ADDITIONAL ENGINEERING DATA ON TOKAPOLE II

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On May 17, 1984 the upper inner hanger at 60^{o} on Tokapole II was broken during normal pulsing. This provided both a reason and an opportunity to measure more precisely some of the electrical and mechanical properties of the machine in order to better quantify operational limits and expected life of various components. This note contains a summary of these measurements.

I. Hoop and Hanger Stresses

The stresses acting on the hoops and their hangers during a magnetic field pulse are described in PLP 744. In the original design, no consideration was given to the time dependence of the forces other than to allow an additional safety factor of 1.7 for a half-sine-wave excitation of the worst possible frequency (see PLP 30). This frequency turns out to be twice the natural resonant frequency of the mechanical system, since the force is proportional to the square of the magnetic field. The natural frequencies and Q's of the various mechanical modes have been measured.

The technique for measuring vibrations of the hoops consists of biasing the hoop under test to ~67 volts using a battery and series 10 kΩ resistor for current limiting. An electrode of ~1 cm^2 area is then placed ~1 mm from the hoop and connected to a 1 MΩ input oscilloscope. The displacement appears as a voltage signal through the relation

$$V_{out} = R_{input} V_{bias} \frac{dC}{dt}$$

where C is the capacitance between the electrode and the hoop (~10^{-12} farads). The signal is typically $V_{out} \lesssim 1$ mV, and thus careful shielding and bandpass filtering are required to reduce noise and pickup (especially 60 Hz). The oscillations can be excited either by tapping the hoop with a hammer or by pulsing the field at low amplitude (typically a single, 240 μF capacitor was used, charged to 4 kV, with no crowbar). The various modes can be distinguished by the method of excitation and by the toroidal location of the detector. Signal-to-noise ratio is tested by reversing the bias polarity and triggering the scope on the driving excitation. Figure 1 shows a typical output signal. The measurements were subsequently retaken with a piezoelectric accelerometer with similar results.

The hoop/hanger system has several modes in which it can oscillate. These are most conveniently catalogued by specifying their toroidal mode number n, where the amplitude of the displacement is assumed to vary as $e^{in\phi}$ and ϕ is the toroidal angle. The simplest (and most important from the standpoint of hanger stress) is n = 0 which is strongly driven by the normal method of excitation. It simply represents a longitudinal vibration of the hangers coupled to a mass equal to the portion of the hoop that they support (one-third).

Modes with n > 0 can be excited by striking the hoop at an appropriate location with a hammer. The modes which are most strongly excited by this method are those for which n is a multiple of 6 (n = 6, 12, 18, ...) since the hangers act as nodes and the periodic boundary condition does not allow multiples of 3. The n = 6 mode is overwhelmingly the most dominant, and it oscillates with a large amplitude and extremely high Q. During normal pulsing of the machine, this mode is not excited, however, because of the symmetry of the driving force.

For normal excitation, the dominant mode has n = 3 and involves a sharp bending of the hoop at the supports. This is the mode that is considered in PLP 744, and is the most serious candidate for breaking the hoops. It is this mode that ultimately lead to the death of Tokapole I after 15 years of operation. The frequencies and Q's of the various modes mentioned above are listed in Table I.

From a knowledge of the frequencies and Q's of the modes, one can calculate the time-dependent stresses $\sigma(t)$ in the hoops and hangers from the harmonic oscillator equation

$$\frac{1}{\omega^2}\frac{d^2\sigma}{dt^2} + \frac{1}{\omega Q}\frac{d\sigma}{dt} + \sigma = \sigma_0(t)$$

where $\sigma_0(t)$ is the stress produced by the driving force in the dc limit, which is proportional to the square of the hoop current. The constants of proportionality are taken from PLP 744 and listed in Table II. In Table II, I is the total hoop current (all four) and is derived from case 19 in Table III of PLP 744. The results are slightly conservative because soak-in has been neglected. A naive reading of Table II suggests that in the absence of resonance effects, the yield limit is first exceeded on the inner hoops at a hoop current of 700 kA, and that the outer hangers have the most conservative design.

The equation above has been solved for a normal Tokapole discharge (30-240 μF capacitors charged to 2.5 kV and discharged into a 40:1 turns ratio with a 0.96 F/400 volt power crowbar). The results are plotted in figures 2-5.

Although the peak stresses are well below the yield stresses for the hangers and hoops, this is not to say there is no cause for concern. Rather, one must look at the so-called "S-N" curves in which the number of cycles to failure is plotted vs the stress. Unfortunately, such curves are not available for the copper alloys used in Tokapole II. However, a curve for a similar hardened, malleable, copper alloy taken from Russell and Welcker, Proc. Am. Soc. Test. Mat., 36 118 (1936) is shown in figure 6. Although there is some scatter in the data, a reasonable fit is

$$N = 0.36\ e^{12.5\ \sigma_y/\sigma}$$

In estimating the number of machine pulses to expect before failure, one has to consider the fact that each machine pulse results in a succession of stress peaks as the mechanical system oscillates. If the oscillations have sufficiently high Q, the number of pulses before failure is reduced by a factor of $\sim 12.5\ \pi\sigma_y/Q\sigma_p$ where σ_p is the peak stress during the first cycle of oscillation. Unless Q considerably exceeds $12.5\ \pi\sigma_y/\sigma_p$, which is usually not the case for Tokapole II, this factor can be ignored.

