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VARIABLE RELUCTANCE DISPLACEMENT TRANSDUCER

TEMPERATURE COMPENSATED TO 650°F

I. INTRODUCTION

In pressurized water reactor tests, compact instruments for accurate measurement of small displacements in a 650°F environment are often required. In the case of blowdown tests such as the Loss of Fluid Test (LOFT) or Semiscale computer code development tests, not only is the initial environment water at 650°F and 2200 psi but it undergoes a severe transient due to depressurization. The pressure drops from 2200 psi to ambient in a few seconds and the temperature of the coolant drops from 650°F to 212°F. The transducer temperature then heads toward either about 400°F (the vessel temperature after blowdown) or room temperature if emergency core coolant is used. Since the LOFT and Semiscale tests are run just for the purpose of obtaining data during the depressurization, instruments used to obtain the data must not give false outputs induced by the change in environment. Figures 1 and 2 show respectively a LOFT ρv^2 probe and a Semiscale drag disk; each utilizes a variable reluctance transducer (VRT) such as described in this paper for indication of the drag-disk location and a torsion bar for drag-disk restoring force. The VRT, in addition to being thermally gain and null offset stable, is fabricated from materials known to be resistant to large nuclear radiation levels and has successfully passed a fast neutron radiation test of 2.7 x 10^{17} nvt without failure.

II. THEORY OF OPERATION

A VRT, being somewhat different than an LVDT (linear variable differential transformer), consists of only two, series connected, cylindrically wound coils. A magnetic core placed on the cylinder axis serves to vary the self and mutual inductances of the two coils which electronically form two legs of a four-arm bridge as shown in basic form in Figure 3. Because thin sections of austenitic stainless steel have little effect on the coil magnetic flux distribution at the drive frequency of 3 kHz, the coil region of the transducer can be hermetically sealed from the environment in which the core of the unit resides.

The theory related to obtaining constant sensitivity and low null-drift versus temperature can be summarized as follows: The transducer's magnetic core hysteresis loss decreases with temperature increase (see Appendix A). For constant current through the transducer, the decrease in hysteresis loss would cause an increase in transducer sensitivity with temperature. By winding the transducer with wire having a large resistance temperature coefficient and shunting this with the appropriate constant ohmage bridge completion resistance (see Figure 3), the increase in sensitivity due to core behavior can be canceled by the decrease in current through the transducer. The shunt resistance effectively bypasses a portion of the constant ac drive current from the drive transformer T_1 (see Appendices A and B for details). Pushbutton switch Sw1 allows the transducer bridge to be resistively imbalanced so that the reference to the demodulator can be set to that phase where no dc output change occurs when the button is pushed. This makes the output insensitive to thermal-induced resistive imbalances. Because resistive changes are the primary source of bridge imbalance with temperature and particularly of thermal transients, this technique of setting the reference to the demodulator maximizes transducer null-drift stability. Transformer T_1 must be selected to approach ideal transformer characteristics (low series impedance and high shunt impedance) so that it does not introduce phase angle changes or act as a variable shunt on the constant ac current being supplied to the four-arm bridge.

III. MECHANICAL DESIGN

The VRT coil bobbin is shown in Figure 4 with the coil in place. To accomplish this: The 304 stainless steel bobbin is fir-t vacuum annealed to 1800°F to remove any trace of magnetic permeability induced by work hardening in fabrication. The bobbin is next sand blasted and immediately flame sprayed with ceramic to serve as an undercoat for the coil (BHL 215020-H Al_2O_3 rod is used). Platinum wire with ceramic insulation is used for the coil wire. The wire with insulation is .0088" diameter and the bare wire is .007" diameter and is supplied by Secon Metals Corp. of White Plains, New York. Secon Metals Corp. supplies the wire with their type E insulation. The coils are wound on the flame sprayed bobbin in a sense such that the mutual inductance aids the self-inductances when the two center leads are connected together to form the VRT common lead. The ends of the coils are secured in place with Aremco 503 ceramic cement (Briarcliff Manor, New York) as shown in Figure 4, and the coil fired in air to 1500°F to cure the ceramic. After the leads have been gently folded into the hole of Conetic B magnetic shield (Perfection Mica Company, Chicago, Illinois) that is spot welded to the ridge at each end of the bobbin, it is slid into position in the transducer body. The leads are then fished out through a lead connection hole and brazed to the sheathed cable leads which also protrude into the lead connection hole. With the finished connections tucked neatly back into the lead connection hole and cemented into place away from metallic parts with a small amount of Saureisen #8 ceramic cement (Pittsburgh, Pa.), a seal cover is welded into place on the lead connection hole after the cement has cured.

