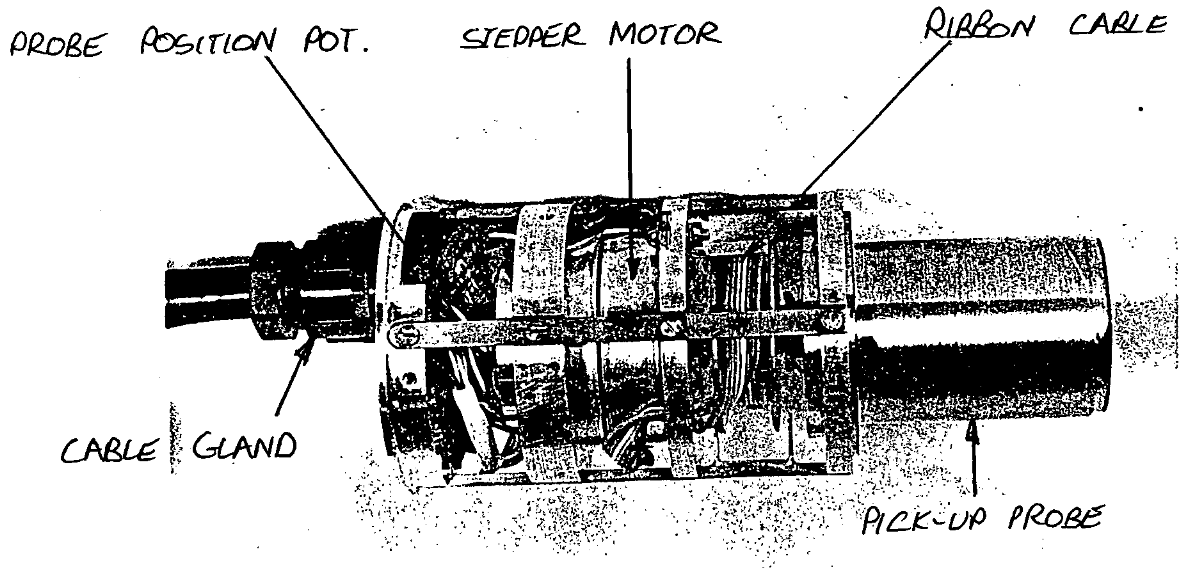


Figure 5.9 ARR-3 Probe (with cover removed).

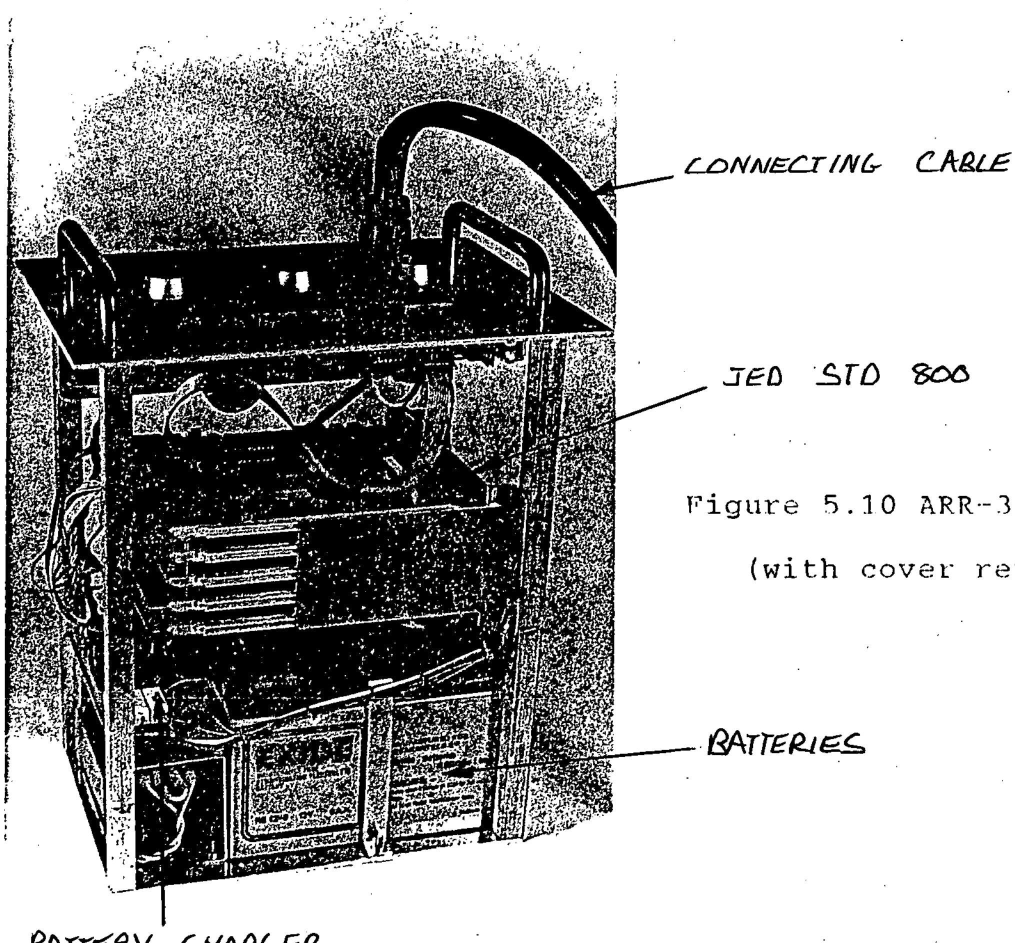


Figure 5.10 ARR-3 Chassis (with cover removed).

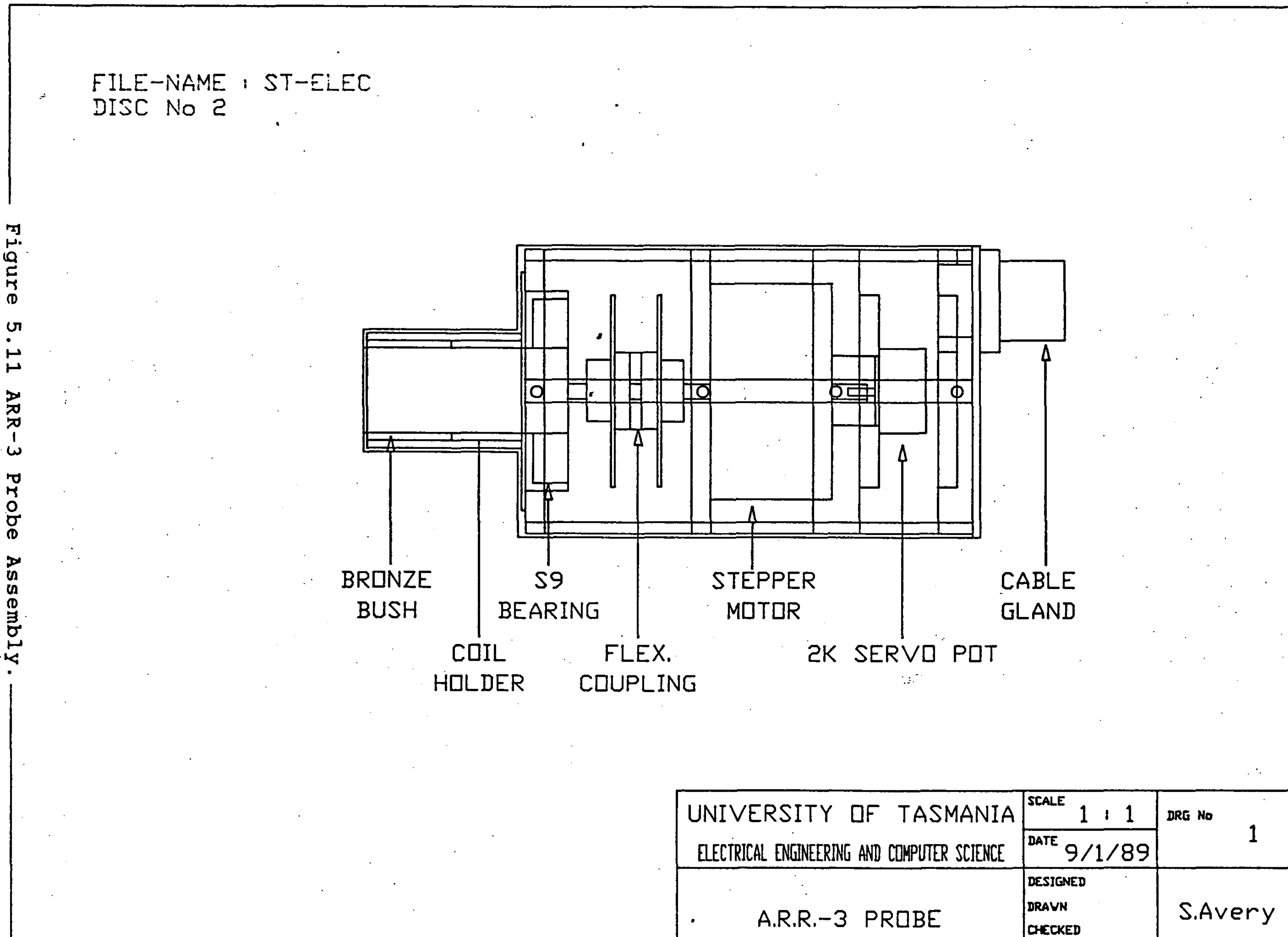
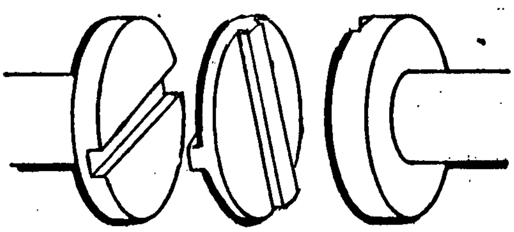


Figure 5.11 ARR-3 Probe Assembly.
(Designed and Drawn by S. Avery)

The rotating probe is connected to the rest of the probe chassis by a ribbon cable. This is coiled around a spool which is connected to a flexible coupling between the stepper motor and the pick-up probe. The ribbon cable was made from a length of "rainbow" cable. This has not given any trouble in service, but the fatigue life of the connection is difficult to predict. The flexible coupling was originally chosen to be a bellows coupling on ARR-1, but was later changed to a sliding disc coupling (as shown in Figure 5.12). The flexible ribbon cable around the spool should be adjusted so that it is wound up when the probe is at its starting position. The length of the ribbon cable should also be adjusted so that the coil is not too loose when the probe is at its full angular rotation position. The reason for this adjustment is so that the ribbon cable does not fall off the spool while the rotation rigs are being transported or being used.



Sliding Disc Coupling

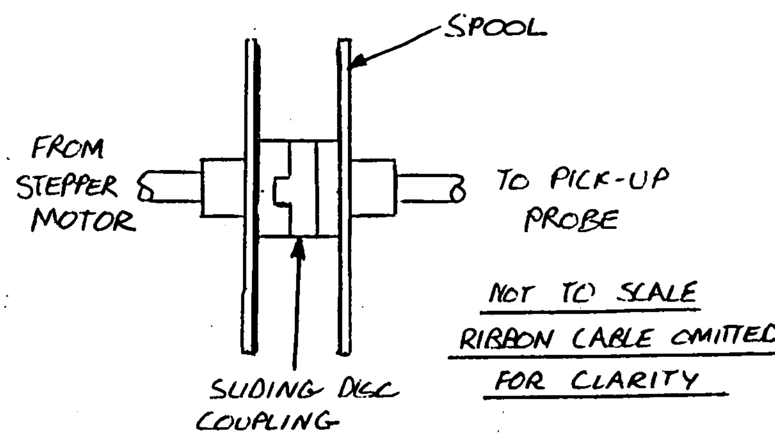


Figure 5.12 Sliding Disc Coupling Between Stepper Motor and Probe.

The rotating probe runs in a ball bearing race and a bronze bush (see Figure 5.11). The grease in the ball bearing was washed out and replaced with thin oil. The reason for doing this, was that in cold temperatures (less than 0° C), the grease was too viscous to allow reliable rotation of the probe. This sometimes caused step errors.

The end of the pickup coil is protected from the ingress of dust and liquid by a thin (0.33 mm) shim glued to the Bakelite end cover (as in ARR-1), to the aluminium end cover (as in ARR-2), or to the stainless steel cover (ARR-3). Note that this shim and the cover need to be non-magnetic as the magnetic excitation field needs to penetrate them in order to make stress measurements. All the material used in the probe should also be, as much as possible, non magnetic, as the device is quite sensitive and may give false stress readings due to these (even small steel screws may be detected if the are within approximately 50mm of the end of the probe).

To detect the angular position of the probe in ARR-2 and ARR-3, a 360° rotation potentiometer is connected to the shaft of the stepper motor. This potentiometer is designed for servo applications and is of the conductive plastic variety. During manufacture, the potentiometer it set up so that the end of the plastic conductive track corresponds to the mechanical stop (this is provided so that the probe can only rotate one turn). Note that although the potentiometer can rotate through 360° it is not recommended that the wiper continually crosses the end of the conductive track as this will reduce its service life.

In order to connect the potentiometer shaft to the stepper motor shaft the stepper motor must first be disassembled. This is not a very difficult task with the stepper motor chosen (RS 332-953, see Reference 5). The motor shaft is then concentrically counterbored to take a coupling piece. The coupling piece is pressed (slight interfernce fit) and glued into the shaft of the stepper motor. The motor is then reassembled and checked for ease of rotation. The potentiometer can now be connected to the motor shaft. Note that using this method for ARR-3 caused some problems that were not encountered on ARR-2. It seemed impossible to eliminate the misalignment between the potentiometer and motor shaft. This caused the motor to sieze and give step errors. This problem was cured by using a short length of flexible tubing between the stepper motor and the potentiometer shaft as a coupling.

The internal components of the probe for ARR-1 were held in place by an external plastic tube of 90 mm diameter. This was found to be unsatisfactory as it caused misalignment between the motor and the probe. To cure this problem, ARR-2 and ARR-3 were built in chassis form (see Figures 5.3, 5.9 and 5.11). The chassis is inserted into a 80 mm diameter stainless steel outer cover. Screws are then inserted through the outer cover into the chassis in order to hold the probe together.

ARR-1 was designed with a "G" clamp to hold it to the railway wheel. The probe slides in the clamp and is spring loaded so that it presses the end of the pick-up probe flat against the flange of the wheel. The springs are chosen so that the probe is held firmly against the steel surface, but not so hard as to damage the end of the probe, or the shim covering it. The spring loading was carried onto ARR-2, but the probe was held onto the wheel by magnets (see Figures 5.2 and 5.4). These worked well, but the probe assembly slipped down the flange of the wheel sometimes. This problem was cured by glueing emery cloth to the poles of the holding magnets (see Figure 5.4). The magnetic clamping method proved to be very easy to use in practice, but the probe must not be placed on the wheel where the magnets have been, as the residual magnetism from them will give a false stress reading. Residual magnetism from the magnets has been found to effect the stress measurement by up to 40 MPa (from Reference 12) which is too much to ignore.

The clamping mechanism for ARR-3 was designed to allow rapid attachment to a rail (see Figures 5.6 to 5.8). Because rails come in 6 different sizes (related to their mass per meter) from 39 Kg/m to 60 Kg/m then the probe had to be designed to fit all of these.

The end of the probe is located symetrically onto the curved face of the web by 3 prongs (see Figure 5.7 and 5.8). These were made from tungsten carbide (from broken printed circuit board drills) to reduce the wearing effect on them from the rough rail surface (rails are made from quite hard steel). The original design used three prongs, but after a suggestion from ROA this was changed to four, as it was found that some people had trouble correctly aligning the probe on the rail with three prongs. The prongs are designed to be adjustable, so that they can be set during manufacture to make the probe perpendicular to the surface of the rail web.

The vertical height of the probe is set by stepped aluminium blocks screwed to the sides of the probe. These were designed to give approximately the correct vertical height on all of the rail sizes (see Figure 5.8).

The probe is held in place by the use of a spring loaded toggle clamp. This can be set by the operator of ARR-3 so that it holds the probe holder to the rail reliably, but without excessive force. The probe slides in the probe holder and is spring loaded against the rail to allow the end of the probe to be firmly held against the rail. To aid the operator in aligning the probe against the rail, the probe can be pulled back against the springs and held by a simple clamp. When the probe has been correctly located, then the clamp is released and the probe slides so that it is snug against the web of the rail. The end of the probe is machined to a dome shape so that it fits the curve of the web of the rail and brings the end of the probe as close as possible to the steel surface. This helps to increase the sensitivity of the device.

All the connecting cables between the probe and the main electronics chassis are sealed and clamped by the use of 20mm industrial cable glands. During final assembly of the probe all joins and screws are sealed with silicon rubber. This effectively makes the probe completely waterproof.

The excitation, SCm and SCp coils are encapsulated in the rotating pick-up probe. The outside of the probe is a thin non-magnetic stainless steel tube (about 22 mm in diameter). These were designed by Richard Langman and built by Steve Avery. The excitation coil is wound directly onto a C-core made of mu-metal laminations with 200 turns of 34 B & S enamelled copper wire. This coil has been designed to have an impedance of approximately 8 Ω at 144 Hz, to match the output impedance of the excitation amplifier. There are two SCp coils and these are connected in series. These coils are placed so that they line up with the magnetic field between the ends of the C-core. As the signal level in these coils is high, then they do not need to be as carefully aligned as the SCm coils. Both the SCp coils consist of 1500 turns of 44 B & S wire wound on a small plastic bobbin (approximatly 6 mm in diameter by 8mm in length).

The probes are difficult to construct, as the coil for SCm uses very fine (48 B & S) wire. As many turns as possible are wound onto a plastic former of similar size to that used for SCp.

For ARR-2, 4700 turns were wound onto the SCm coil. This coil then needs to be aligned with the magnetic field between the poles of the excitation C-core. This is achieved by carefully aligning it and looking at the output voltage from the SCm filter, while the probe is in air. The SCm coil is adjusted so that the output from the filter is as close to zero as possible. The stainless steel tube is placed around the completed probe and filled with Araldite core potting epoxy. This will hold the SCp, SCm and excitation coils in place and make the probe quite robust.

5.2 Chassis Design.

Both ARR-1 and ARR-2 chassis's were made with a sheet metal cover screwed directly to a frame work of 10mm by 10mm square section aluminium. The front and back panels were made of 3mm thick Aluminium sheet. The layout of the ARR-2 front panel can be seen in Figure 5.1.

ARR-3 was constructed in a similar fashion (see Figure 5.10), but the chassis slides into a welded sheet steel cover. The front panel of ARR-3 has a groove machined into its back. A rubber O-ring is placed in this groove and this seals the front panel to the steel case. The three switches mounted on the front panel (see Figure 5.5), are sealed industrial pushbuttons and all other additions have been sealed with silicone rubber. This means that the case for ARR-3 is waterproof. To protect the glass LCD display, it is has a surrounding bezel. This has been designed so that the bezel and the front panel will hopefully absorb any shock loads, if something is dropped on ARR-3, instead of the LCD display.

All three rotation rigs have their batteries mounted in the bottom of the chassis to make them more stable. This puts the weight distribution towards the bottom of the chassis and helps to prevent them falling over. In ARR-2 and ARR-3, the battery charger circuit and mains transformer are also mounted in the bottom of the chassis (see Figure 5.10). Above the batteries the excitation oscillator, filter and stepper motor drive electronics are mounted on a printed circuit board (PCB). This has been designed to fit onto a "STD" size card (115 mm by 165 mm) to match the JED STD 800 computer board.

Above the Excitation/Filter and Stepper Motor Drive PCB, the SCm preamplifier circuit is mounted. This is enclosed in an aluminium box and mounted onto a sheet of aluminium that has the same dimensions as a STD card. Above the SCm preamplifier the JED STD 800 board is mounted. All three of these boards are mounted in a card rack.

The connections between the boards, batteries and the probe, consist of a STD edge connect for both the JED STD 800 and the Excitation/Filter and Stepper Motor Drive PCB (see Appendix F) and various interboard connectors (see Appendix G). The layouts for the SCm preamplifier, Battery Charger and the Excitation/Filter and Stepper Motor Drive circuit boards for ARR-3 are also shown in Appendix G.

5.3 Conclusions.

The ROA decided that the case for ARR-2 was not adequately sealed against water and dust for extended field use. ARR-3 was designed to overcome this problem and was generally successful with the exception of being slightly too large and heavy. As most of the weight of the ARR is in the batteries (which cannot be reduced in capacity) and the chassis, then to reduce the weight, the chassis must be made out of lighter materials. The cover for the chassis on ARR-3 is made from steel. If this was replaced with an aluminium or fiberglass cover, then there would be a useful reduction in weight.

Some problems were encountered with the interboard wiring connections. These were needed in the field prototypes because they had to be easy to build and modify. In production versions, the interboard wiring should be soldered to the boards permanently. Another modification which will also improve the reliability of the rotation rig is to remove the card rack and bolt the boards directly to the chassis.

The probe design worked reasonably well except that it is difficult to manufacture and has the problem, in the case of ARR-2, of having the mass of the stepper motor away from the holding magnets. This means that it is easy to dislodge the probe from the flange of the railway wheel. Because the probe assembly is heavy, then if it were to fall onto a hard surface, it may be damaged. To reduce this possibility, it is proposed that a revised layout for the probe should be considered if they are to be manufactured. A schematic of the probe design is shown in Figure 5.13.

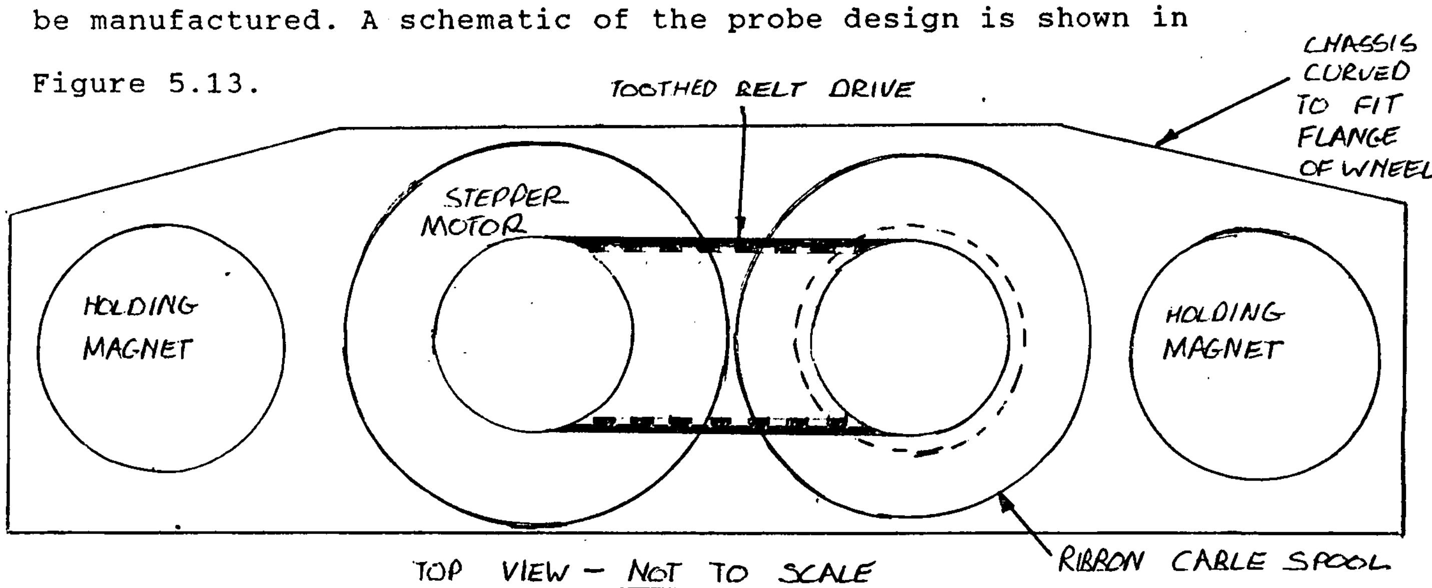


Figure 5.13 Revised Probe Chassis Scematic.

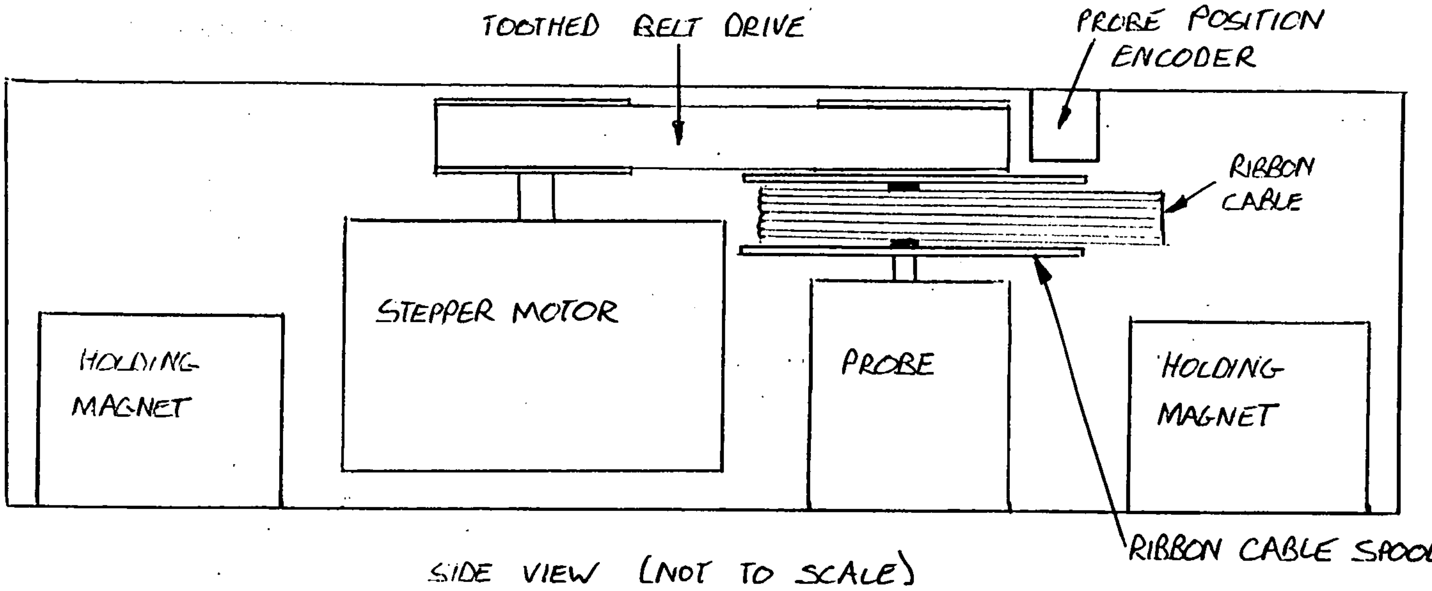


Figure 5.13 (Continued) Revised Probe Chassis Schematic.

The stepper motor has been placed alongside the pick-up probe, with both placed between the magnets. This would mean that the magnets would not need to be as strong as those used on ARR-2 as the cantilevered weight of the stepper motor has been removed. The probe is rotated by a toothed belt and the signals are fed to and from it via a ribbon cable connection, similar to that used in ARR-2 and ARR-3 (but without the sliding disc coupling).

The probe position potentiometer could be replaced by an optical position encoder attached to the top of the ribbon cable spool. This could be connected to one of the I/O ports on the JED STD 800 board (this would also mean some modifications to the control program).

If the chassis for the probe was machined from a block of aluminium, then the completed probe would weigh far less than the current design. Note that the springs used to hold the end of the probe to the metal surface of the wheel have been removed in this design. This means that far more care would be needed in making sure that this surface was clean and free from excessive roughness, as this may prevent the probe sitting flat.

CHAPTER 6

CALIBRATION AND TESTING OF THE ROTATION RIGS

All three automatic rotation rigs were tested in similar manners. The stress measurement method gives an arbitrary sensitivity of the variation of SCm with stress. This means that the ARR's need to be calibrated by taking SCm and SCp readings while the probe is on a stressed sample. The stress in the sample is measured by resistive strain gauges. Thus, a calibration graph showing the variation of SCm with stress can be produced. The steel sample used in the calibration procedure must be of the same material as the object to be measured in the field. This is because the sensitivity of SCm with stress, changes with different types of steel (i.e. different steels have different magnetic "hardness").

The SCm sensitivity is also dependant on the actual state the sample is in, i.e. whether or not it has been heat treated, work hardened or demagnitised. Hence, in order to get an accurate calibration curve, a sample must be taken from the object to be tested, such as a donor wheel (or from material of the same caracteristics). For example, in the case of railway wheels, a section is cut from a wheel which is large enough to be used as a tension sample in a testing machine. This sample must not undergo any excessive heating during the cutting operation as this may affect the sensitivity of the SCm calibration. The size of the sample determines the method of calibration, but all samples need to be at least 10mm wider than the width of the pole pieces of the probe (22mm). This is so that the calibration will not be influenced by edge effects. These can be caused by stray magnetic flux from the poles of the excitation coil or by the stress gradient close to the edges of the sample.

Several types of testing machines were used during the calibrating of the automatic rotation rigs at the University of Tasmania. A Shimadzu Universal Testing Machine (type RH-10 T.V.) was used for the majority of the tension testing. It was not possible to do compression testing in this machine due to bending of the samples. The larger samples cut from railway track needed larger loads to be placed on them than could be supplied by the Shimadzu Universal Testing Machine. These samples were tensioned on an Avery 7104 Universal testing machine (up to 1000 kN). Resistive stain gauges were placed either on a position opposite to the location of the rotation rig probe or on a surface of the sample close to the location of the probe. The strain gauges are connected to a commercial strain gauge bridge. Thus the strain at the surface of the sample due to the applied stress can be measured. This can be converted to a stress using the usual stress/strain relationship (using the Young Modulus).

The sample is the progressivly tensioned and then relaxed. This gives a calibration for the sample for increasing and decreasing values of tension. From these results the effects of stress hysterisis can be seen (see Figure 2.4). The cause of this effect is not known at present, but some investigations have been carried out in Japan by Kashiwaya et. al.(see Reference 20) and also by R.A. Langman at the University of Tasmania. It has been found that demagnetising the steel in the direction of the principal stresses eliminates the effect of stress hysteresis to some extent. However, more investigation needs to be done into this problem before a definate solution is found.

Another method of obtaining a calibration curve is to use a bending rig (see Figure 6.1). In this method the sample is bent (elastically) causing tension on the convex side and compression on the concave side of the sample. Thus, with the use of strain gauges, calibration curves for both tension and compression can be obtained. Using this method, though, it must be noted that the slight amount of curvature caused by the bending will effect the calibration curve. The curvature will induce an offset to the stress calibration. To try and reduce this effect, relatively large and stiff samples should be used so that at high stress levels (say >100 MPa) the curvature is small (i.e. radius of curvature > 1.5m).

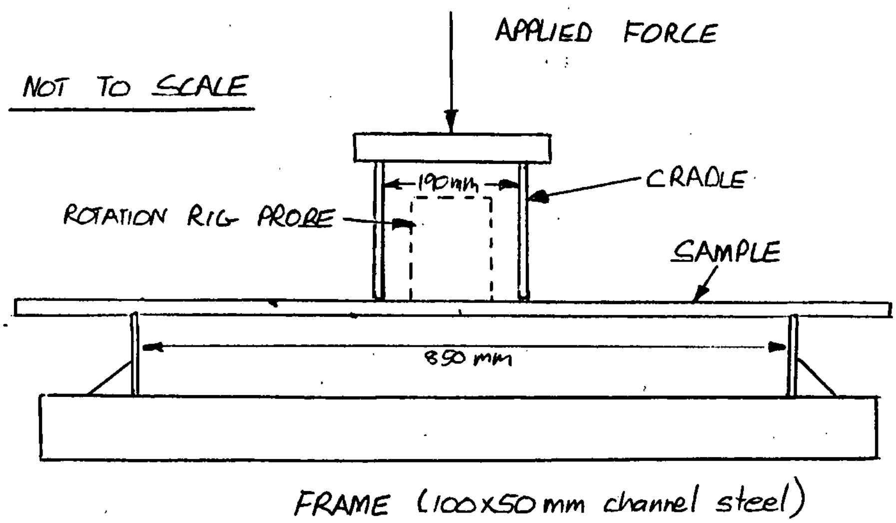


Figure 6.1 Bending Rig.