On the basis of these considerations, one can estimate the number of pulses before failure for various hoop currents, obtained by raising and lowering the voltage on the B_p capacitor bank. The results are shown in Table III. The implication of these numbers is that the observed failure was probably not a normal fatigue failure, but rather indicates a flaw (scratch, etc.) in the material.

II. Poloidal Field Circuit Losses

When the poloidal field capacitor bank is discharged into the Tokapole, some of the energy is lost resistively in the transmission line, ignitron, primary windings, continuity windings, and walls of the machine, and some is stored inductively in the transmission line and in leakage inductance in the iron core. Some of these losses were predicted in PLP 744, but most have never been measured carefully. We report here the results of such measurements.

Figure 7 shows the poloidal field circuit and the measured values of the various circuit elements. These measurements were made using a carefully calibrated pair of X10,000 attenuators (500 kΩ to 50 Ω) connected to the differential input of a Tektronix 466 oscilloscope. The inductive components come from early-time measurements, before the current has risen significantly, and the resistive components are from later in the pulse after the current has risen to near its peak value.

The V-I characteristic of the class E, B_T crowbar ignitron was measured and is plotted in figure 8. The voltage, over the range of currents of interest, is remarkably constant at ~10-16 volts, which probably represents the sum of the work function of the cathode (4.5 volts) plus the ionization potential of mercury (10.44 volts). There is also a slight tendency for the voltage drop to decrease in time during the pulse, especially at low currents.

The dc resistance of the hoops is calculated to be $R_1 = 24.823\ \mu\Omega$ for each inner hoop and $R_2 = 44.798\ \mu\Omega$ for each outer hoop. At very late times ($t \gg L/R \sim 27$ msec), the hoops all appear in parallel, and the net resistance is 7.98 μΩ. At early times ($t \ll L/R \sim 27$ msec), the currents divide inductively, and the equivalent series dc resistance is

$$R = \frac{L_1^2 R_2 + L_2^2 R_1}{2(L_1 + L_2)^2} = 7.99\ \mu\Omega$$

where $L_1 = 0.688\ \mu H$ and $L_2 = 1.2\ \mu H$ are the inductances of the inner and outer hoops respectively (from case 19 PLP 744). The ac resistance of the hoops has been calculated by Kerst in PLP 893. His results, fitted to an exponential function of time over the range 1-20 msec give

$$R = R_{dc}\ (1 + 1.2513\ e^{-419.664t}) \quad .$$

His results are strictly valid only for a step function hoop current, but probably are not unreasonable for our case with a power crowbar. Putting it all together gives

$$R = 8.0 + 10.0\ e^{-420t}\ \mu\Omega \quad .$$

III. Toroidal Field Circuit Losses

In similar fashion, the toroidal field circuit losses have been measured, and the results were reported in PLP 924.

Table I

Frequencies and Q's of the normal modes of vibration of the Tokapole II hoops.

UPPER INNER

n	f	Q
0	295 Hz	45
3	180 Hz	50
6	430 Hz	1.2×10^4

UPPER OUTER

n	f	Q
0	280 Hz	30
3	70 Hz	125
6	130 Hz	2×10^4

LOWER INNER

n	f	Q
0	290 Hz	70
3	180 Hz	50
6	430 Hz	1.2×10^4

LOWER OUTER

n	f	Q
0	310 Hz	30
3	70 Hz	125
6	130 Hz	2×10^4

Table II

Stress Coefficients for Tokapole II

	Stress/MA^2 (σ_o/I^2)	Yield Stress (σ_y)
Outer hanger	128 kpsi/MA^2	165 kpsi
Inner hanger	184 kpsi/MA^2	165 kpsi
Outer hoop	67 kpsi/MA^2	43 kpsi
Inner hoop	89 kpsi/MA^2	43 kpsi

Table III

Estimated Fatigue Life of Various Components of Tokapole II

Hoop current	270 kA	390 kA	520 kA	650 kA
Outer hanger	10^{61}	10^{28}	10^{16}	10^{10}
Inner hanger	10^{42}	10^{19}	10^{11}	10^{7}
Outer hoop	10^{30}	10^{16}	10^{9}	10^{6}
Inner hoop	10^{21}	10^{10}	10^{5}	10^{3}