IV. RESULTS

Results of thermal cycling and transient tests on the completed ±0.100 inch stroke VRT are as follows: Sensitivity change from room temperature to 650°F was 1.8% or 0.003%/°F. Zero null remains fixed to within ±0.5% of full scale in the room temperature to 650°F range. With core locked at null and unit plunged horizontally into 70°F water from 650°F heat, transient output variations of about two seconds duration and of ±3% of full scale occurred. Failure to vacuum anneal a VRT bobbin has occurred once or twice and has led to irratic behavior of the VRT versus temperature because the work hardening from machining the bobbin leaves the bobbin with a magnetic permeability greater than unity.

APPENDIX A

EFFECT OF VARIATION IN HYSTERESIS LOSS

The equivalent circuit of Figure A1 can be used to approximate the behavior of a single side of the VRT coil with core in place. Resistance R_2 increases as the hysteresis loss of the core decreases with increasing temperature [a]. R_1 and X are the coil resistance and reactance for the core in some fixed position. The simple theory outlined in Appendix C shows that moderate changes in core permeability, μ_r, with temperature do not change X significantly. However, the change in R_2 with temperature results in an effective change in the coil reactive component, X_{in}.

$$Z = R + jX_{in} = R_1 + \frac{R_2 jX}{R_2 + jX} = R_1 + \frac{R_2 X^2}{R_2^2 + X^2} + j\frac{R_2^2 X}{R_2^2 + X^2} \qquad \text{(A-1)}$$

This leads to

$$\frac{\Delta X_{in}}{X_{in}} = \frac{2X^2}{R_2^2 + X^2} \cdot \frac{\Delta R_2}{R_2} . \qquad \text{(A-2)}$$

For a 17-4 PH core heat treated H-1100, $\Delta X_{in}/X_{in}$ has been found, by measurement, to equal + 0.068 for a temperature change from 75 to 650°F. This $\beta = 0.068/575^\circ F = 0.00012/^\circ F$, of course, agrees with the increase in sensitivity experienced if a constant current bridge drive is used with no current shunting resistor. Other core materials such as 410 stainless and Remendur were tested and found to have $\Delta X_{in}/X_{in}$ values as large as +0.095 for the same temperature change.

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a Actually, R_2 would vary with variations in either hyseresis or eddy-current losses. But for the design presently being described, it was determined (by using slit cores and cores of nonmagnetic 300 series stainless) that eddy-current losses are constant or are insignificant enough that they cause no variation of R_2 with temperature.

APPENDIX B

MATHEMATICAL FORMULATION OF VRT TEMPERATURE COMPENSATION

Referring to Figure 3 of the text and being informed that at 3 kHz the total transducer imaginary impedance component is only about 3 ohms while the room temperature real impedance component is 30 ohms, analysis of current flow through the shunt and transducer can be done fairly accurately using only resistances.

Let i_c be the constant current from T_1, V be the voltage across T_1,i_2 be the current through the transducer, $R_0(1+a\Delta T)$ be the resistance of the transducer coils, and R_1 the constant resistive shunt placed across T_1.a is, of course, the temperature coefficient of resistance for the wire used in the transducer.

