W NUCLEAR SERVICES INTEGRATION DIVISION

INSTRUMENT & CONTROL DEPARTMENT

ANALOG ROD POSITION INDICATION SYSTEM

SPECIAL REPORT

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1. INTRODUCTION

This report presents the results of testing and analysis by Westinghouse to study and quantify the performance of the Analog Rod Position Indication Systems which are currently in use at over 30 NSS Systems provided by Westinghouse.

The primary areas of concern are the system accuracy, thermal sensitivities and calibration procedures. This is a companion report prepared by Westinghouse for Duquesne Light Company to respond to an NRC staff request.

2. BACKGROUND

In the past 4 years Westinghouse has been asked by a number of customers to analyze various anomilies found with their Analog Rod Position Indication Systems. Typical problems have been non-linear response, temperature sensitivity, supply line voltage and frequency sensitivity and the overall need to continuously adjust the system in an attempt to prevent false rod deviation alarms. In response to the customers' requests Westinghouse initiated a program in the R&D laboratory, performed field tests, mathematically modeled the important sections of the system and reviewed customer supplied calibration data in an effort to reduce the various system problems. To understand the problems and solutions it is important to study the main sections of the system.

3. DETECTOR CONSTRUCTION AND OPERATION

The analog rod position detector can be described as a 12* foot long variable transformer consisting of primary and secondary coils, alternately arranged on a non-magnetic stainless steel coil form as depicted in Figure 1. There are 72 separate coils, approximately 5.4 inches in diameter, on each full length detector. The detector is mounted over a non-magnetic stainless steel rod travel housing which is attached to the top of the reactor vessel, and is not in direct contact with the reactor coolant. Each coil on the detector is approximately 2 inches high with both the primary and secondary coil stacks wired in series and terminated in a top plate mounted connector. With a constant current AC source applied to the primary windings, the vertical position of the control rod drive line changes the primary to secondary coupling and produces a unique AC secondary voltage, which is proportional to the position of the drive line.

* Some 10 foot long detectors have been supplied.

SIMPLIFIED ANALOG
ROD POSITION DETECTOR

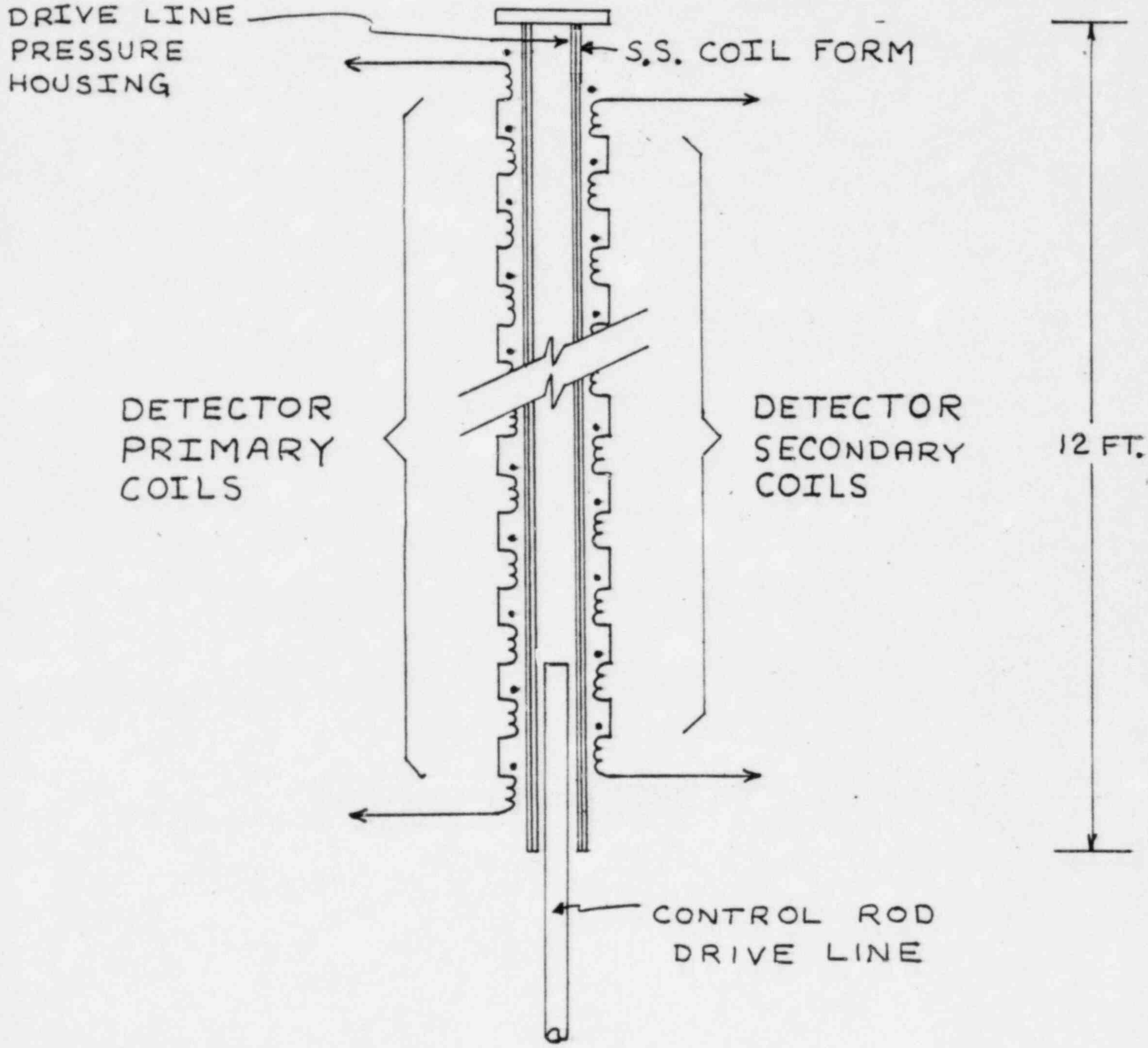


FIG. 1

4. SYSTEM DESCRIPTION

The primary connections of all of the detectors are connected in parallel and energized by a common source. This source is typically a voltage regulator and filter connected to a 118 VAC supply as shown in Figure 2. The regulator and filter are sized to provide ±1% regulation, at 60HZ±1% with less than 5% harmonic distortion at 5.0 KVA.

With the drive line out of the detector (control rods inserted in the core) approximately 0.2 AMPS of current are drawn by each detector and 18 ±2 VAC is developed across the primary winding of each detector (at ambient temperature), which results in a secondary voltage of 8.0 ±1 VAC. As the drive line moves into the detector (control rods moving out of the core) the primary voltage increases to 26 ±2 VAC with a corresponding increase in secondary voltage to 12.5 ±1 VAC at 230 steps.

Each detector primary circuit has:

a) A fuse in the primary wiring to provide isolation if the wiring is shorted.

b) A 500 Ω series resistor which:

  b-1) Limits the fault currents
  b-2) Acts as a psuedo current source
  b-3) Uncouples one detector circuit from another

c) A 118 VAC signal to the individual signal conditioner circuits as a reference voltage.