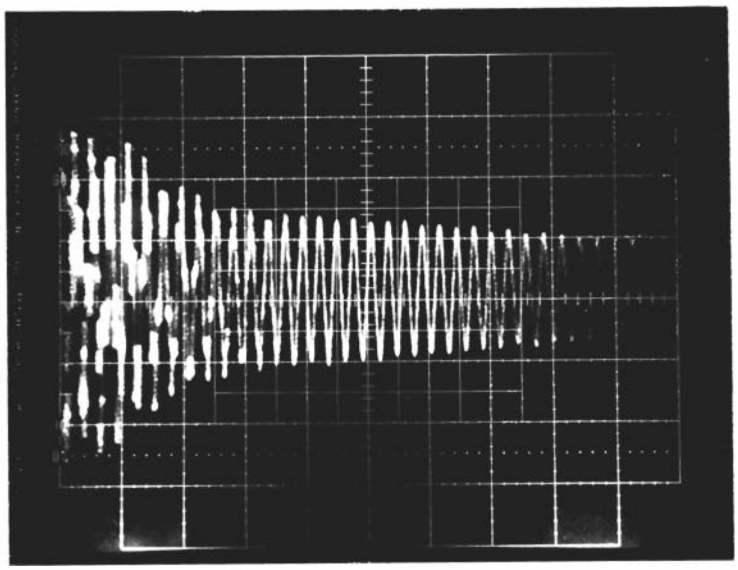
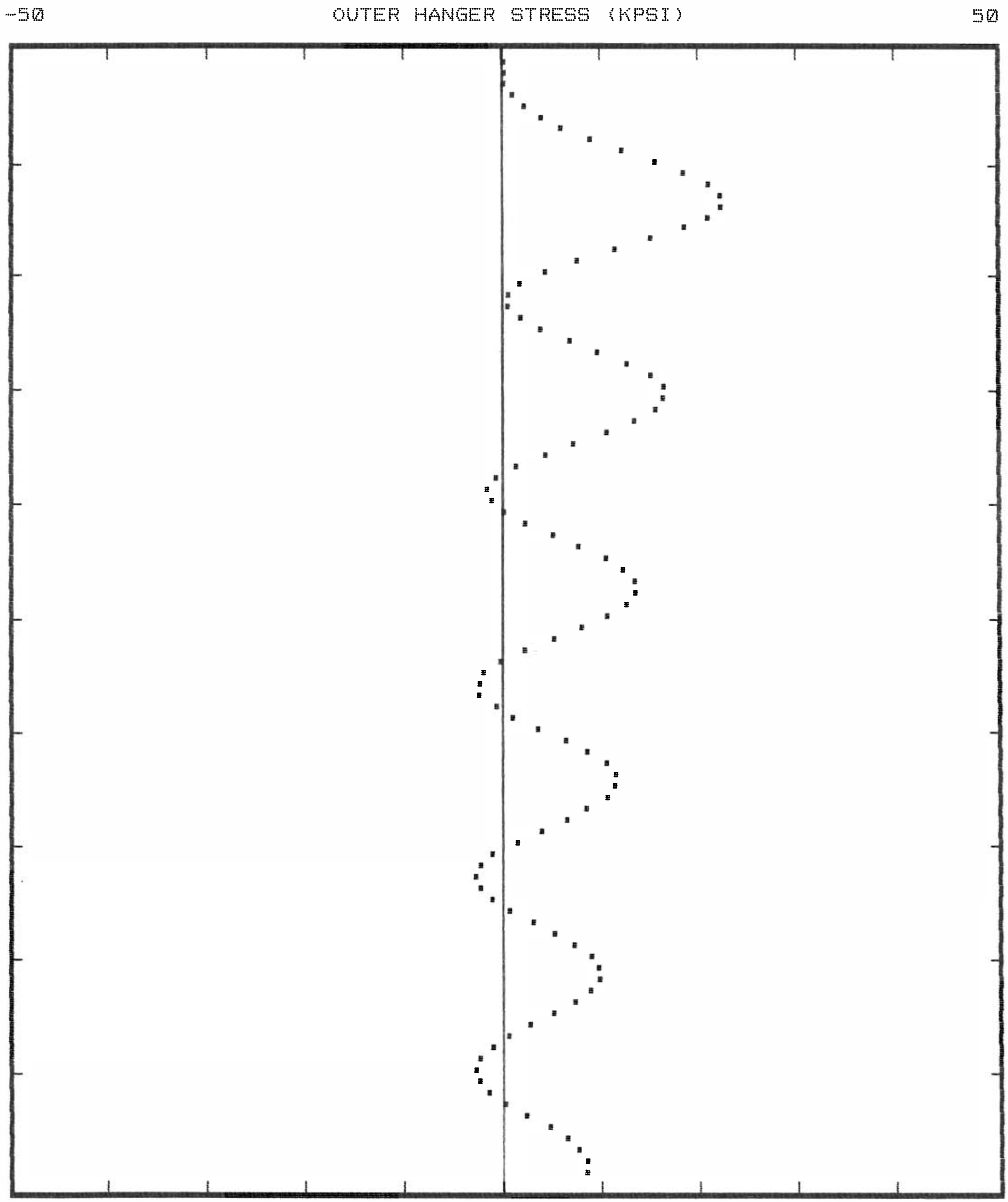