The force is applied to the bending rig by either using long bolts from the cradle to the frame, or by pushing between the cradle and frame using a testing machine (Amsler 8766). The testing machine was the more convienient method of the two.

Curvature is also a problem with the measurement of residual stress in railway lines. The web of the rail, where the stress measurement is taken, is curved. The web was chosen as the best position for the stress measurement (by ROA and R.A. Langman).

This is the closest position to the neutral axis of the rail that the stress measurement can be taken. Thus the stress measurement will be less susceptable to residual stresses induced by the manufacturing process or any following bending of the rail.

The radius of curvature of the web of the rails varies between values of 300 mm and 483 mm depending on the size of the rail. This value, in practice tends to vary a reasonable ammount compared to those specified in the Australian Standards for railway tracks (see AS 1085, Reference 18). This will of course affect the calibration of ARR-3 to some (unknown) extent.

Reliability testing of the rotation rigs consisted of using them in field trials. The field trials for ARR-1 and ARR-2 in Tasmania consisted mainly of using the rigs at the Australian National Railway (ANR) workshops in Hobart on free wheels and some locomotive wheels. ARR-3 was tested at the Hobart ANR railway yard on railway track by R.A. Langman. This enabled a "feel" for the equipment to be obtained and allowed time for any minor faults to show up before the rigs were sent over to ROA in Victoria.

When ARR-2 was sent to the ROA it was field trialled in order to find any faults. Some minor faults were found and these are described in the summary for ARR-2. At time of writing, ARR-3 has not undergone any field trials with ROA.

In order to test for the drift of SCm with temperature, ARR-2 was placed in a cabinet with a heater. The probe was placed outside the cabinet on a sample with residual stress in it. The cabinet was heated and the SCm value versus temperature was noted. It was found that the SCm reading did not change with temperature to any significant amount, until the temperature of the case rose above 70°. Hence it is recommended that any stress measurements taken at temperatures in excess of this should be treated with suspicion.

To check the variation of the calibration with temperature a sample was heated with resistive heaters and placed in a bending rig. Calibration graphs were obtained for variation in temperature. The results were related to the values of SCp and thus these can be used with the Δ SCp method (as described in the operators manual for ARR-2, see Appendix A). Thus from these results the rotation rigs were corrected for changes in calibration due to ambient temperature (this being due to the resistance of the excitation coil changing with temperature).

The change in SCp value with airgap between the end of the probe and the sample surface was measured. This was achieved by placing 0.1 mm paper spacers under the probe and taking a set of calibration readings using a testing machine. Thus the change in calibration of SCm, that may be caused by temperature or rust or scale under the probe can be corrected for using the Δ SCp method.

CHAPTER 7

CONCLUSIONS.

All the automatic rotation rigs have performed to expectations. They have all given some minor problems with their operation, but these have been eliminated by "running repairs" and by carrying out improvements to each successive rig. ARR-3 is the most advanced automatic rotation rig, but it still needs to undergo some further development, particularily in the probe design, to make it cheaper and easier to manufacture (see Chapter 5).

At present, full Australian Patent Applications have been lodged for the automatic rotation rig by the University of Tasmania (Research Company) and the Railways of Australia Committee. Procedures for filing for International Patents have also been undertaken. As the results from the comparative tests between the Trepan-ring, Barkhausen noise and Automatic Rotation Rig residual stress measurement techniques look promising, then the manufacture of more automatic rotation rigs may proceed in 1989. It is proposed by ROA that these rigs, based on ARR-2 and ARR-3, will be used around Australia in order for a data base of results to be accumulated. These will be used to further validate the ability of this stress measurement technique in detecting unsafe, thermally damaged railway wheels.

The changes that would be needed to make the rotation rigs suitable for manufacture have been described previously in this thesis. Although the automatic rotation rigs as described in this thesis has been built to solve particular stress measurment problems, that is, the stress in the rim of the wheel and the stress in railway tracks, does not mean that it is limited only to these applications. The ARR could be used to measure the differences in principal stresses in any reasonably flat, magnetic material. The most important thing to note is that magnetic anisotropy can only measure the differences in principal stresses. Thus if the device is placed onto a steel surface which has equal amounts of tension or compression in the principal directions then the rotation rig will give the value of the stress as zero. This may make the ARR unsuitable for stress measurement in magnetic materials in some cases.

As an overall conclusion, at the present time, little further development needs to be done to the automatic rotation rig design, but more research needs to be carried out to understand the principal of magnetic anisoptropy better. This may lead to the technique becoming more accurate, especially if the problem of stress hysterisis can be eliminated.

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APPENDIX A

INSTRUCTION MANUAL FOR AUTOMATIC ROTATION RIG 2 (ARR-2)

Automatic Rotation Rig Number 2 (ARR-2)

Operator's Instruction Manual

By: I. Hutchinson,
Department of Electrical Engineering,
University of Tasmania.
January 1988.

Contents

1. Introduction

The ARR-2 (Automatic Rotation Rig, version 2) was designed and built during 1987, at the Electrical Engineering Department, University of Tasmania, with funds provided by Railways of Australia.

It is based on a previous Automatic Rotation Rig (ARR-1) that was developed in order to measure the magnitude and direction of residual stresses in the rims of railway wheels. (Strictly, only the difference in the principal stresses and their direction are measured. However, for brevity, "stress" is used here rather than "stress-difference").

ARR-2 consists of a main case which houses the batteries, battery charger, control electronics and visual display, and a probe which is connected to the main case by a flexible cable. The probe contains a laminated magnetising C-core and 3 small pick-up coils, all encapsulated in a 22 mm diameter tube, which may be rotated through 360° by an electric motor as shown in figure 1. Magnets are used to hold the probe against the rim of the wheel.

The C-core is wound with a coil that carries 144 Hz alternating current. This magnetises the surface of the wheel rim and the alternating magnetisation induces voltages in the pick-up coils that give information about the amplitude and direction of the stress pattern inside the steel.

Because of the need to make measurements "in the field" ARR-2 is completely portable and operates off its own internal batteries. It can operate for a full (8 hour) working day, with its batteries being recharged overnight from a normal 240V AC mains socket via an internal battery charger.

The following instruction manual has been written in order to help the operator of ARR-2 to use the instrument correctly, and to provide some information on the range of readings to be expected.

Note: It is recommended that the probe not be picked up or carried by its cable, as this could put undue force on the cable connector.

2. Turning on ARR-2

Note: ARR-2 should not be connected to the mains while stress measurements are being made.

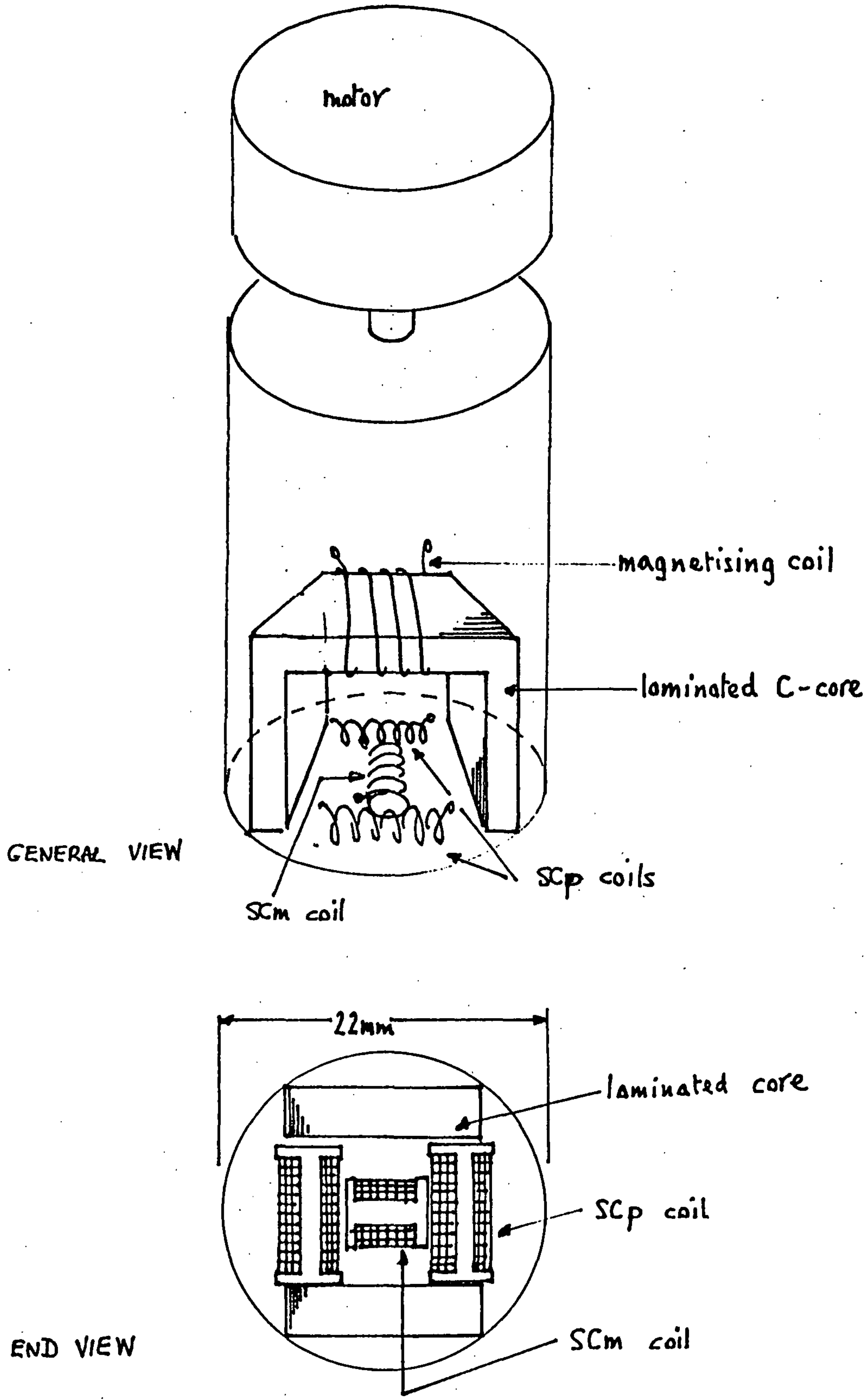


FIGURE 1

The probe, showing the magnetising C core, and pick-up coils.

Turn the key-switch clockwise towards "ON". The "ON" indicator should light up, and ARR-2 should display the following message, on its liquid crystal display, for a few seconds:

```
      *****        ARR - 2/01        *****
Mechanical Stress Measurement Instrument
```

and should then display:

```
<GREEN> = Run, <AMBER> = Abort Run
<RED> = Goto Support Menu, BATTERIES OK
```

ARR-2 is now ready for operation.

In the panel display, in the box, <GREEN> means press the green key, <AMBER> means press the amber key, etc.

The fold-out chart shows the program logic. The writing in blue is the "main menu". If the green key is pressed, the instrument takes a reading of stress. If the red key is pressed, it goes into the "support menu" which gives battery voltage and temperature.

(If the above operation is not correct then consult the "Incorrect Operation" section in this manual for further information).

3. <u>Taking stress measurements with ARR-2</u>

With ARR-2 turned on and with the probe placed flat against the rim of the wheel, pressing the green button on the keyboard will instruct ARR-2 to take a stress measurement (see chart of operation on last page). Each measurement takes about 15 seconds and at each placement of the probe as many readings as wished can be taken. After each reading has been taken, ARR-2 will display the numerical values of three parameters: "SCm", "SCp", and "Θ". SCm is a voltage induced in the middle pick-up coil (see fig. 1) and is proportional to the magnitude of the residual stress in the rim of the wheel. Reference should be made to the type of steel the wheel is made of and SCm related to the stress difference via the calibration curve for the steel. (see APPENDIX A).

SCm is affected by surface roughness which alters the effective air-gap between the end of the probe and the wheel steel. In order to be able to correct for this, the value "SCp" is displayed: this is the voltage induced in the end pick-up coils, and which also depends on the air-gap. The value of SCp with the probe in air is also needed. Appendix A gives calibration curves for different values of SCp (air) - SCp (steel), plus an example of how the stress difference is estimated from the readings obtained.

ARR-2 also displays the angle Θ, with respect to the red line on the back of the probe (parallel to the holding magnets), of the direction of principal tension. From this angle it can be deduced whether the rim of the wheel is in compression or tension.

The following precautions must be taken to ensure that accurate readings are taken with ARR-2:

(i) Any loose rust, thick dust, dirt or grease should be removed from the surface of the rim of the wheel where the stress measurement is to be taken.

(ii) The end of the probe should be flat against the steel surface and the probe end, as defined by the copper circle on the end of the probe, should not overhang any edges on the rim of the wheel.

(iii) Major defects should be avoided, ie. holes, gouges, severe corrosion etc.

(iv) The probe must not be placed on the steel surface where the probe holding magnets have been as the residual magnetism from these will effect SCm and give an incorrect stress reading.

(v) Wait for 3 minutes after the initial turn-on for the instrument to stabilise.

If ARR-2 is turned off whilst it is taking a reading, its program returns to the starting point (see section 2) when it is turned on again. It is recommended that ARR-2 be turned off for any break in operation of more than 10 minutes, in order to save the batteries.

4. Expected results

The following should be used *only as a guide* to determine whether or not ARR-2 is giving correct readings.

(i) SCm. This varies with stress and as such can take almost any value. When a reading is taken with the probe away from any metallic objects SCm should be small, about 0 to 10 (excluding the case when ARR-2 may give a "Suspect SCm reading"). When the probe is on steel, suspect any SCm reading which is above 400.

(ii) SCp. This should be between 590 and 660, the lower end values being for low carbon steel, and the higher end values for the probe in air. Suspect any readings outside this range. Also suspect incorrect operation if the SCp value varies by more than 3 when repeated readings are taken without the probe being moved.

(iii) Angle Θ. This should give a reading from 0 to 180 degrees and should not vary by more than 4 degrees in repeated readings.

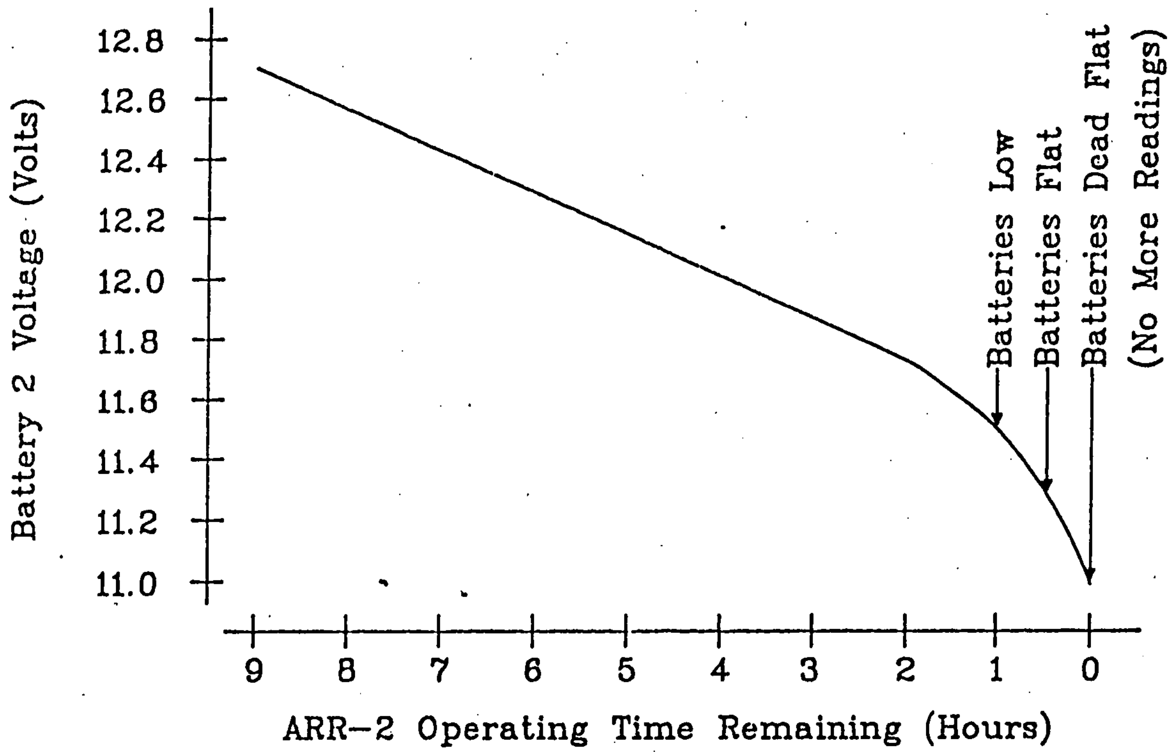
(iv) Any of the "Error Messages" shown in the "ERROR MESSAGES" section should not occur regularly. (The exception is the "suspect SCm reading" message, which can occur normally and quite correctly when a reading is taken in air or on a wheel with a very low residual stress at the surface. It should not occur when a stress measurement is taken on a steel sample known to have a measurable stress).

If any of the above conditions are not met then the operation of ARR-2 is incorrect, and any readings taken should be suspect. ARR-2 may need to be returned for servicing and recalibration.

5. Support menu

The support menu can be reached from both the main menu and the run menu. If has been included so that the battery voltages and case temperature can be read.

The normal voltage range is from about 13V (fully charged batteries) to 11.3V (discharged batteries). It is normal for battery 2 to discharge faster than battery 1. With the aid of the battery voltage and the following graph the operator can predict approximately how much operating time remains. (The operating time of ARR-2 totals about 8 hours).



The case temperature can be displayed. This feature has been included since excessive temperatures may corrupt readings. ARR-2 has been designed to operate correctly over a temperature range of 0° C to 70° C. If the operator feels that high case temperatures are influencing the accuracy of the readings then the temperature can be measured using this facility.

6. <u>Charging the batteries</u>

The batteries can be recharged at any time, as the battery charger included within ARR-2 will not overcharge them. To recharge the batteries the following procedure should be followed:

(i) Turn the key switch (if it is not already so) anti-clockwise to point at the "Boost Charge" push button switch.

(ii) Connect the IEC mains lead to ARR-2 and to a 240 V AC mains socket.

(iii) Turn on the mains.

(iv) If the batteries are discharged then the "Battery Charged" indicator will not be lit and the batteries will be charged at the "Boost" charge rate.

(v) If the "battery charged" indicator lights then the batteries are being float charged.

(vi) The "Boost" charge rate can be applied to the batteries at any time ARR-2 is connected to the mains by pressing the "Boost charge" push-button switch. The battery charger will switch back to float charge automatically when the batteries are charged.

Note: (a) The batteries are not being charged when ARR-2 is turned on. This is to prevent the possibility of interference to ARR-2 from noise on the mains supply. If ARR-2 is connected to the mains while it is turned on then the "battery charged" indicator will light up regardless of whether or not the batteries are in fact charged. The purpose of this is to remind the operator to disconnect ARR-2 from the mains supply while ARR-2 is being used to take stress measurements.

(b) If the batteries are partially discharged and the battery charger has just been connected to the mains supply then the "battery charged" indicator may light up even though the batteries are not fully charged. To check this it is recommended that every time that ARR-2 is connected to the mains for the batteries to be charged and the "batteries charged" indicator comes on, then the "Boost charge" push-button switch should be pressed. The "battery charged" indicator will relight after a short period of time if indeed the batteries were charged.

7. <u>Error messages</u>

ARR-2 has been designed to inform the operator if some identifiable incorrect operation has taken place. The following paragraphs show the Error messages that ARR-2 can display, their cause, and any action that the operator can take.

```
NO PROBE SIGNALS!!!,<0> = Try Again
Is the Probe Connected ?
```

ARR-2 does not detect signals from the probe. Check that the probe is properly connected, and press the <0> key on the keyboard to proceed with the operation of ARR-2. If the probe is connected to ARR-2 then there is some other fault in the probe or its connecting lead. This cannot be serviced by the operator and ARR-2 must be returned for service. (refer to section 8).

```
STEP ERROR AT POSITION        9
<0> = Try Again
```

The coils in the probe have not rotated correctly. Hence the stress reading is incorrect. Pressing <0> key on the keyboard will return the user to the menu. If this problem is persistent, return ARR-2 for service.

```
INCORRECT REWIND!!!
<0> = Try Again
```

The coils have not rewound correctly after its operation. This indicates mechanical problems with the coil rotation mechanism. It will not affect any other operation of ARR-2, but ARR-2 should be returned for service if this problem persists. Pressing <0> on the keyboard will continue the operation of ARR-2. If the problem has not cleared the error message will persist.

```
NO PROBE REWIND
Technical Repairs Needed Now
```

After three attempts to rewind correctly, ARR-2 has not succeeded. Therefore is has deduced that something is wrong with the rewind mechanism and further operation of ARR-2 has been suspended. ARR-2 should be returned for service if this problem occurs.

```
BATTERIES DEAD FLAT!!!!
No More Readings, Recharge Now....
```

The batteries are dead flat and the correct operation of ARR-2 is threatened. Operation of ARR-2 is suspended. The batteries should be recharged immediately.

```
SUSPECT Scm READING!!!
<0> = Continue
```

The readings taken by ARR-2 in determining the SCm value were not in the correct form to enable a reliable result to be computed. This can occur when a reading is taken with the probe in air, away from metallic objects, or when the probe is placed on steel with very small residual stresses. If this message persists when a reading is taken on a sample with a known stress in it, then ARR-2 should be returned for servicing.

8. Servicing ARR-2

The amount of digital and analogue electronics incorporated in ARR-2 makes quick repair difficult for anyone who is not suitably trained and familiar with it.

If it is thought that ARR-2 is not operating correctly then either Ian Hutchinson or Richard Langman should be contacted by telephone at the University of Tasmania on (002) 202109 or 203135. If advice by phone is no use in eliminating the problem then ARR-2 should be returned to the University for servicing.

Return it to the following address:

Department of Electrical Engineering,
University of Tasmania,
GPO Box 252C,
HOBART, 7001,
Tasmania.

APPENDIX A : Calibration curves for wheel steels

Figures 2, 3, and 4 are sets of calibration curves that were measured in the laboratory on samples of steel cut from wheels. They relate the SCm voltage to the difference in the principal stresses in the steel. The error in the stress-difference corresponding to a particular value of SCm could be up to ± 40 MPa. This is mainly a result of a stress-hysteresis effect in the steel, and does not imply such inaccuracy in ARR-2 itself.

Each set of curves contain three curves that are for different effective air gaps between the end of the probe and the surface of the wheel. The larger the effective gap, the smaller is the SCm voltage for the same stress-difference. The effective gap will increase if a wheel is corroded; it cannot be measured directly, of course, but is detected automatically by ARR-2 by the change it causes in the SCp voltage. Each curve is marked with a value of ΔSCp, which is the difference between SCp on the wheel, SCp (steel), and SCp with the probe in air, SCp (air). (The latter should be read as soon as the reading(s) on a wheel have been taken; to do this, take the probe off the wheel and press the green key). Since SCp changes slightly with temperature as well as with air-gap, use of ΔSCp rather than just SCp (steel) means that the curves can be used over a range of temperature of at least 10°C - 45°C.

The direction of the more tensile principal stress is given by the angle Θ that is displayed. Θ is measured anticlockwise from the red line on the end of the probe.

Example of estimating stress-difference:

Suppose ARR-2 readings on a wheel made of AAR-C cast steel are:

SCm = 60, SCp = 603, Θ = 85°. Also, SCp (air) = 654.

Calculate: ΔSCp = SCp (air) - SCp (steel)

= 654 - 603

= 51

This corresponds to a curve about mid-way between those for ΔSCp = 54 and ΔSCp = 49 in figure 3. The stress-difference corresponding to an SCm value of 60 would be about 160 MPa, with an error of ± 40 MPa.

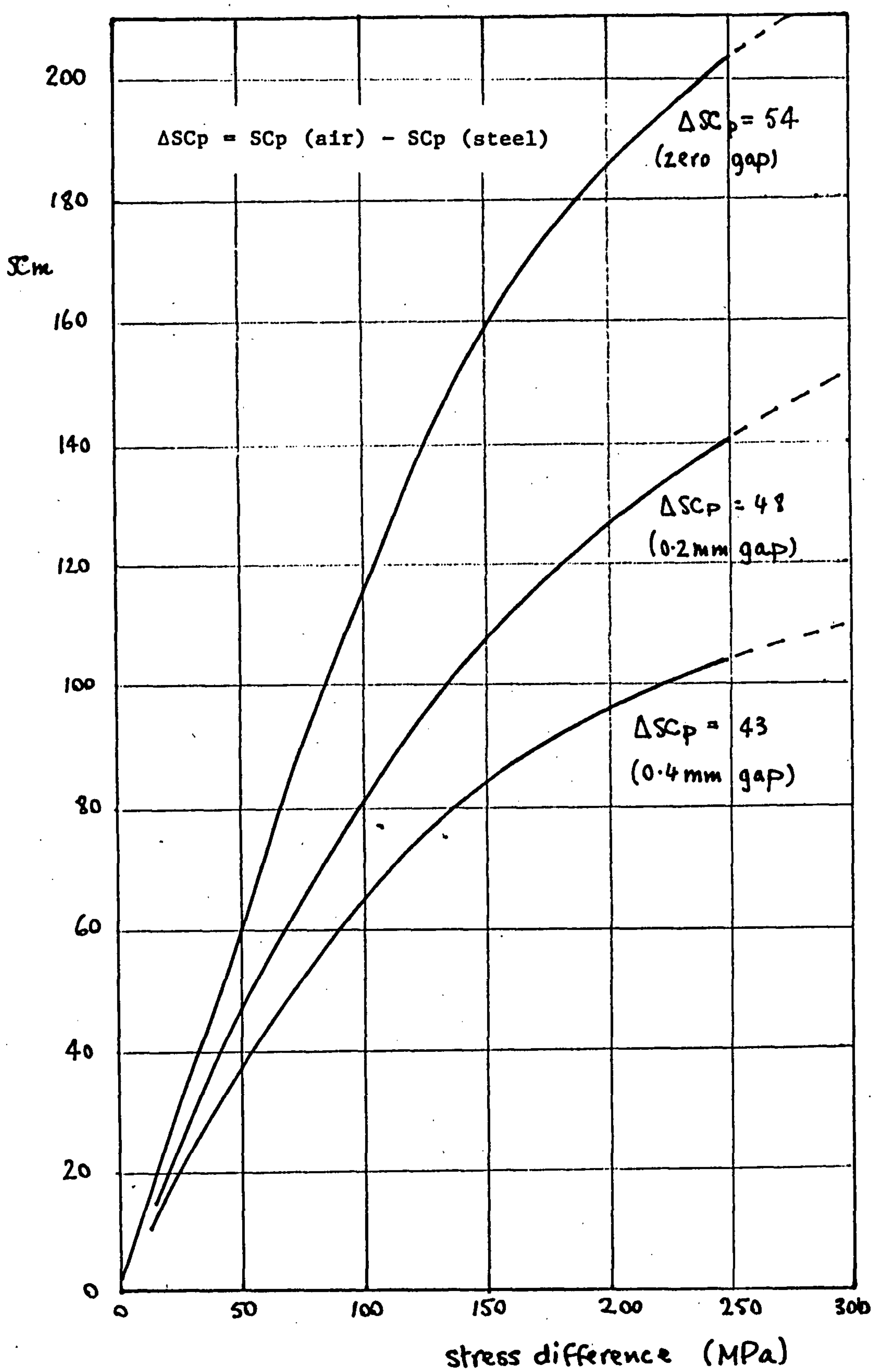


FIGURE 2

Calibration curves for British Standard C steel, (0.49% Carbon).

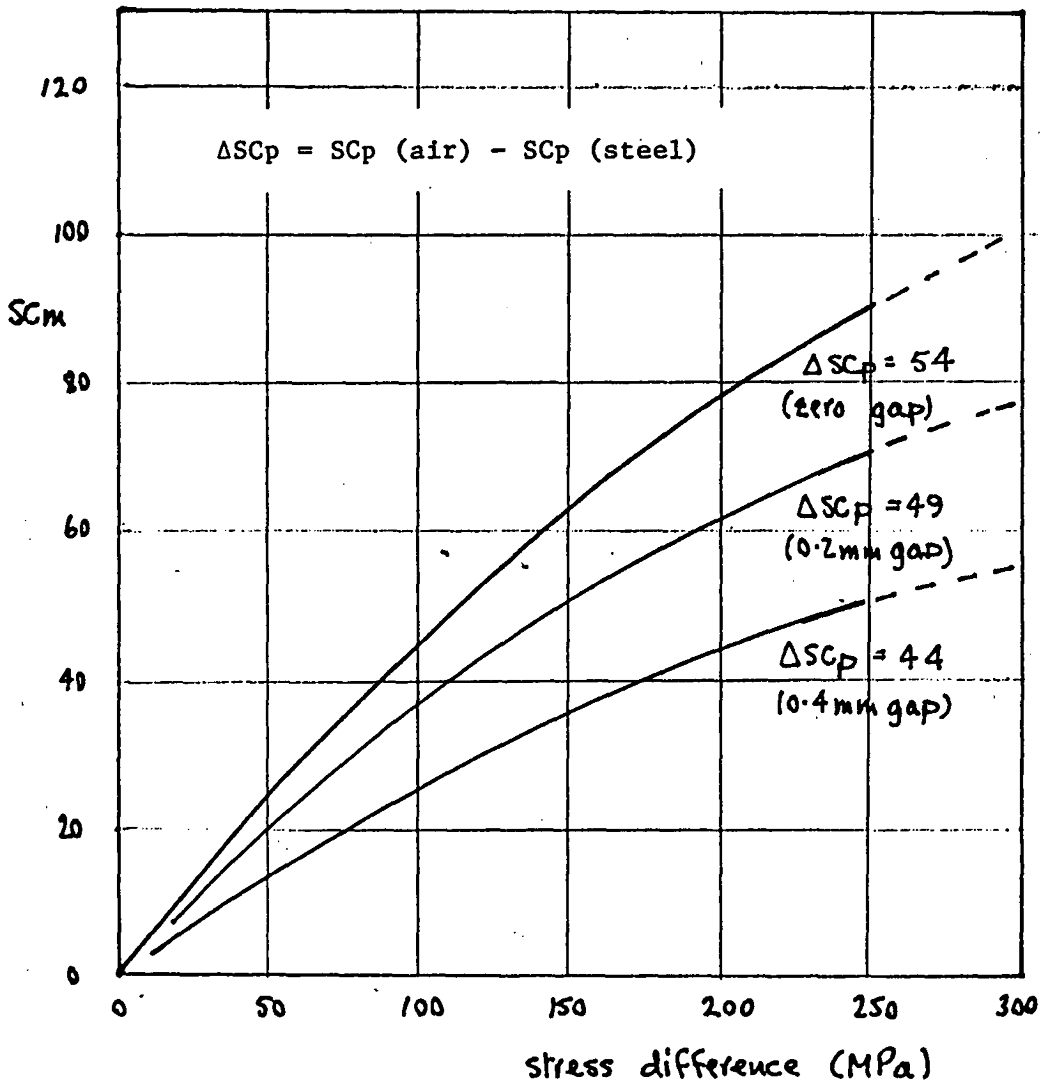


FIGURE 3

Calibration curves AAR M208 Grade C steel (cast, 0.72% Carbon).