Each detector secondary circuit has its own signal conditioner module and rod bottom bistable module. The signal conditioner module rectifies and filters the detector secondary AC voltage to produce a DC voltage which is proportional to the drive line position. See Figure 3.

Each signal conditioner card provides:

a) A DC "null" voltage referenced to the individual detector primary voltage.

b) A front panel "zero" adjustment to provide 0 VDC at 0 steps.

c) A front panel "span" adjustment to provide +3.45 VDC at 230 steps.

d) An isolated rod position signal to the plant computer which provides the rod deviation alarm.

TYPICAL PRIMARY WIRING

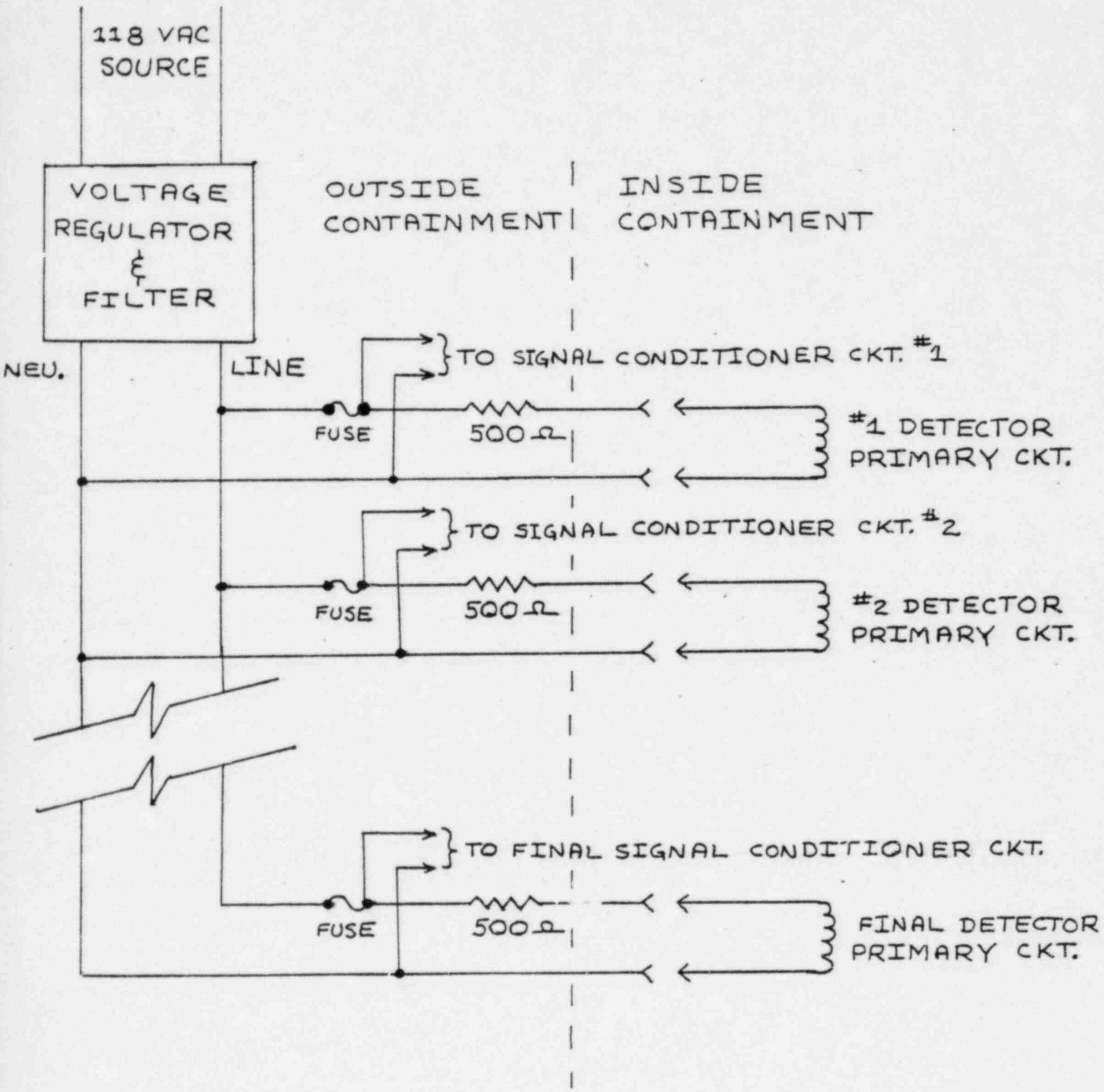


FIG. 2

TYPICAL DETECTOR
SECONDARY CIRCUIT

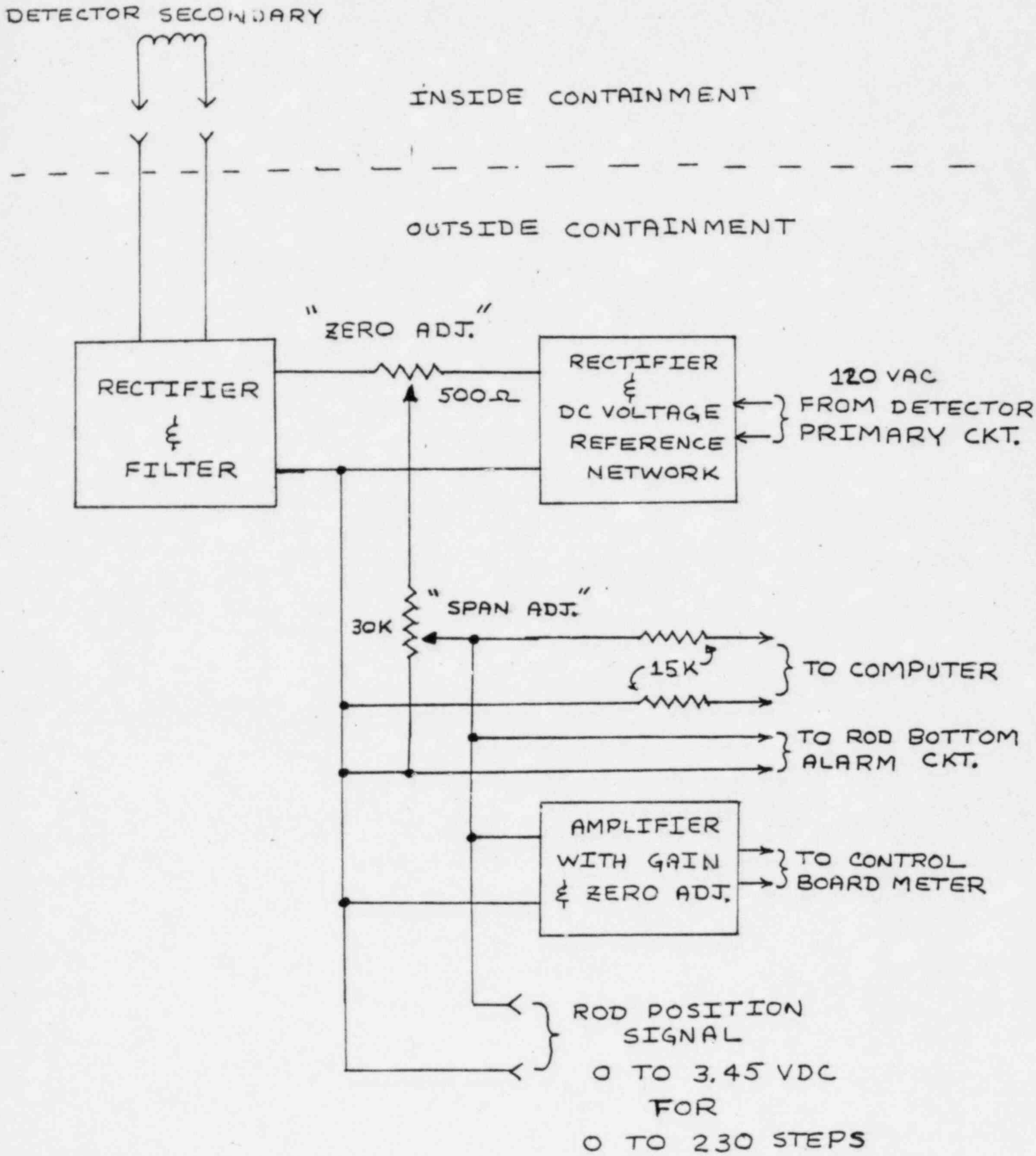


FIG. 3

e) A rod position signal to the rod bottom bistable module which provides the rod bottom alarm.

f) An amplified rod position signal with its own internal, gain and zero adjustments to the individual control board mounted position indicating meters.

g) Front panel mounted test jacks for monitoring the position signal.

5. SYSTEM PERFORMANCE

The ideal system results in a linear DC position signal versus rod position as shown in Figure 4. Here the output is adjusted to give 0 VDC at 0 steps and 3.45 VDC at 230 steps.

Actual systems however have non-linearities from detector to detector and are sensitive to the reactor coolant temperature. When the system is calibrated at the hot (547°F)reactor shutdown condition, the overall accuracy is ±5% of full rod travel as shown in Figure 5. This includes inaccuracies arising from the normal range of coolant temperature variation from hot shutdown (547°F) to full power (590°F) operation. The error band is typically split by adjusting the 20 and 200 step output value to match the ideal performance curve.