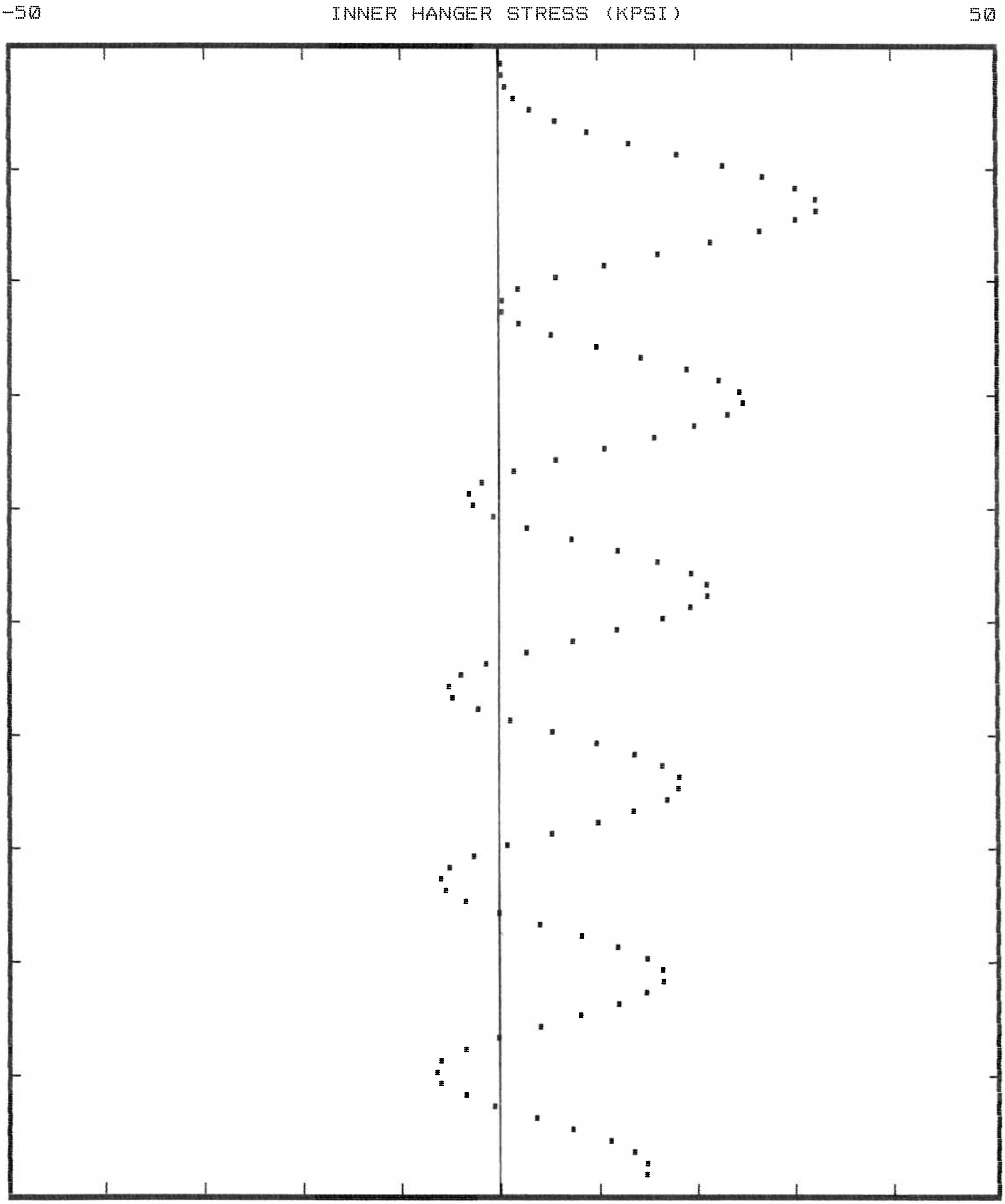