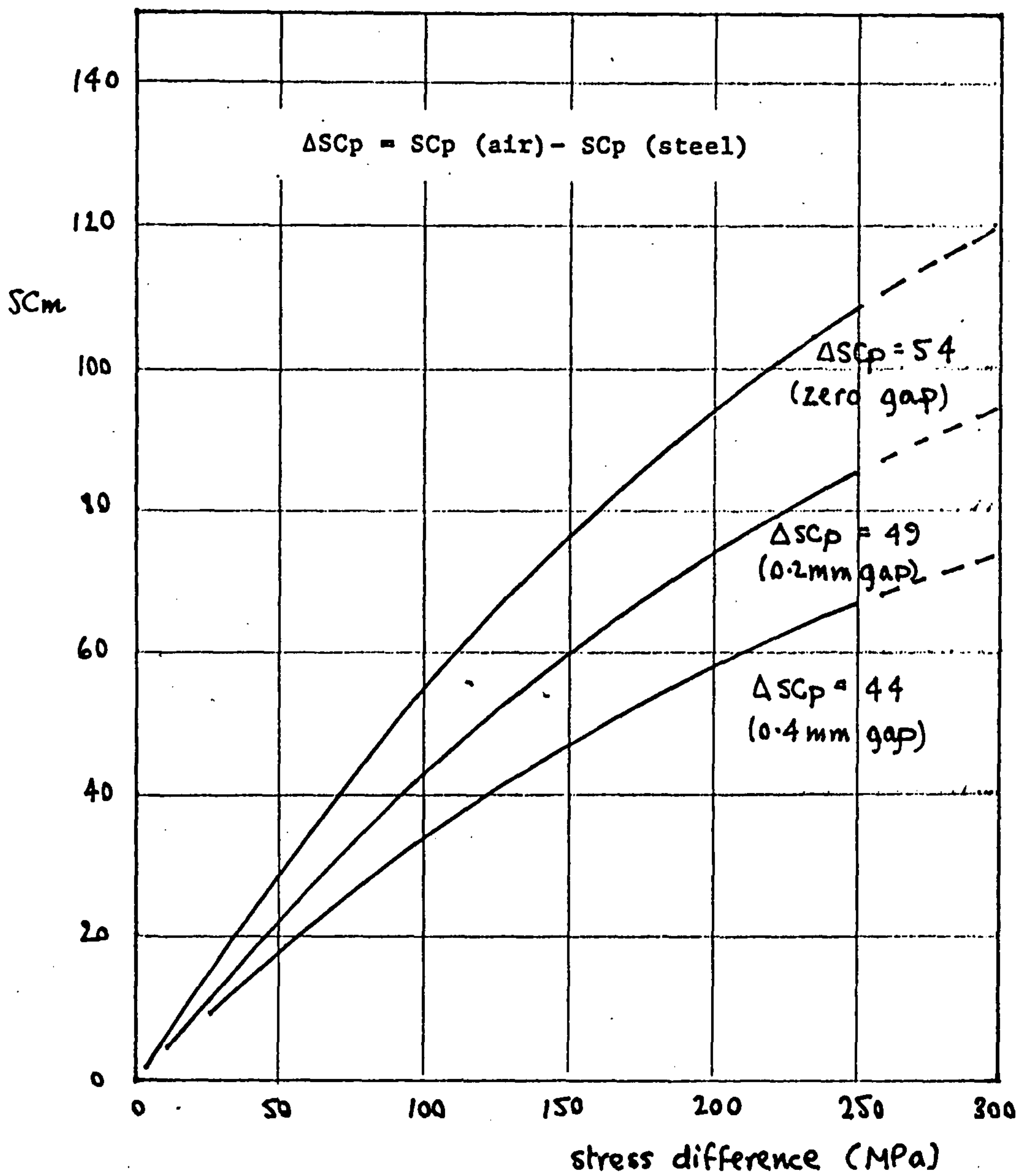
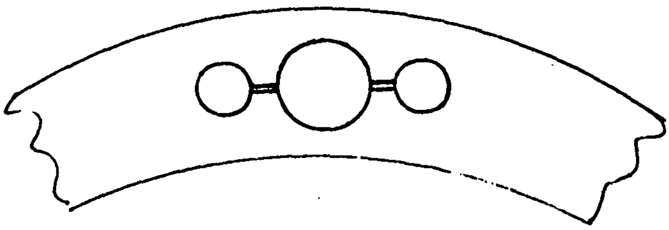


FIGURE 4

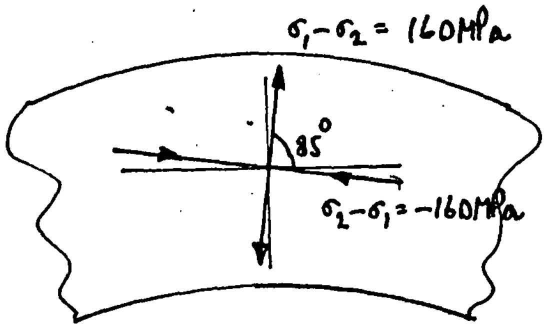
Calibration curves for AAR M107 Grade C steel (wrought, 0.68% Carbon).

$\Theta = 85°$ indicates the principal stresses σ_1 and σ_2 are at 85° and -5° to the red line on the probe, and that in the 85° direction the difference between the principal stresses is tensile. Since 85° is very close to 90°, the radial direction, ARR-2 tells us that the radial stress is more tensile (or less compressive) than the circumferential stress by about 160 MPa.

This is shown in figure 5.



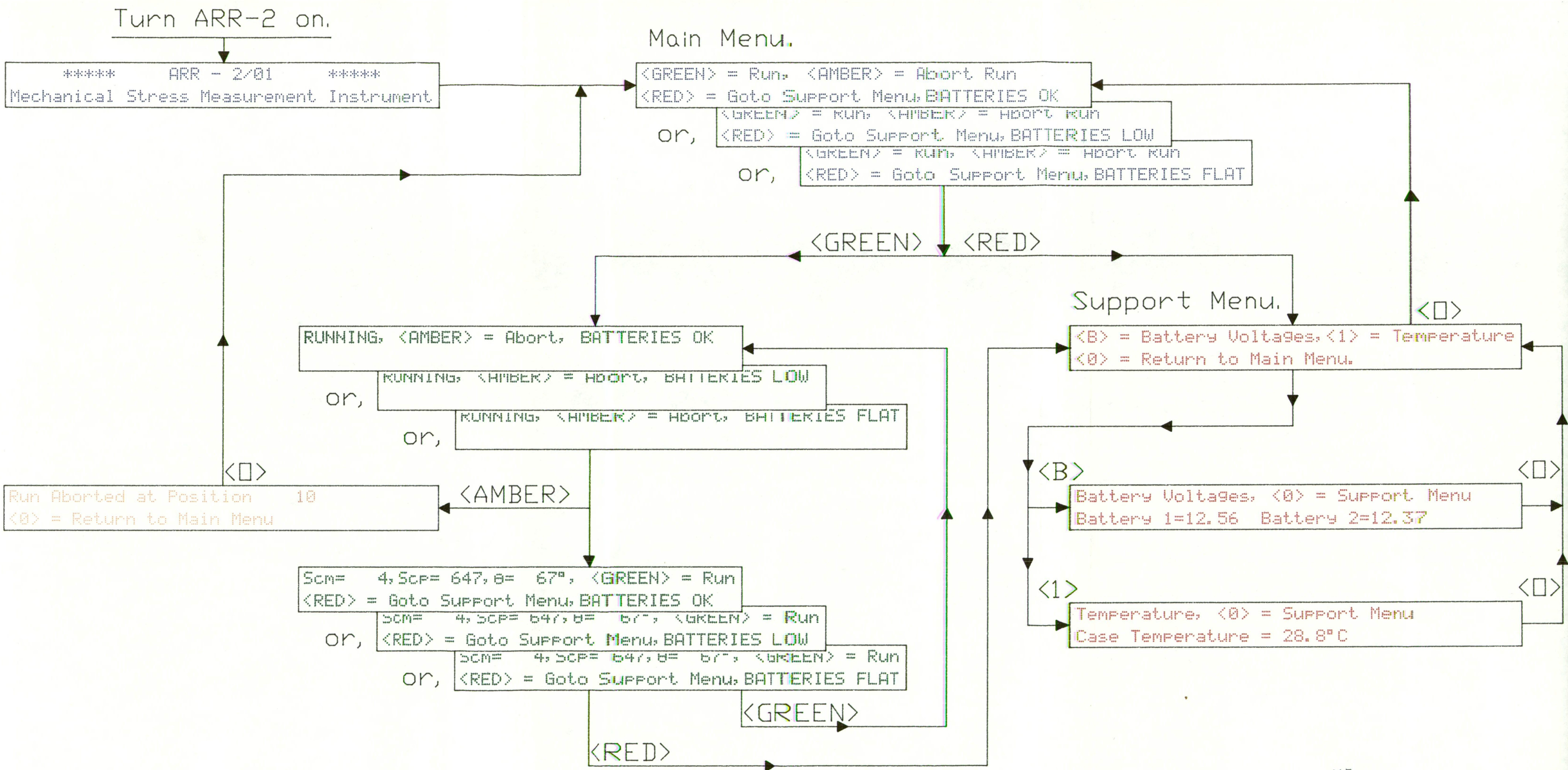
probe on the flange side of the wheel rim



directions and amplitude of difference of the principal stresses

FIGURE 5

Diagram to go with numerical example.


Turn ARR-2 on.
***** ARR - 2/01 *****
Mechanical Stress Measurement Instrument
Main Menu.
<GREEN> = Run, <AMBER> = Abort Run
<RED> = Goto Support Menu, BATTERIES OK
or,
<RED> = Goto Support Menu, BATTERIES LOW
or,
<RED> = Goto Support Menu, BATTERIES FLAT
<GREEN>
<RED>
RUNNING, <AMBER> = Abort, BATTERIES OK
or,
RUNNING, <AMBER> = Abort, BATTERIES LOW
or,
RUNNING, <AMBER> = Abort, BATTERIES FLAT
<0>
Run Aborted at Position 10
<0> = Return to Main Menu
<AMBER>
Scm= 4, Scp= 647, θ= 67°, <GREEN> = Run
<RED> = Goto Support Menu, BATTERIES OK
or,
<RED> = Goto Support Menu, BATTERIES LOW
or,
<RED> = Goto Support Menu, BATTERIES FLAT
<GREEN>
<RED>
Support Menu.
<0>
<B> = Battery Voltages, <1> = Temperature
<0> = Return to Main Menu.
<B>
<0>
Battery Voltages, <0> = Support Menu
Battery 1=12.56 Battery 2=12.37
<1>
<0>
Temperature, <0> = Support Menu
Case Temperature = 28.8°C

APPENDIX B

AUSTRALIAN PROVISIONAL PATENT APPLICATION FOR THE AUTOMATIC ROTATION RIG

NOTICE

1. This form is used to describe, in general terms, all the main essentials of the invention.

2. The description must start on the first page of this form and may continue on as many sheets of A4 International size paper as are necessary and should end on the last page of this form.

3. This form must be dated, show the applicant's name in block letters and be accompanied by a True and exact copy of the description.

ORIGINAL

FORM 9

COMMONWEALTH OF AUSTRALIA

The *Patents Act* 1952

PROVISIONAL SPECIFICATION FOR THE INVENTION ENTITLED—

Here insert Title of Invention as in Application Form.

A Method of Measuring Mèchanical Stress in Magnetic Materials

The invention is described in the following statement:

This invention relates to a non-destructive method of measuring the magnitude and direction of the mechanical stress within the surface of magnetic material.

The principle of this invention will now be described with reference to the accompanying drawings in which:-

Figure 1 is a side view of the magnetic core and coils.

Figure 2 is a plan view of the poles of the magnetic core and the detecting coil.

Figure 3 shows the appearance of the magnetic field between the poles of the core.

P/00/009

Figure 4 shows the direction of tension relative to the poles of the core.

Figure 5 shows the appearance of the magnetic flux density in the steel when the core is on a stressed steel surface with tension as in figure 4.

Figure 6 shows the appearance of the magnetic field between the poles for the conditions of figure 4 and figure 5.

Figure 7 shows the variation of detecting coil voltage with angular position.

Figure 8 shows the variation of detecting coil voltage, after filtering, with angular position.

Figure 9 shows the variation of voltage V_m (as defined in figure 8) with stress.

Figure 10 shows the variation of voltage V_m with difference in principal stresses.

A C-shaped magnetic core 1 is made of laminated magnetic material wound with an exciting coil 2 which carries alternating current (AC). An air-cored coil 3 is placed midway between the poles 5. When the core 1 and coils 2 and 3 assembly (hereafter called "the probe") is in air, well away from the magnetic materials, the direction of the magnetic field H is substantially straight between the poles as shown in figure 3.
During the manufacture of the probe, coil 3 is orientated and secured so that its axis 4 is perpendicular to the magnetic field H, with the probe in air. In this condition no voltage will be induced in coil 3 from the magnetic field between the poles 5.
For the following example let the magnetic material under examination be steel. It can be shown experimentally that the magnetic permeability of steel is higher in the direction of tension than it is in the direction perpendicular to tension. Suppose the probe is placed with its poles against the steel surface at an arbitrary angle α (between 0° and 90°)

relative to the axis 4 of coil 3 as shown in figure 4. The magnetic flux density B in the steel between the poles is then shifted towards the direction of the tension, as shown in figure 5, and the direction of the accompanying magnetic field H is shifted away from the direction of tension as shown in figure 6. As a result of this effect a small AC voltage V_3 is induced in coil 3.

If the probe is rotated on the surface of the steel under test, so that angle α changes, it can be shown experimentally that the R.M.S. value of V_3 changes approximately as a rectified sine wave with change of α, as shown in figure 7.

V_3 can be rectified electronically, using a phase sensitive filter, so that it is a positive voltage for values of angle α between 0° and 90° and between 180° and 270°, and a negative voltage for values of angle α between 90° and 180° and between 270° and 360°. This is shown in figure 8 and is denoted by V_{DC}. V_{DC} has a maximum value, denoted by $\hat{V}_{DC}$, when angle α equals 45° or 225°, and has a minimum value, denoted by $\check{V}_{DC}$, when angle α equals 135° or 315°.

Voltage V_m is defined here as the algebraic difference between the maximum voltage, $\hat{V}_{DC}$, and the minimum voltage $\check{V}_{DC}$. i.e. $V_m = \hat{V}_{DC} - \check{V}_{DC}$. For the purpose of this description, V_m is further defined to be positive for a tensile stress and negative for a compressive stress. In practice the sign V_m is derived from the angular positions of $\hat{V}_{DC}$ and $\check{V}_{DC}$. Experiment also shows that for the more general case of two principal stresses σ_1 and σ_2 in the surface of the steel, V_m depends on the difference between these principal stresses, i.e. $\sigma_1 - \sigma_2$. In this case V_m varies with $\sigma_1 - \sigma_2$, typically as shown in figure 10.

A particular embodiment of the invention is an automatic instrument for measuring mechanical stress in ferromagnetic materials. It will now be described, with reference to the accompanying drawings in which:-

Figure 11 is a cross-section of the rotating probe and driving motor assembly.

Figure 12 is a block diagram, partly in schematic form, of the electronic signal processing.

Figure 13 is a block diagram of the electronic control of the instrument.

The C-core 1 and the coils 2 and 3 are encapsulated in a cylindrical tube to form the probe assembly 6, that can be rotated inside a fixed sleeve 7. Wires from the coils 2 and 3 are connected to fixed terminals 9 via a trailing ribbon cable 8. Wires from the coils 2 and 3 and the electric motor 12 are connected to the electronic control and signal processing via a flexible multicore cable 10. The probe is connected by a coupling 11 to the electric motor 12, which can rotate the probe backwards and forwards through angular increments giving 360° rotation.

The fixed frequency oscillator 13 supplies a sinusoidal AC signal to a power amplifier 14, which in turn supplies the excitation coil 2 with alternating current. The oscillator is fixed in frequency and amplitude during the operation of the instrument, i.e. while it is measuring stress in magnetic materials, but can be changed at will in order that the instrument may measure the average stress to a different depth within the magnetic material under test. Any voltage induced in coil 3 is rectified by a phase sensitive filter 15 and smoothed by the low pass filter 16. The resulting DC voltage is measured by a digital voltmeter 17.

The operation of the instrument is automatically controlled by a digital computer 18. This is programmed to switch the motor 12 (via an electronic control circuit 19) on and off in order to rotate the probe through augular increments. Each time the motor stops, the computer instructs the voltmeter 17 to read the rectified and filtered voltage V_{DC} from coil 3. The voltmeter then converts this DC voltage into a digital signal and supplies this information to the digital computer 18.

The computer calculates the maximum and minimum voltages $\hat{V}_{DC}$ and $\check{V}_{DC}$ from the plurality of V_{DC} readings taken by the voltmeter at each of the angular positions of the probe. The computer substracts $\check{V}_{DC}$ from $\hat{V}_{DC}$ to give V_m and displays this result for use by the user of the instrument. The computer also calculates and displays the direction of the larger principal stress which is calculated from the angular positions at which $\hat{V}_{DC}$ and $\check{V}_{DC}$ occur.

Dated this Tenth day of August 1987

Ian Hutchinson — IAN M. HUTCHINSON

Richard Langman — RICHARD A. LANGMAN

(Name of Applicant)
(BLOCK LETTERS)

Fig.1

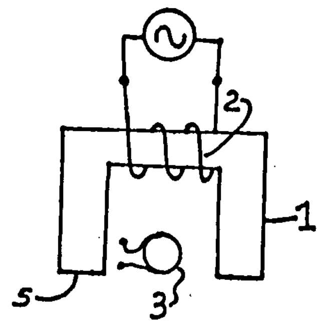


Fig.2.

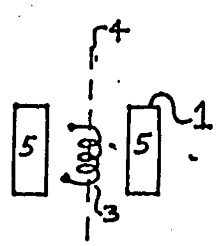


Fig.3

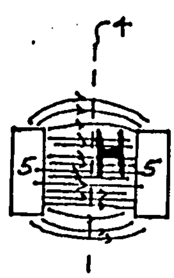


Fig. 4

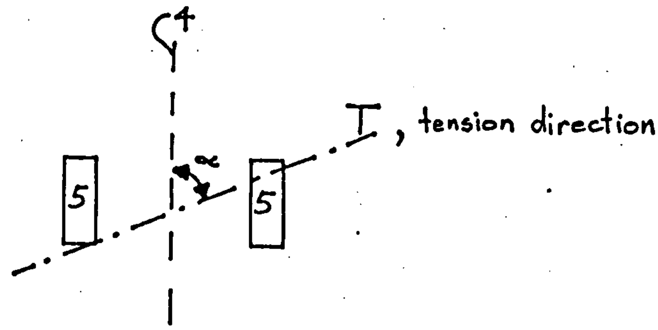


Fig. 5

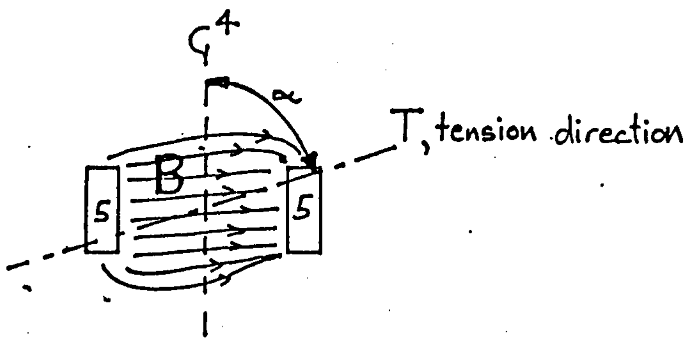


Fig. 6

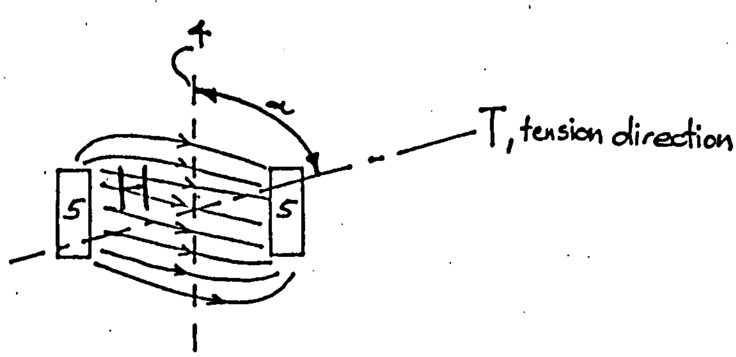


Fig.7

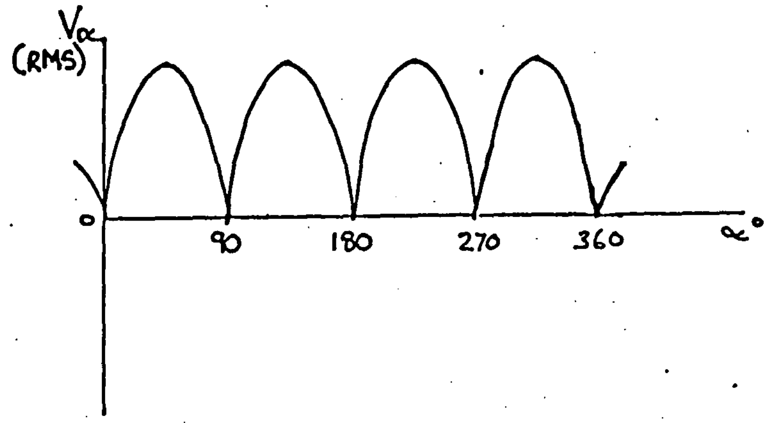


Fig.8

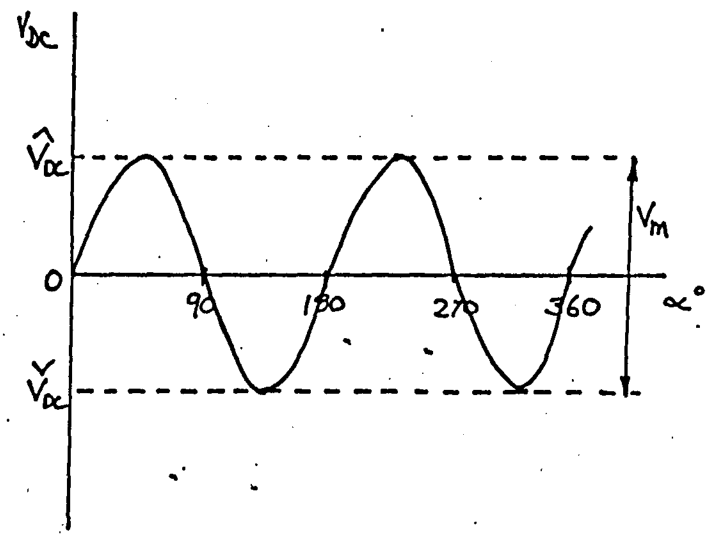


Fig.9

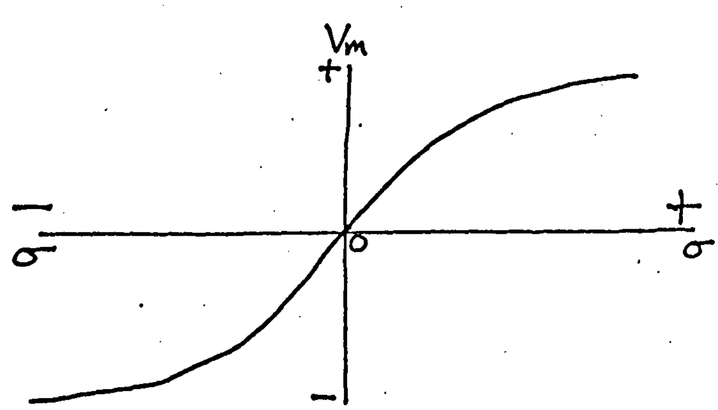


Fig 10

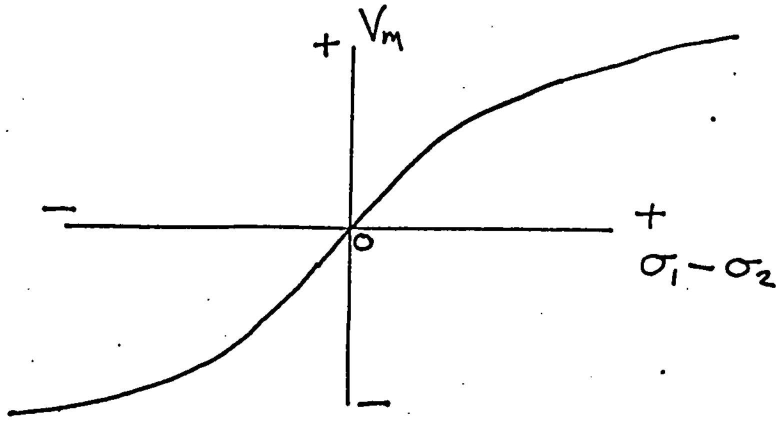


Fig.. 11

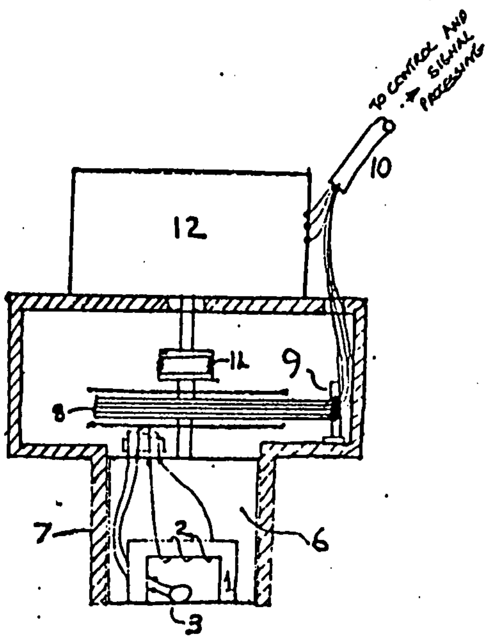


Fig. 12

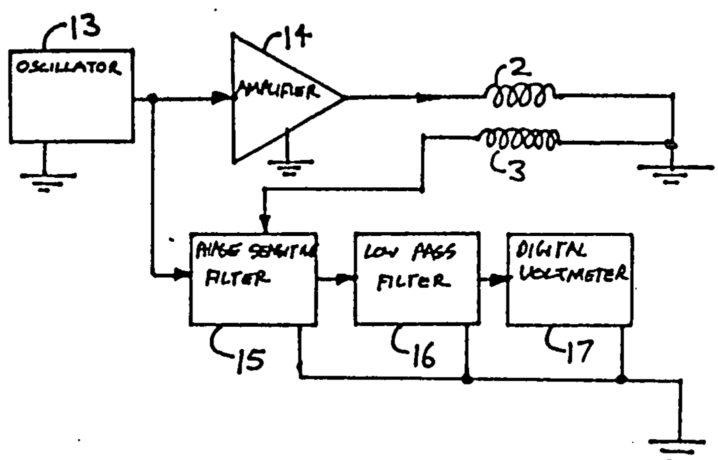
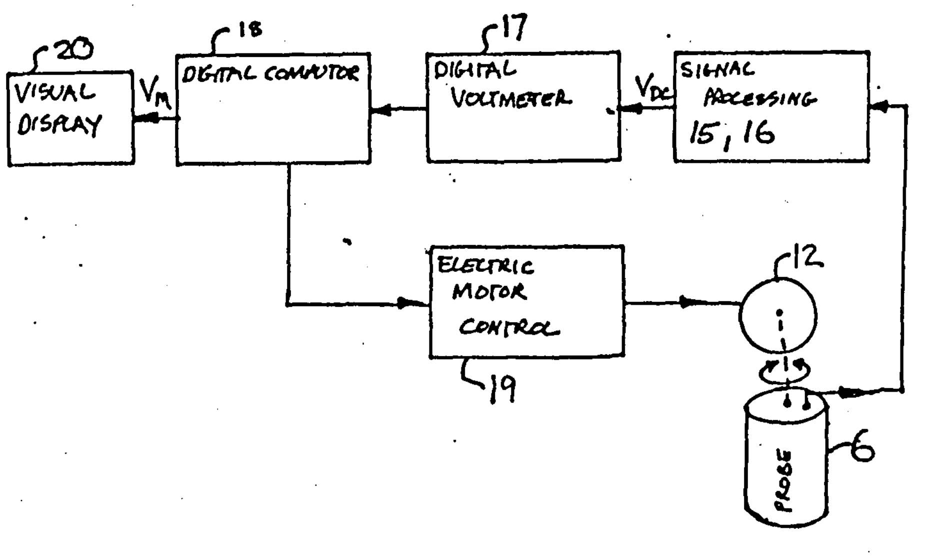


Fig. 13



20
VISUAL DISPLAY
V_M
18
DIGITAL COMPUTOR
17
DIGITAL VOLTMETER
V_{DC}
SIGNAL PROCESSING 15, 16
ELECTRIC MOTOR CONTROL
19
12
6
PROBE

APPENDIX C (a)