Then

$$R_{11} = \frac{R_1 R_o(1+\alpha\Delta T)}{R_1+R\ (1+\alpha\Delta T)} \qquad \text{(B-1)}$$

or

$$V = i_c R_{11} = \frac{i_c R_1 R_o(1+\alpha\Delta T)}{R_1+R_o(1+\alpha\Delta T)} \qquad \text{(B-2)}$$

Thus

$$i_2 = \frac{V}{R_o(1+\alpha\Delta T)} = \frac{i_c R_1}{R_1+R_o(1+\alpha\Delta T)} \qquad \text{(B-3)}$$

The sensitivity, S, of the system will be

$$S = Ki_2\ (1+\beta\Delta T) \qquad \text{(B-4)}$$

where B is the temperature coefficient of the coil inductance caused by changing core hysteresis loss. Let K equal unity. Then,

$$S = \frac{i_c R_1\ (1+\beta\Delta T)}{R_1+R_o(1+\alpha\Delta T)} \qquad \text{(B-5)}$$

This can be rearranged to give

$$\frac{S}{i_c} = \frac{1+\beta\Delta}{1+\frac{R_o}{R_1}(1+\alpha\Delta T)} \qquad \text{(B-6)}$$

If $\frac{R_o}{R_1}(1+\alpha\Delta T)$ is a fair amount less than unity in value, the denominator may be brought to the numerator using the approximation $\frac{1}{1+\gamma} \sim 1-\gamma$ for $\gamma \ll 1$. Assuming this approximation holds for the R_o, R_1, a, and ΔT involved,

$$\frac{S}{i_c} = (1+\beta\Delta T) \quad (1- \frac{R_o}{R_1} (1+\alpha\Delta T)) \qquad \text{(B-7)}$$

Dropping terms quadratic in ΔT,

$$\frac{S}{i_c} \approx 1- \frac{R_o}{R} + \Delta T(\beta- \frac{R_o}{R_1}\alpha) \qquad \text{(B-8)}$$

Clearly, adjusting the R_o/R_1 ratio permits this approximate expression to be made independent of ΔT.

By Appendix A, $\beta = 0.00012/^oF$. α, for platinum wire, is $0.002/^oF$. R_o = 30 ohms.

And, the value of R_1 found experimentally to give minimal change in S with T was 500 ohms.

Checking: 30/500x0.002 = 0.00012. Thus, since this is also the value of β, the ΔT coefficient is zero with the value of R_1 found to give minimal temperature sensitivity. Furthermore, 30/500(1+0.002x575)=0.129 so γ is $\ll 1$, and the approximations made in obtaining Equation (B-8) are valid.

Because of the large temperature coefficient of platinum wire R_o varies from 30 ohms at room temperature to 30 (1+0.002x575)=64.5 ohms at 650^oF. The presence of the 500 ohm shunt across this changes the phase of the current through the transducer to vary by only 0.3 degree for the 575^oF temperature change. Use of coil wire with a smaller temperature coefficient would have required a smaller value of R_1 and this would then lead to larger changes in the phase of the current through the rransducer for the given temperature variation. Constancy of the phase of the current passing through the transducer is, of course, necessary so that the demodulator reference phase need not be adjusted as temperature changes.

APPENDIX C

EFFECT OF VARIATIONS IN CORE U_r ON VRT SENSITIVITY

Because the demodulator used to process the VRT signal is driven with a reference voltage of phase such that the filtered demodulator output is insensitive to resistive bridge imbalance, the resultant transducer sensitivity is only affected by changes in VRT coil reactance. For a coil with a core but having an appreciable air gap,

$$L = \frac{\mu_o N^2 A}{\frac{\ell - X}{\mu_r} + h - \ell + X + \ell_A} = \frac{\mu_o \mu_r N^2 A}{(\ell - X) + \mu_r (h - \ell + X + \ell_A)} \quad \text{(C-1)}$$

where μ_o is the permeability of free space, μ_r is the relative permeability of the coil core, 2ℓ is the core length, ℓ is the length of the core in each coil of the VRT at null, X is the offset of the core from this null position, h is the length of each of the two VRT coils, N is the number of turns on each coil, A is the effective area of the ID of the coil, and ℓ_A is a small constant, representing the fact that the coil is not actually too long a solenoid. See Figure C-1.