Fig. 1: A typical output signal using the displacement current technique or a piezoelectric acclerometer. This case is the hammer-struck n = 3 mode for the lower outer hoop.



TOKAPOLE II/TOK WITH N = 40 TURNS, C = 7.2E-03 FARADS, 20 MSEC FULL SCALE
INITIAL CAPACITOR VOLTAGE = 2500   VOLT-SECONDS CONSUMED = .070537
CORE BIAS = 0 KG (.268 AMP-TURNS)   PRIMARY RESISTANCE = .0485 OHMS
INITIAL PLASMA RESISTANCE = .01 OHMS   CROWBAR VOLTAGE = 400

Fig. 2



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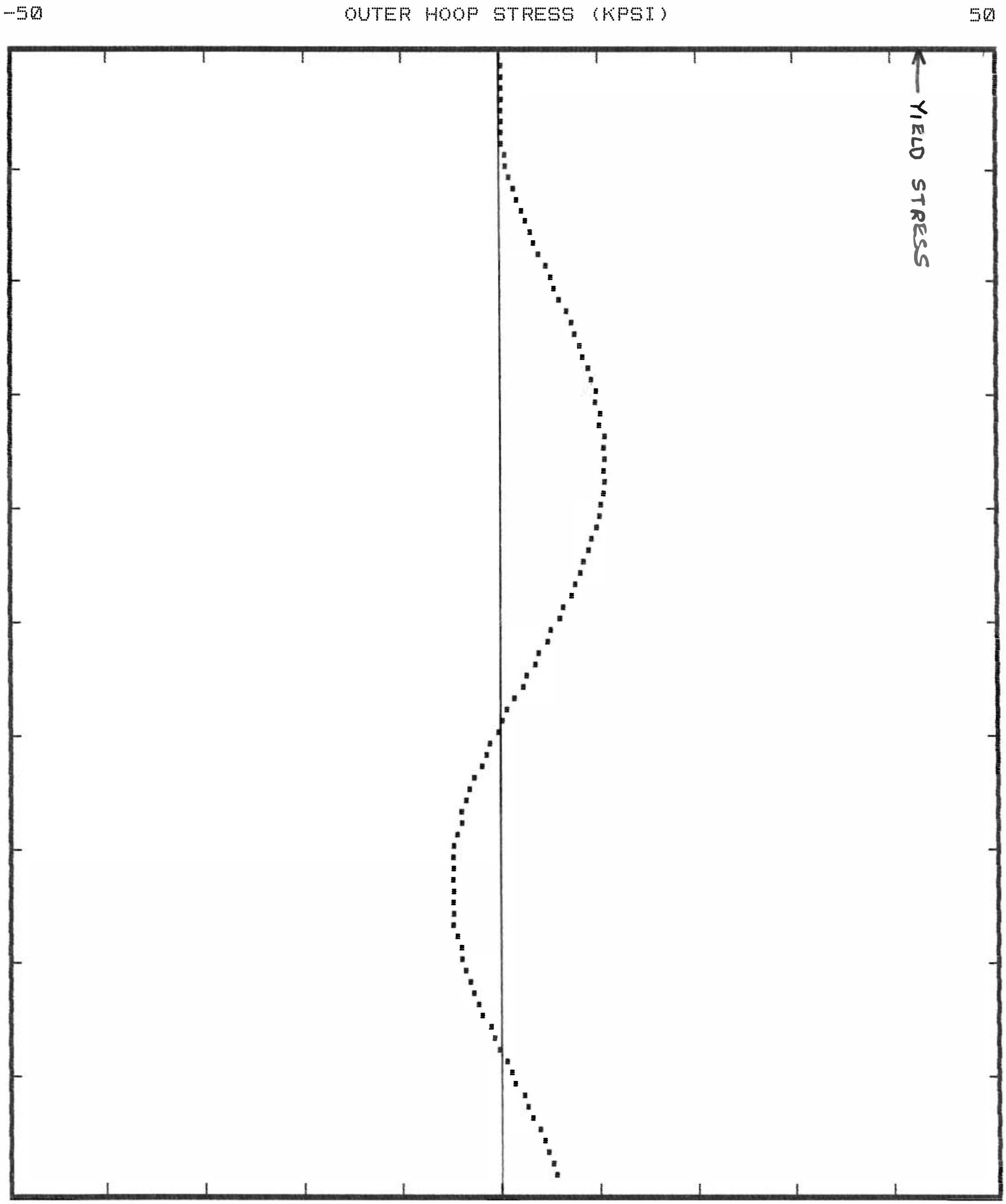
INITIAL PLASMA RESISTANCE = .01 OHMS   CROWBAR VOLTAGE = 400

