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Accelerator Development Department

BROOKHAVEN NATIONAL LABORATORY

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THE APPLICATION OF STRAIN GAGES FOR MEASURING COIL STRESSES IN HERA DIPOLE MAGNETS AT DESY/ RESULTS OF COIL STRESS MEASUREMENTS ON A 1M HERA MAGNET AT DESY

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The Application of Strain Gages for Measuring Coil Stresses in HERA Dipole Magnets at DESY/Results of Coil Stress Measurements on a 1M HERA Magnet at DESY

INTRODUCTION

This paper is composed in two sections. The first section attempts to be a comprehensive description of the suggested use of strain gages in HERA Dipole Magnets, as demonstrated by the authors from July 27, 1987 to August 7, 1987 at DESY and BBC. Material to be discussed shall include the gages themselves, the strain gage circuit, transducer geometry and construction details, calibration methods and tooling, and instrumentation. (Although the system as presented is complete and may be implemented intact to the HERA magnet program, no claim to optimization of the system is made, as this would require an iterative R&D program). The second section is a description of the work done while at DESY and BBC, along with results of coil stress measurements during collaring at 300°K and magnet testing at 4°K.

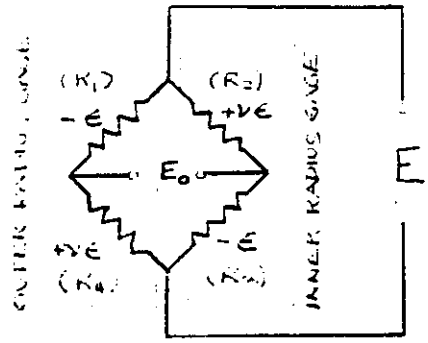
SECTION (I) - Application of Strain Gages in HERA Dipole Magnets

1. STRAIN GAGES

The strain gages used on HERA dipole transducers made at BNL are WK-13-062TT-350 strain gages manufactured by Micro-Measurements Division of Measurements Group, Inc., Raleigh, N.C., U.S.A. They are dual element metal foil resistance strain gages with grids at right angles to each other. The explanation of the gage code, as explained in Micro Measurements short form catalog 95A and Tech. Note TN-505, "Strain Gage Selection", (copies of both to be left at DESY), can be found in Table 1. This particular gage is rated by the manufacturer from 4°K to 563°K, and to ± 1.5% strain.

2. STRAIN GAGE CIRCUIT

Two identical gages of the same type and lot (for consistent behavior) are mounted to each transducer using MM type AE-15 two part epoxy, as described in MM Instruction Bulletin B-137-11, "Strain Gage Applications With M Bond AEIO/15, etc." (copy to be left at DESY). The position of the gages is such that a gage element reads compressive strain near both the inner and outer radii of a given coil. The other gage elements then, by geometry of the gages, read poisson tension strain at these locations. The four gage elements are wired into a full bridge circuit as shown below, using Tensolite 32 AWG Teflon coated silver plated copper wire, which are cut in equal lengths where possible to reduce leadwire effects, and twisted to reduce electrical noise.



The output equation of this circuit is as follows:

$$E_0 = \left[\frac{R_1}{R_1+R_4} - \frac{R_2}{R_2+R_3} \right] E$$

Note that at zero load, since $R_1 = R_2 = R_3 = R_4 = 350\Omega$, $E_0/E = 0$. Also, since a change in temperature would cause the transducer to contract isentropically, each gage element would read an equal compressive strain (i.e., equal change in resistance), thereby keeping the bridge circuit balanced at zero. In principle then, the full bridge circuit is perfectely compensated for temperature (and magnetic field if effects are independent of orientation in the field). Under compressive load, the output equation becomes:

$$\frac{E_0}{E} = \left[\frac{(R+\Delta R)}{(2R+\Delta R-\nu\Delta R)} - \frac{(R-\nu\Delta R)}{(2R+\Delta R-\nu\Delta R)} \right]$$

$$= \left[\frac{(\Delta R/R)(1+2)}{2+(\Delta R/R)(1-\nu)} \right]$$

By definition, $\Delta R/R = S_g\varepsilon$[1], where

ε = uniaxial strain
s_g = gage factor, a calibration constant provided by the gage manufacturer