The VRT, of course, consists of two such coils connected as a half bridge with X negative of the above in the expression for the other coil).

$$\Delta L = L_2 - L_1 = \mu_o \mu_r N^2 A \left[\frac{1}{\ell + X + \mu_r (h - \ell - X + \ell_A)} - \frac{1}{\ell - X + \mu_r (h - \ell + X + \ell_A)} \right] \quad \text{(C-2)}$$

After separating out the X portion, cross multiplying, and condensing, this becomes

$$\Delta L = \frac{2 \mu_o \mu_r (\mu_r - 1) N^2 A X}{[\ell + \mu_r (h - \ell + \ell_A]^2 - X^2 (\mu_r - 1)^2} \quad \text{(C-3)}$$

Since X is always small compared to $h-\ell$, the X^2 term in the denominator may be dropped. Compared to $h-\ell$ both ℓ_A and ℓ/μ_r are quite small so Eq(C-3) can be written:

$$\Delta L = \frac{2 \mu_o \mu_r (\mu_r - 1) N^2 A X}{\mu_r^2 (h - \ell)^2} \approx \frac{2 \mu_o N^2 A X}{(h - \ell)^2} \quad \text{(C-4)}$$

Using Eq(C-3) for ΔL, the VRT sensitivity is

$$S = \frac{\partial(\Delta L)}{\partial X} = \frac{2\mu_0 \mu_r (\mu_r - 1) N^2 A \{[\ell + \mu_r (h - \ell + \ell_A)]^2 + X^2 (\mu_r - 1)^2\}}{\{[\ell + \mu_r (h - \ell + \ell_A)]^2 - X^2 (\mu_r - 1)^2\}^2} \quad \text{(C-5)}$$

Using $h-\ell \gg \ell_A$ and ℓ/μ_r or glancing at Eq(C-4) shows that the approximate value for S is:

$$S \approx \frac{2\mu_0 N^2 A}{(h-\ell)^2} \quad \text{(C-6)}$$

Performing $\partial S/\partial \mu_r$ on the expression of Equation(C-5) gives an involved expression which reduces, upon using $\mu_r \gg 1$, $h-\ell \gg \ell_A$, and $h-\ell \gg \ell/\mu_r$ to:

$$\frac{\partial S}{\partial \mu_r} = \frac{4\mu_0 N^2 A \ell}{\mu_r^2 (h-\ell)^3} = \frac{2S\ell}{\mu_r^2 (h-\ell)} \quad \text{(C-6)}$$