PROGRAM LISTING AND FLOWCHART FOR ARR-1

HP 41CV Calculator program to control stepper motor and to calculate the stress value and it's direction.

```
LBL'STRESS
XEQ'INIT                 Call initialisation routine.
LBL'SET                  Program label to bypass initialisation.
LBL 06                   Main loop label.
XEQ'REWIND               Rewind stepper motor.
1.023                    Set loop counter for correct no. of steps.
STO 01
0
STO 04                   Clear registers used later in the program.
STO 06                   First minimum.
STO 07                   Second minimum.
STO 08                   First maximum.
STO 09                   Second maximum.
STO 13
XEQ'READING              Get first Scm reading.
STO 05
STO 18                   Store it to compare later with last reading.
XEQ'STEP
CF 08
CF 09                    Clear program flags.
CF 10
LBL 01                   Reading loop.
PSE
XEQ'READING              Take Scm reading.
STO 12
ISG 01                   Have we taken 24 readings of Scm?
GTO 27                   No,go and take some more readings.
GTO 08                   Yes,see if we have found 2 max. and 2 min.
LBL 27
XEQ'STEP
FS?  10                  Has  there been 2 minimums and 2 maximums foun
XEQ'EXIT                 Yes,go to exit routine.
RCL 05                   Recall previous Scm value.
RCL 12                   recall present Scm value.
STO 05
X>Y?                     Is new value of Scm bigger than the old one?
GTO 10                   Yes,go to relavent section.
LBL 12
XEQ'READING              Get another Scm reading.
STO 12
RCL 05                   Recall previous Scm value.
RCL 12                   Recall present Scm value.
X>Y?                     Is new reading of Scm bigger than the old one?
GTO 13                   Yes,go to relavent section.
STO 05                   No,go back and get another Scm reading.
ISG 01                   Have we taken 24 readings?
GTO 17                   No,go and take some more readings.
GTO 20                   Yes,go and check for last reading.
LBL 17
XEQ'STEP                 Step stepper motor.
GTO 12
LBL 13                   A minimum has been found!!
RCL 05                   Recall minimum value.
FS? 09                   Is this the first minimum found?
GTO 14                   No,go to relavent section.
STO 06                   Store first minimum Scm value.
SF 09                    Set flag to indicate that 1st. min. found.
```

```
FC? 08          Has first maximum been found yet?
GTO 03          No,go to relavent program section.
GTO 26          Yes,go to store minimum angulr position.
LBL 14
STO 07          Store second minimum Scm value.
CF 09           Clear flag to indicate that 2nd. min. found.
FS? 10          Has the angular position already been found?
GTO 03          Yes,continue with rest of program.
LBL 26          No,find angular position of the first minimum.
RCL 01          after the first maximum Scm found and store
1               it in register 10.
-
STO 10
SF 10           Set flag to indicate that the angular position
GTO 03          of the Scm value has been found.
LBL 10          Scm values are increasing.
XEQ'READING     Get new Scm reading.
STO 12          Trying to find a maximum.
RCL 05          Recall last Scm value.
RCL 12          Recall present Scm values.
X<=Y?           Is new Scm value smaller than the old one?
GTO 15          Yes,go to relavent program section.
STO 05          No,keep going to find the maximum.
ISG 01          Have we taken 24 readings of Scm?
GTO 18          No keep on going.
GTO 21          Yes,go and check last Scm value.
LBL 18
XEQ'STEP        Step stepper motor.
GTO 10          Go and get another Scm reading.
LBL 15          We have found a maximum!!
RCL 05
FS? 08          Is this the first maximum?
GTO 16          No,go to relavent program section.
STO 08          Yes,store the first maximum.
SF 08           Set flag to indicate this fact.
RCL 01
1
-
STO 11          Find angular position of first maximum.
GTO 03          Go to next relavent program section.
LBL 16          We have found second maximum.
STO 09          Store 2nd. maximum Scm value in register 09.
CF 08           Clear flag to indicate that 2nd. max. found.
LBL 03          Section to find Scp value after finding a
RCL 02          maximum or minimum Scm value.
SELECT          Select interface kit.
SF 17
'A
OUTA            Select Scp output to the multimeter.
XEQ'READING     Get Scp reading.
ST+ 04          Add this onto the Scp accumulative total.
1
ST+ 13          Increment the number of Scp readings counter.
ISG 01          Has there been 24 readings taken?
GTO 23          No,keep going,get more Scm readings.
GTO 08          Yes,go to output routine.
LBL 23
XEQ'STEP        Step stepper motor.
RCL 12          Recall present Scm value.
STO 05          Make it the new old SCm value.
GTO 01          Go back to main loop.
```

```
LBL'EXIT           Exit routine.
FS? 08             Has second minimum been found?
RTN                No,then return to find it.
FS? 09             Has second maximum been found?
RTN                No,then return to find it.
GTO 01
LBL 20             Check last Scm value for minimum.
RCL 18             Recall first Scm value.
RCL 12             Recall last Scm value.
X>Y?               Is the last Scm value greater than the first
GTO 22             Yes,go to relavent section.
STO 07             Store last Scm value as second minimum.
GTO 25             Go to get Scp reading.
LBL 22
RCL 18             Store first Scm value as the second minimum
STO 07
GTO 25             Go to get Scp reading.
LBL 21             Check last Scm reading for maximum.
RCL 18             Recall first Scm reading.
RCL 12             Recall last Scm reading.
X>Y?               Is last Scm greater than the first?
GTO 23             Yes,go to relavent section.
RCL 18
STO 09             No,store first Scm reading as second max.
GTO 25             Go and get Scp reading.
LBL 23
STO 09             Store last Scm reading as second maximum.
LBL 25             Get Scp reading.
RCL 02
SELECT             Select HP-Il interface.
SF 17
'A
OUTA               Select Scp output to multimeter.
XEQ'READING        Get reading of Scp.
ST+ 04             Accumulate Scp readings.
1
ST+ 13             Increment the Scp reading counter.
LBL 08             All readings taken,has the probe reached
RCL 02             the correct number of steps?
SELECT
CF 17
PSE
INSTAT             Get status of stepper motor.
FC? 00             Is stepper motor at stop?
GTO 05             Yes,continue on.
TONE 5             Audio warning.
'STEP ERROR        Display that a step error has occured.
PROMPT
LBL 05             Calculation section.
RCL 13             Recall number of Scp values taken.
4
X<>Y?              Has there been four Scp values taken?
GTO 24             No,go to relavent warning section.
RCL 04             Recall accumulated Scp values.
RCL13
/                  Get average Scp value.
FIX 4
'SCP=
'+
ARCL X
AVIEW              Display average Scp value.
```

```
TONE 9          Audio tone to indicate that a reading has
STOP            been taken.
FIX 6
RCL 08          Recall first maximum Scm value.
RCL 09          Recall second maximum Scm value.
+
2               Get average Scm maximum.
/
RCL 06          Recall first minimum Scm value.
RCL 07          Recall second minimum Scm value.
+
2               Get average Scm minimum.
/
-               Find Scm double hat value
STO 14          and store it in register 14.
RCL 10          Recall step position of minimum Scm value.
RCL 11          Recall step position of maximum Scm value.
+
2
/               Find step position of maximum stress.
INT             Find integer value of this position.
15
*               Find angular direction of maximum in degrees
STO 15          and store it in register 15.
135
X>Y?            Is the position of max. stress >135 degrees?
GTO 25          No,go to relavent program section.
RCL 14          Recall Scp double hat.
CHS             Set it to compression value.
STO 14          Store compression Scm double hat in  reg. 14.
LBL 25
RCL 14          Recall Scm double hat.
'SCM=
'+
ARCL X
AVIEW           Display Scm double hat value on calculator
STOP            display in micro-volts.
RCL 15          Recall angle of maximum stress.
'<=
FIX 0
'+
ARCL X
AVIEW           Display angular position of maximum stress
LBL'SCP         on calculators display.
RCL 02
SELECT          Select HP-IL Interface Kit.
SF17
'A
OUTA            Select Scp coil reading for display
STOP            on multimeter
GTO 06          Return to main loop.
LBL 24          Not enough Scp readings taken.
TONE 3          Audio warning.
'SMALL SCM
PROMPT          Display error message.
GTO 06          Return to main loop.
END             End of program.
```

```
LBL'READING        Program to get reading from multimeter.
RCL 03             Recall HP3468B identification.
CF 17              Set normal end of line conditions.
SELECT             Select HP3468B multimeter.
TRIGGER            Trigger multimeter to take reading.
IND                Get reading from mutimeter.
RTN                Return to main program.
END
```

```
LBL'STEP           Program to step probe 15 degrees.
RCL 02             Recall HP-IL interface identification.
SELECT             Select HP-IL interface.
SF 17              Select no end of line characters.
'F
OUTA               Tell stepper motor to step twice.
'P
OUTA               Turn off power to stepper motor.
RTN                Return to main program.
END
```

```
LBL'INIT           Initialisation program.
CF 33
AUTOIO             Set up HP-IL.
'HP82166C
FINDID             Find identification of interface kit.
STO 02
'HP3468B           Find identification of loop.
FINDID
STO 03
SELECT
REMOTE             Make multimeter remote device.
SF 17              Set normal end of line characters.
'F1R1Z1N5T1        Set up multimeter for manual range,no
OUTA               autozero,internal trigger,5 1/2 digits.
2
ENTER
24
XEQ'WGPIO          Set up HP-IL interface handshake.
3
ENTER
255
XEQ'WGPIO          Set up  HP-IL interface handshake.
REG 20             Set statistical registers to register 20.
RTN                Return to main program.
END
```

```
LBL'REWIND         Program to rewind stepper motor.
.005               Set error counter.
STO 18             Store error counter in register 18
LBL 00             Rewind loop counter.
RCL 02
SELECT             Select HP-IL interface.
CF 17              Set normal end of line characters.
TRIGGER            Reset direction flip-flop (7473).
'J                 Rewind character.
SF 17              Delete normal end of line characters.
OUTA               Send out rewind character to interface.
PSE                Wait for stepper to rewind.
```

```
ISG 18          Error count?
GTO 02          No,wait for stepper to rewind.
GTO 01          Yes,go to error message routine.
LBL 02
INSTAT
FS? 00          Has stepper motor rewound?
GTO 00          No,go back to check again.
RTN             Yes,return to main program.
LBL 01          Error message routine.
'NO REWIND
PROMPT
XEQ'STRESS      Start main program again.
END
```

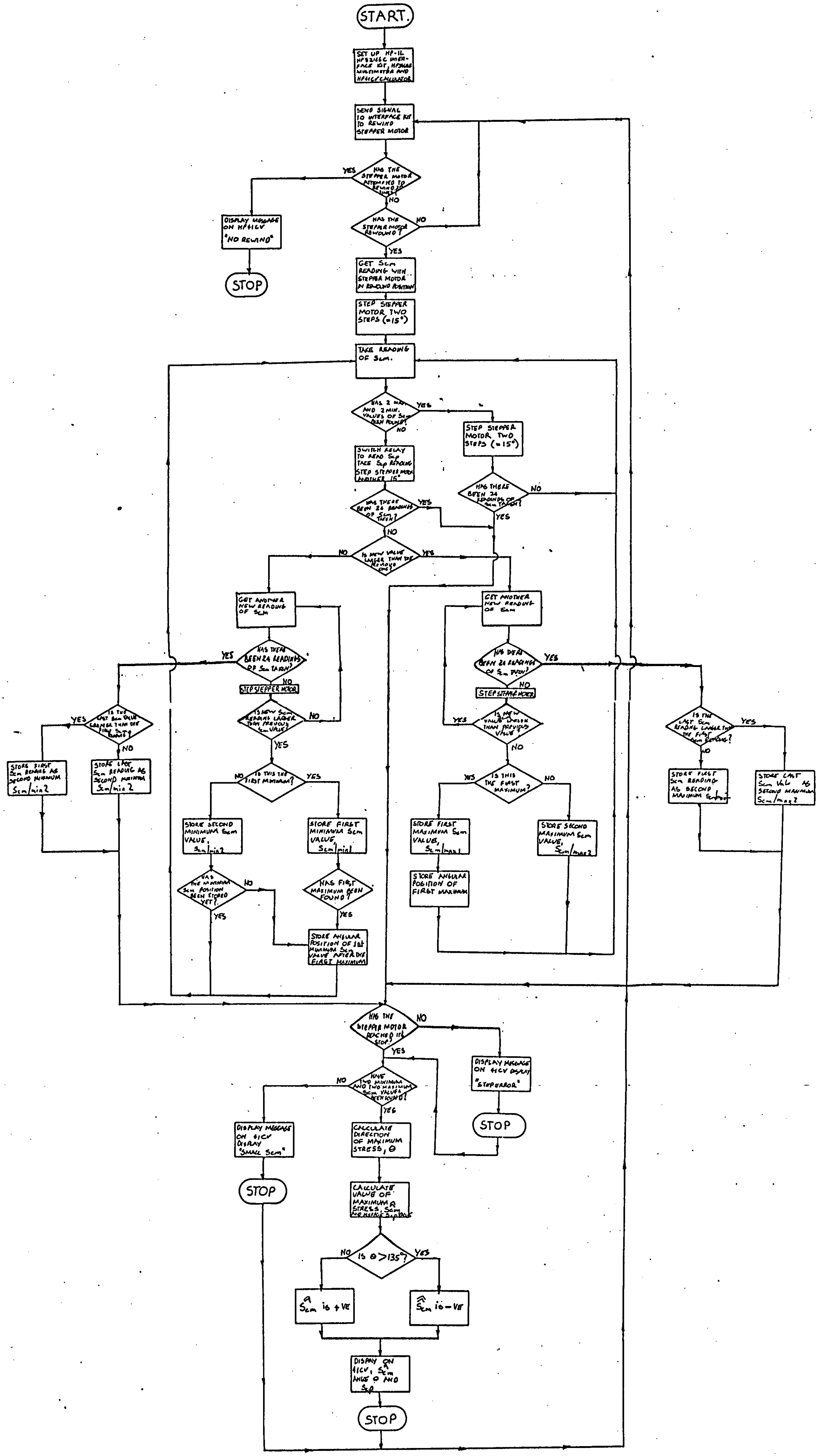
The following programs are from the HP-IL Development Module Owners Manual (HP 00041-15043) (with some modifications to suit this application)

```
LBL'WGPIO
STO 01          Save the new register contents.
RDN             Move the register number into the X-register
MIPT            Don't advance the buffer.
XEQ'RGPIO       Get the registers into the buffer.
RCL 01          Put the new contents into the X-register.
X-BUF           Store it using the PT value from RGPIO.
RCL 02          Get the GPIO address.
LAD             Make it listener active.
0
DDL             Tell it to write its registers.
0
PT=             Start at the beginning of the buffer.
RCL 00
1
+               Get the register number again.
OUTBUFX         Send out all registers.
UNL             Unlisten the GPIO.
FS? 09          Restore flag 33 to its original value.
CF 33
END
```

```
LBL'RGPIO
STO 00          Save the desired register.
RCL 02          Find the desired GPIO.
TAD             Make it talker addressed.
0
DDT             Tell it to send the registers.
0
PT=             Start at the beginning of the buffer.
RCL 00
1
+
INBUFX          Read only up to the wanted register.
RCL 00
PT=             Point to the wanted register.
1
BUF-XB          Get one register from the buffer.
UNT             Tell the GPIO to stop sending registers.
FS? 09          Restore flag 33 to its original value.
CF 33
RTN
END
```

HP-41CV PROGRAM FLOWCHART

9/6/87



164

APPENDIX C (b)

PROGRAM LISTING FOR ARR-2

XTBASIC PROGRAM FOR ARR-2

Note that the comments have been added and are not part of the program as stored in the user EPROM in the JED STD 800 board.

```
10 D=%COAO:D$="BATTERIES OK  "           Set up battery warning

15 E=%COBO:E$="BATTERIES OK  "           strings, D$@%COAO, E$@COBO

20 OUT%E7,%00:OUT%E6,%80:OUT%F8,%AD:OUT%F0,200:OUT%F1,%00
                                          Set up counters for buzzer
80 POKE%DF4D,%C5:POKE%DF4E,%A8:POKE%DF4B,%E
                                          Set up LCD display.
110 ARRAY%C000,%C0FF                      Set up array for SCm and
                                          probe position values.
120 PV=PUTM                               Print Vector=Microwire.

130 PRINTASC(%FE),ASC(%38),

140 REMDELAYALITTLEBIT,

150 PRINTASC(%FE),ASC(%38),

160 PRINTASC(%FE),ASC(%38),
                                          Set up and clear LCD
170 PRINTASC(%FE),ASC(1),                 display.

180 PRINTASC(%FE),ASC(6),

190 PRINTASC(%FE),ASC(%E),

200 WPOKE%DF49,%DA00

210 POKE %DA00,%0D,%33,%32,%31

220 POKE %DA08,%8,%36,%35,%34
                                          Set up keyboard look-up
230 POKE %DA10,%42,%39,%38,%37            table from %DA00.

240 POKE %DA18,%47,%41,%52,%30

250 GV=GETK,IV=ITSTK                      GetVector=GETKeyboard.
                                          InterruptVector=InterruptSTK
255 IF ADC10(5)<100GOTO9000               Check if probe is connected

290 OUT %F5,%00

295 FOR I=1 TO 300:NEXT I                 Give single beep.

296 OUT%F4,%00

300 PRINT ASC(%FE),ASC(1),"     *****     ARR - 2/01      *****"

310 PRINT"\Mechanical Stress Measurement Instrument"

320 FORI=1TO8000:NEXTI               Wait after printing initial
                                     message to user.
400 GOSUB7000                        Check battery condition.
```

MAIN MENU SECTION

```
405 PRINTASC(%FE),ASC(1),"<GREEN> = Run, <AMBER> = Abort Run"

410 PRINT"<RED> = Goto Support Menu.",D$
                                          Main Menu with D$.
411 GOSUB7000                     Check batteries again.

412 FORI=1TO500:NEXTI             Wait loop for flashing display

415 PRINT"<RED> = Goto Support Menu.",E$
                                          Main menu with E$.
417 FORI=1TO500:NEXTI             Wait loop for flashing display

420 IFKEY(:R)<>0GOTO2000          If input = red goto support
                                           menu.
430 IFKEY(:A)<>0GOTO3000          If input = amber abort run.

440 IFKEY(:G)<>0GOTO4000          If input = green get stress
                                           measurement.
450 IFKEY(:1)<>0GOTO5000          If input = 1 get probe posit-
                                           ion calibration.
460 GOTO410                       Return to flash display and
                                  get input from user.
```

SUPPORT MENU SECTION.

```
2000 PRINTASC(%FE),ASC(1),"<B> = Battery Voltages,<1> = Temperature"

2020 PRINT"\<0> = Return to Main Menu."      Support Menu.

2030 IFKEY(:B)<>0GOTO2100         If input = B display battery
                                             voltages.
2040 IFKEY(:1)<>0GOTO2200         If input = 1 display
                                             temperature
2050 IFKEY(:0)<>0GOTO400          If input = 0 return to Main
                                             Menu.
2060 GOTO2030                     Return to get user input.

2100 PRINTASC(%FE),ASC(1),"Battery Voltages, <0> = Support Menu"

2110 PRINT##4.2,"Battery 1=",ADC10(3)*2,"  Battery 2=",ADC10(4)*2

2120 FORI=1TO1000:NEXTI           Display battery voltages

2130 IFKEY(:0)<>0GOTO2000         If input = 0 return to support
                                             menu.
2140 GOTO2110                     Return to get user input.

2200 PRINTASC(%FE),ASC(1),"Temperature, <0> = Support Menu"

2210 T=49*ADC10(6)/10-2732        Calculate temperature.
```

```
2230 PRINT##4.1,"\Case Temperature = ",T,ASC(223),"C"

2235 FORI=1TO1000:NEXTI              Display temperature.

2240 IFKEY(:0)<>0GOTO2000            If input = 0 return to support
                                              menu.
2240 GOTO2210                        Return to get user input.
```

RUN ABORT SECTION

```
3000 OUT%E1,%00                      Turn off stepper motor.

3010 PRINTASC(%FE),ASC(1),"Run Aborted at Position ",I

3020 PRINT"\<0> = Return to Main Menu"
                                     Run aborted message.
3030 IFKEY(:0)<>0GOTO400             If input = 0 return to Main
                                              Menu.
3040 GOTO3030                        Return to get user input.
```

RUN SECTION.

```
4000 GOSUB6000                       Goto rewind subroutine.
                                     Start of "RUN" section.
4010 GOSUB7000                       Check battery condition.

4012 IF ADC10(5)<100 GOTO9000        Chech if probe connected.

4015 PRINTASC(%FE),ASC(1),"RUNNING, <AMBER> = Abort. ",D$
                                     Display running menu.
4020 P=0

4030 FORI=1TO20:P=P+ADC10(0):NEXTI       Get 20 values of
                                         SCp and average them.
4060 S=P/20

4070 P=0

4080 FORI=1TO20:P=P+ADC10(1):NEXTI       Get 20 values of SCm and
                                         average them and store in
4110 @(1)=P/20                           array.

4120 OUT%E1,%D0                          Reset stepper motor.

4122 I=1                                 Set position counter.

4123 IFKEY(:A)<>0GOTO3000                If abort key pressed goto
                                         abort section.
4130 FORI=2TO24                          Loop to get rest of
                                         probe readings.
4140 FORK=1TO2
```

```
4150 FORJ=1TO10:NEXTJ

4160 OUT%E1,%90                           Step the motor twice
                                          to give 15° rotation.
4170 FORJ=1TO10:NEXTJ

4180 OUT%E1,%80

4190 NEXTK

4200 P=0

4205 FORK=1TO750:NEXTK                    Wait for prode to stop
                                          moving.
4206 K=ADC10(2)                           Get probe position.

4207 IF(K<@(I*2+23)-12)OR(K>@(I*2+23)+12)GOTO8000
                                          Check for correct stepping.
4210 FORJ=1TO20:P=P+ADC10(0):NEXTJ
                                          Get 20 SCp readings and
4240 S=S+P/20                             average them.

4250 P=0

4260 FORJ=1TO20:P=P+ADC10(1):NEXTJ
                                          Get 20 SCm readings and
4290 @(I)=P/20                            average them.

4295 IFKEY(:A)<>0GOTO3000                 If abort key pressed goto
                                          abort section.
4300 NEXTI                                Loop back to get more
                                          readings.
4310 T=0

4320 FORI=1TO24:T=T+@(I):NEXTI            Find average SCm value.

4350 T=T/24

4360 Q=0:W=0:R=1

4390 FORI=1TO24

4391 IFI=24R=-23                          Set R so that last SCm
                                          value is compare to 1st.
4395 U=ABS(@(I)-T):V=ABS(@(I+R)-T)        Get differences between
                                          SCm values and average T.
4410 Q=Q+U                                Integrate all SCm values.

4420 IF(@(I)>=T)AND(@(I+R)<T)GOTO4440     Check for negative slope
                                          "zero" crossing.
4430 GOTO4500                             Return to check next pair
                                          of SCm values.
4440 IF U>218 W=3                         Check for suspect SCm
                                          values.
4444 W=W+1                                Increment "zero" crossing
                                          counter.
4450 IFW<>1GOTO4500                       If this is not the first
                                          crossing jump to 4500.
```

```
4460 B=150*(I-5)+(150*U)/(U+V)          Calculate angular
                                        position of crossing
4465 B=B/10                             to get direction of
                                        tension.
4470 IF B<0 B=180+B                     Make angle allways
                                        positive.
4500 NEXTI                              Return to check other
                                        SCm readings.
4510 GOSUB6000                          Rewind the probe to its
                                        starting position.
4550 GOSUB 10000                        Sound buzzer.

4592 P=S/24                             Find average SCp value.

4595 IFW=2GOTO4606                      Check for 2 negative
                                        slope zero crossings
4595 PRINTASC(%FE),ASC(1),"SUSPECT Scm READING!!!"

4597 PRINT"\<0> = Continue"             Indicate to user that
                                        the Scm readings are
4598 GOSUB10000                         suspect, and beep.

4599 IFKEY(:0)<>0GOTO4606               If input = 0 continue.

4600 GOTO4599                           Return to get user input.

4606 Q=Q/10                             Scale SCm reading.
```

RUN MENU SECTION.

```
4610 PRINTASC(%FE),ASC(1),#4,"Scm=",Q,",Scp=",P,",",ASC(242),"=",B,

4611 PRINT ASC(223),", <GREEN> = Run"
                                        Display results.
4615 GOSUB 7000                         Check battery condition.

4620 PRINT"\<RED> = Goto Support Menu.",D$
                                        Flashing result menu, D$.
4625 FORI=1TO500:NEXT I

4630 PRINT"\<RED> = Goto Support Menu.",E$
                                        Flashing result menu, E$.
4635 FORI=1TO500:NEXT I

4640 IFKEY(:G)<>0GOTO4000               If input = green take
                                        another set of results.
4650 IFKEY(:R)<>0GOTO2000               If input = red goto
                                        support menu.
4670 GOTO 4615                          return to get user input.
```

PROBE POSITION CALIBRATION SECTION.

```
5000 INPUTASC(%FE),ASC(1),"CODE?",A          Get code from user via
                                             keyboard.
5005 IFA<>4803GOTO400                        If code is not correct
                                             return to Main Menu.
5010 OUT%E1,%C0:OUT%E1,%80:P=0               Reset stepper motor.

5040 FORI=1TO20:P=P+ADC10(2):NEXTI           Get 20 probe position
                                             readings and average them.
5070 @(25)=P/20

5080 FORI=26TO73:OUT%E1,%90

5100 FORJ=1TO100:NEXTJ

5120 OUT%E1,%80                              Step stepper motor to
                                             next position.
5130 FORJ=1TO100:NEXTJ:P=0

5160 FORJ=1TO20:P=P+ADC10(2):NEXTJ           Get 20 SSp readings and
                                             average them at each
5190 @(I)=P/20                               position.

5200 NEXTI:GOSUB6000                         Get all positions and
                                             rewind stepper motor.
5220 RETURN                                  Return from subroutine.
```

REWIND SECTION.

```
6000 FORG=1TO3
                                     Step error loops.
6010 FORF=1TO3

6020 FORI=1TO1000:NEXTI              Wait for any movement of the
                                     probe to subside.
6040 K=ADC10(2)                      Get probe position reading.

6050 FORI=1TO48

6060 IF(K>@(I+24)-12)AND(K<@(I+24)+12)GOTO6100
                                     Find step position of the
6070 NEXTI                           probe.

6080 I=2                             Position not found
                                     so step back one position.
6100 IFI=1GOTO6220                   Probe is rewound.

6110 FORC=1TOI-1

6120 OUT%E1,%B0                      Step back correct number
                                     of steps to starting
6130 FORA=1TO10:NEXTA                position.

6150 OUT%E1,%A0
```

```
6160 FORA=1TO10:NEXTA
6180 NEXTC
6190 NEXTF                              Try this 3 times if needed.
6200 PRINTASC(%FE),ASC(1),"INCORRECT REWIND!!!"
6201 PRINT"\<0> = Try Again"
6202 GOSUB10000                         Warn operator of no rewind
                                        condition.
6203 OUT%E1,%00                         Turn stepper motor off.
6204 IFKEY(:0)<>0GOTO6206
6205 GOTO 6204
6206 NEXTG
                                          If no rewind then
6207 PRINTASC(%FE),ASC(1),"NO PROBE REWIND"  warn operator.
6208 PRINT"\Technical Repairs Needed Now"
6209 GOSUB10000                           Beep.
6210 STOP                                 Stop operation.
6220 OUT%E1,%00                       Turn stepper motor off.
6500 RETURN                           Return to main program.
```

BATTERY CONDITION CHECK SECTION.

```
7000 REM CHECK BATTERY CONDITION
7010 B=ADC10(3)*2                    Battery 1 voltage reading.
7020 BO=ADC10(4)*2                   Battery 2 voltage reading.
7030 IF(B<1100)OR(BO<1100)GOTO7300       Are batteries dead flat?
7040 IF(B<1130)OR(BO<1130)GOTO7200       Are batteries flat?
7050 IF(B<1150)OR(BO<1150)GOTO7100       Are batteries low?
7060 D$="BATTERIES OK   "
7070 E$="BATTERIES OK   "                Batteries OK!
7080 RETURN                              Return to main program.
7100 D$="BATTERIES LOW "                 Batteries low!!
7110 E$="              "                 Clear E$ for flashing
```

```
                                              display.
7120 RETURN                                   Return to main program.

7200 D$="BATTERIES FLAT"                      Batteries flat!!!

7230 E$="                 "                   Clear E$ for flashing
                                              display.
7240 OUT%F5,%00

7243 FORI=1TO300:NEXTI

7244 OUT%F4,%00                               Beep once.

7250 RETURN

7300 PRINTASC(%FE),ASC(1),"BATTERIES DEAD FLAT!!!!"
                                              Warn about batteries.
7310 GOSUB 10000                              Beep.

7320 PRINT"\No More Readings, Recharge NOW...."

7330 STOP                                     Terminate operation.
```

STEP ERROR WARNING SECTION.

```
8000 PRINTASC(%FE),ASC(1),"STEP ERROR AT POSITION ",I

8010 PRINT"\<0> = Try Again"                  Step error warning.

8020 GOSUB10000                               Beep.

8030 IFKEY(:0)<>0GOTO400                      If input = 0 return to
                                              Main Menu.
8040 GOTO8030                                 Return for user input.
```

PROBE NOT CONNECTED WARNING SECTION.

```
9000 PRINTASC(%FE),ASC(1),"NO PROBE SIGNALS!!!,<0> = Try Again"

9020 PRINT"\Is the Probe Connected ?"             User warning.

9025 GOSUB10000                                   Beep.

9030 IFKEY(:0)<>0GOTO255                          If input = 0
                                                  return to start.
9040 GOTO9030                                 Wait for user input.
```

WARNING BUZZER SECTION.

```
10000 FORJ=1TO3                Set loop to beep 3 times.

10020 OUT%F5,%00               Turn on counter.

10030 FORI=1TO750:NEXTI        Set buzzer on time.

10040 OUT%F4,%00               Turn off counter.

10060 FORI=1TO750:NEXTI        Set buzzer off time.

10080 NEXTJ                    Loop for next beep.

10090 RETURN                   Return from subroutine.

10100 STOP
```

END OF PROGRAM.