Fig. 3



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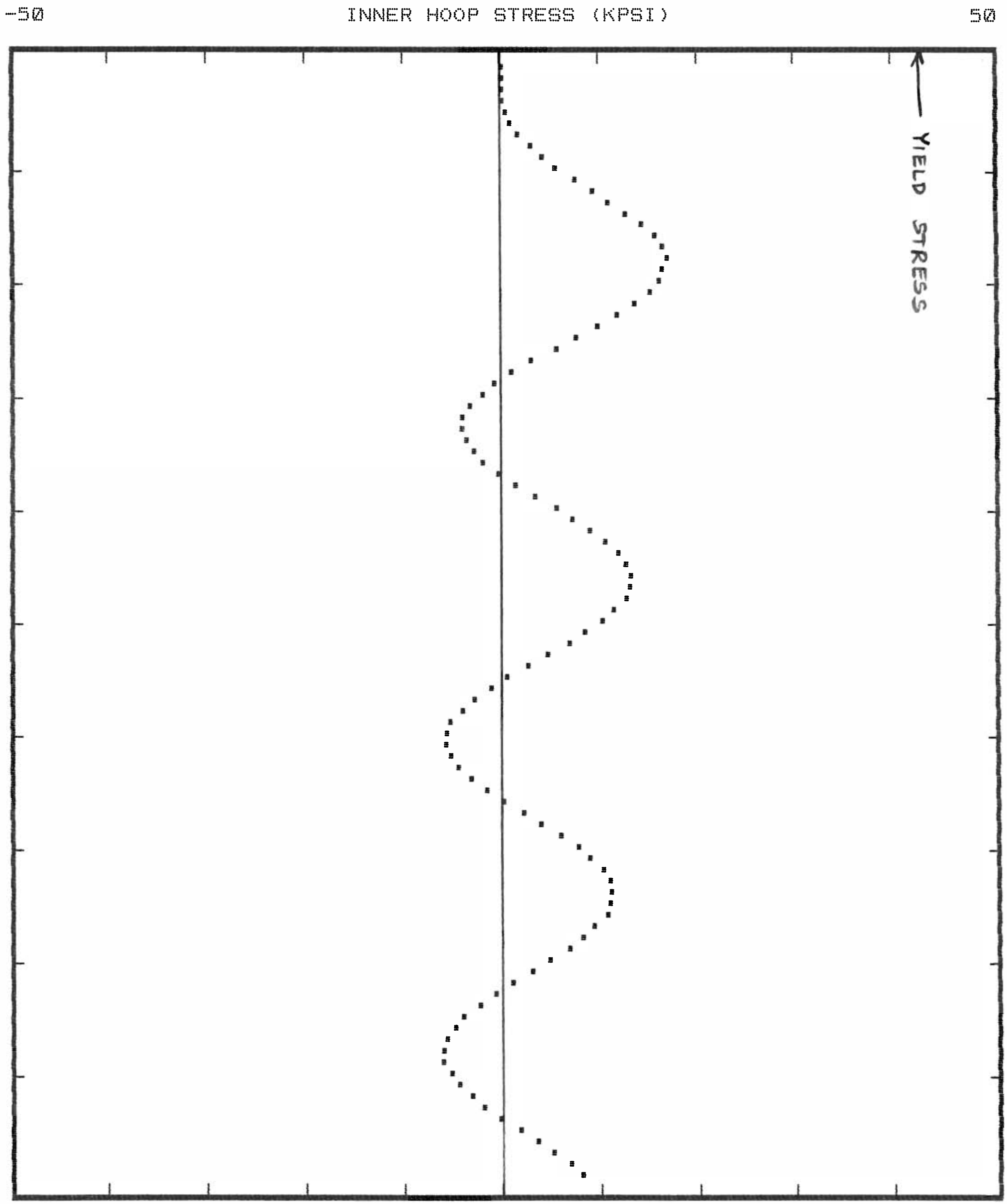
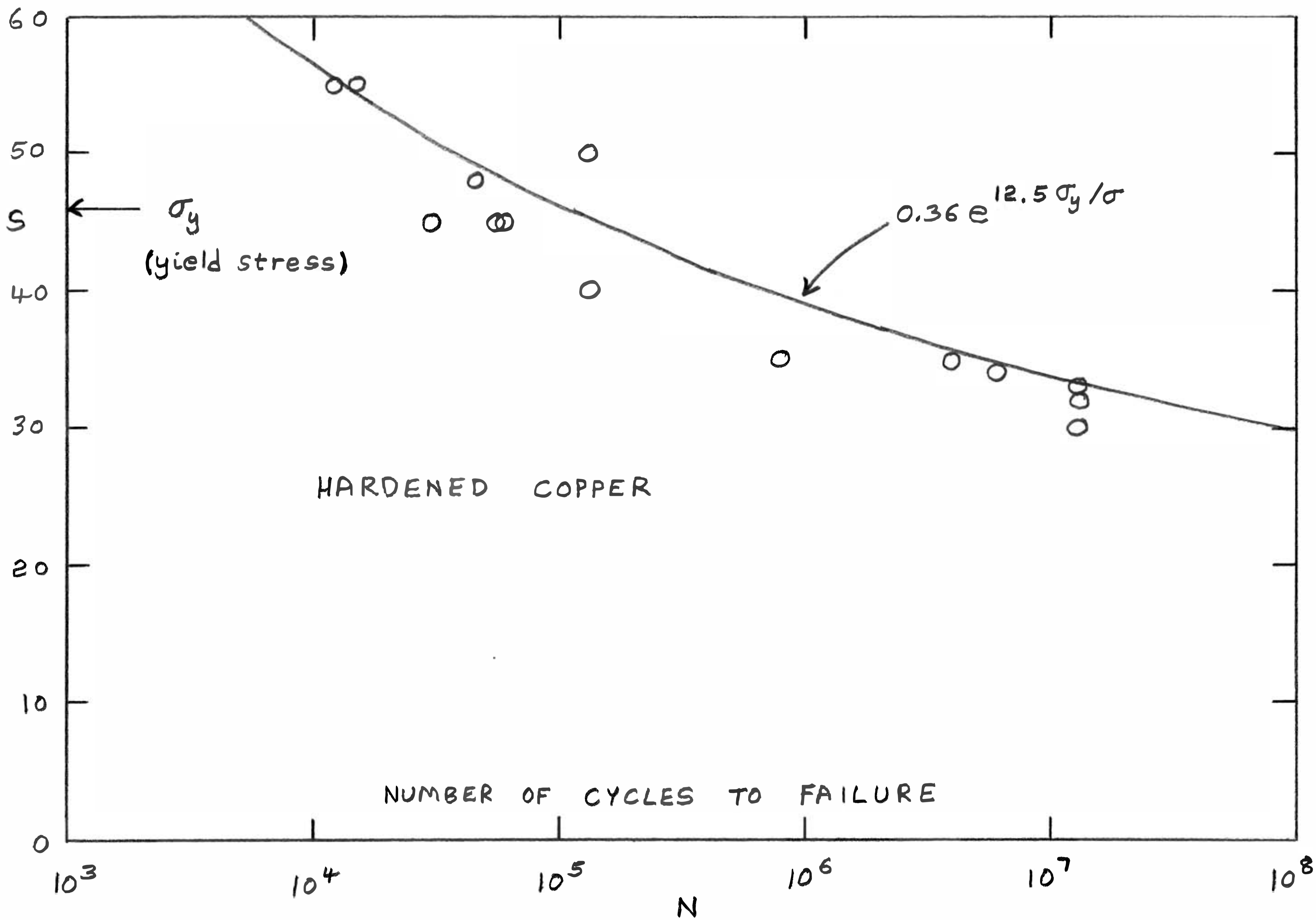
INITIAL PLASMA RESISTANCE = .01 OHMS   CROWBAR VOLTAGE = 400