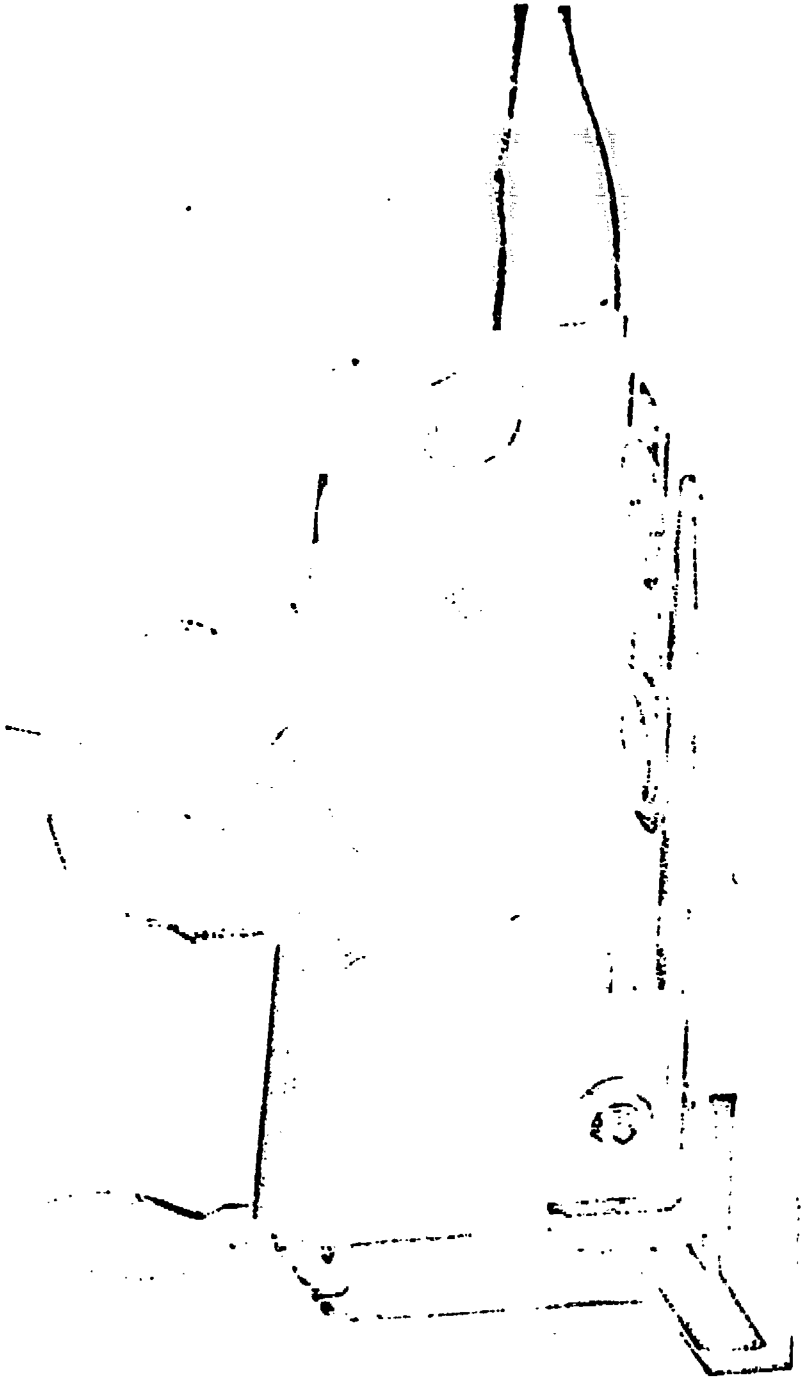
This may be rewritten

$$\frac{\Delta S}{S} = \frac{2\ell}{(h-\ell)} \frac{\Delta \mu_r}{[\mu_r]^2} \quad \text{(C-7)}$$

Since a typical value for μ_r is 150, a typical value for $\Delta\mu_r/\mu_r$ is 0.3 for the 575°F temperature change involved, and $2\ell/(h-\ell) \approx 1.1$

$$\left.\frac{\Delta S}{S}\right|_{typ} = 1.1 \times \frac{.3}{150} = .002 \cong .2\% \quad \text{(C-8)}$$

Thus, changes in μ_r do not significantly affect the VRT sensitivity. But, as shown in Appendix A, variations in VRT core hysteresis loss do cause significant values of $\Delta S/S$.