Therefore, $$\frac{E_0}{E} = \left[\frac{S_g\varepsilon(1+\nu)}{2+S_g\varepsilon(1-\nu)} \right]$$, where

S_g, ν, and E are known constants so that the equation reduces to:

$$E_0 = f(\varepsilon)$$

3. TRANSDUCER GEOMETRY

Strain gage transducers for both inner and outer coils are machined from Type 7075-T6 Aluminum, a high strength material intended to match the material of the collars. Transducers are located radially to be centered about the mean radius of the respective coil to minimize bending effects. Outer coil transducers are designed to fit in a pocket removed from the outer coil post face, parallel to the original surface. In the case of the inner coil transducers, the collar lamination post is completely removed and a parallel sided transducer is installed between tapered housings so that the assembly matches the geometry of the inner post. Details of the transducers can be seen in Fig. 1, Appendix A and BNL Dwg. #22-366.01-2. (Copy to be left at DESY).

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[1]Dolly, "Experimental Stress Analysis", p. 170.

4. STRAIN GAGE INSTRUMENTATION

The instrumentation brought along to be used at DESY is a MM V/E-20 Amplifier with an SB2 Switch and Balance Unit. The V/E-20 is a constant current power supply, with an output that can be "tuned" by knowing parameters of the application to read out directly in strain. (The "tuning" procedure is best understood by reading the operator's manual and shall not be discussed here.) The SB2 unit allows for several channels of data to be monitored at once. (This application for HERA dipole magnet has two inner coil transducers and four outer coil transducers = six channels of data).

Should DESY decide not to use micromeasurement group equipment as described above, an equivalent system may be attained by using a constant current or constant voltage power supply along with one or more digital voltmeters [calibrations will be $\sigma = f(v)$ instead of $\sigma = f(\mu\varepsilon)$].

5. STRAIN GAGE CALIBRATIONS

Each strain gage transducer undergoes three distinct calibrations prior to installation in a magnet. These are: calibrations on transducers in a compression cage at both 300°K and 4°K (liquid helium at atmospheric pressure); and calibrations at 300°K after installation in a collar pack using coil sections as load members. During each calibration a known load is applied in distinct increments, and output strain is read at each increment. A calibration is always performed and recorded twice for each gage to ensure repeatability (usually within .25% on transducer calibartions, 1.0% on collar pack calibrations). Stress/strain formulas for each calibration of each gage are then calculated using a linear curve fit (in this case using the linear regression function of a Texas Instrument TI-55III hand held calculator). The formulas are of the form:

$$\sigma_{coil_{i,t,T}} = (E)_{i,t,T}\,|\mu\varepsilon| + (N/mm^2)_{i,t,T}$$

where i = gage number
t = temperature
T = Type (trans. or collar)

For each calibration, the correlation coefficient is also recorded, which is the statistical measure of closeness of the data to a straight line (Perfect = ±1.0, Scatter = 0.0).

The 300K collar calibrations are required, of course, to monitor coil stresses at assembly. Note that in the case of these calibrations, data has been taken with increasing and decreasing loads, to investigate hysterisis effects. It is generally accepted that with normal methods of collaring coils, as much as 50% of the load applied to the coils in the press is lost after the magnet is collared. If hysteris effects are large, they should be accounted for in calibrations, if only informally, to better represent the data. Calibrations at BNL showed significant hysterisis in HERA Dipole Coils; it was noted that inner and outer coil are actually epoxied together and that no Teflon or other friction reducing material appears to be used in the assembly. Since it may be argued that hysterisis effects will decrease in time as coils creep, the formulas of hysteris (decreasing load stress/strain curves) are not combined with others but are presented for consideration.

It has been desired of late to monitor coil stresses after thermal losses have been incurred, at 4^0K. To do this presently a 4^0K collar calibration is contrived from the other three calibrations in the following manner:

$$\sigma_{\substack{\text{coil}\\ 4K,\\ \text{collar}}} = \left[\frac{E_{4K,Trans}}{E_{300K,Trans}} \times E_{\substack{300K\\ \text{collar}}} \right] \times |\mu\varepsilon| + \left[\left(\frac{N}{mm^2}\right)_{\substack{4K\\ Trans}} - \left(\frac{N}{mm^2}\right)_{\substack{300K\\ Trans}} + \left(\frac{N}{mm^2}\right)_{\substack{300K\\ collar}} \right]$$

6. CALIBRATION RESULTS

Table II is a grand summary of strain gages installed in the HERA prototype strain gage collar pack brought to DESY, which were calibrated as described herein.