Fig. 4



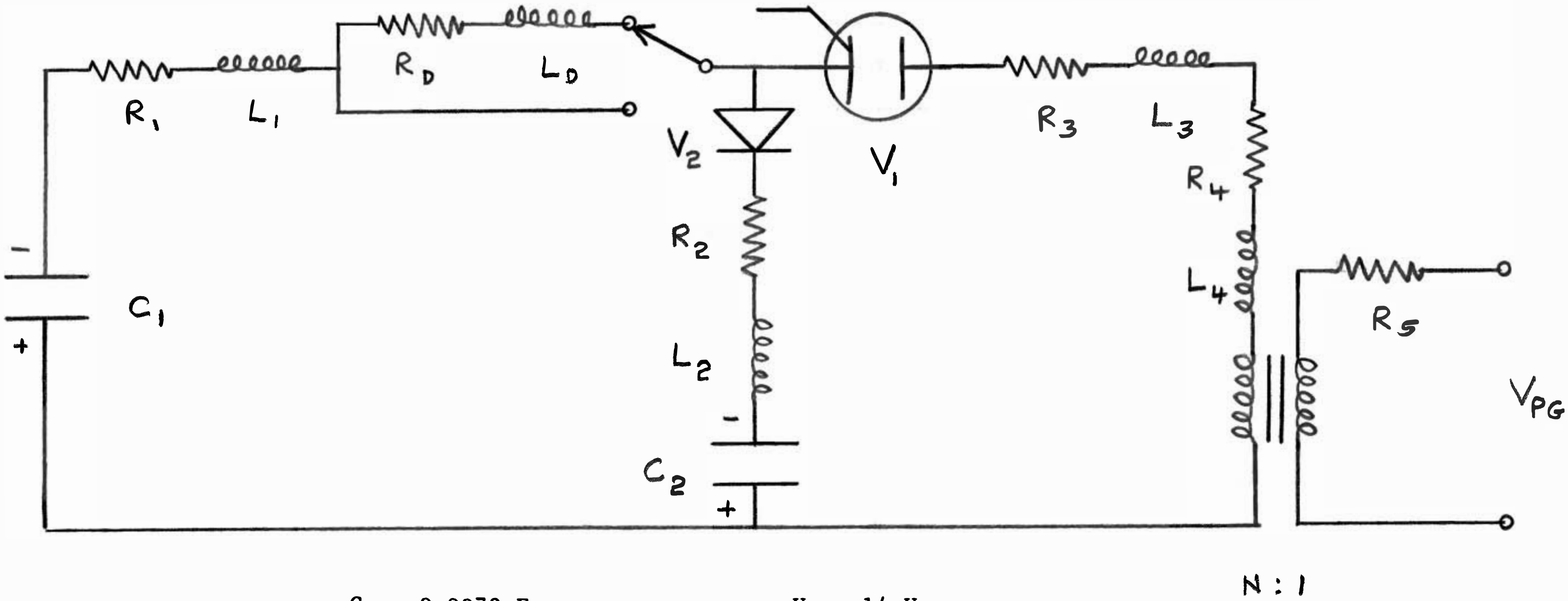
TOKAPOLE II/TOK WITH N = 40 TURNS, C = 7.2E-03 FARADS, 20 MSEC FULL SCALE
INITIAL CAPACITOR VOLTAGE = 2500   VOLT-SECONDS CONSUMED = .070537
CORE BIAS = 0 KG (.268 AMP-TURNS)   PRIMARY RESISTANCE = .0485 OHMS
INITIAL PLASMA RESISTANCE = .01 OHMS   CROWBAR VOLTAGE = 400