APPENDIX C (c)

PROGRAM LISTING FOR ARR-3

XTBASIC PROGRAM FOR ARR-3

Note that the comments have been added and are not part of the program as stored in the user EPROM in the JED STD 800 board.

```
10 D=%C0A0:D$="BATTERIES OK  "            Set up battery warning

15 E=%C0B0:E$="BATTERIES OK  "            strings, D$@%C0A0, E$@C0B0

20 OUT%E7,%00:OUT%E6,%80:OUT%F8,%AD:OUT%F0,200:OUT%F1,%00
                                          Set up counters for buzzer
80 POKE%DF4D,%C5:POKE%DF4E,%A8:POKE%DF4B,%E
                                          Set up LCD display.
110 ARRAY%C000,%C0FF                      Set up array for SCm and
                                          probe position values.
120 PV=PUTM                               Print Vector=Microwire.

130 PRINTASC(%FE),ASC(%38),

140 REMDELAYALITTLEBIT,

150 PRINTASC(%FE),ASC(%38),

160 PRINTASC(%FE),ASC(%38),
                                          Set up and clear LCD
170 PRINTASC(%FE),ASC(1),                 display.

180 PRINTASC(%FE),ASC(6),

190 PRINTASC(%FE),ASC(%E),

200 WPOKE%DF49,%DA00

210 POKE %DA00,%30                        Set up RUN button symbol.

250 GV=GETK,IV=ITSTK                      GetVector=GETKeyboard.
                                          InterruptVector=InterruptSTK
290 OUT %E1,%08

295 FOR I=1 TO 400:NEXT I                 Give single beep.

296 OUT%E1,%00

300 PRINT ASC(%FE),ASC(1),"     *****     ARR - 3/01     *****"

310 PRINT"\Mechanical Stress Measurement Instrument"

320 FORI=1TO8000:NEXTI                Wait after printing initial
                                      message to user.
400 GOSUB7000                         Check battery condition.

401 GOSUB6000                         Rewind Probe to start.

402 IF(ADC10(0)<100)OR(ADC10(7)<100)GOTO 9000
                                      Check for probe signals.
```

START MENU SECTION

```
405 PRINTASC(%FE),ASC(1),"<GREEN> = Run,                             ",D$

411 GOSUB7000                       Check batteries again.

412 FORI=1TO500:NEXTI               Wait loop for flashing display

415 PRINTASC(%FE),ASC(1),"<GREEN> = Run,                             ",E$

417 FORI=1TO500:NEXTI               Wait loop for flashing display

440 IFKEY(:0)<>0GOTO4000            If input = run goto 4000

460 GOTO405                         Return to flash display and
                                    get input from user.
```

RUN SECTION

```
4000 GOSUB6000                      Goto rewind subroutine.
                                    Start of "RUN" section.
4010 GOSUB7000                      Check battery condition.

4015 PRINTASC(%FE),ASC(1),"RUNNING,                 ",D$
                                    Display running menu.
4020 P=0

4030 FORI=1TO20:P=P+ADC10(0):NEXTI      Get 20 values of
                                        SCp and average them.
4060 S=P/20

4070 P=0

4080 FORI=1TO20:P=P+ADC10(1):NEXTI      Get 20 values of SCm and
                                        average them and store in
4110 @(1)=P/20                          array.

4120 OUT%E1,%D0                         Reset stepper motor.

4122 I=1                                Set position counter.

4130 FORI=2TO24                         Loop to get rest of
                                        probe readings.
4140 FORK=1TO2

4150 FORJ=1TO10:NEXTJ

4160 OUT%E1,%90                         Step the motor twice
                                        to give 15° rotation.
4170 FORJ=1TO10:NEXTJ

4180 OUT%E1,%80

4190 NEXTK

4200 P=0
```

```
4205 FORK=1TO750:NEXTK                      Wait for prode to stop
                                            moving.
4206 K=ADC10(7)                             Get probe position.

4207 IF(K<@(I*2+23)-12)OR(K>@(I*2+23)+12)GOTO8000
                                            Check for correct stepping.
4210 FORJ=1TO20:P=P+ADC10(0):NEXTJ
                                            Get 20 SCp readings and
4240 S=S+P/20                               average them.

4250 P=0

4260 FORJ=1TO20:P=P+ADC10(1):NEXTJ
                                            Get 20 SCm readings and
4290 @(I)=P/20                              average them.

4300 NEXTI                                  Loop to get more values.

4310 T=0

4320 FORI=1TO24:T=T+@(I):NEXTI              Find average SCm value.

4350 T=T/24

4360 Q=0:W=0:R=1

4390 FORI=1TO24

4391 IFI=24R=-23                            Set R so that last SCm
                                            value is compare to 1st.
4395 U=ABS(@(I)-T):V=ABS(@(I+R)-T)          Get differences between
                                            SCm values and average T.
4410 Q=Q+U                                  Integrate all SCm values.

4420 IF(@(I)>=T)AND(@(I+R)<T)GOTO4440       Check for negative slope
                                            "zero" crossing.
4430 GOTO4500                               Return to check next pair
                                            of SCm values.
4440 IF U>218 W=3                           Check for suspect SCm
                                            values.
4444 W=W+1                                  Increment "zero" crossing
                                            counter.
4450 IFW<>1GOTO4500                         If this is not the first
                                            crossing jump to 4500.
4460 B=150*(I-5)+(150*U)/(U+V)              Calculate angular
                                            position of crossing
4465 B=B/10                                 to get direction of
                                            tension.
4470 IF B<0 B=180+B                         Make angle allways
                                            positive.
4500 NEXTI                                  Return to check other
                                            SCm readings.
4510 GOSUB6000                              Rewind the probe to its
                                            starting position.
4550 GOSUB 10000                            Sound buzzer.

4592 P=S/24                                 Find average SCp value.
```

```
4595 IFW=2GOTO4606                            Check for 2 negative
                                              slope zero crossings
4595 PRINTASC(%FE),ASC(1),"SUSPECT Scm READING!!!"

4597 PRINT"\<GREEN> = Continue"               Indicate to user that
                                              the Scm readings are
4598 GOSUB10000                               suspect, and beep.

4599 IFKEY(:0)<>0GOTO4606                     If input = 0 continue.

4600 GOTO4599                                 Return to get user input.

4606 Q=Q/10                                   Scale SCm reading.

4607 TO=ADC10(4)/2-277

4610 PRINTASC(%FE),ASC(1),#4,"Scm=",Q,",Scp=",P,",",ASC(242),"=",B,

4611 PRINT ASC(223),", <GREEN> = Run"
                                              Display results.
4615 GOSUB 7000                               Check battery condition.

4620 PRINT#4,"\Probe Temperature=",TO,ASC(223),"C  ",D$

4625 FORI=1TO500:NEXT I

4630 PRINT#4,"\Probe Temperature=",TO,ASC(223),"C  ",E$

4635 FORI=1TO500:NEXT I

4640 IFKEY(:0)<>0 GOTO4000

4670 GOTO 4615                                return to get user input.
```

PROBE POSITION CALIBRATION SECTION.

```
5000 REMCALIBRATIONSECTION

5010 OUT%E1,%C0:OUT%E1,%80:P=0                Reset stepper motor.

5040 FORI=1TO20:P=P+ADC10(7):NEXTI            Get 20 probe position
                                              readings and average them.
5070 @(25)=P/20

5080 FORI=26TO73:OUT%E1,%90

5100 FORJ=1TO100:NEXTJ

5120 OUT%E1,%80                               Step stepper motor to
                                              next position.
5130 FORJ=1TO100:NEXTJ:P=0

5160 FORJ=1TO20:P=P+ADC10(7):NEXTJ            Get 20 SSp readings and
                                              average them at each
5190 @(I)=P/20                                position.
```

```
5200 NEXTI:GOSUB6000                        Get all positions and
                                            rewind stepper motor.
5220 RETURN                                 Return from subroutine.
```

REWIND SECTION.

```
6000 FORG=1TO3
                                     Step error loops.
6010 FORF=1TO3

6020 FORI=1TO1000:NEXTI              Wait for any movement of the
                                     probe to subside.
6040 K=ADC10(7)                      Get probe position reading.

6050 FORI=1TO48

6060 IF(K>@(I+24)-12)AND(K<@(I+24)+12)GOTO6100
                                     Find step position of the
6070 NEXTI                           probe.

6080 I=2                             Position not found
                                     so step back one position.
6100 IFI=1GOTO6220                   Probe is rewound.

6110 FORC=1TOI-1

6120 OUT%E1,%B0                      Step back correct number
                                     of steps to starting
6130 FORA=1TO10:NEXTA                position.

6150 OUT%E1,%A0

6160 FORA=1TO10:NEXTA

6180 NEXTC

6190 NEXTF                           Try this 3 times if needed.

6200 PRINTASC(%FE),ASC(1),"INCORRECT REWIND!!!"

6201 PRINT"\<GREEN> = Try Again"

6202 GOSUB10000                      Warn operator of no rewind
                                     condition.
6203 OUT%E1,%00                      Turn stepper motor off.

6204 IFKEY(:0)<>0GOTO6206

6205 GOTO 6204

6206 NEXTG
                                               If no rewind then
6207 PRINTASC(%FE),ASC(1),"NO PROBE REWIND"    warn operator.

6208 PRINT"\Technical Repairs Needed Now"
```

```
6209 GOSUB10000                              Beep.

6210 STOP                                    Stop operation.

6220 OUT%E1,%00                          Turn stepper motor off.

6500 RETURN                              Return to main program.
```

BATTERY CONDITION CHECK SECTION.

```
7000 REMCHECKBATTERYCONDITION

7010 B=ADC10(5)                       Battery 1 voltage reading.

7020 BO=ADC10(6)                      Battery 2 voltage reading.

7030 IF(B<580)OR(BO<580)GOTO7300       Are batteries dead flat?

7040 IF(B<585)OR(BO<585)GOTO7200       Are batteries flat?

7050 IF(B<590)OR(BO<590)GOTO7100       Are batteries low?

7060 D$="BATTERIES OK   "

7070 E$="BATTERIES OK   "                Batteries OK!

7080 RETURN                              Return to main program.

7100 D$="BATTERIES LOW  "                Batteries low!!

7110 E$="               "                Clear E$ for flashing
                                         display.
7120 RETURN                              Return to main program.

7200 D$="BATTERIES FLAT"                 Batteries flat!!!

7230 E$="               "                Clear E$ for flashing
                                         display.
7240 OUT%E1,%08

7243 FORI=1TO300:NEXTI

7244 OUT%E1,%00                          Beep once.

7250 RETURN

7300 PRINTASC(%FE),ASC(1),"BATTERIES DEAD FLAT!!!!"
                                         Warn about batteries.
7310 GOSUB 10000                         Beep.

7320 PRINT"\No More Readings, Recharge NOW...."

7330 STOP                                Terminate operation.
```

STEP ERROR WARNING SECTION.

```
8000 PRINTASC(%FE),ASC(1),"STEP ERROR AT POSITION ",I
8010 PRINT"\<GREEN> = Try Again"          Step error warning.
8020 GOSUB10000                           Beep.
8030 IFKEY(:0)<>0GOTO400                  If input = 0 return to
                                          Main Menu.
8040 GOTO8030                             Return for user input.
```

PROBE NOT CONNECTED WARNING SECTION.

```
9000 PRINTASC(%FE),ASC(1),"NO PROBE SIGNALS!!!!!"
9020 PRINT"\Technical Repairs Needed Now"        User warning.
9025 GOSUB10000                                  Beep.
9030 STOP                                     Terminate operation.
```

WARNING.BUZZER SECTION.

```
10000 FORJ=1TO3                Set loop to beep 3 times.
10020 OUT%E1,%08               Turn on counter.
10030 FORI=1TO750:NEXTI        Set buzzer on time.
10040 OUT%E1,%00               Turn off counter.
10060 FORI=1TO750:NEXTI        Set buzzer off time.
10080 NEXTJ                    Loop for next beep.
10090 RETURN                   Return from subroutine.
10100 STOP
```

END OF PROGRAM.

APPENDIX D

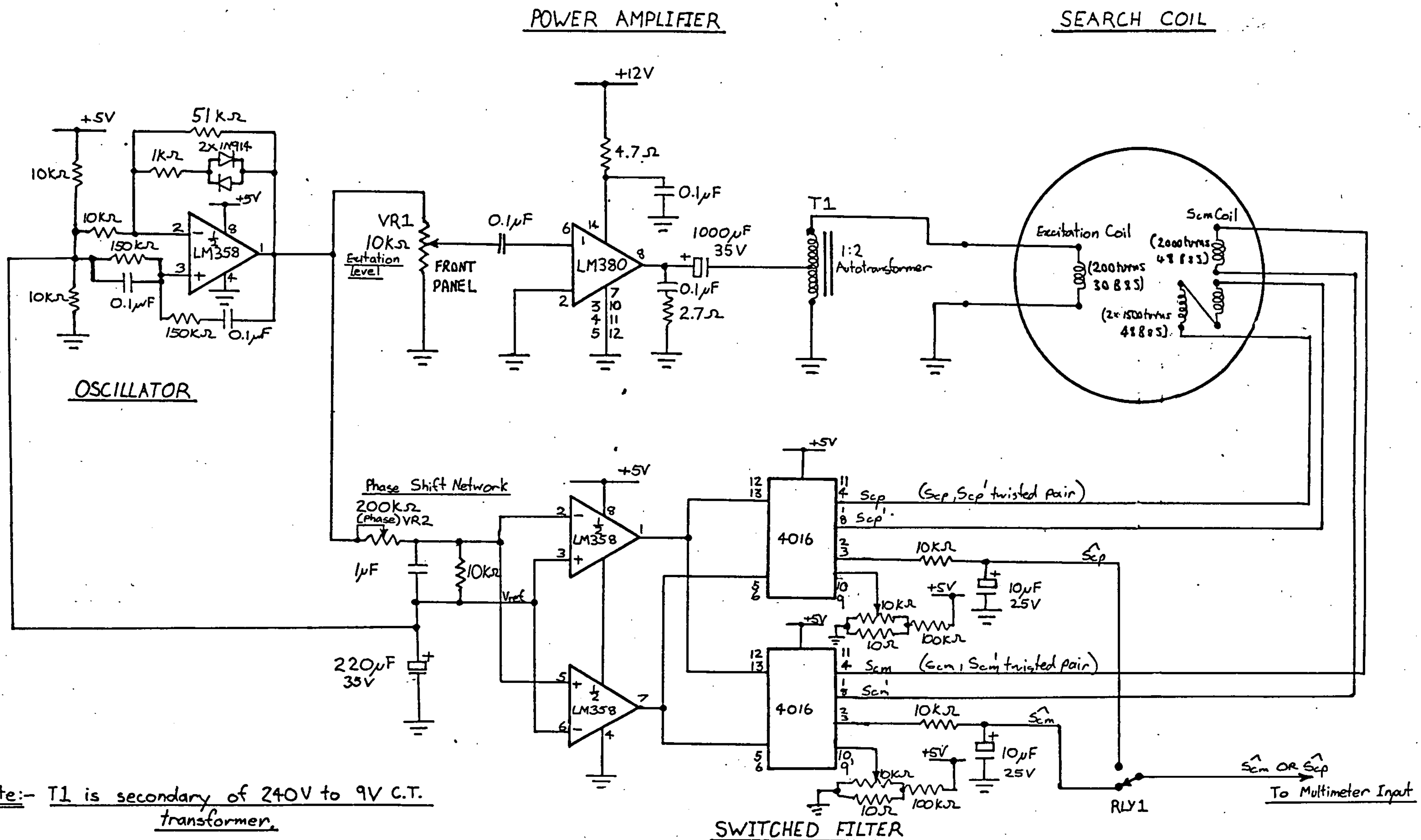
EPROM MEMORY DUMP (ARR-2 AND ARR-3)

```
#0000.DA.D9.D9.D9.D9.D8.D8.D8.D7.D7.D7.D7.D6.D6.D6.D5.
#0010.D5.D5.D5.D4.D4.D4.D3.D3.D3.D2.D2.D2.D2.D1.D1.D1.
#0020.D0.D0.D0.CF.CF.CF.CF.CE.CE.CE.CD.CD.CD.CC.CC.CC.
#0030.CB.CB.CB.CB.CA.CA.CA.C9.C9.C9.C8.C8.C8.C7.C7.C7.
#0040.C6.C6.C6.C5.C5.C5.C4.C4.C4.C3.C3.C3.C2.C2.C2.C1.
#0050.C1.C1.C0.C0.C0.BF.BF.BF.BE.BE.BE.BD.BD.BD.BC.BC.
#0060.BC.BB.BB.BB,BA.BA,BA.B9.B9,B8,B8.B8.B7.B7.B7.B6,
#0070.B6.B6.B5.B5.B5.B4.B4.B4.B3,B3.B2,B2.B2.B1.B1.B1.
#0080.B0.B0.B0.AF.AF,AE.AE.AE.AD.AD.AD.AC.AC.AC.AB.AB.
#0090.AA.AA.AA.A9.A9.A9.A8.A8.A7.A7.A7.A6.A6.A6.A5.A5.
#00A0.A5.A4.A4.A3.A3.A3.A2,A2.A2,A1.A1,A0.A0.A0,9F,9F,
#00B0.9E.9E.9E.9D.9D.9D.9C.9C.9B.9B.9B.9A.9A.9A.99.99.
#00C0.98.98.98.97,97,96.96.96.95,95.95.94.94.93.93.93,
#00D0.92.92.91.91.91.90.90.8F.8F.8F.8E.8E.8E.8D.8D.8C.
#00E0.8C.8C.8B.8B,8A.8A.8A.89.89.88.88.88.87.87.87.86.
#00F0.86.85.85.85.84.84.83.83.83.82.82.81.81.81.80.80.
#0100.80.7F.7F.7E,7E.7E.7D.7D.7C,7C.7C,7B.7B.7A,7A.7A.
#0110.79.79.78.78.78.77.77.77.76.76.75.75.75.74.74.74.
#0120.73.73,72,72,71,71,71,70.70.70.6F,6F.6E.6E,6E.6D,
#0130.6D.6C.6C.6C.6B.6B.6A.6A.6A.69.69.69.68.68.67.67.
#0140.67,66,66,65,65,65,64,64,64,63,63,62,62,62,61,61,
#0150.61,60,60.5F.5F.5F.5E,5E.5D,5D.5D.5C.5C.5C.5B.5B.
#0160.5A,5A.5A.59,59,59,58.58.57.57,57,56.56,56,55,55,
#0170,55.54.54,53,53,53.52,52,52.51.51,51.50,50,4F.4F.
#0180.4F.4E.4E.4E.4D.4D,4D.4C.4C,4B,4B,4B.4A,4A.4A.49,
#0190.49.49.48.48.48.47.47,47.46.46.45.45.45.44.44.44.
#01A0.43,43,43.42.42.42.41.41.41.40.40.40.3F.3F.3F.3E.
#01B0.3E.3E.3D.3D.3D.3C.3C.3C.3B.3B.3B.3A.3A.3A.39.39.
#01C0.39.38.38.38,37,37,37.36.36,36,35.35,35,34,34.34,
#01D0.34.33.33.33.32.32.32.31.31.31.30.30.30.30.2F.2F.
#01E0.2F.2E.2E.2E,2D,2D,2D,2D.2C,2C.2C.2B,2B,2B,2A.2A.
#01F0.2A.2A.29.29.29.28.28.28.28.27.27.27.26.26.26.26.
#0200,25,25,25.25,24,24,24,23,23,23,23,22,22,22,22,21,
#0210,21,21,21,20,20,20,1F,1F,1F,1F,1E,1E,1E,1E.1D.1D.
#0220,1D,1D,1C.1C,1C,1C,1B,1B,1B,1B,1B,1A,1A,1A,1A,19,
#0230,19.19.19.18.18,18,18,17,17,17,17,17,16.16,16.16.
#0240,15.15.15,15,15,14,14,14,14,14,13,13,13,13,13,12.
#0250,12,12,12,12,11,11,11,11,11,10,10.10,10,10.0F.0F.
#0260,0F.0F,0F.0F,0E.0E.0E,0E.0E,0D.0D.0D.0D.0D.0D,0C,
#0270.0C.0C.0C.0C.0C.0B.0B.0B.0B.0B.0B.0A.0A.0A.0A.0A.
#0280.0A.0A.09.09.09.09.09.09.09.09.08.08.08.08.08.08.
#0290.08.07.07.07.07.07.07.07.06.06.06.06.06.06.06.05.
#02A0.05.05.05.05.05.05.05,05.05.04.04.04.04,04,04,04,
#02B0.04.04.04.03.03.03.03.03.03.03.03.03.03.03.03.03.
#02C0.02,02,02,02,02,02,02.02.02,02,02,02.02.01,01.01,
#02D0.01.01,01.01.01,01.01.01.01,01.01.01.01.01.01.01.
#02E0.01.01,00,00,00,00,00,00,00,00,00,00,00,00,00,00,
#02F0,00,00,00.00,00,00,00,00.00,00.00,00,00,00,00,00,
#0300,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,00,
#0310,00,00,00,00,00,00,00,00,00,00,00,00,00,00,01,01,
#0320.01,01,01,01,01,01,01,01,01,01,01,01,01,01,01,01,
#0330.01,01,01,02,02,02,02,02,02,02,02,02,02,02,02,02.
#0340.03.03.03.03,03.03,03,03,03.03,03,03.03,04,04,04,
#0350.04,04.04.04.04.04.04,05.05,05.05.05.05.05.05.05.
#0360.05,06.06.06.06.06.06,06,07,07,07,07,07,07.07,08,
#0370.08.08.08.08.08.08.09.09.09.09.09.09.09.09.0A.0A.
#0380.0A,0A,0A,0A,0A,0B,0B,0B.0B,0B,0B,0C.0C,0C.0C,0C.
#0390.0C.0D.0D.0D.0D.0D.0D,0E.0E,0E.0E.0E,0F.0F,0F.0F.
#03A0.0F.0F,10.10,10.10,10,11,11,11,11,11,12,12,12,12,
#03B0.12.13,13,13,13,13,14,14,14,14,14,15,15,15,15,15.
#03C0.16,16,16,16,17,17,17,17,17,18,18,18,18,19,19,19,
#03D0.19.1A,1A.1A,1A,1B,1B,1B,1B,1B,1C,1C,1C,1C,1D,1D.
#03E0.1D,1D,1E,1E,1E,1E,1F,1F,1F,1F,20,20.20,21,21,21,
#03F0.21.22,22,22,22,23,23,23.23.24,24,24.25.25.25.25.
```

```
#0400,26,26,26,26,27,27,27,28,28,28,28,29,29,29,2A,2A,
#0410,2A,2A,2B,2B,2B,2C,2C,2C,2D,2D,2D,2D,2E,2E,2E,2F,
#0420,2F,2F,30,30,30,30,31,31,31,32,32,32,33,33,33,34,
#0430,34,34,34,35,35,35,36,36,36,37,37,37,38,38,38,39,
#0440,39,39,3A,3A,3A,3B,3B,3B,3C,3C,3C,3D,3D,3D,3E,3E,
#0450,3E,3F,3F,3F,40,40,40,41,41,41,42,42,42,43,43,43,
#0460,44,44,44,45,45,45,46,46,47,47,47,48,48,48,49,49,
#0470,49,4A,4A,4A,4B,4B,4B,4C,4C,4D,4D,4D,4E,4E,4E,4F,
#0480,4F,4F,50,50,51,51,51,52,52,52,53,53,53,54,54,55,
#0490,55,55,56,56,56,57,57,57,58,58,59,59,59,5A,5A,5A,
#04A0,5B,5B,5C,5C,5C,5D,5D,5D,5E,5E,5F,5F,5F,60,60,61,
#04B0,61,61,62,62,62,63,63,64,64,64,65,65,65,66,66,67,
#04C0,67,67,68,68,69,69,69,6A,6A,6A,6B,6B,6C,6C,6C,6D,
#04D0,6D,6E,6E,6E,6F,6F,70,70,70,71,71,71,72,72,73,73,
#04E0,74,74,74,75,75,75,76,76,77,77,77,78,78,78,79,79,
#04F0,7A,7A,7A,7B,7B,7C,7C,7C,7D,7D,7E,7E,7E,7F,7F,80,
#0500,80,80,81,81,81,82,82,83,83,83,84,84,85,85,85,86,
#0510,86,87,87,87,88,88,88,89,89,8A,8A,8A,8B,8B,8C,8C,
#0520,8C,8D,8D,8E,8E,8E,8F,8F,8F,90,90,91,91,91,92,92,
#0530,93,93,93,94,94,95,95,95,96,96,96,97,97,98,98,98,
#0540,99,99,9A,9A,9A,9B,9B,9B,9C,9C,9D,9D,9D,9E,9E,9E,
#0550,9F,9F,A0,A0,A0,A1,A1,A2,A2,A2,A3,A3,A3,A4,A4,A5,
#0560,A5,A5,A6,A6,A6,A7,A7,A7,A8,A8,A9,A9,A9,AA,AA,AA,
#0570,AB,AB,AC,AC,AC,AD,AD,AD,AE,AE,AE,AF,AF,B0,B0,B0,
#0580,B1,B1,B1,B2,B2,B2,B3,B3,B4,B4,B4,B5,B5,B5,B6,B6,
#0590,B6,B7,B7,B7,B8,B8,B8,B9,B9,BA,BA,BA,BB,BB,BB,BC,
#05A0,BC,BC,BD,BD,BD,BE,BE,BE,BF,BF,BF,C0,C0,C0,C1,C1,
#05B0,C1,C2,C2,C2,C3,C3,C3,C4,C4,C4,C5,C5,C5,C6,C6,C6,
#05C0,C7,C7,C7,C8,C8,C8,C9,C9,C9,CA,CA,CA,CB,CB,CB,CB,
#05D0,CC,CC,CC,CD,CD,CD,CE,CE,CE,CF,CF,CF,CF,D0,D0,D0,
#05E0,D1,D1,D1,D2,D2,D2,D2,D3,D3,D3,D4,D4,D4,D5,D5,D5,
#05F0,D5,D6,D6,D6,D7,D7,D7,D7,D8,D8,D8,D9,D9,D9,D9,DA,
#0600,DA,DA,DA,DB,DB,DB,DC,DC,DC,DC,DD,DD,DD,DD,DE,DE,
#0610,DE,DE,DF,DF,DF,E0,E0,E0,E0,E1,E1,E1,E1,E2,E2,E2,
#0620,E2,E3,E3,E3,E3,E4,E4,E4,E4,E4,E5,E5,E5,E5,E6,E6,
#0630,E6,E6,E7,E7,E7,E7,E8,E8,E8,E8,E8,E9,E9,E9,E9,EA,
#0640,EA,EA,EA,EA,EB,EB,EB,EB,EB,EC,EC,EC,EC,EC,ED,ED,
#0650,ED,ED,ED,EE,EE,EE,EE,EE,EF,EF,EF,EF,EF,F0,F0,F0,
#0660,F0,F0,F0,F1,F1,F1,F1,F1,F2,F2,F2,F2,F2,F2,F3,F3,
#0670,F3,F3,F3,F3,F4,F4,F4,F4,F4,F4,F5,F5,F5,F5,F5,F5,
#0680,F5,F6,F6,F6,F6,F6,F6,F6,F7,F7,F7,F7,F7,F7,F7,F8,
#0690,F8,F8,F8,F8,F8,F8,F8,F9,F9,F9,F9,F9,F9,F9,F9,FA,
#06A0,FA,FA,FA,FA,FA,FA,FA,FA,FA,FB,FB,FB,FB,FB,FB,FB,
#06B0,FB,FB,FB,FC,FC,FC,FC,FC,FC,FC,FC,FC,FC,FC,FC,FD,
#06C0,FD,FD,FD,FD,FD,FD,FD,FD,FD,FD,FD,FD,FD,FE,FE,FE,
#06D0,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,
#06E0,FE,FE,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,
#06F0,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,
#0700,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,
#0710,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FF,FE,FE,
#0720,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,FE,
#0730,FE,FE,FE,FD,FD,FD,FD,FD,FD,FD,FD,FD,FD,FD,FD,FD,
#0740,FD,FC,FC,FC,FC,FC,FC,FC,FC,FC,FC,FC,FC,FB,FB,FB,
#0750,FB,FB,FB,FB,FB,FB,FB,FA,FA,FA,FA,FA,FA,FA,FA,FA,
#0760,FA,F9,F9,F9,F9,F9,F9,F9,F9,F8,F8,F8,F8,F8,F8,F8,
#0770,F8,F7,F7,F7,F7,F7,F7,F7,F6,F6,F6,F6,F6,F6,F6,F5,
#0780,F5,F5,F5,F5,F5,F5,F4,F4,F4,F4,F4,F4,F3,F3,F3,F3,
#0790,F3,F3,F2,F2,F2,F2,F2,F2,F1,F1,F1,F1,F1,F0,F0,F0,
#07A0,F0,F0,F0,EF,EF,EF,EF,EF,EE,EE,EE,EE,EE,ED,ED,ED,
#07B0,ED,ED,EC,EC,EC,EC,EC,EB,EB,EB,EB,EB,EA,EA,EA,EA,
#07C0,EA,E9,E9,E9,E9,E8,E8,E8,E8,E8,E7,E7,E7,E7,E6,E6,
#07D0,E6,E6,E5,E5,E5,E5,E4,E4,E4,E4,E4,E3,E3,E3,E3,E2,
#07E0,E2,E2,E2,E1,E1,E1,E1,E0,E0,E0,E0,DF,DF,DF,DE,DE,
#07F0,DE,DE,DD,DD,DD,DD,DC,DC,DC,DC,DB,DB,DB,DA,DA,DA,
```

APPENDIX E (a)

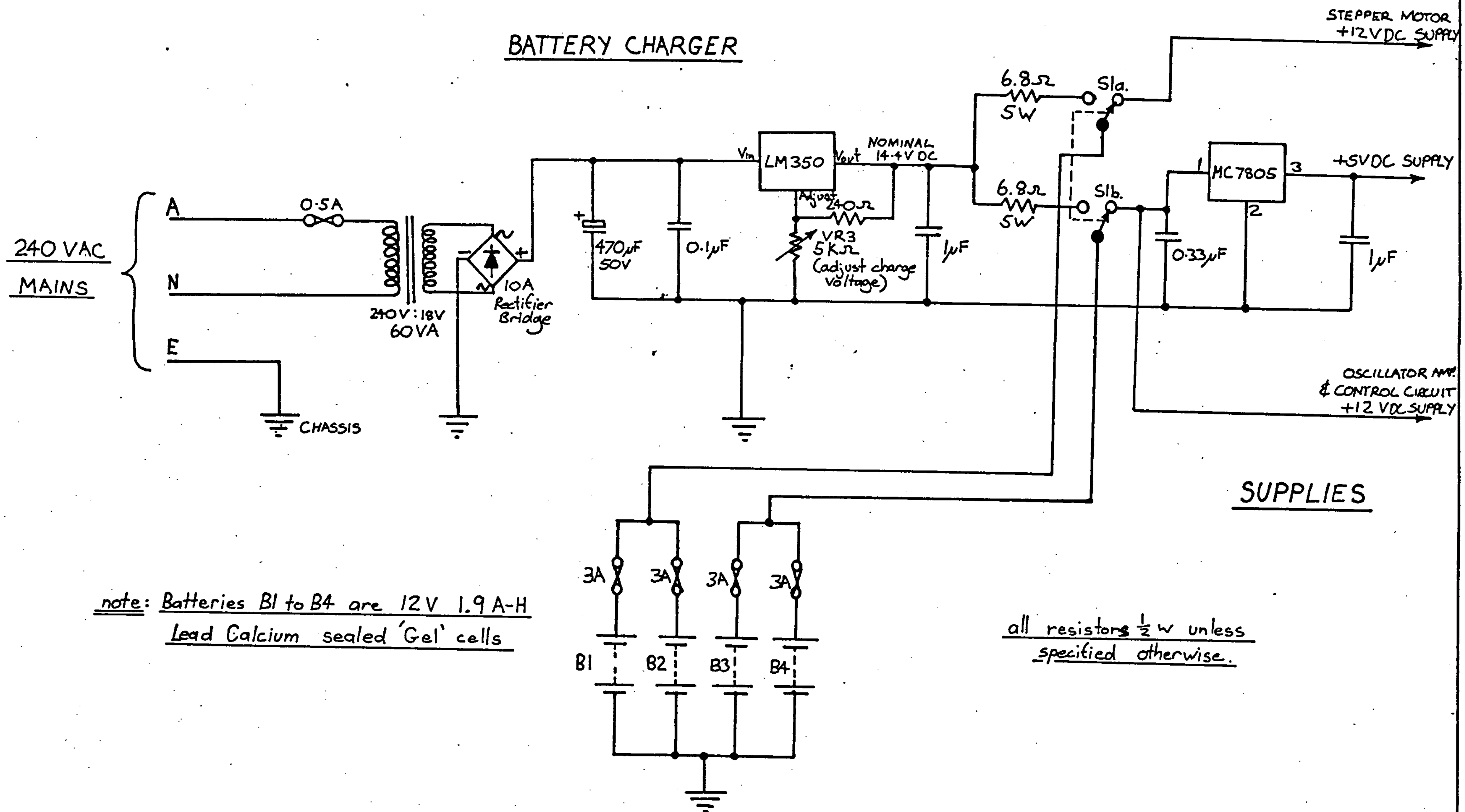
CIRCUIT DIAGRAM FOR ARR-1



note:- T1 is secondary of 240V to 9V C.T. transformer.

(all resistors ¼w except where specified)

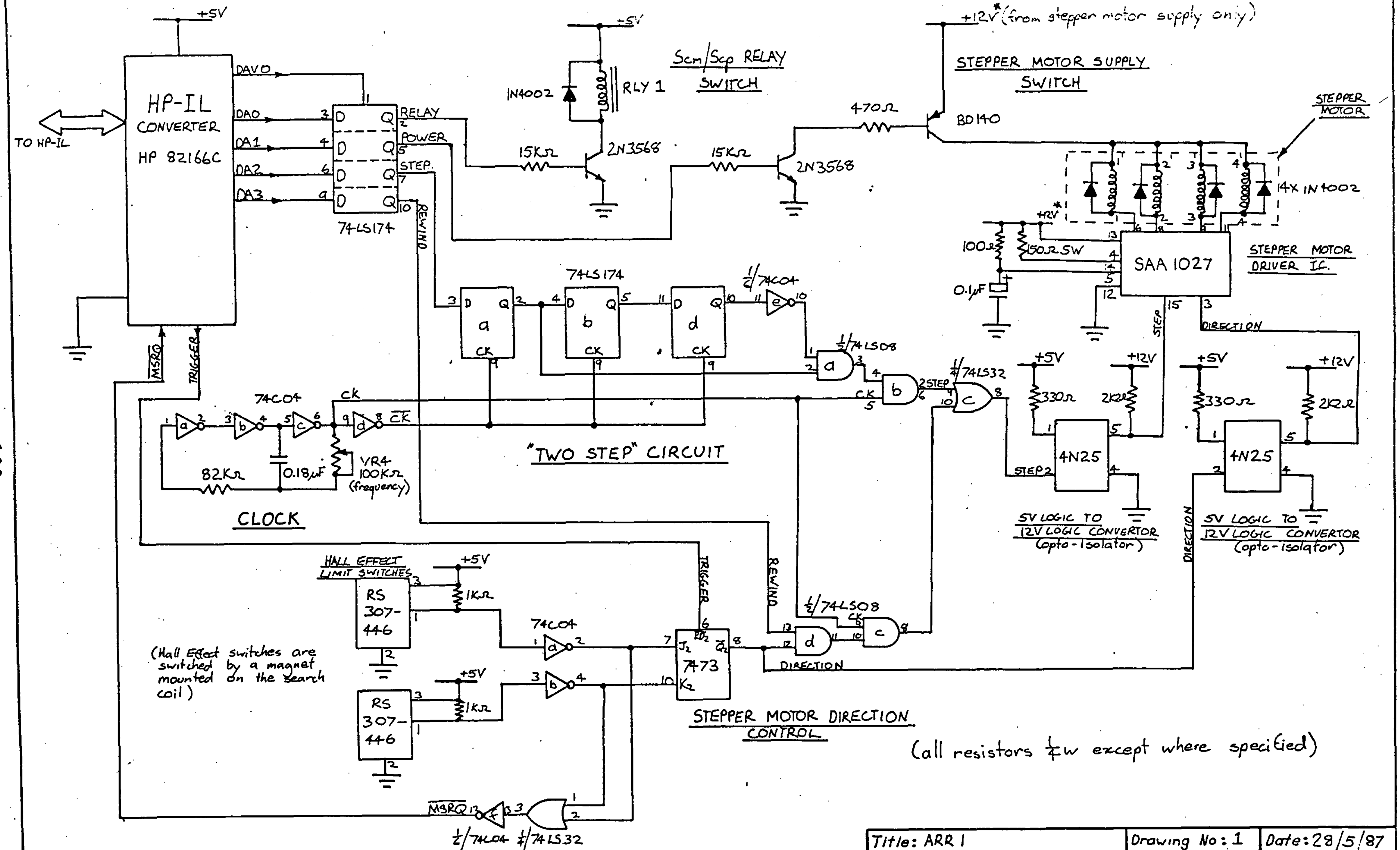
Title: ARR I Oscillator, Filter Circuit.	Drawing No: 1	Date: 27/5/87
Rev: Q 1	Sheet: 1/3	Drawn By: I. Hutchinson.



note: Batteries B1 to B4 are 12V 1.9 A-H Lead Calcium sealed 'Gel' cells

all resistors ½ W unless specified otherwise.