The 300K transducer calibration on both inner coil and outer coil transducers, by virtue of the small variation in slope from gage to gage, prove the transducers to be good quality load cells at room temperature. Although the slope of the stress strain curves vary somewhat from calculated values (~ 15% for inner coil transducer, ~ 30% for outer coil transducers), this may be attributable to non uniform stress fields inherent, (but constant from transducer to transducer) in the design.

The increase in slope of the stress strain curves of transducer calibrations (+ 17% for inner coil transducers, + 8.6% for outer coil transducers is consistent with the notions that a) modulus of elasticity of aluminum increases from 300K to 4K and, b) gage factor of the gage increases from 300K to 4K.

The apparent stress offset from 300K to 4K is significant in magnitude (7 N/mm^2 avg) so that is cannot be claimed that the gage circuit is truly compensated for temperature over this range. However, since calibrations are done at 4K, this is not a problem for taking data at 4K.

The increase in apparent modulus from transducer calibration to collar pack calibration shows that here is the largest change and the most random variation. Therefore it is crucial to perform accurate calibrations in collar packs if any data is to have meaning.

A final note; in taking data at 4K, it would be far more accurate, and less work, if strain gage calibrations in collar packs could be performed at 4K. Such a fixture is currently being worked on to be used by BNL for SSC magnets. It is suggested that this method be used by DESY for HERA magnets if coil stress data at $4^{0}K$ is desired from magnets on a routine basis.

7. COLLAR ASSEMBLY DATA ANALYSIS

During collaring it is suggested that the load applied by the assembly press be done in steps. At each step coil stress data may be obtained through the strain gages, using the 300K collar calibrations. These measured forces may be verified at each step by comparing the total measured force of inner and outer coil to the applied force, as given by the press. This "Force Balance" is performed as follows:

$$\frac{\text{Measured Load}}{\text{Applied Load}} = \frac{\text{Inner Coil Stress} \times \text{Inner Coil Area (in Press)} + \text{Outer Coil} \times \text{Outer Coil Area (in Press)}}{\text{Hydraulic Pressure} \times \text{Cylinder Area} \times \text{No. of Cylinders}}$$

This force balance generally equals 100% ± 20% for all load levels.

8. COIL STRESS DATA DURING MAGNET TESTING

While at $4^{0}K$, either in magnet field or not, coil stress data may be taken using the 4K collar calibrations. This is done, using the V/E-20, by turning the channel selector to the proper channel only monentarily, then off again, to minimize self heating errors in the gages. This data to date has been less dependable than room temperature coil stress data, but even in cases where quantitative results are suspect, qualitative results have proven quite useful (i.e., although the magnitude of stress loss from zero amps to full field may seem peculiar, the current at which the gage unloads is clear, and is useful information).

SECTION (II) - 1M HERA DIPOLE MAGNET COIL STRESS MEASUREMENTS

1. CALIBRATION VERIFICATIONS

It was desired to repeat all the strain gage calibrations done at BNL while at DESY, to demonstrate procedure and also to instill faith that the data was accurate to the DESY people. The $4^{0}K$ calibrations require a sophisticated loading device inside a liquid helium dewar; since this was not available, only the calibrations in collar packs at $300^{0}K$ were to be repeated. To this end, the HERA strain gage calibration fixture built at BNL (P/N 25-723.01-5) was shipped in advance to DESY.

The press frame used at DESY for the calibrations was crude and undercapacity. For these reasons, the calibrations at DESY varied somewhat randomly from the original calibrations and were significantly more nonlinear. The average change in slope of the stress-strain curves of all six transducer calibrations was + 0.8% ± 15.8% when compared to the original calibrations. Therefore, the original BNL calibrations were used to interpret all data; however, agreement was good enough to demonstrate the methods and expected results. Refer to Appendix D for actual data sheets.

2. COLLAR ASSEMBLY DATA

The 1 meter long HERA dipole magnet was collared at BBC in Mannheim, W. Germany using the four central cylinders of their 9M collaring/curing press. Pressure was applied to the magnet in steps of 50 bar, which translate into roughly 560 Kn per meter. At each step, coil stresses were determined from the strain gage output, and measured load was compared to applied load having a force balance spread sheet (Appendix E). Also, average coil stress versus load was plotted (Fig. 2). Refer to Appendix F for all raw data concerning strain gages.