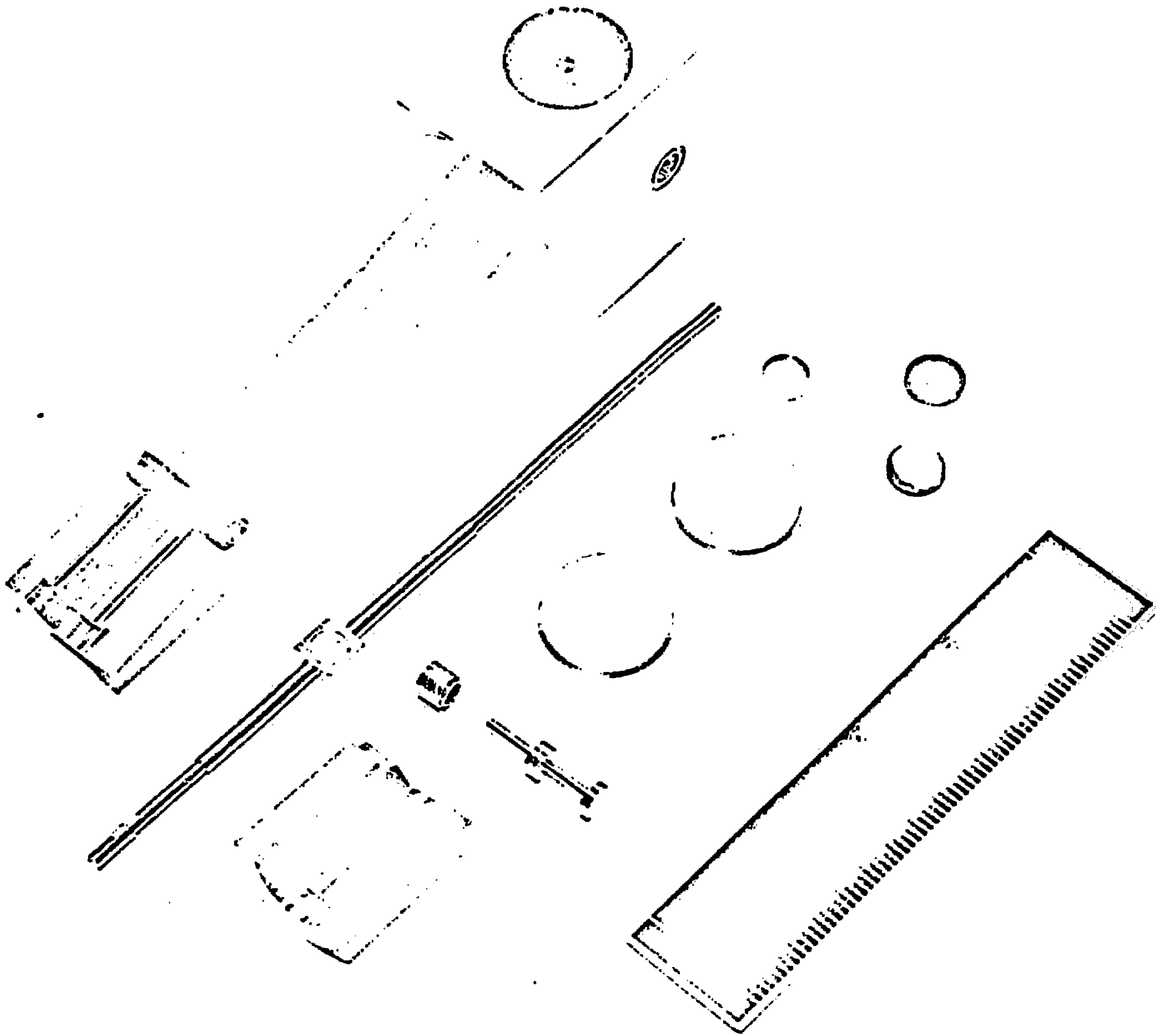
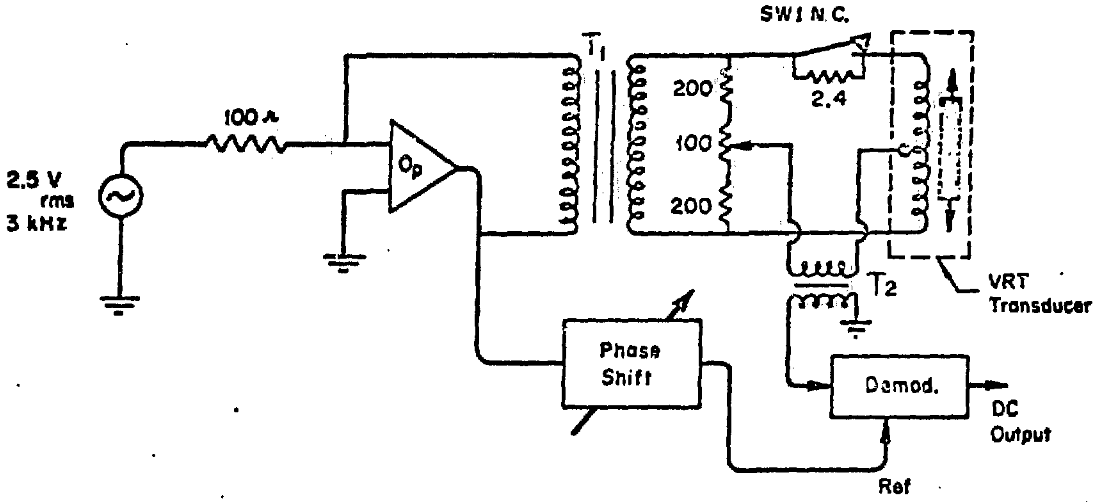