Title: ARR I POWER SUPPLY, BATTERY CHARGER	Drawing No: 1	Date: 27/5/87
Rev: O	Sheet: 2/3	Drawn By: I. HUTCHINSON

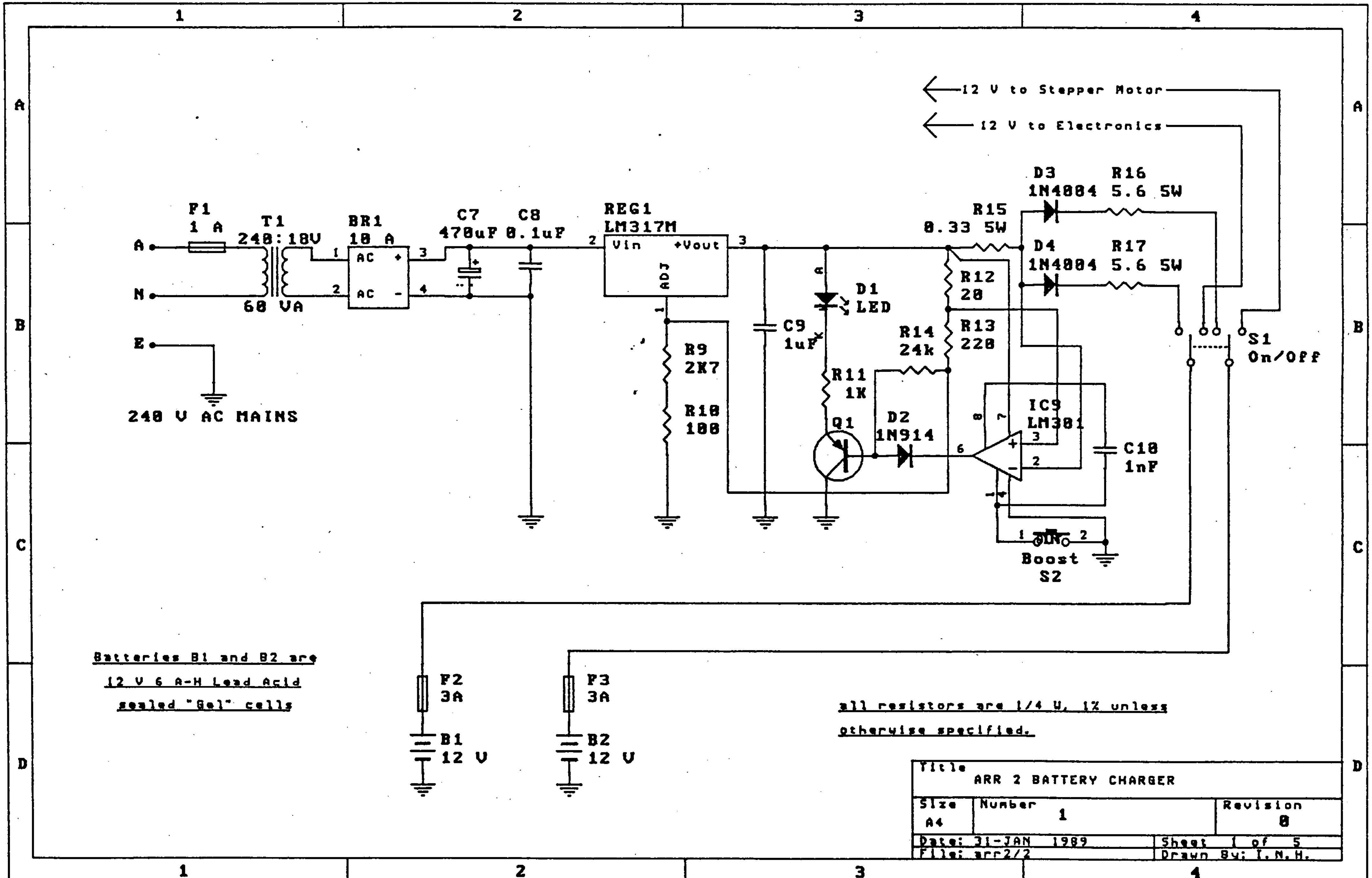


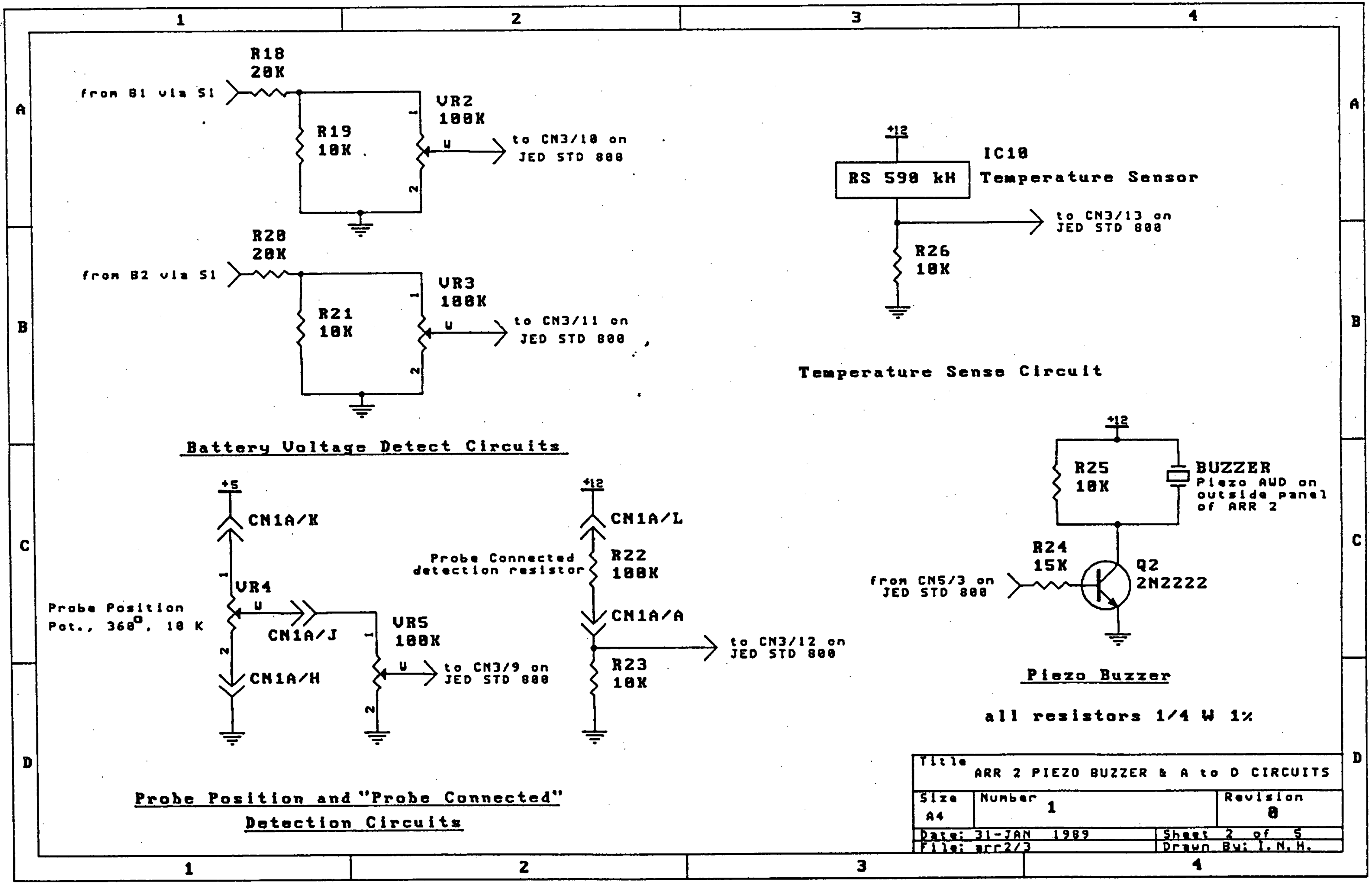
Note:- some supplies to I.C's have been ommitted for clarity.
:- all logic supplies bypassed.

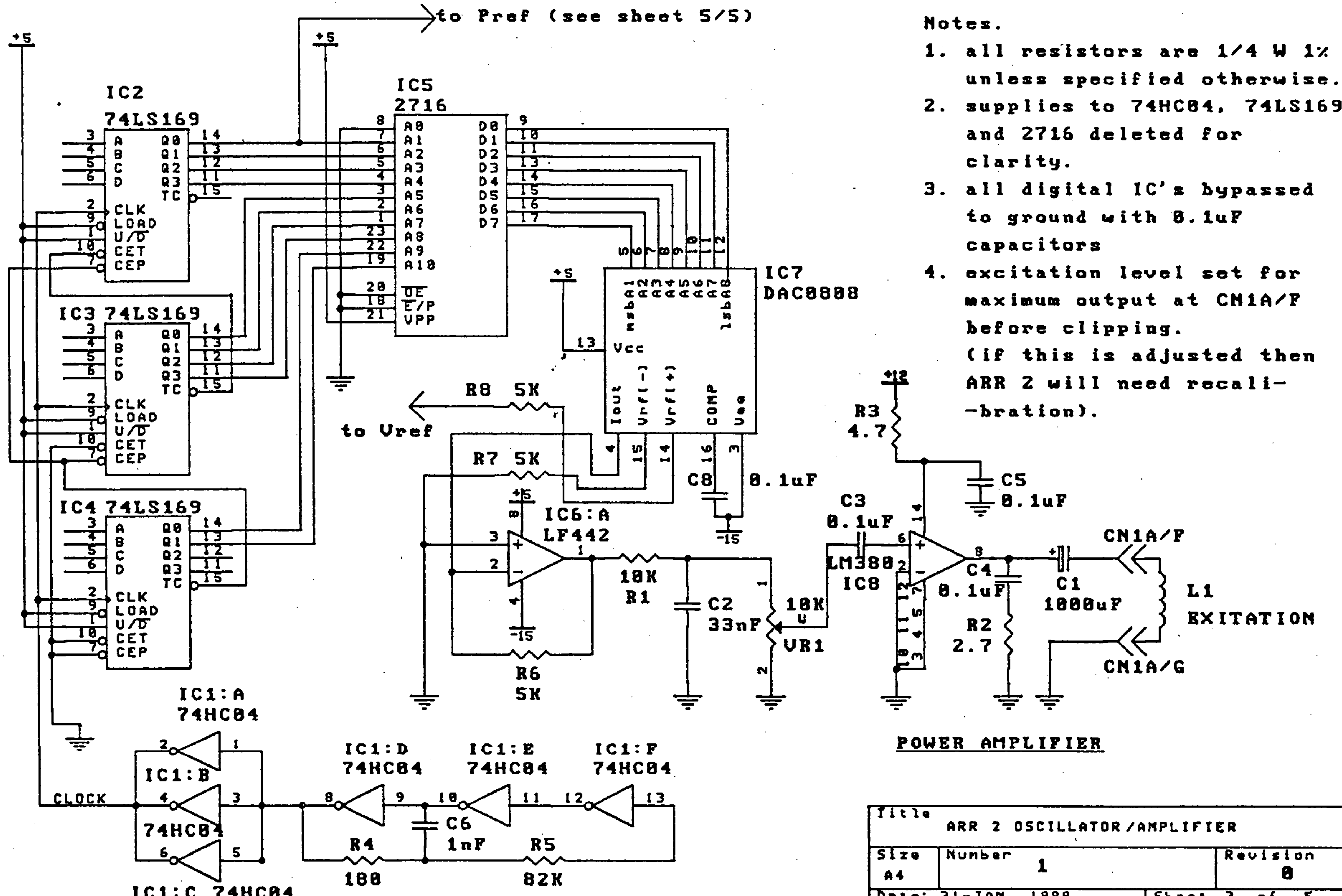
Title: ARR I CONTROL CIRCUIT.	Drawing No: 1	Date: 28/5/87
Rev: 0	Sheet: 3/3	Drawn By: I. Hutchinson

APPENDIX E (b)

CIRCUIT DIAGRAMS FOR ARR-2


12 V to Stepper Motor
12 V to Electronics
F1 1 A
T1 240:18V
60 VA
BR1 10 A
AC +
AC -
C7 470uF
C8 0.1uF
REG1 LM317M
Vin +Vout
ADJ
R15 0.33 5W
D3 1N4004
R16 5.6 5W
D4 1N4004
R17 5.6 5W
R12 20
R13 220
D1 LED
C9 1uF
R14 24k
R11 1K
R9 2K7
R10 100
Q1
D2 1N914
IC9 LM301
C10 1nF
S1 On/Off
Boost S2
A
N
E
240 V AC MAINS
Batteries B1 and B2 are
12 V 6 A-H Lead Acid
sealed "Gel" cells
F2 3A
F3 3A
B1 12 V
B2 12 V
all resistors are 1/4 W, 1% unless
otherwise specified.
Title
ARR 2 BATTERY CHARGER
Size A4
Number 1
Revision 0
Date: 31-JAN 1989
File: arr2/2
Sheet 1 of 5
Drawn By: I.N.H.

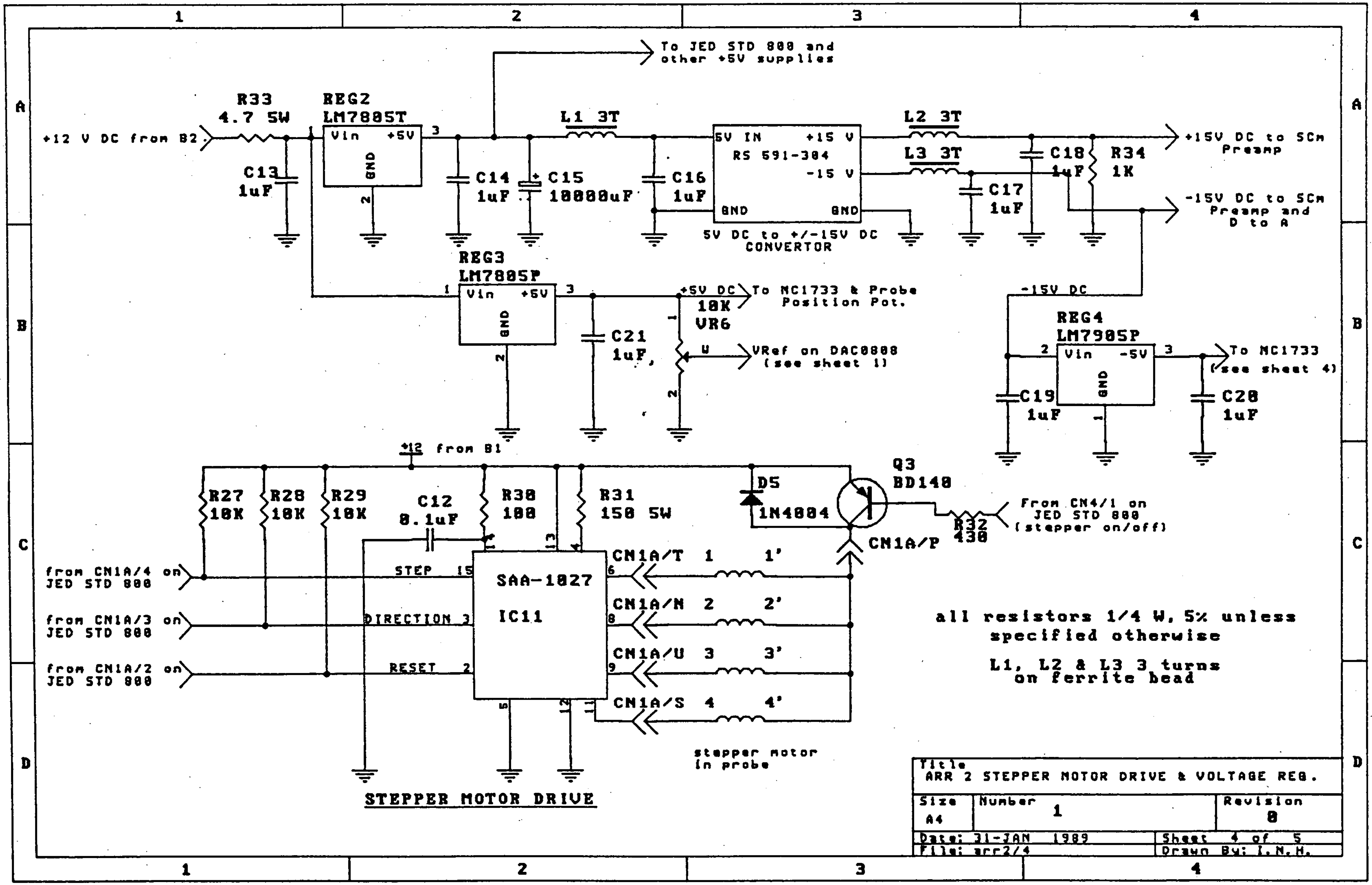

from B1 via S1
R18
20K
R19
10K
VR2
100K
W
to CN3/10 on
JED STD 800
from B2 via S1
R20
20K
R21
10K
VR3
100K
W
to CN3/11 on
JED STD 800
Battery Voltage Detect Circuits
+12
IC10
RS 590 kH
Temperature Sensor
to CN3/13 on
JED STD 800
R26
10K
Temperature Sense Circuit
+5
CN1A/K
VR4
W
Probe Position
Pot., 360°, 10 K
CN1A/J
CN1A/H
VR5
100K
W
to CN3/9 on
JED STD 800
+12
CN1A/L
Probe Connected
detection resistor
R22
100K
CN1A/A
to CN3/12 on
JED STD 800
R23
10K
Probe Position and "Probe Connected"
Detection Circuits
+12
R25
10K
BUZZER
Piezo AWD on
outside panel
of ARR 2
R24
15K
from CN5/3 on
JED STD 800
Q2
2N2222
Piezo Buzzer
all resistors 1/4 W 1%
Title
ARR 2 PIEZO BUZZER & A to D CIRCUITS
Size
A4
Number
1
Revision
0
Date: 31-JAN 1989
Sheet 2 of 5
File: arr2/3
Drawn By: I.N.H.

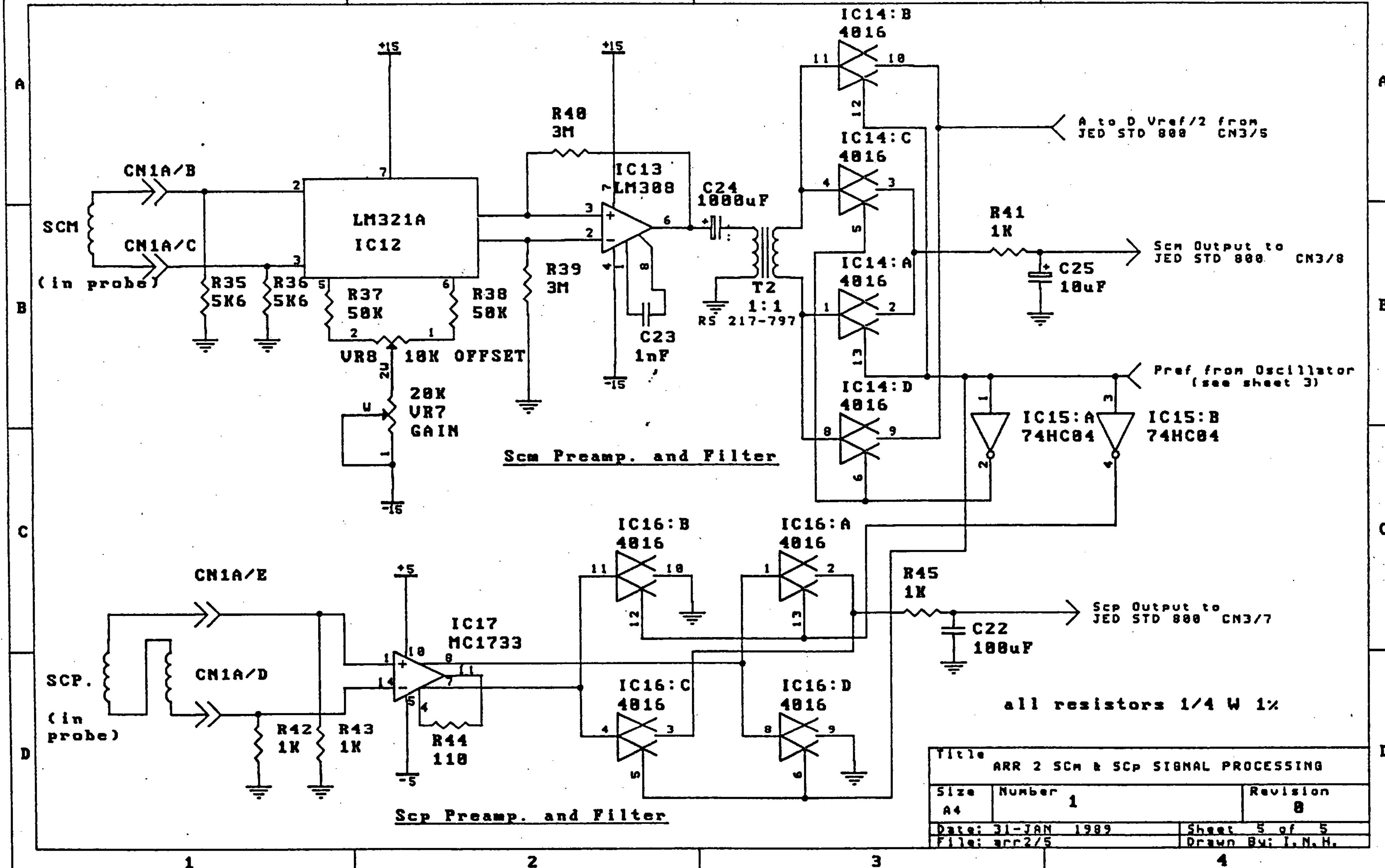


Notes.

1. all resistors are 1/4 W 1% unless specified otherwise.
2. supplies to 74HC04, 74LS169 and 2716 deleted for clarity.
3. all digital IC's bypassed to ground with 0.1uF capacitors
4. excitation level set for maximum output at CN1A/F before clipping. (if this is adjusted then ARR 2 will need recali- -bration).

Title: ARR 2 OSCILLATOR/AMPLIFIER		
Size: A4	Number: 1	Revision: 0
Date: 31-JAN 1989		Sheet 3 of 5
File: arr2/1		Drawn By: I.N.H.

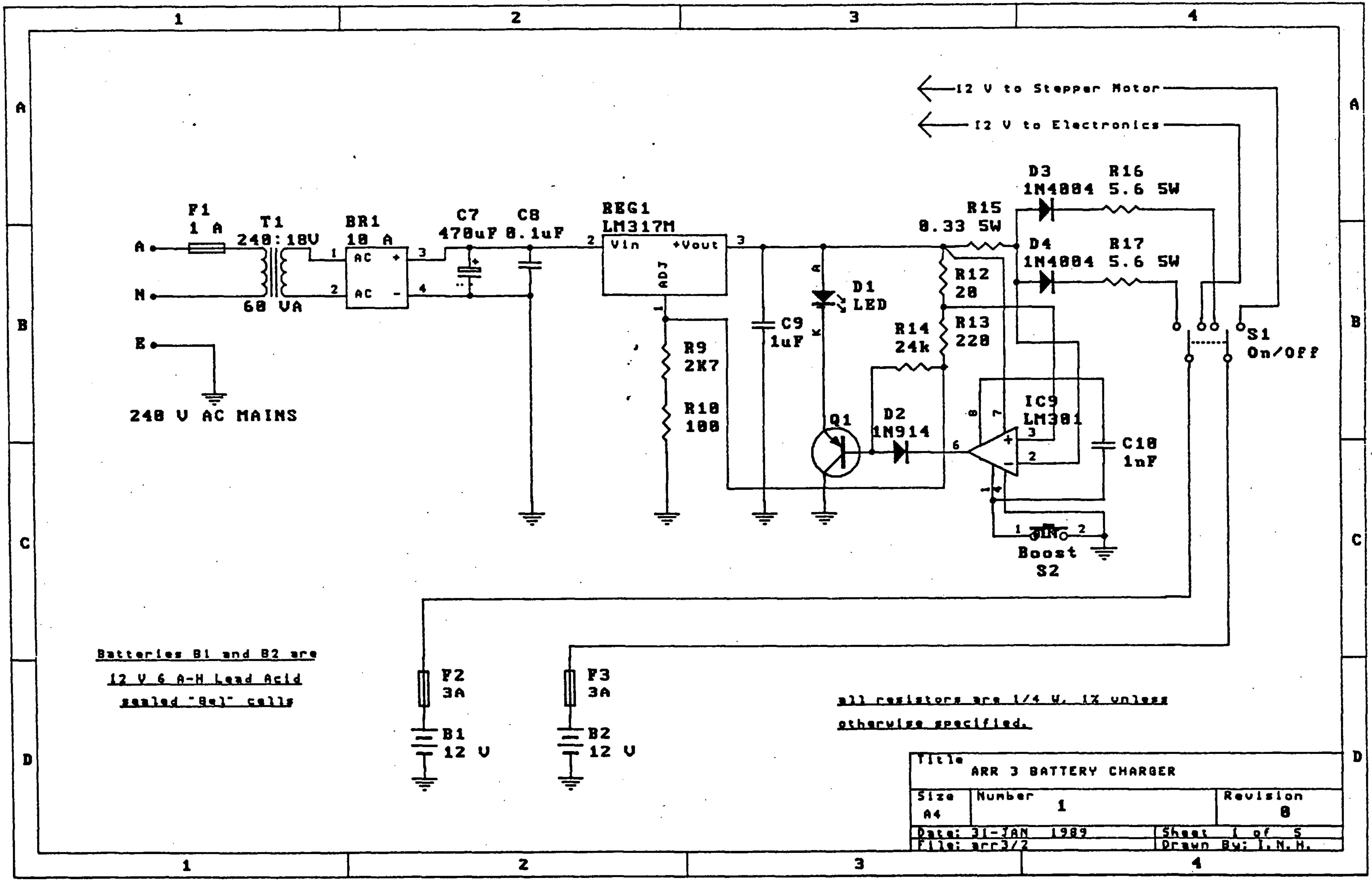

To JED STD 800 and other +5V supplies
R33 4.7 5W
REG2 LM7805T
+12 V DC from B2
Vin +5V
GND
C13 1uF
C14 1uF
C15 10000uF
L1 3T
C16 1uF
5V IN +15 V
RS 591-304
-15 V
GND GND
5V DC to +/-15V DC CONVERTOR
L2 3T
L3 3T
C17 1uF
C18 1uF
R34 1K
+15V DC to SCm Preamp
-15V DC to SCm Preamp and D to A
REG3 LM7805P
+5V DC
To MC1733 & Probe Position Pot.
10K VR6
C21 1uF
VRef on DAC0808 (see sheet 1)
-15V DC
REG4 LM7905P
Vin -5V
To MC1733 (see sheet 4)
C19 1uF
C20 1uF
+12 from B1
R27 10K
R28 10K
R29 10K
C12 0.1uF
R30 100
R31 150 5W
D5 1N4004
Q3 BD140
From CN4/1 on JED STD 800 (stepper on/off)
R32 430
CN1A/P
from CN1A/4 on JED STD 800
from CN1A/3 on JED STD 800
from CN1A/2 on JED STD 800
STEP
DIRECTION
RESET
SAA-1027
IC11
CN1A/T 1 1'
CN1A/N 2 2'
CN1A/U 3 3'
CN1A/S 4 4'
stepper motor in probe
all resistors 1/4 W, 5% unless specified otherwise
L1, L2 & L3 3 turns on ferrite bead
STEPPER MOTOR DRIVE
Title
ARR 2 STEPPER MOTOR DRIVE & VOLTAGE REG.
Size A4
Number 1
Revision 0
Date: 31-JAN 1989
Sheet 4 of 5
File: arr2/4
Drawn By: I.N.H.

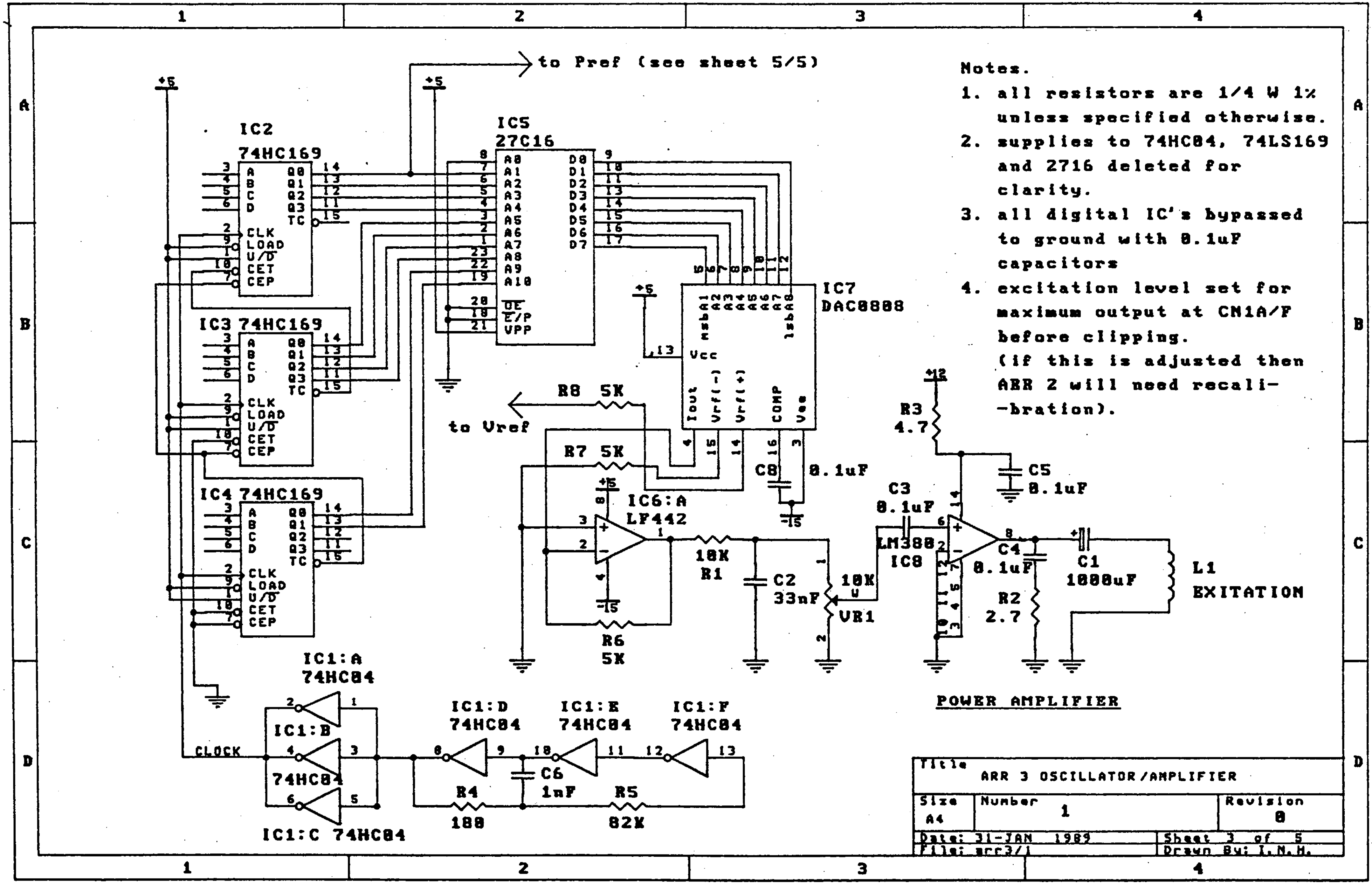


Scm Preamp. and Filter
Scp Preamp. and Filter
SCM
(in probe)
CN1A/B
CN1A/C
LM321A
IC12
R35 5K6
R36 5K6
R37 50K
R38 50K
VR8 10K OFFSET
20K VR7 GAIN
R40 3M
R39 3M
IC13 LM308
C23 1nF
C24 1000uF
T2 1:1
RS 217-797
IC14:B 4016
IC14:C 4016
IC14:A 4016
IC14:D 4016
A to D Vref/2 from JED STD 800 CN3/5
R41 1K
C25 10uF
Scm Output to JED STD 800 CN3/8
Pref from Oscillator (see sheet 3)
IC15:A 74HC04
IC15:B 74HC04
SCP.
(in probe)
CN1A/E
CN1A/D
R42 1K
R43 1K
IC17 MC1733
R44 110
IC16:B 4016
IC16:A 4016
IC16:C 4016
IC16:D 4016
R45 1K
C22 100uF
Scp Output to JED STD 800 CN3/7
all resistors 1/4 W 1%
Title ARR 2 SCm & SCp SIGNAL PROCESSING
Size A4
Number 1
Revision 0
Date: 31-JAN 1989
Sheet 5 of 5
File: arr2/5
Drawn By: I.N.H.