6. OPERATING OUTSIDE THE SYSTEM DESIGN LIMITS

From the model developed in Appendix A, the non-linearity of the detector secondary voltage is seen to contribute approximately 15 steps of error (at 600°F) due to the roll-off in the output voltage from 200 to 230 steps. Adjusting the "span" and "zero" adjustments can bring the non-linear output to within the error band as required by the calibration procedure. With these settings fixed, however, lowering the operating temperature to 75°F results in an indicated rod position of approximately 160 steps which is greatly outside the error band. This sensitivity to temperature is mainly caused by changes in the magnetic properties of the drive line and cannot be measured or compensated for easily. A transient thermal sensitivity has also been measured which results in as much as a 10 step positive error and takes from 20 to 60 minutes to reach equilibrium. This sensitivity varies from rod to rod and is dependent on rod position since with the rods fully inserted in the core there is little or no change in the output voltage with time.

The detector output voltage is very sensitive to the source voltage frequency, with the most linear operation occurring at 60HZ.

Changes in the system position signal output voltage with source voltage amplitude is dependent on the "zero" and "span" adjustments and is therefore rod dependent.

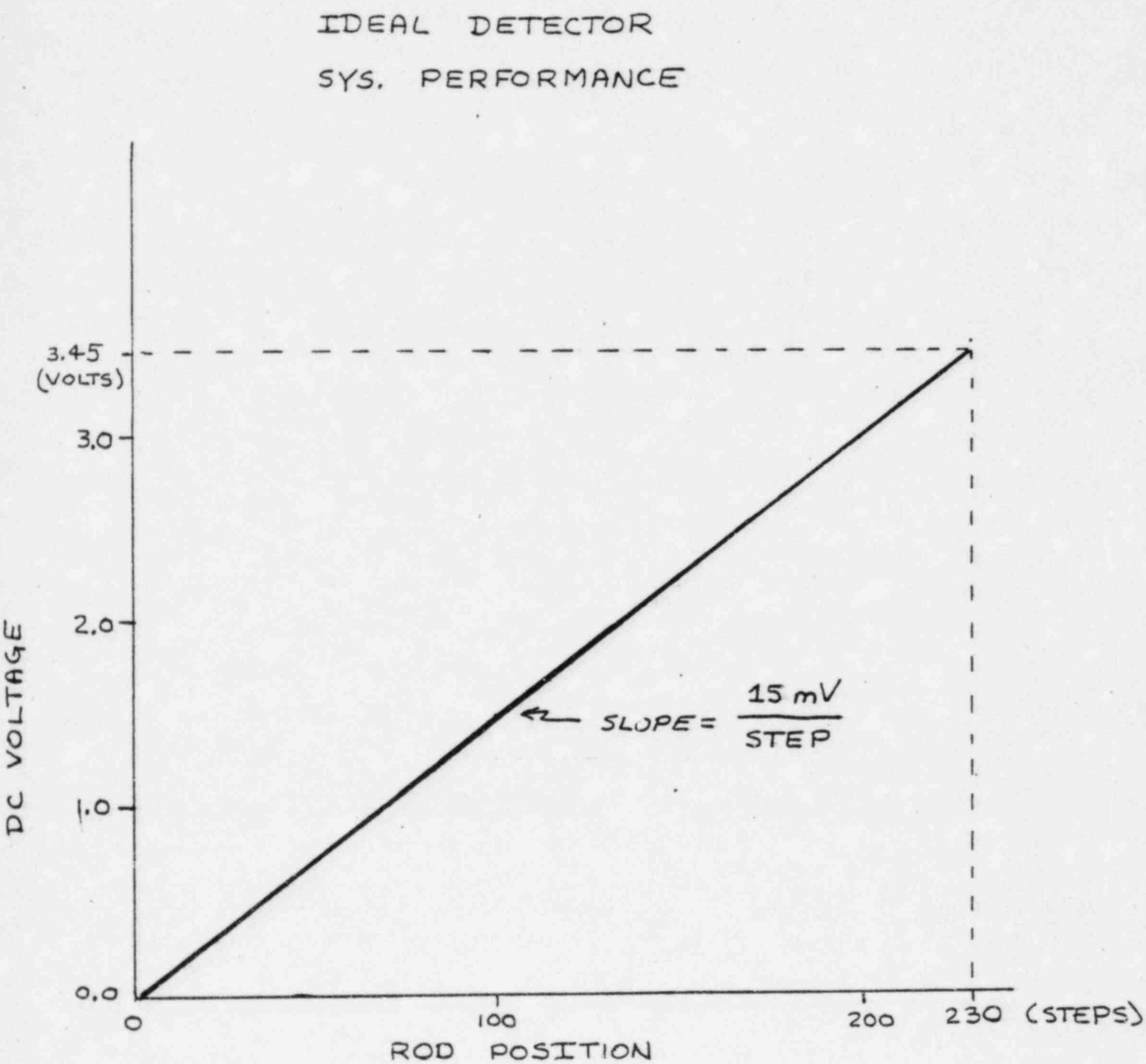

IDEAL DETECTOR
SYS. PERFORMANCE
3.45
(VOLTS)
3.0
2.0
1.0
0.0
DC VOLTAGE
SLOPE = 15 mV / STEP
0
100
200
230
(STEPS)
ROD POSITION