Inner coils measured 84.4 N/mm^2 (12.2 kpsi) under maximum press load and 46.3 N/mm^2 (6.7 kpsi) as collared, for a springback loss of 38.1 N/mm^2 (5.5 kpsi). Outer coils measured 106.4 N/mm^2 (15.4 kpsi) under maximum press load and 40.2 N/mm^2 (5.8 kpsi) as collared, for a springback loss of 66.2 N/mm^2 (9.6 kpsi). These values are achieved using thick (28.5 mm radially) aluminum collars with rods in the interior of the collar inserted axially, rather than the SSC design of 15 mm stainless steel collars with keys on the exterior of the collar inserted radially (see Fig. 1).

3. MAGNET TEST DATA

Upon cooldown from 300K to 4K, the inner coils measured a slight increase in stress of 4.1 N/mm^2 (600 psi) while the outer coils measured a slight decrease in stress of 3.4 N/mm^2 (500 psi). S. Wolff explained that he had expected an increase in stress upon cooldown; however, it seems that at least the aluminum collars prevent the cooldown losses experienced with SSC stainless steel collars.

The magnet was energized twice to quench while taking strain gage data. Data was recorded to 500 amp steps, with current being held constant while taking data. Quenches occurred at 6800 A and 6750 A. Inner coils measured decreases in prestress from 0 A to 6500 A (last data point before quench) of 46.0 N/mm^2 (6.6 kpsi) and 44.0 N/mm^2 (6.4 kpsi) respectively, for the two quenches. This compares to Wolff's calculated prestress loss on inner coils from 0 A to 6500 A of 46 N/mm^2! In addition, the measured values of prestress on one inner coil just prior to quench (at 6500 A) were 0.3 N/mm^2 and 0.9 N/mm^2, respectively. Outer coils measured somewhat random slight increases and decreases in prestress with increasing current, very similar to results on SSC outer coils.

Probably the outer coils do not show consistent losses of prestress with increasing magnetic field because of the increasing radial load impacted on the outer coils by the inner coils with field tending to restrict motion of the outer coils. Plots of inner and outer coil average stresses vs. current may be seen on Fig. 3, and plots of individual strain gage channels of inner and outer coils stresses vs. current may be seen on Figs. 4 and 5, respectively.

cc: P. Hinz (DESY)
S. Wolff (DESY)

Table 1

Strain Gage Coding Description

"WK-13-062TT-350"

[W]: Gage Backing (insulation) - full encapsulation in glass-fiber reinforced epoxy-phenolic resin; high endurance lead wires.