APPENDIX E (c)

CIRCUIT DIAGRAMS FOR ARR-3

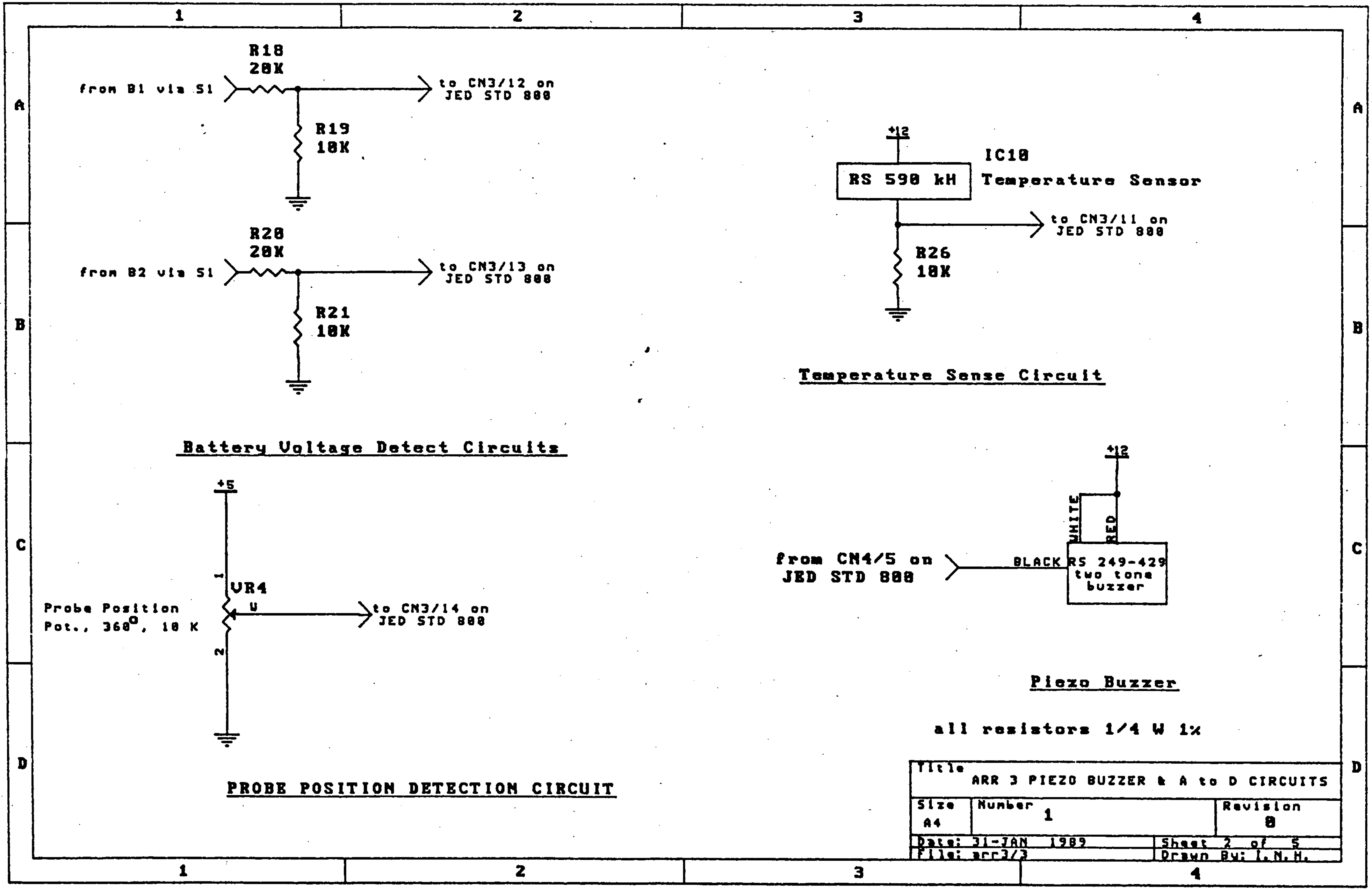

12 V to Stepper Motor
12 V to Electronics
F1
1 A
T1
240:18V
60 VA
BR1
10 A
AC
C7
470uF
C8
0.1uF
REG1
LM317M
Vin
+Vout
ADJ
R15
0.33 5W
D3
1N4004
R16
5.6 5W
D4
1N4004
R17
5.6 5W
D1
LED
R12
20
R13
220
R14
24k
C9
1uF
R9
2K7
R10
100
Q1
D2
1N914
IC9
LM301
C10
1nF
S1
On/Off
Boost
S2
240 V AC MAINS
F2
3A
F3
3A
B1
12 V
B2
12 V
Batteries B1 and B2 are
12 V 6 A-H Lead Acid
sealed "Gel" cells
all resistors are 1/4 W, 1% unless
otherwise specified.
Title
ARR 3 BATTERY CHARGER
Size
A4
Number
1
Revision
0
Date: 31-JAN 1989
Sheet 1 of 5
File: arr3/2
Drawn By: I.N.H.

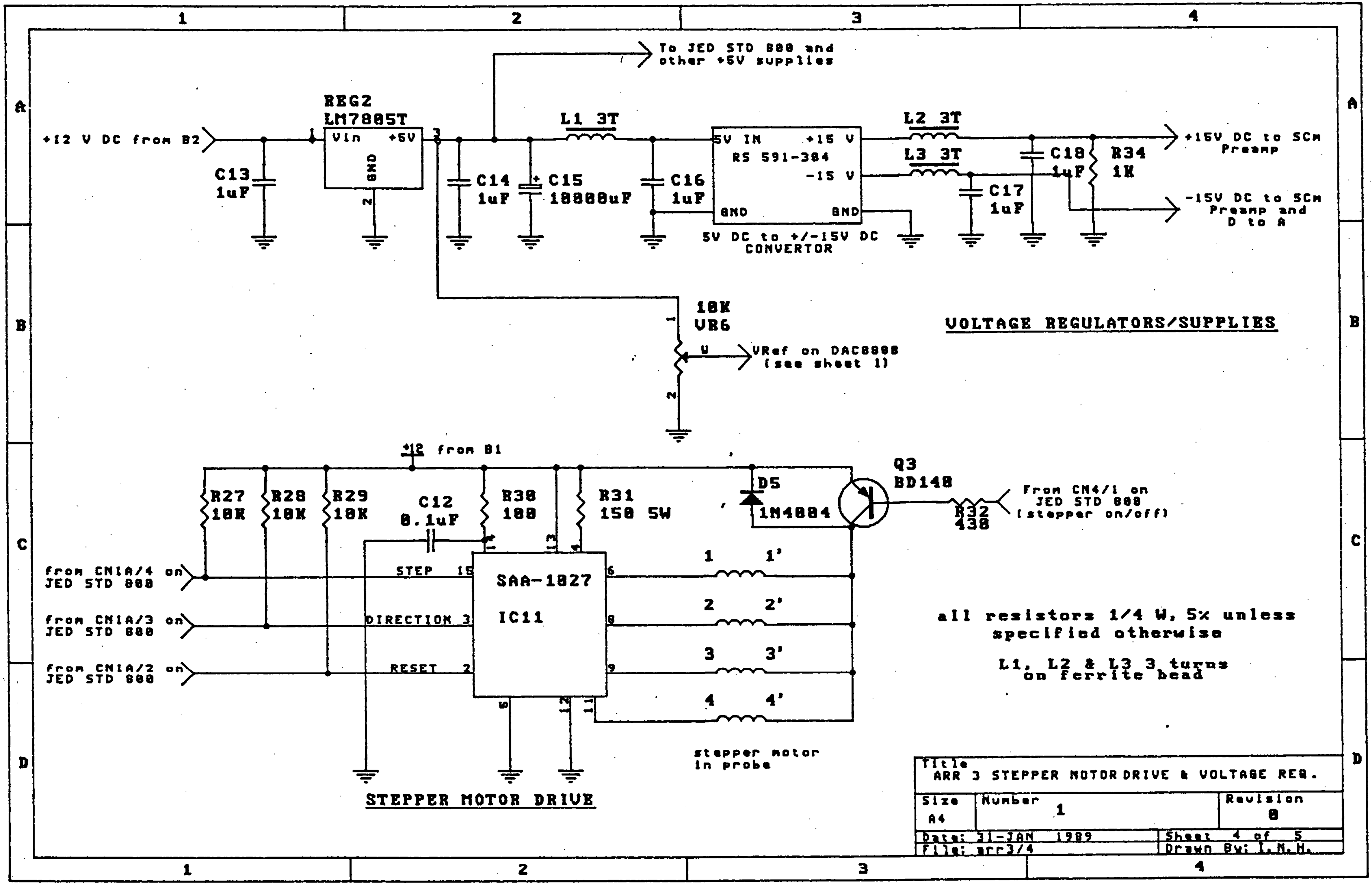


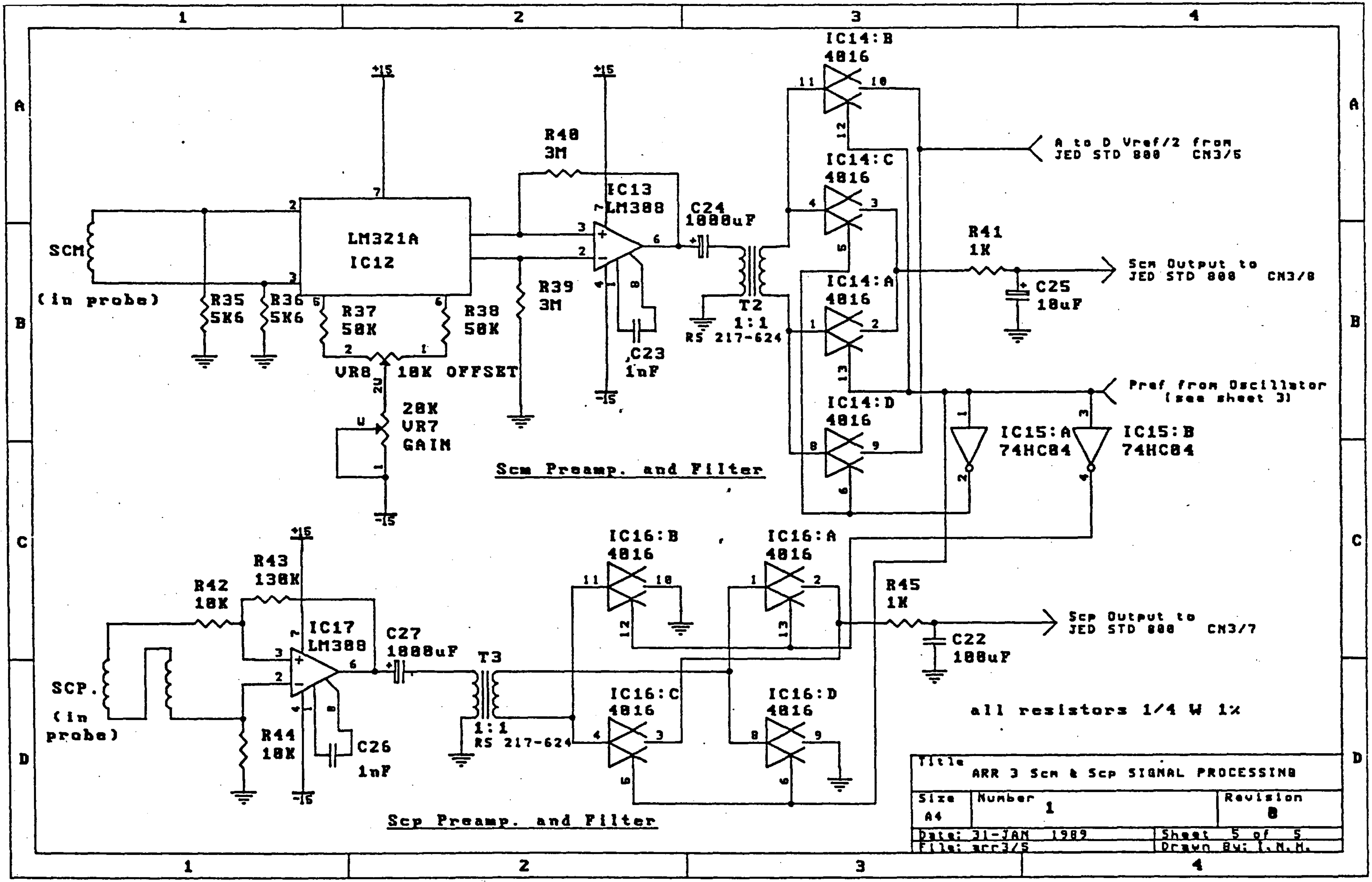
Notes.

1. all resistors are 1/4 W 1% unless specified otherwise.
2. supplies to 74HC04, 74LS169 and 2716 deleted for clarity.
3. all digital IC's bypassed to ground with 0.1uF capacitors
4. excitation level set for maximum output at CN1A/F before clipping. (if this is adjusted then ARR 2 will need recali- -bration).

Title		
ARR 3 OSCILLATOR/AMPLIFIER		
Size A4	Number 1	Revision 0
Date: 31-JAN 1989		Sheet 3 of 5
File: arr3/1		Drawn By: I.N.H.

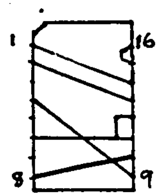

R18
20K
from B1 via S1
to CN3/12 on JED STD 800
R19
10K
R20
20K
from B2 via S1
to CN3/13 on JED STD 800
R21
10K
Battery Voltage Detect Circuits
+12
IC10
RS 590 kH
Temperature Sensor
to CN3/11 on JED STD 800
R26
10K
Temperature Sense Circuit
+5
VR4
Probe Position Pot., 360°, 10 K
to CN3/14 on JED STD 800
PROBE POSITION DETECTION CIRCUIT
+12
WHITE
RED
BLACK
from CN4/5 on JED STD 800
RS 249-429 two tone buzzer
Piezo Buzzer
all resistors 1/4 W 1%
Title ARR 3 PIEZO BUZZER & A to D CIRCUITS
Size A4
Number 1
Revision 0
Date: 31-JAN 1989
Sheet 2 of 5
File: arr3/3
Drawn By: I.N.H.


To JED STD 800 and
other +5V supplies
REG2
LM7805T
Vin
+5V
GND
+12 V DC from B2
C13
1uF
C14
1uF
C15
10000uF
L1 3T
C16
1uF
5V IN
+15 V
RS 591-384
-15 V
GND
GND
5V DC to +/-15V DC
CONVERTOR
L2 3T
L3 3T
C17
1uF
C18
1uF
R34
1K
+15V DC to SCM
Preamp
-15V DC to SCM
Preamp and
D to A
10K
VR6
VRef on DAC0800
(see sheet 1)
VOLTAGE REGULATORS/SUPPLIES
+12 from B1
R27
10K
R28
10K
R29
10K
C12
0.1uF
R30
100
R31
150 5W
D5
1N4004
Q3
BD140
R32
430
From CN4/1 on
JED STD 800
(stepper on/off)
from CN1A/4 on
JED STD 800
from CN1A/3 on
JED STD 800
from CN1A/2 on
JED STD 800
STEP
DIRECTION
RESET
SAA-1027
IC11
1 1'
2 2'
3 3'
4 4'
stepper motor
in probe
STEPPER MOTOR DRIVE
all resistors 1/4 W, 5% unless
specified otherwise
L1, L2 & L3 3 turns
on ferrite bead
Title
ARR 3 STEPPER MOTOR DRIVE & VOLTAGE REG.
Size
A4
Number
1
Revision
0
Date: 31-JAN 1989
Sheet 4 of 5
File: arr3/4
Drawn By: I.M.H.

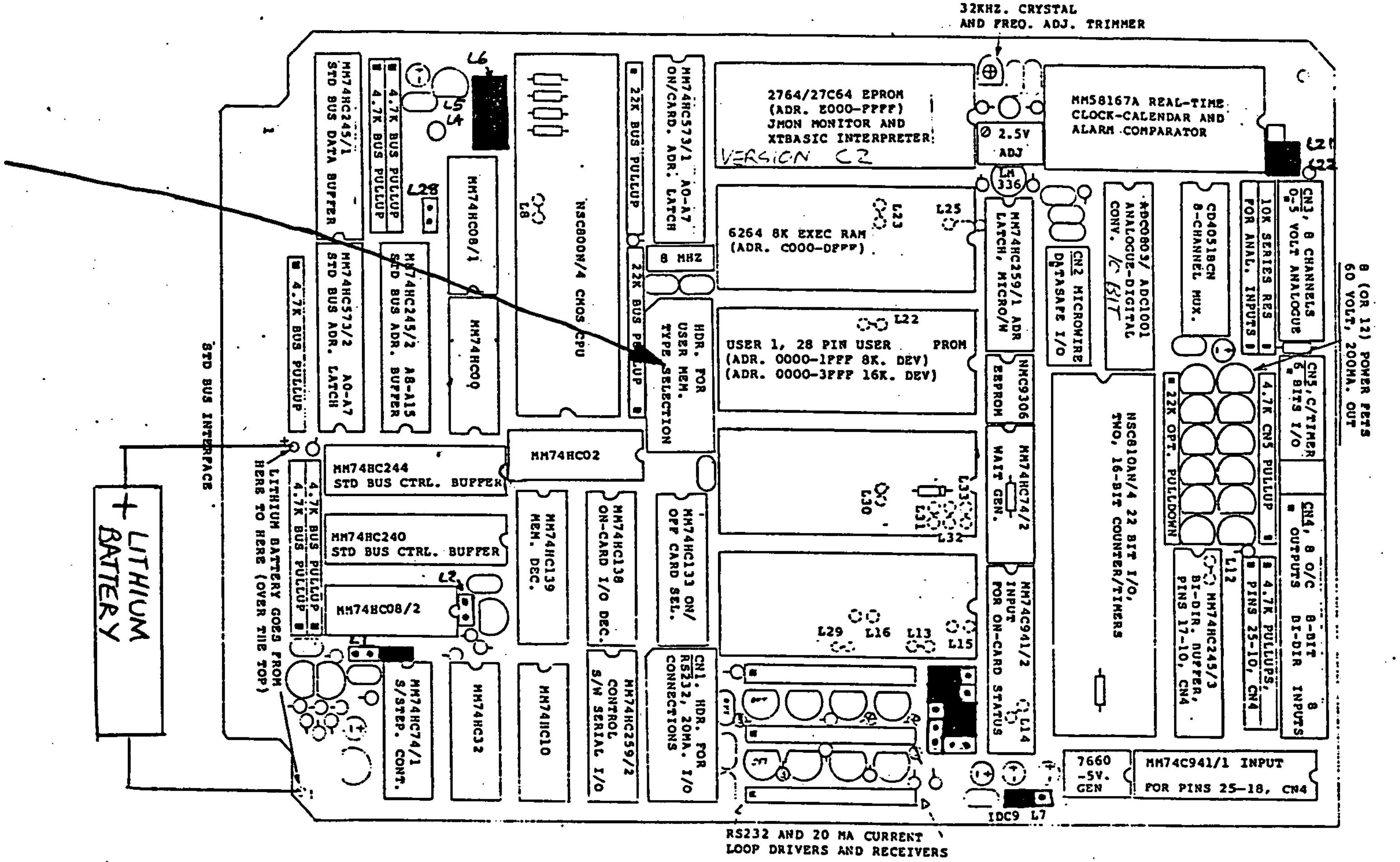

SCM
(in probe)
LM321A
IC12
R35 5K6
R36 5K6
R37 50K
R38 50K
VR8 10K OFFSET
20K VR7 GAIN
+15
-15
R40 3M
R39 3M
IC13 LM308
C24 1000uF
C23 1nF
T2 1:1 RS 217-624
IC14:B 4016
IC14:C 4016
IC14:A 4016
IC14:D 4016
A to D Vref/2 from JED STD 800 CN3/5
R41 1K
C25 10uF
Scm Output to JED STD 800 CN3/8
Pref from Oscillator (see sheet 3)
IC15:A 74HC04
IC15:B 74HC04
Scm Preamp. and Filter
SCP.
(in probe)
R42 10K
R43 130K
IC17 LM308
C27 1000uF
T3
1:1 RS 217-624
R44 10K
C26 1nF
IC16:B 4016
IC16:A 4016
IC16:C 4016
IC16:D 4016
R45 1K
C22 100uF
Scp Output to JED STD 800 CN3/7
all resistors 1/4 W 1%
Scp Preamp. and Filter
Title ARR 3 Scm & Scp SIGNAL PROCESSING
Size A4
Number 1
Revision B
Date: 31-JAN 1989
Sheet 5 of 5
File: arr3/5
Drawn By: I.N.M.

APPENDIX F

JED STD 800 MODIFICATIONS AND WIRING SCHEMATICS (ARR-2 AND ARR-3)



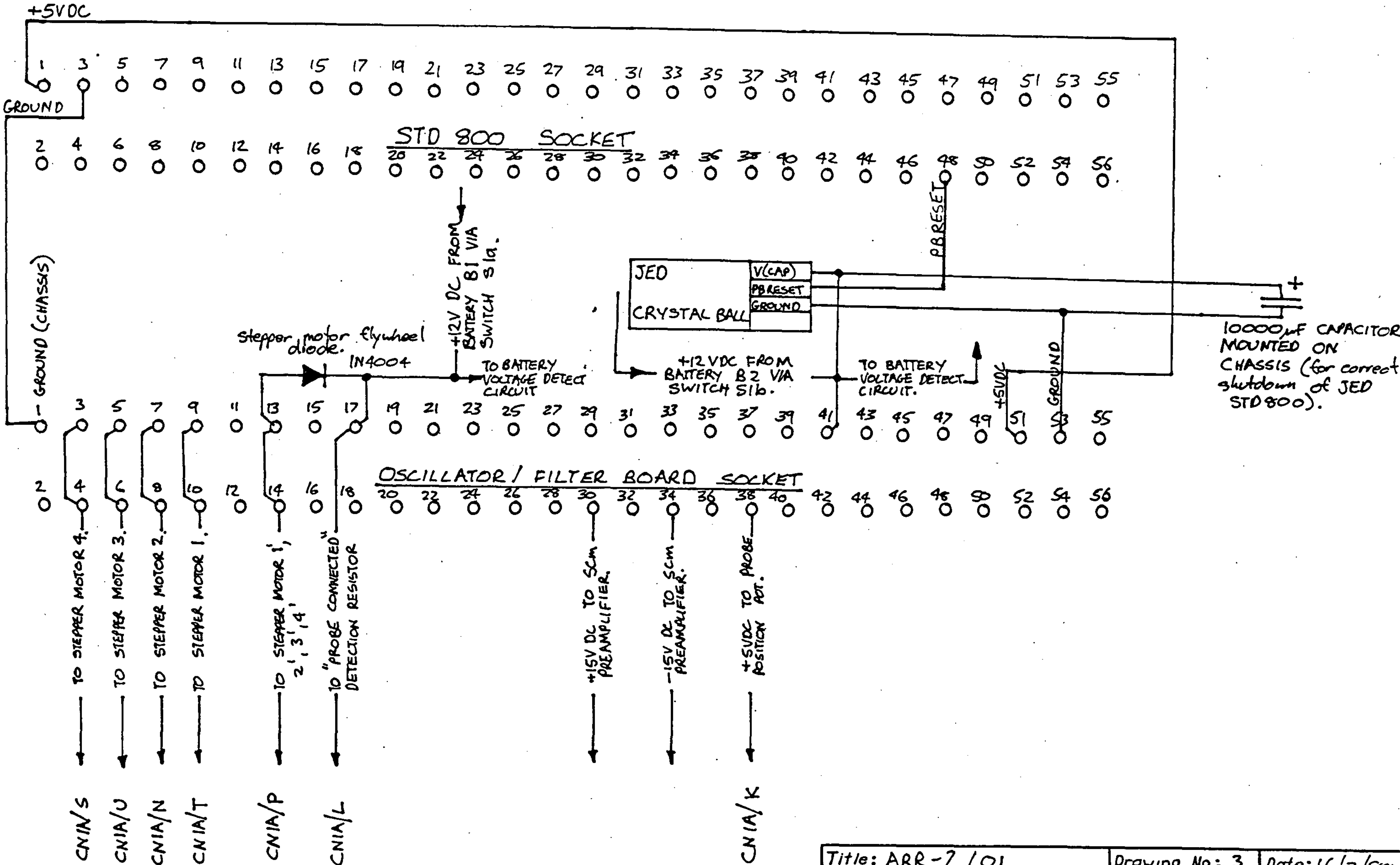
MEMORY HEADER SETUP



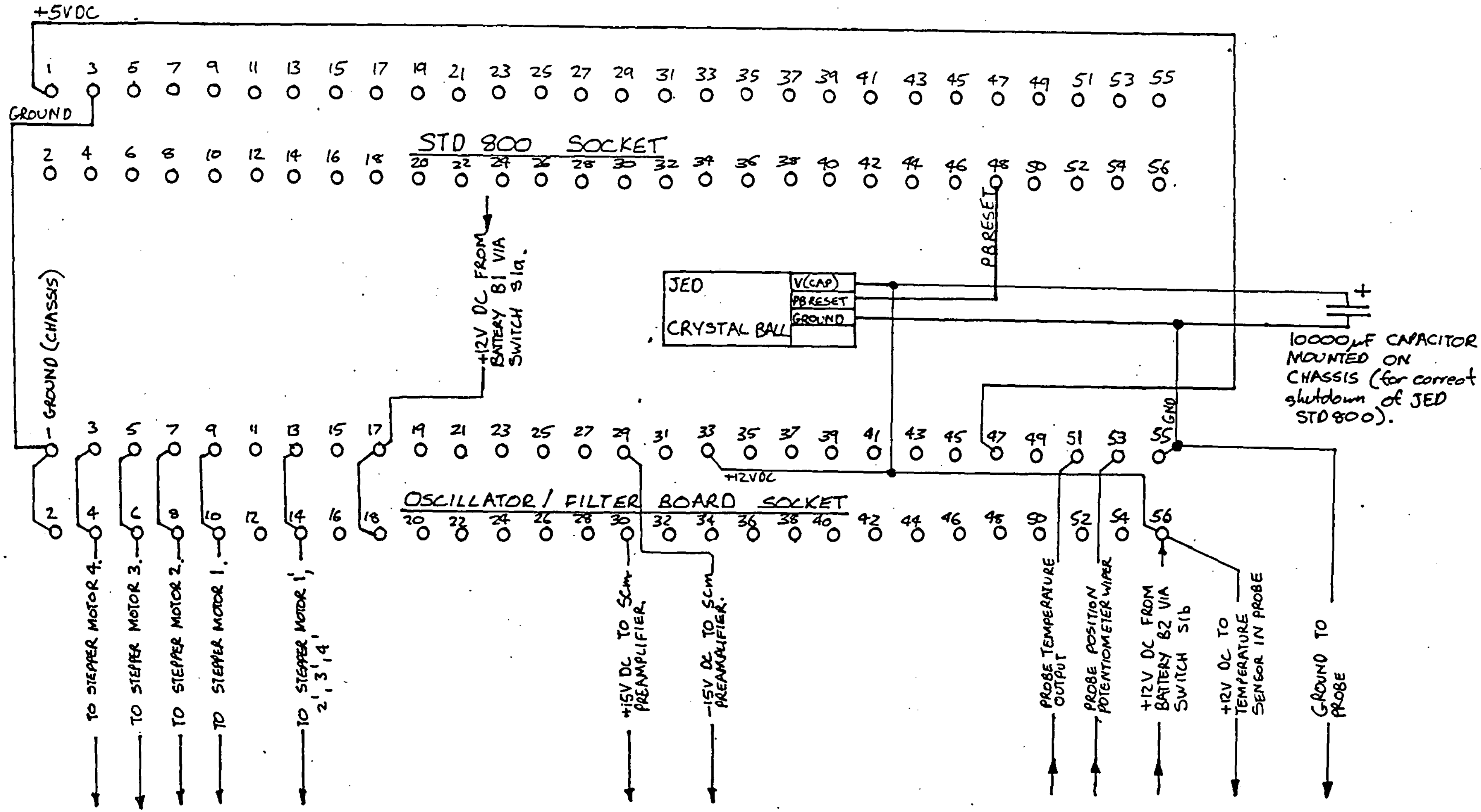
▭ No Shorting Link

■ Add Shorting Link

Title: ARR-2 & ARR-3 JED STD 800 SETUP	Drawing No: 2	Date: 16/2/88
Rev: ~~0~~, 1 (1/9/88)	Sheet: 1/1	Drawn By: I HUTCHINSON



Title: ARR-2/01 STD BUS CONNECTIONS	Drawing No: 3	Date: 16/2/88
Rev: 0	Sheet: 1/1	Drawn By: I HUTCHINSON