FIG. 4

TYPICAL DETECTOR SYS. PERFORMANCE

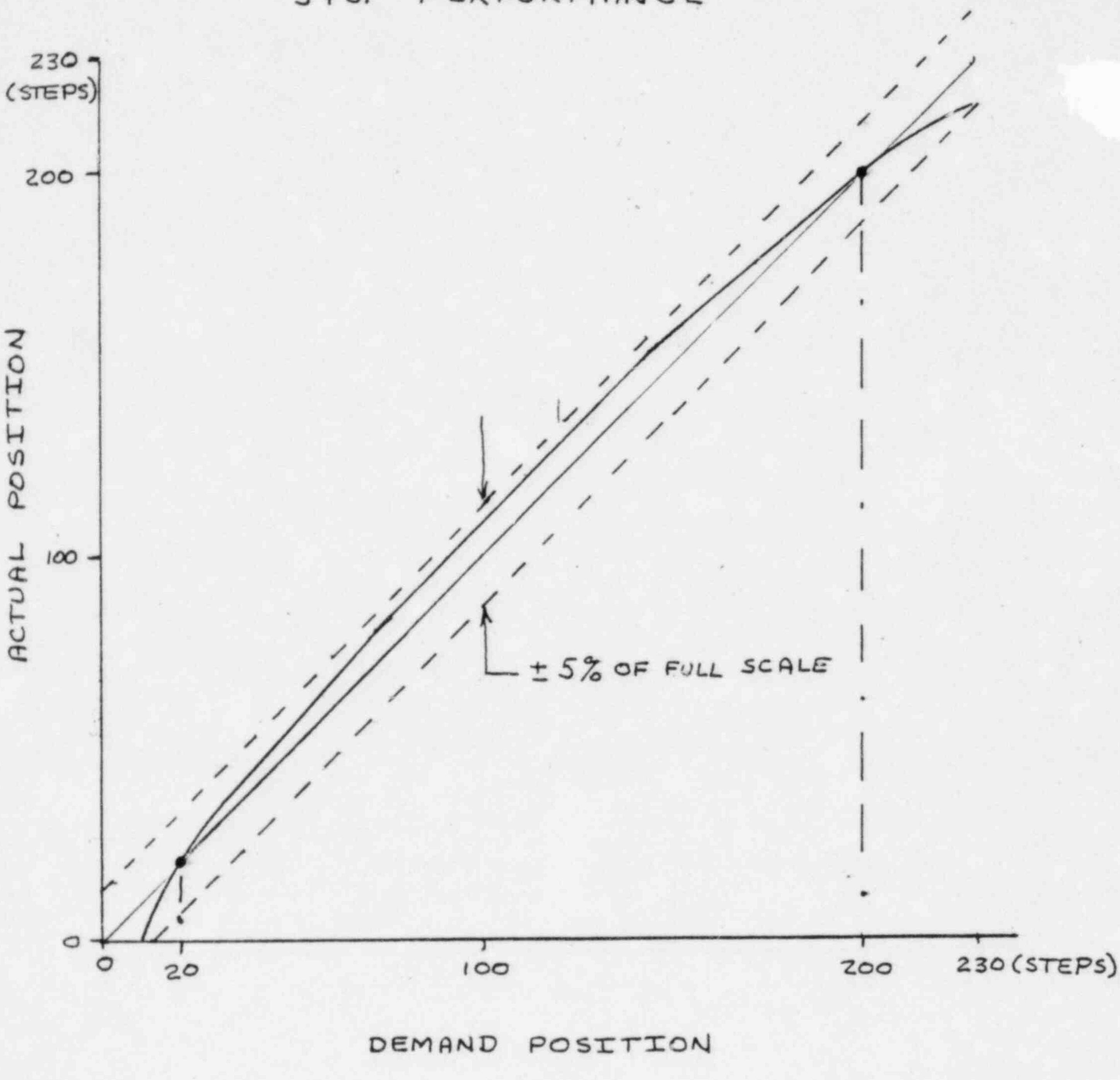


FIG. 5

7. W REVIEW OF BEAVER VALLEY POWER STATION (BVPS) DATA

W has reviewed some of the BVPS data and offers the following comments:

a) The use of the computer generated polynomial compensation curves for linearizing the steady state detector performance appears to be very successful. Of the eight rods in shutdown Bank A the indicated error was reduced to less than 1/3 of the original value.

b) Review of the primary AC voltage and secondary DC voltage changes vs. the reactor coolant system temperature independently confirms the experimental work performed by W. The large changes required re-calibration of each channel if the coolant temperature falls below the 540°F value.

c) The secondary DC voltage vs. demanded position curves confirm the predicted non-linear operation of the system. Use of the non-linear meter scales to compensate this effect should prove successful.

APPENDIX A

ANALOG RPI DETECTOR MODEL

To understand how the detector operates and to predict the detector performance, an electrical model of the detector was selected as shown in Figure A1.

From the model an equation for the output voltage (V_L) was derived.

$$V_L = \frac{118 R_L}{\left(\frac{N1}{N2}\right)(R_L + Z_S)\left(\frac{Z_P + Z_M + 500}{Z_M}\right) + \left(\frac{N_2}{N_1}\right)(Z_P + 500)}$$

Where: R_L = The secondary load resistance connected across the output of the detector; it is approximately 4K Ω (See Appendix B).

Z_P = The detector primary series impedence

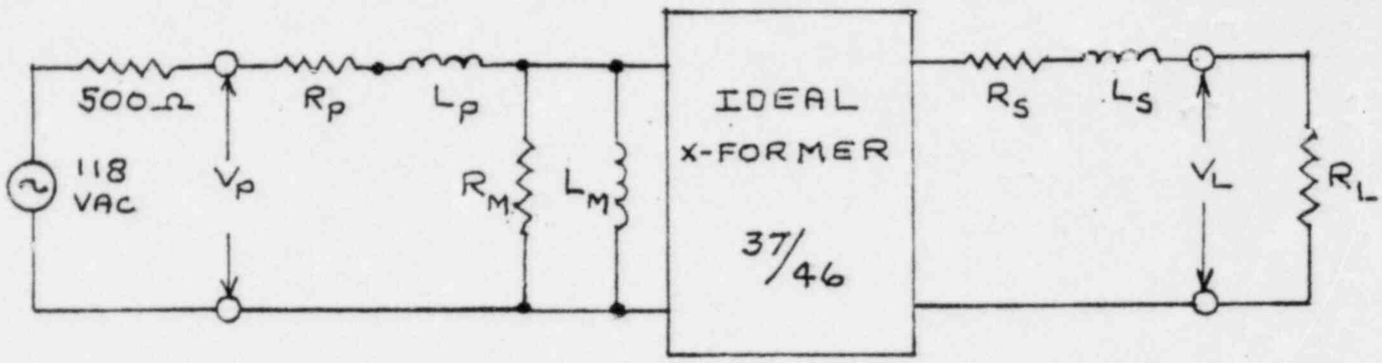
$= R_P + j\omega L_P$

Z_S = The detector secondary series impedence

$= R_S + j\omega L_S$

DETECTOR EQUIVALENT

MODEL



HERE: R_p = Primary Winding Resistance

L_p = Primary Leakage Inductance

R_S = Secondary Winding Resistance

L_S = Secondary Leakage Inductance

R_M = Core Loss Elements

L_M = Magnetizing Inductance

FIGURE A1

Z_M = Mutual parallel impedence

$$= \frac{\omega R_M L_M [\omega L_M + jR_M]}{[R_M]^2 + [\omega L_M]^2}$$

N_1/N_2 = Turns ratio

$\cong$ 37/46

500Ω = The source resistance

118VAC = The source voltage

Table 1A gives typical values for the [illegible] elements of the detector which were measured by Westinghouse on one production detector. These values were determined using a series of amplitude and phase measurements at both ambient and elevated temperatures and various rod positions.