Fig. 2

FIG. 3

BASIC SCHEMATIC OF ELECTRONICS



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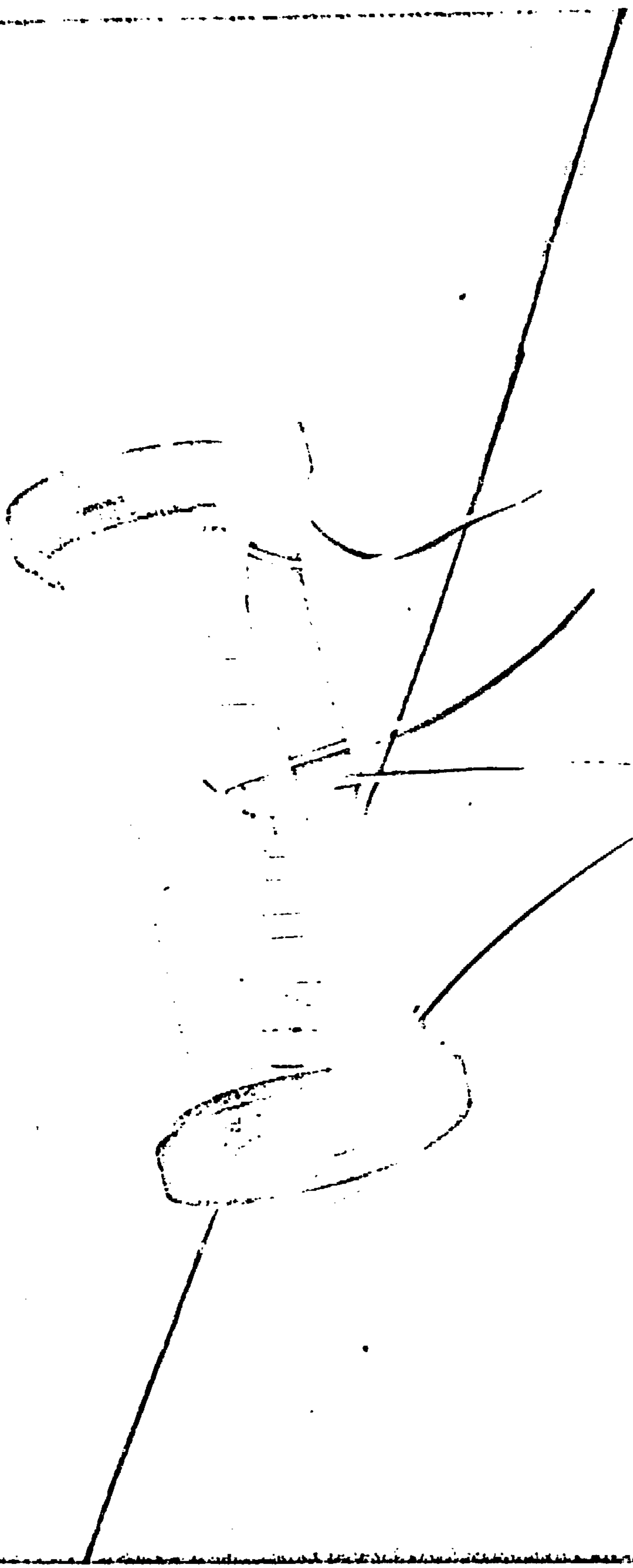