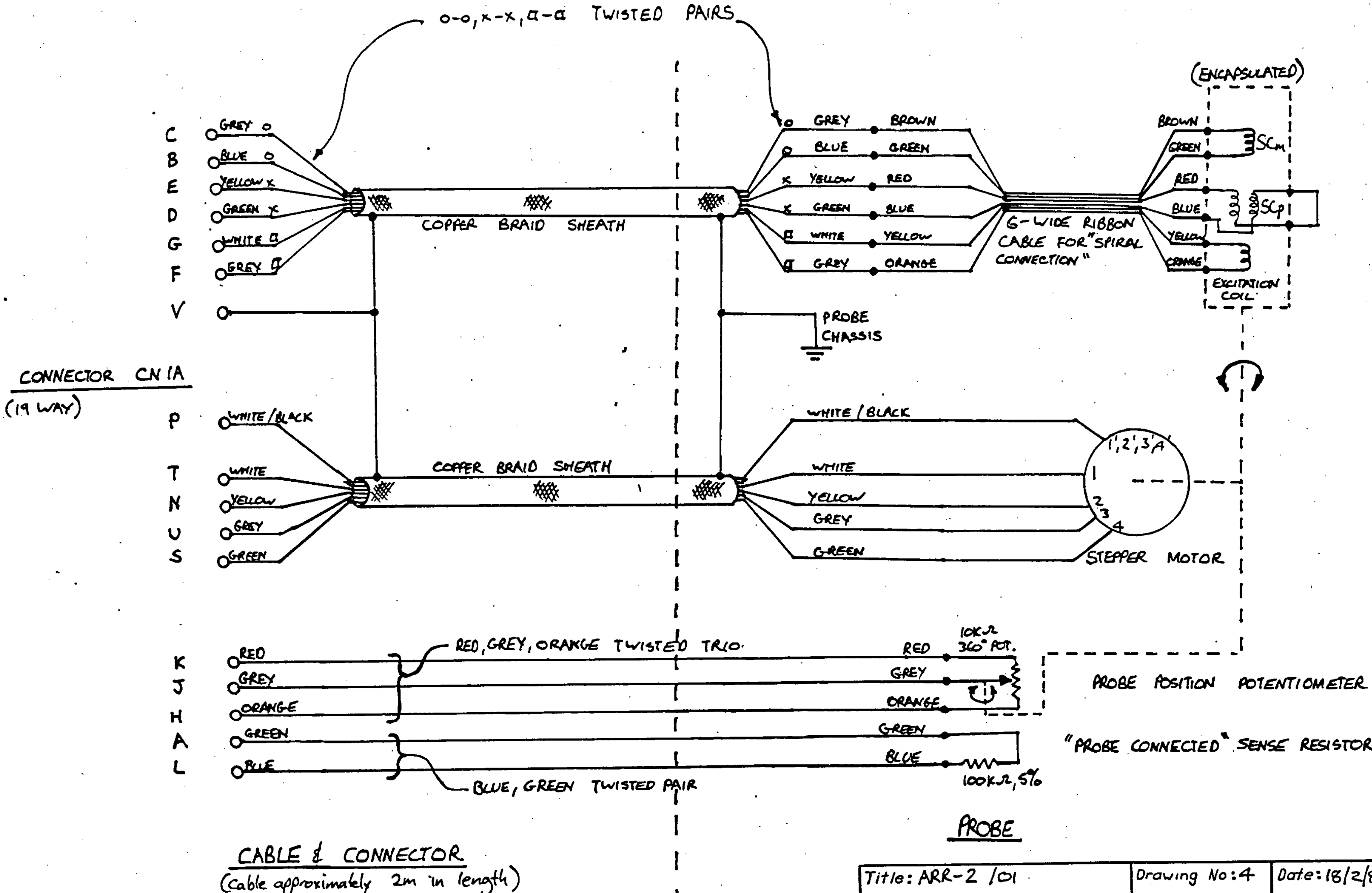


Title: ARR-3 STD BUS CONNECTIONS	Drawing No: 3	Date: 1/9/88
Rev: 0	Sheet: 1/1	Drawn By: I HUTCHINSON

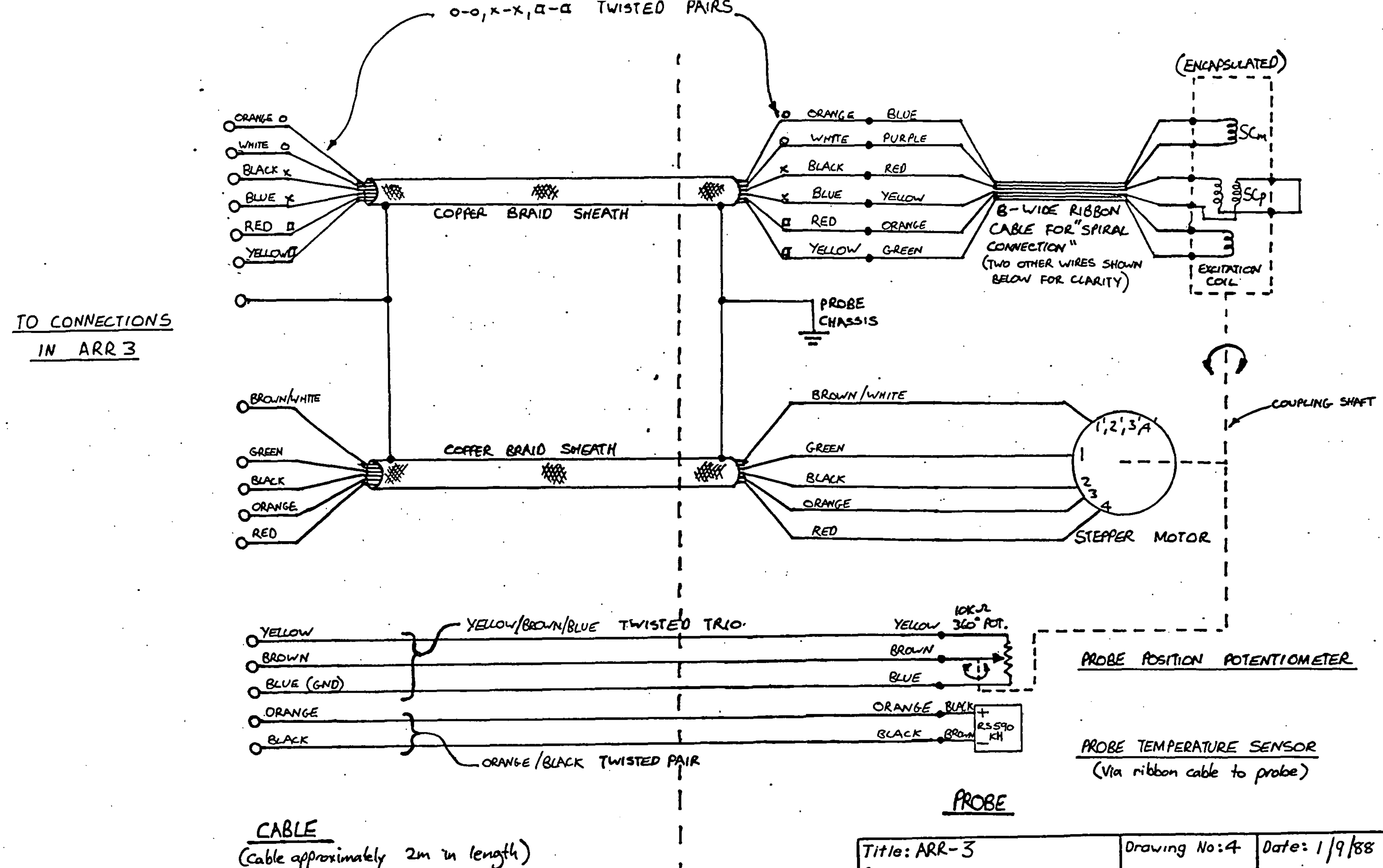
APPENDIX G

PROBE CONNECTING CABLE SCHEMATIC (ARR-2 AND ARR-3)

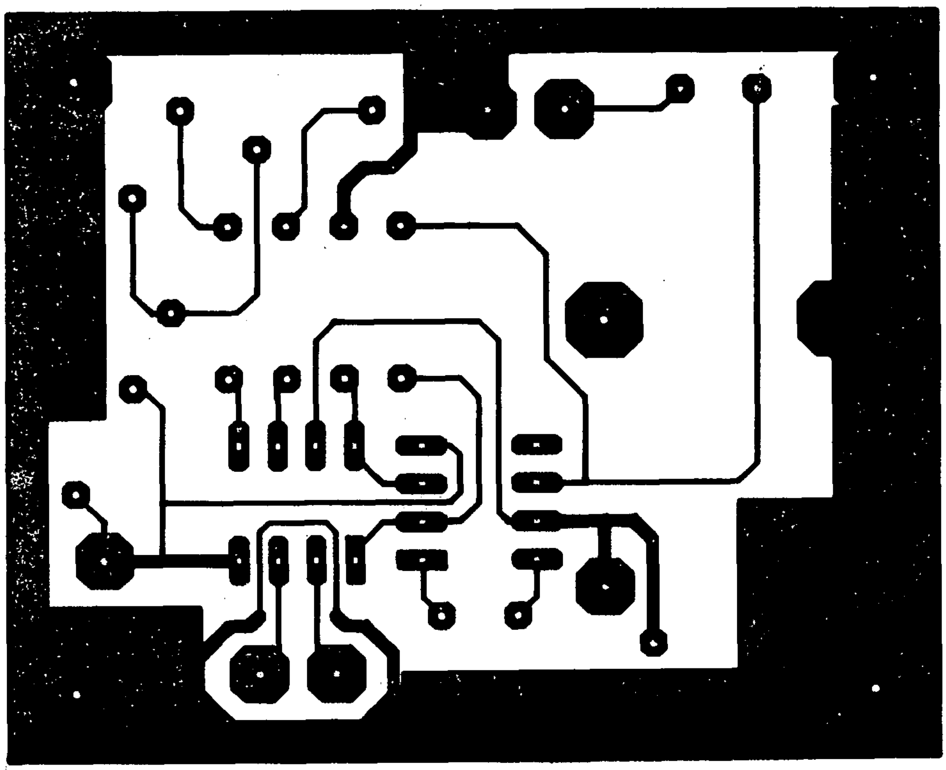
CIRCUIT BOARD LAYOUT (ARR-3)



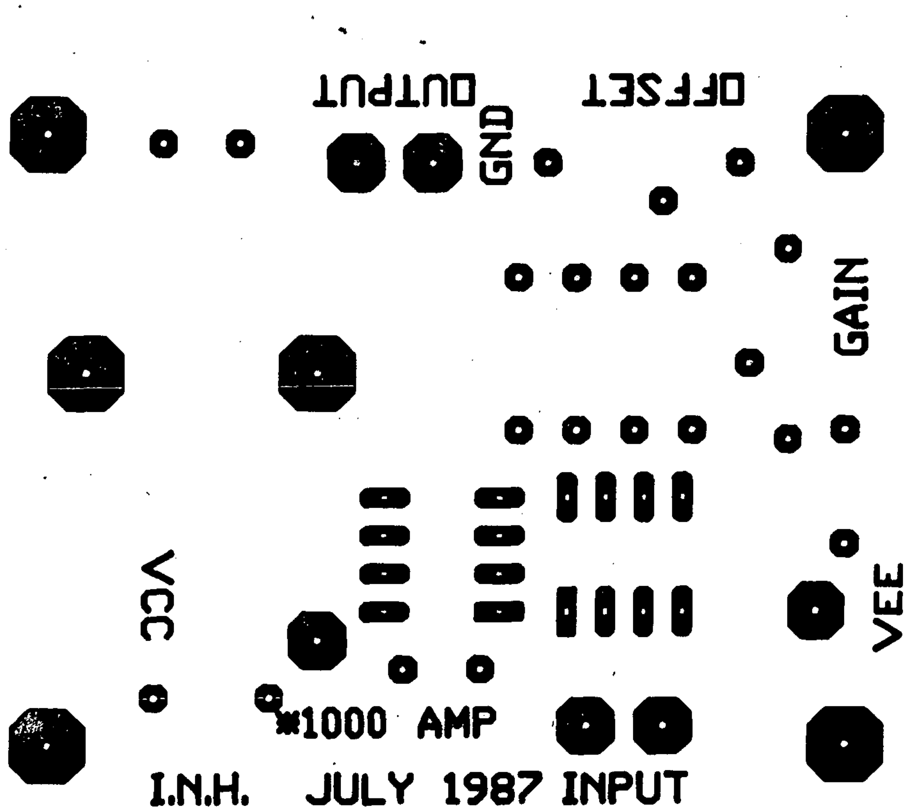
Title: ARR-2 /01 PROBE WIRING DETAILS	Drawing No: 4	Date: 18/2/88
Rev: 0	Sheet: 1/2	Drawn By: I. HUTCHINSON



Title: ARR-3 PROBE WIRING DETAILS	Drawing No: 4	Date: 1/9/88
Rev: 0	Sheet: 2/2	Drawn By: I. HUTCHINSON



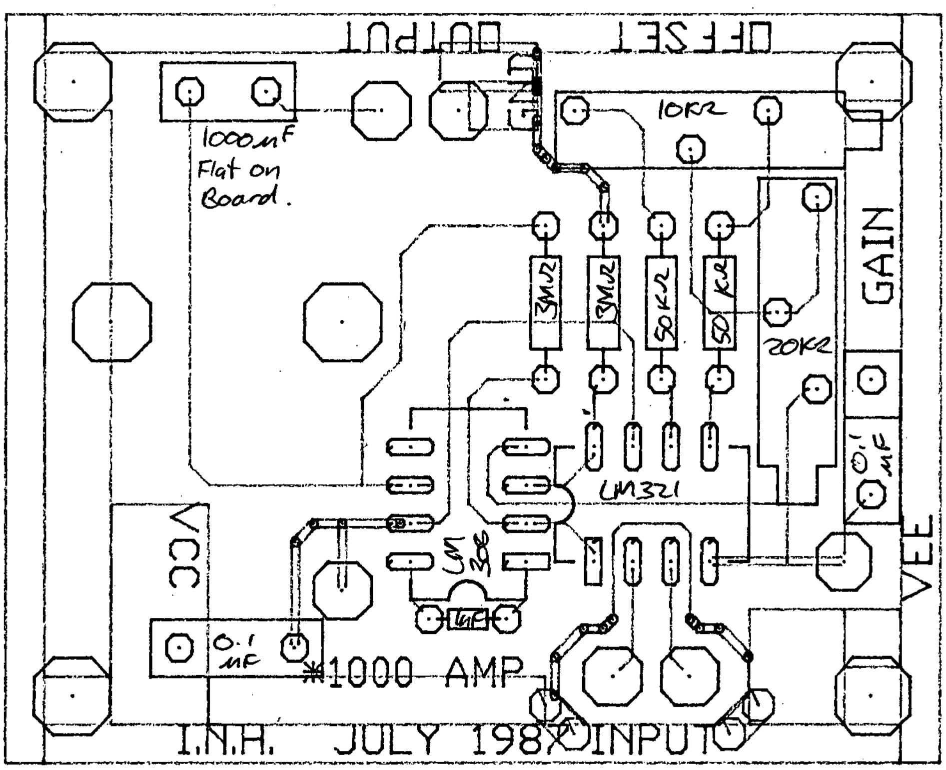
Copper side.



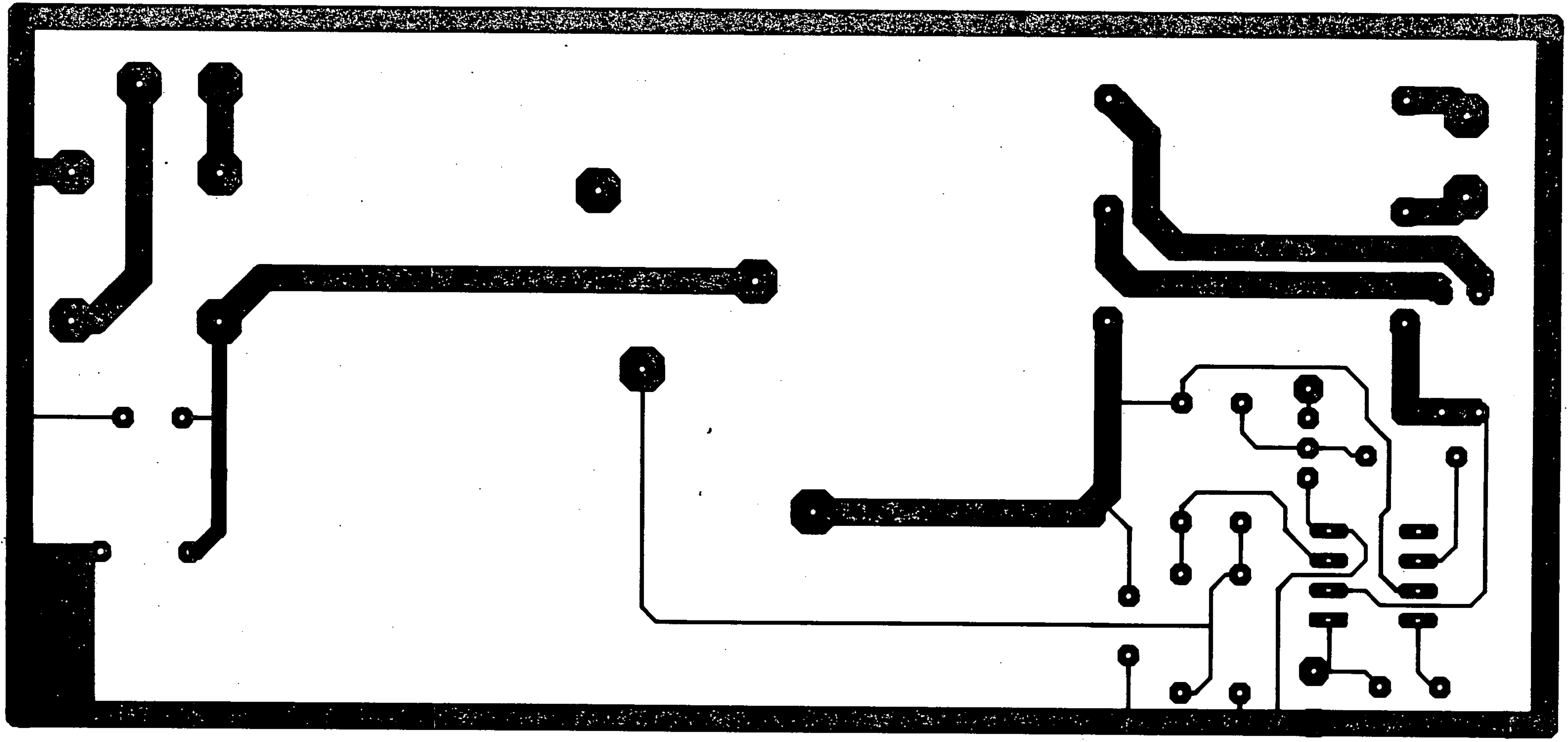
Component side.

PCB Layout for SCm Preamplifier (ARR-2 and ARR-3).
(twice actual size)

Copper side in green, Component side in red, with Component overlay and Pads in black.

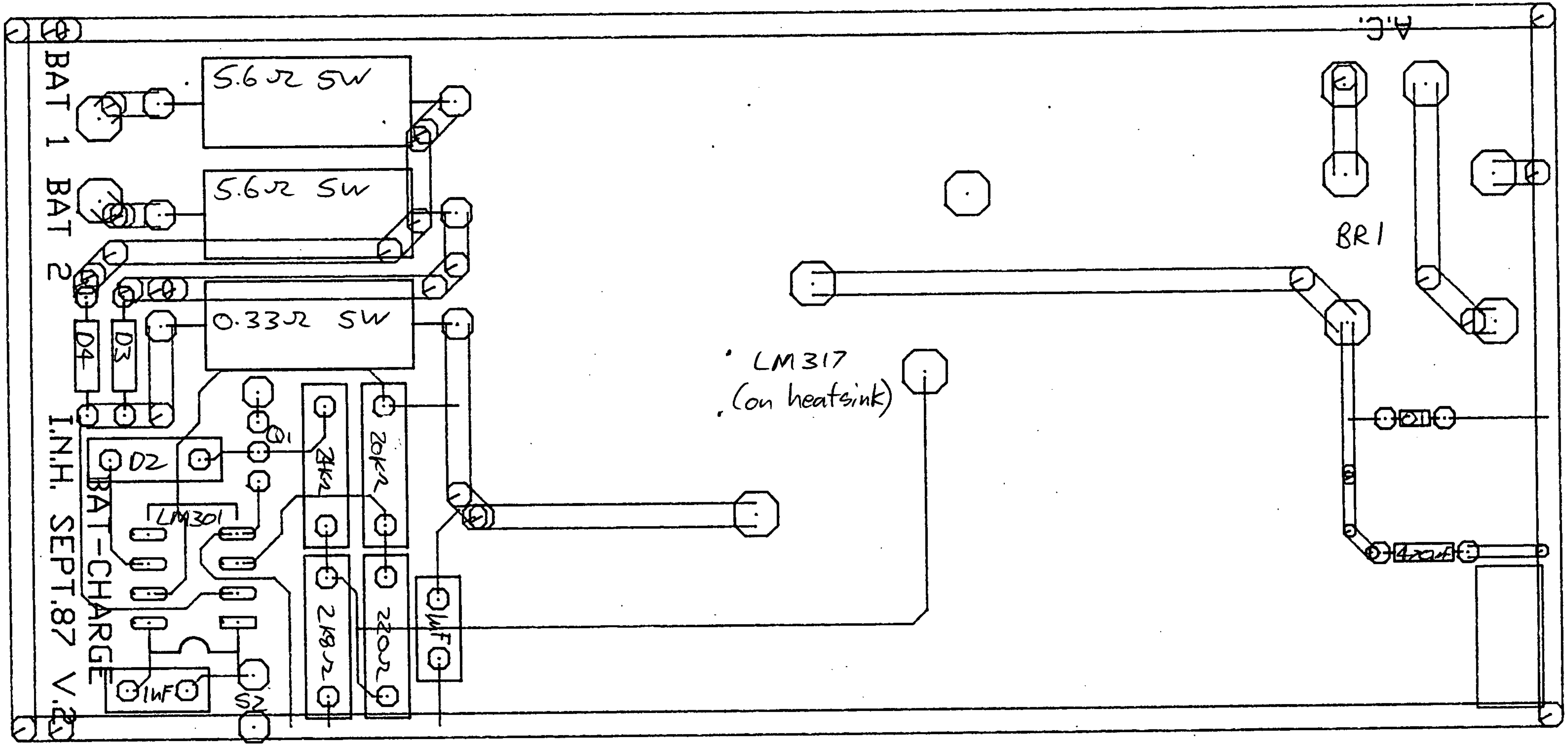


Overlay for SCm Preamplifier (ARR-2 and ARR-3).
(twice actual size)



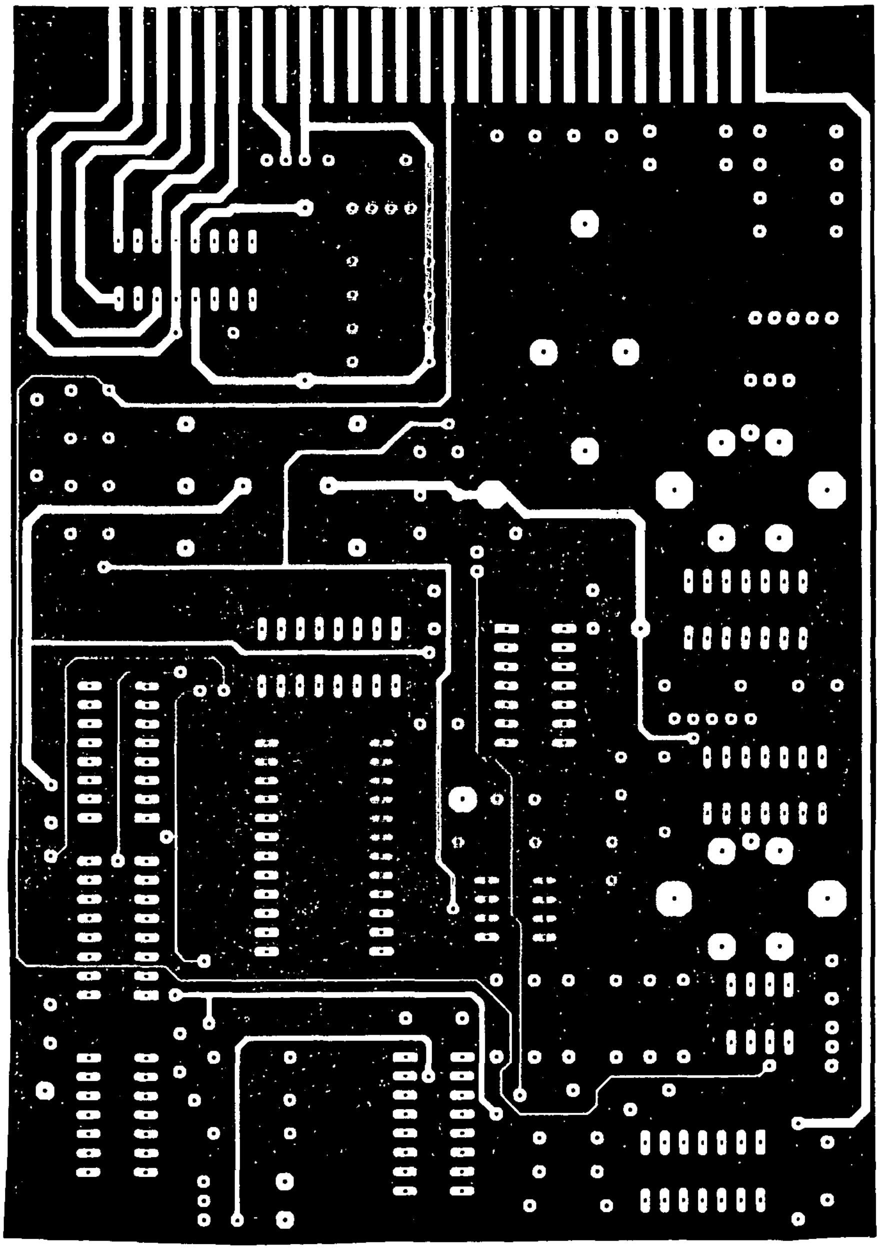
Solder Side

PCB Layout for Battery Charger (ARR-2 and ARR-3)
(Twice Actual Size)



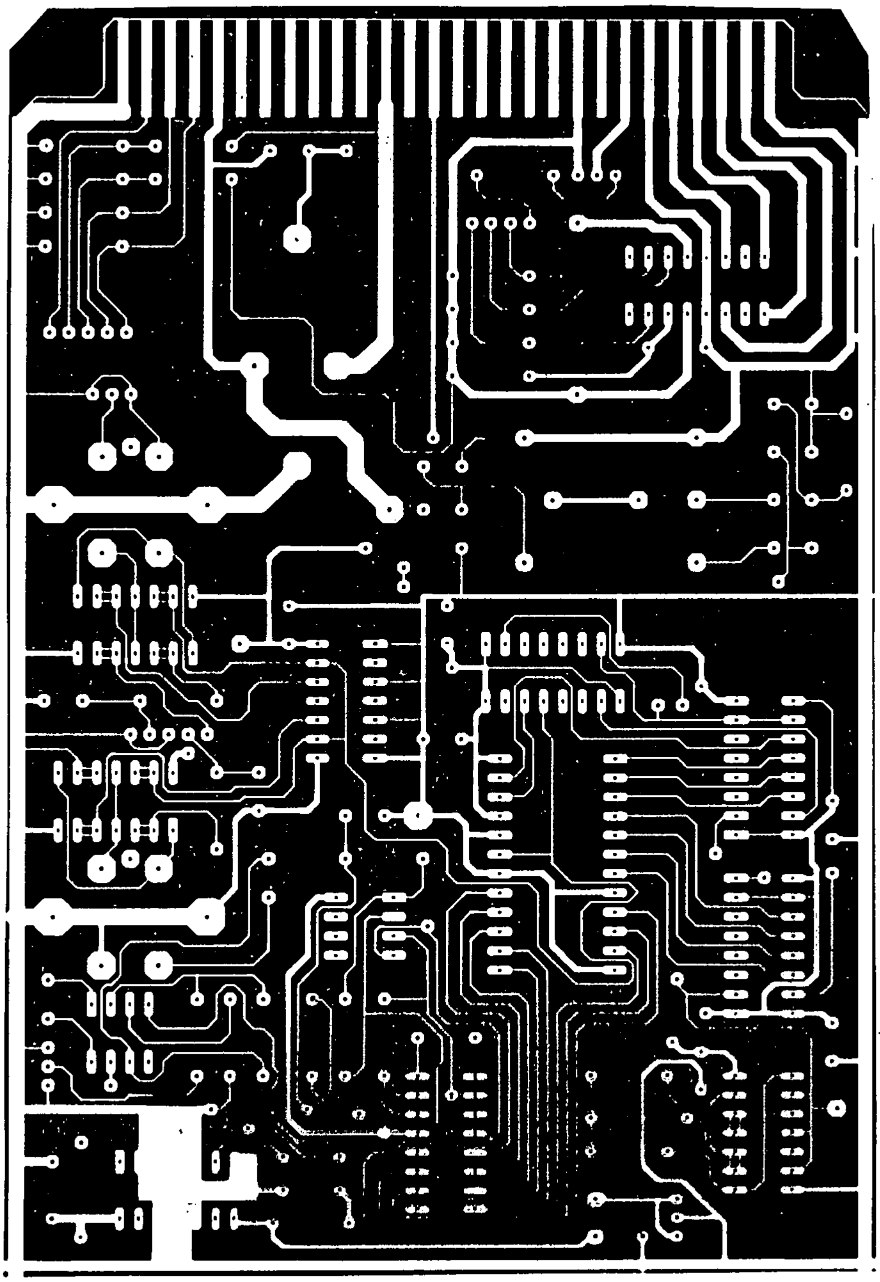
Overlay for Battery Charger for ARR-2 and ARR-3.
(twice actual size)

Copper side in green, Component side in red, with Component overlay and Pads in black.



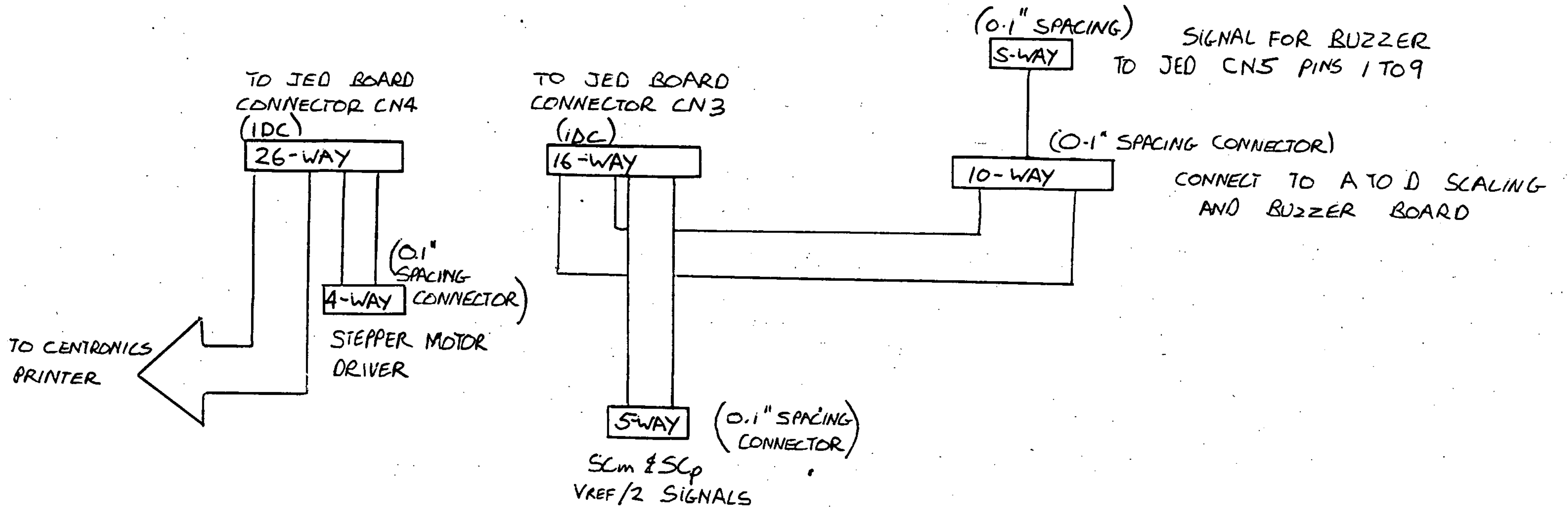
Component side.

PCB Layout for ARR-3
(Actual Size)



Solder Side

PCB layout for ARR-3
(Actual Size)



NOT TO SCALE.

Title: ARR-2/01 INTER BOARD CONNECTIONS	Drawing No: 5	Date: 10/2/89
Rev: 0	Sheet: 1/1	Drawn By: INH