	75°F*		600°F*	
ELEMENT	0 STEPS	228 STEPS	0 STEPS	228 STEPS
R_P(Ω)	---- 36	----	---- 54	----
L_P(MH)	67	65	50	47
R_S(Ω)	---- 45	----	---- 67	----
L_S(MH)	148	142	135	119
R_M(Ω)	362	65	178	64
L_M(MH)	93	277	96	498

TABLE 1A

* This is the temperature of the drive line

From the data in Table 1A it can be seen that the primary and secondary series resistance elements increased with increasing temperature (as expected) but remained constant with rod position changes. Slight changes were measured in the primary and secondary series inductance values that tend to cancel out the changes in series resistance.

With average valves for R_P, R_S, L_P, L_S elements the equation for the output voltage becomes:

$$V_L = \frac{(118)\ (4000)\ (Z_M)}{(\frac{36}{46})\ (4056 + j51.3)\ (Z_M + 545 + j21.6) + (\frac{46}{37})\ (545 + j21.6)\ (Z_m)}$$

which is complex and becomes even more complicated when the Z_M expression is factored in.

Plots of the R_M and L_M elements are given in Figures A2 and A3.

NON-LINEAR OPERATION

Substituting in the values for R_M and L_M shows that the output voltage is a complex, non-linear vector quantity, which varies with both rod position and steady state temperature.

The absolute value of V_L was calculated using the R_M and L_M values of Figures A2 and A3, and plotted in Figure A4.

TYPICAL R_M VARIATIONS

WITH ROD POSITION

& STEADY-STATE TEMP.

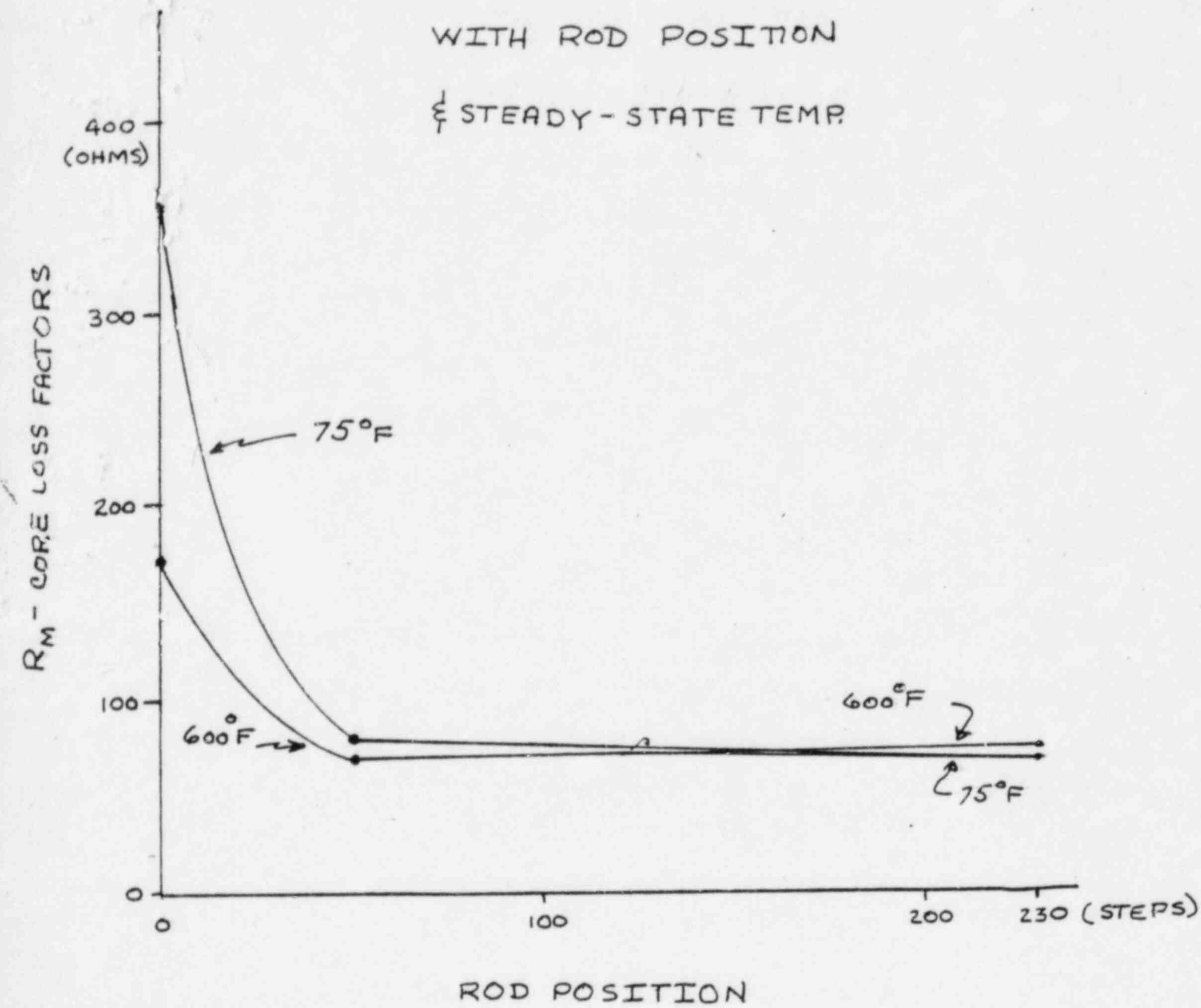


FIG. A2

TYPICAL L_M VARIATIONS

WITH ROD POSITION

& STEADY-STATE TEMP.