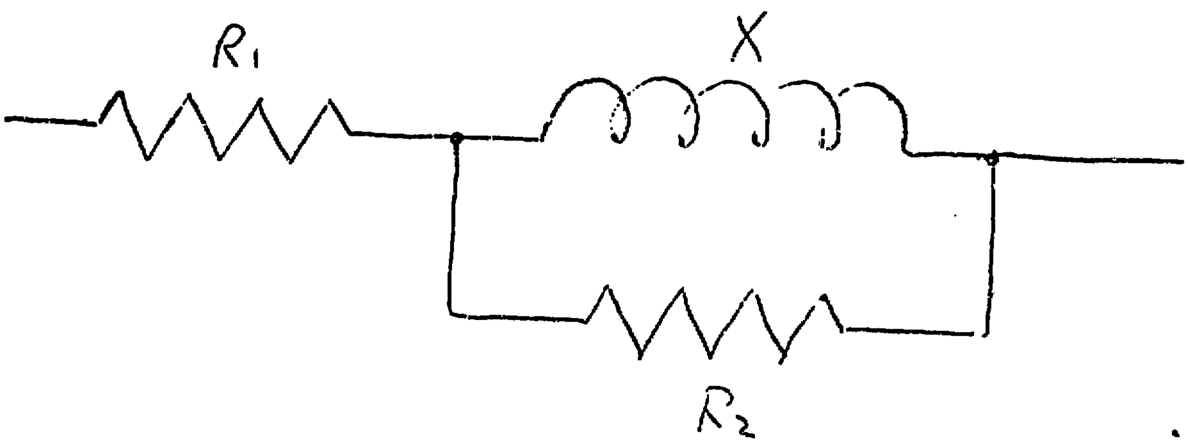

Fig A1 Equivalent Circuit of "1/2" URT

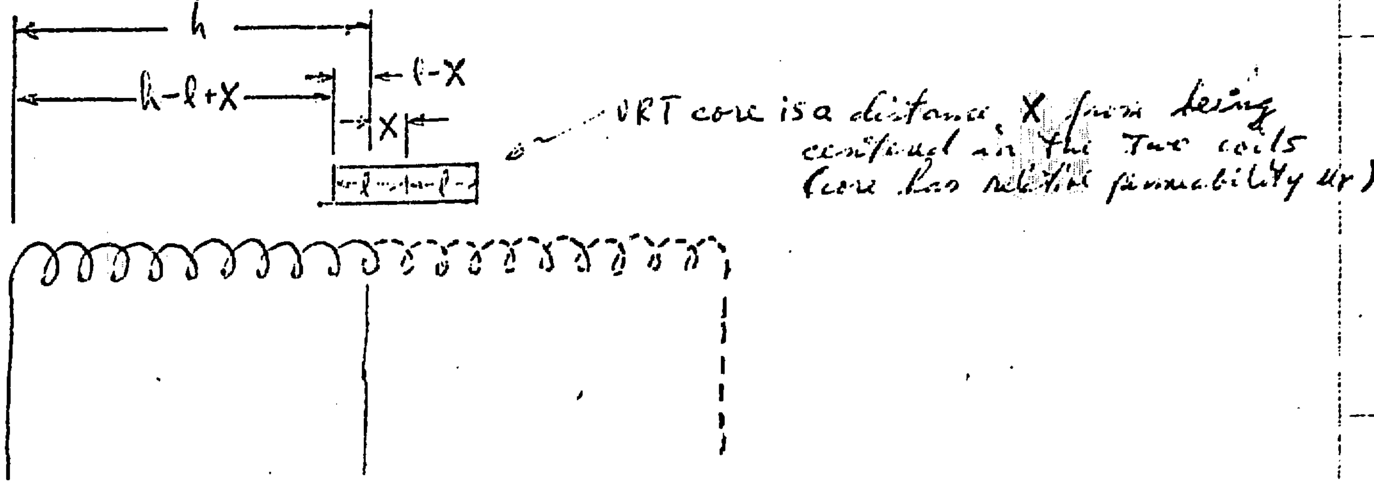

Fig C1 Pictorial Schematic of VRT Coil and Core ~~Placement~~