Fig. 5



60
50
S
40
30
20
10
0
σ_y
(yield stress)
$0.36\, e^{12.5\, \sigma_y / \sigma}$
HARDENED COPPER
NUMBER OF CYCLES TO FAILURE
10^3
10^4
10^5
10^6
10^7
10^8
N

Fig. 6



C_1 = 0.0072 F

R_1 = 6 mΩ

L_1 = 4.5 μH

R_D = 61 mΩ

L_D = 2.5 μH

C_z = 0.96 F

R_2 = 4 mΩ

L_2 ~ 0

V_1 = 14 V

V_2 = 68 V

R_3 = 3 mΩ

L_3 = 3 μH

R_4 = 17 mΩ N = @ 40

70 mΩ N = @ 80

L_4 = 16 μH N = @ 40

70 μH N = @ 80

R_5 = 2μΩ

Fig. 7: Circuit parameters of poloidal field circuit.

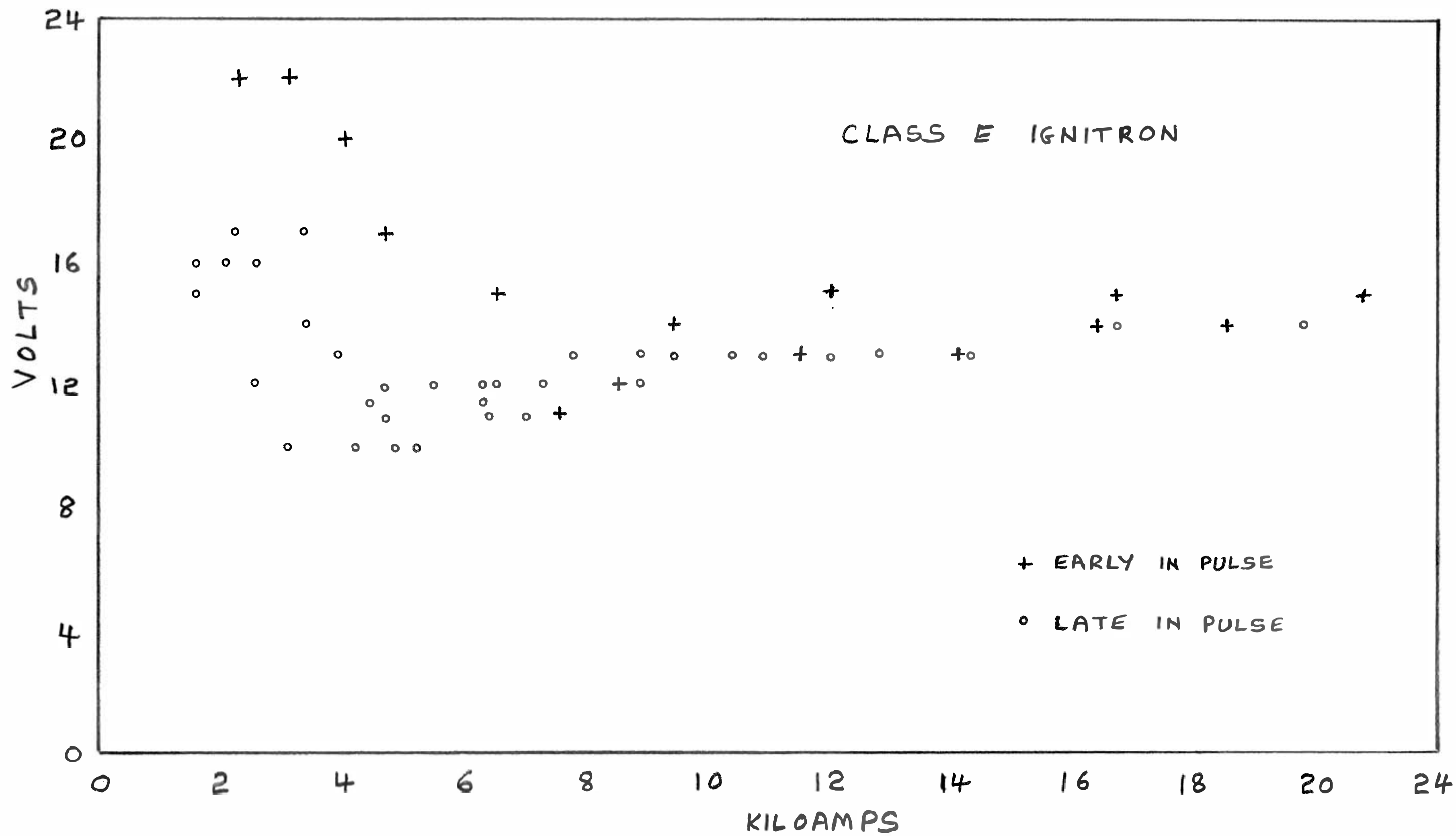

CLASS E IGNITRON
+ EARLY IN PULSE
o LATE IN PULSE
VOLTS
KILOAMPS
0
4
8
12
16
20
24
0
2
4
6
8
10
12
14
16
18
20
24

Fig. 8