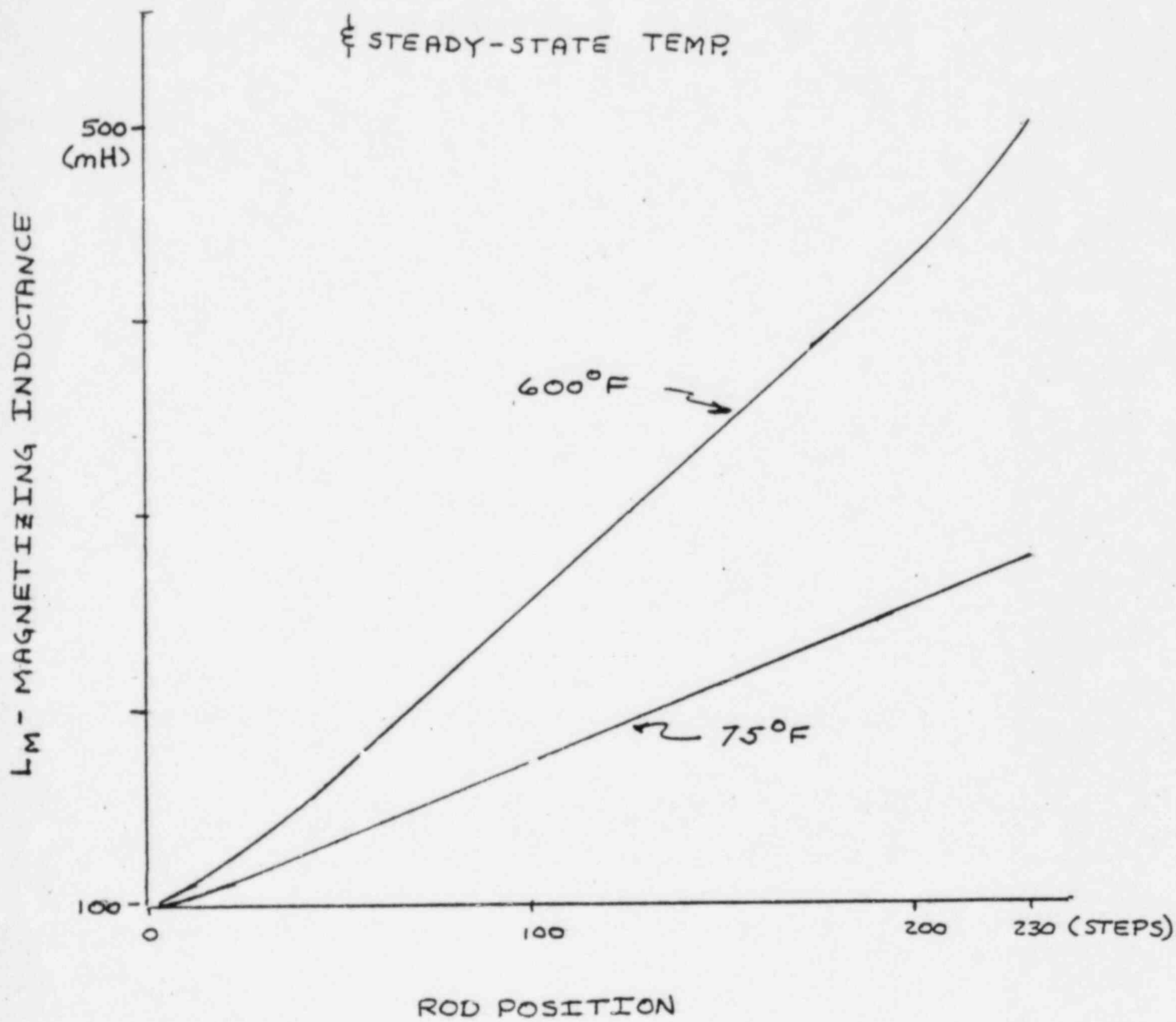
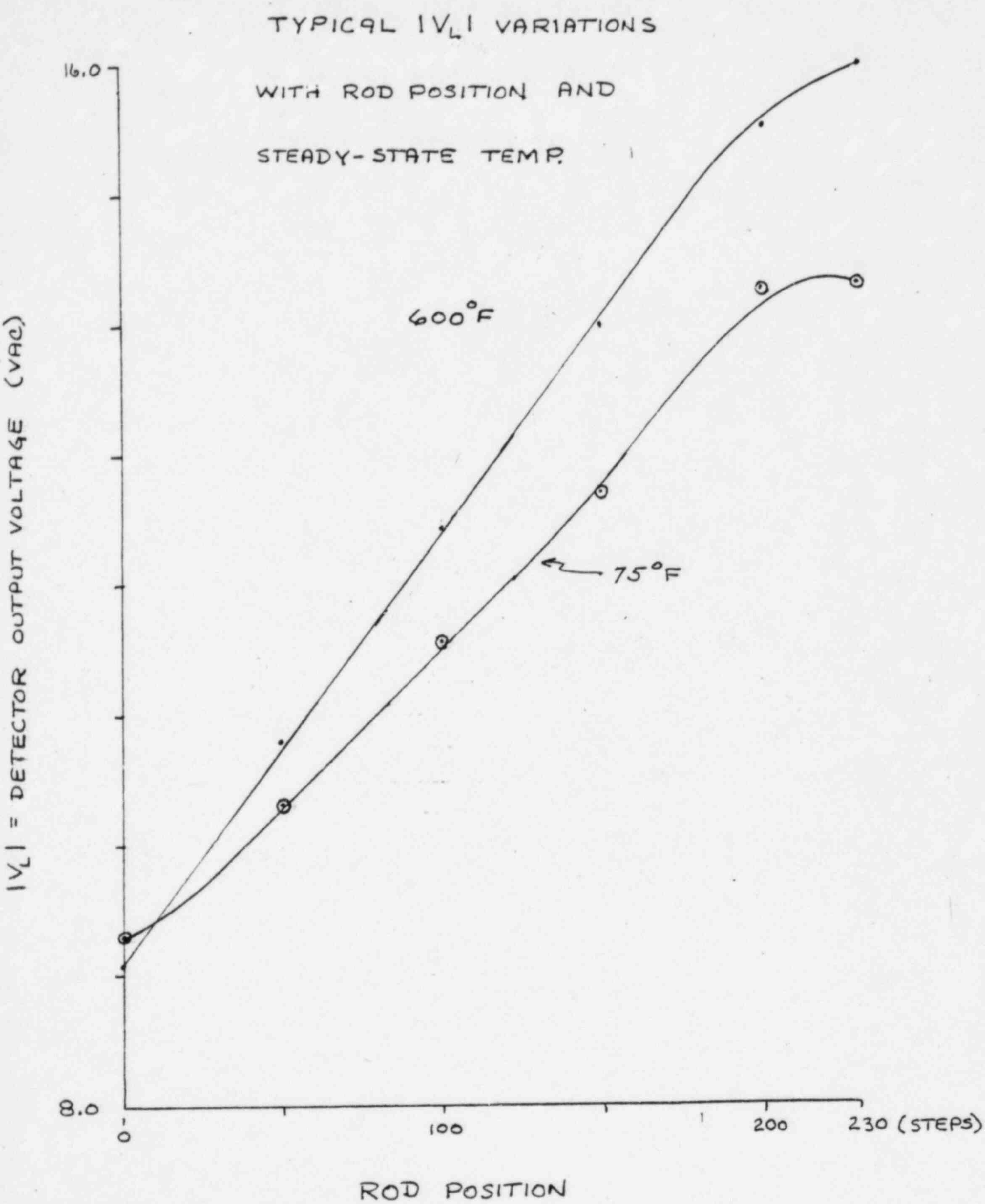


FIG. A3



TYPICAL |V_L| VARIATIONS
WITH ROD POSITION AND
STEADY-STATE TEMP.
16.0
8.0
600°F
75°F
|V_L| = DETECTOR OUTPUT VOLTAGE (VAC)
0
100
200
230 (STEPS)
ROD POSITION

FIG. A4

TRANSIENT TEMPERATURE SENSITIVITY

The preceding analysis assumed steady-state temperatures were reached after rod motion and temperature changes. Field test data taken by Westinghouse on four different rods indicates that if a rod is moved quickly from 0 steps to 228 steps while the coolant is hot, a large positive error in the indicated rod position will be immediately observed. Figure A5 gives the maximum error vs. time for the four rods that were monitored.

The field test data revealed that this transient temperature sensitivity was negligible if the rod is moved quickly from 228 steps to zero steps since now only a small portion of the drive line is inserted into the detector.

SUPPLY VOLTAGE SENSITIVITIES

During the laboratory testing of the single production detector it was possible to vary the frequency and amplitude of the voltage source used to drive the primary of the detector while measuring the secondary voltage. Figure A6 gives the measured secondary voltage values vs. frequency of excitation. The 60HZ curve appears to be the most linear as a result of the non-uniform number of turns in the secondary coils.

Sensitivity to changes in the amplitude of the primary excitation were also observed during the test. From the characteristic equation for the output voltage, it can be seen that variations in the supply voltage will result in different values in output voltage for each value of mutual impedence. At the 228 step position, a larger change in output voltage will result from a supply voltage change than that found at 0 steps since the detector gain at 228 steps is larger than the gain at 0 steps. This supply voltage amplitude change is partially compensated for by the signal conditioning circuit as described in Appendix B.

TYPICAL
ERROR VS TIME

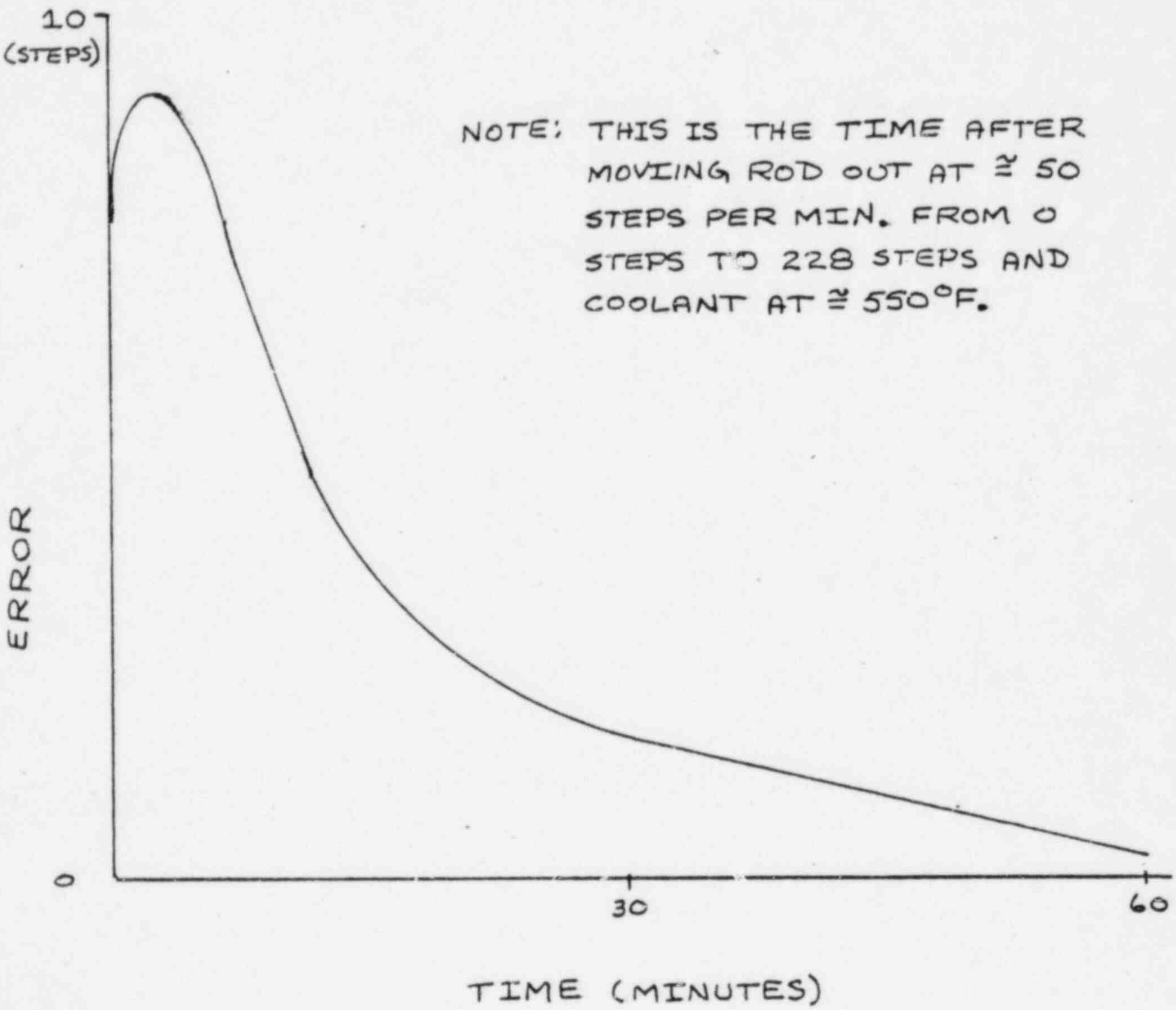


FIG. A5

|VL| VARIATIONS WITH ROD POSITION
AND FREQUENCY VARIATIONS

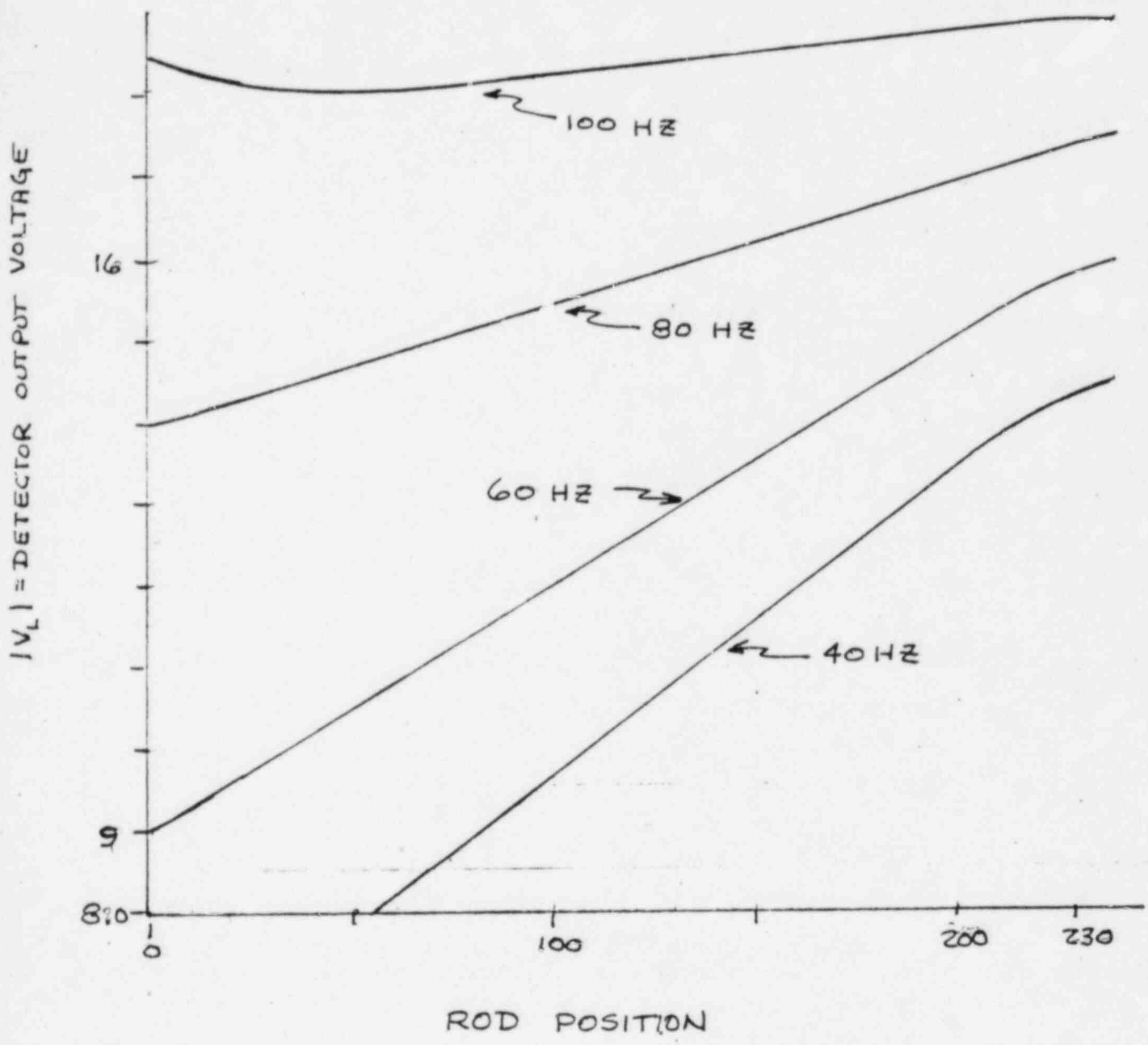


FIG. A6

APPENDIX B

SIGNAL CONDITIONER CIRCUIT MODEL

From Reference Drawing #KD-11191 for the signal conditioner circuit a DC equivalent circuit was developed and is as given in Figure B1.

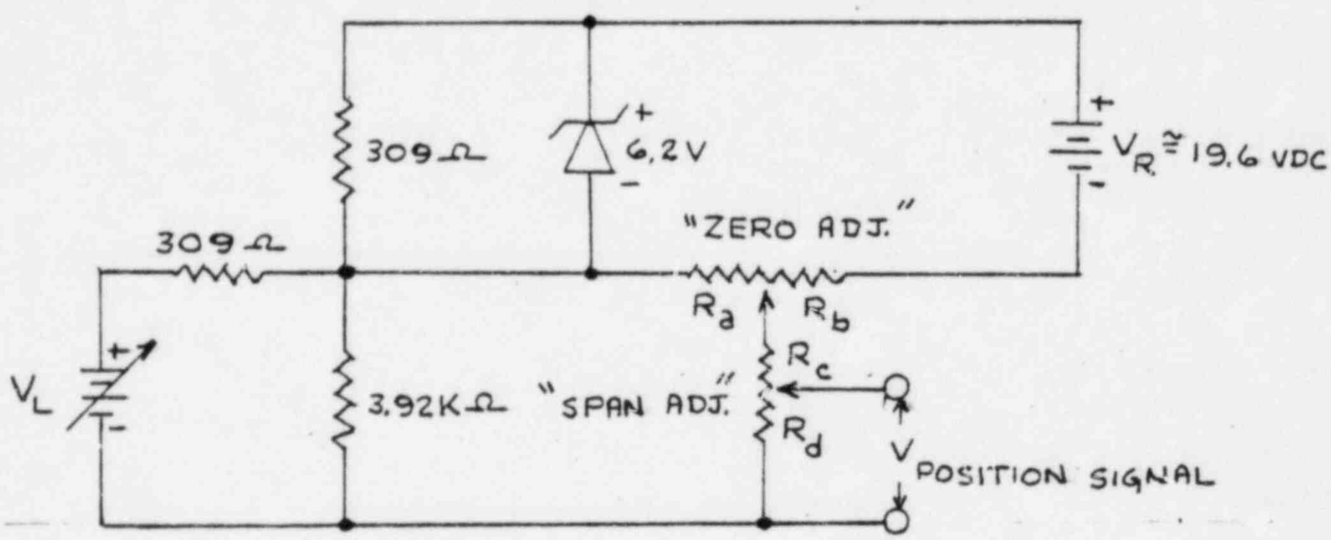


FIGURE B1

$$V_{position\ signal} = \frac{\frac{(V_L)(R_d)}{4.23K} - \frac{(13.4)(R_a)(R_d)}{(500)(3.92K)}}{\left[\frac{33.92K + R_a}{3.92K}\right] - \left[\frac{(R_a)^2}{(500)(3.92K)}\right] + \frac{3.92K}{4.23K}}$$

Where: $R_a + R_b = 500\Omega$ = "zero" Adj.

$R_c + R_d = 30K\Omega$ = "span" adj.

$$\frac{V_L}{I_L} = \text{Input resistance} = R_L \text{ (See Appendix A)}$$

$$\cong 309 + 3920 = 4229\Omega$$

From the instruction book information the zero adjustment is set to give $V_{pos.\ sig.} = +\ 0.300$ VDC at 20 steps and +3.000VDC at 200 steps, with the reactor coolant temperature at 545°F.

Using the typical values for V_L from Figure A4 of Appendix A then approximate values for R_A, R_B, R_C and R_D are:

$R_A = 310\Omega$

$R_B = 500-310 = 190\Omega$

$R_C \cong 15K\Omega$

$R_D \cong 30K - 15K = 15K\Omega$

With these values substituted into the $V_{pos.\ sig.}$ equation then:

$$V_{pos.\ sig.} = (0.46)\ V_L - 4.2 \quad \text{VDC}$$

This indicates that $V_{pos.\ sig.}$ is a linear function of the detector signal output with the settings of the "zero" and "span" adjustments applicable only over a narrow operating range of the coolant temperature.

SUPPLY VOLTAGE AMPLITUDE VARIATIONS

From the formula for the position signal voltage the detector circuit sensitivity to supply voltage variations can be estimated.

For a 1 volt change in supply voltage the reference voltage will change approximately 0.166 volts while the absolute value of the detector secondary voltage will change approxmately 0.135 volts. The approximate change in the $V_{pos.\ sig.}$ would be:

$$\Delta V_{pos.\ sig.} = (.46)\ (.136) - \left(\frac{4.2}{13.4}\right)\ (0.166)$$

$$= 0.01 \text{ volt}$$

which corresponds to less than 1 step.