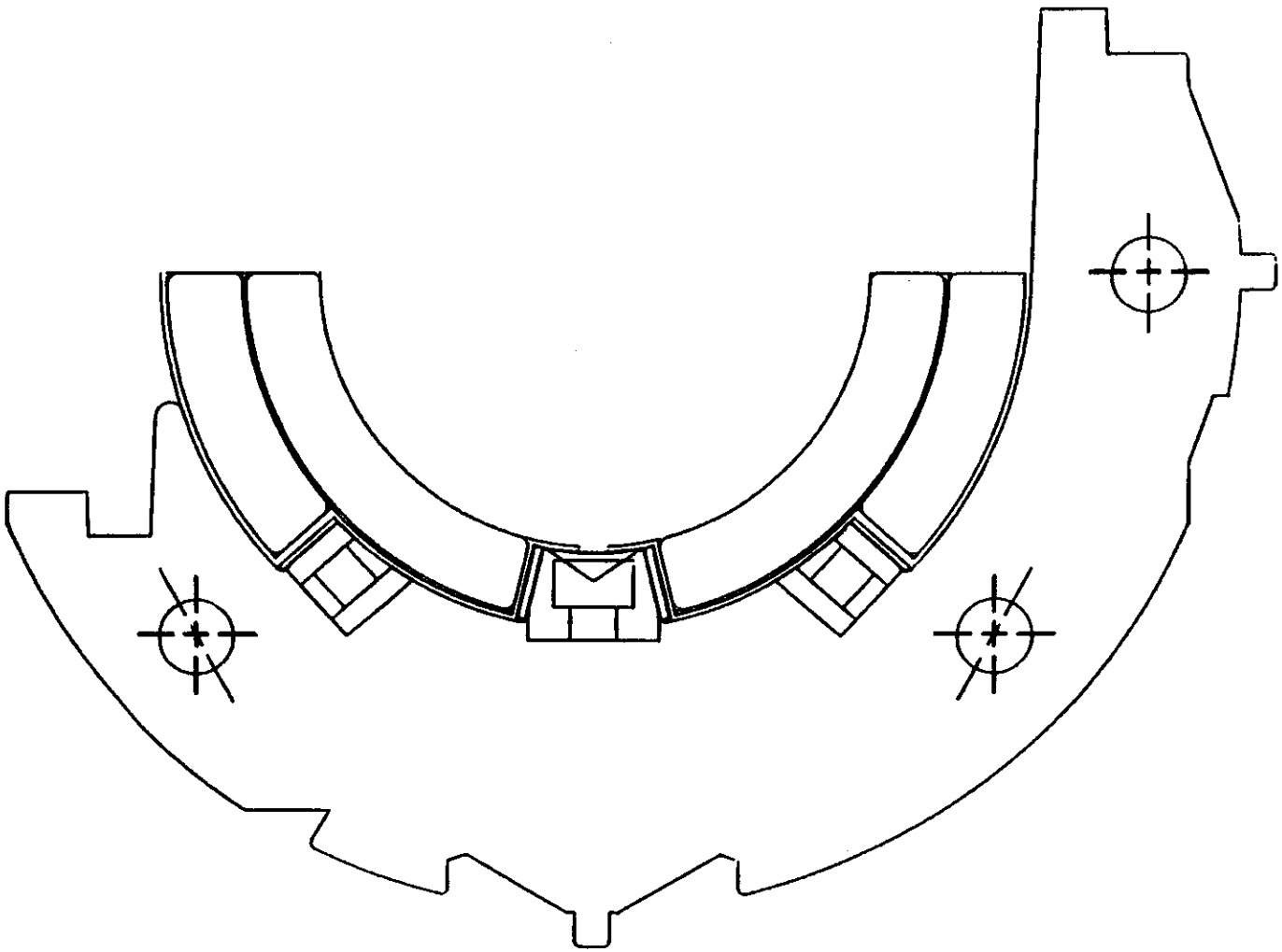
[K]: Foil Alloy - a nickel-chromium alloy (similar to KARMA) used for high performance self-temperature-compensated gages.

[13]: Self-Temperature-Compensation Number - the approximate thermal expansion coefficient in PPM/^{0}F to which the gage is matched (Al ≈ 13 PPM/^{0}F).

[062]: Active Gage Length (in thousands of an inch).

[TT]: Grip and Tab Geometry - general purpose 90^{0} "tee" rosette (grids at right angles to each other). Sections are electrically independent.

[350]: Resistance - of each grid (ohms).



HEPA [illegible]

FIGURE 1

HERA DIPOLE MAGNET STRAIN GAGE TRANSDUCER CALIBRATION SUMMARY

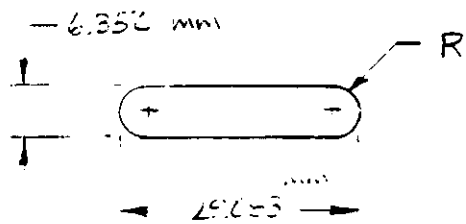
TRANSDUCER ID	300°K TRANSDUCER	4.7K TRANSDUCER	300K IN COLLARS	4.7K "IN COLLARS"	ΔE_{TRANS} $\left[\frac{E_{4K,T}}{E_{300K,T}}-1\right]\times 100$ (%)	APPARENT STRESS OFFSET $\left[N/mm^2_{300K,T} - N/mm^2_{4K,T}\right]$ (N/mm^2)	$\Delta E_{APPARENT}$ $\left[\frac{E_{300K,C}}{E_{300K,T}}-1\right]\times 100$ (%)
INNER COILS CH 1	$\sigma_1 = .046\lvert\mu\epsilon\rvert - .71$	$\sigma_1 = .054\lvert\mu\epsilon\rvert - 8.5$	$\sigma_1\uparrow = .064\lvert\mu\epsilon\rvert - .34$ ($\sigma_1\downarrow = .061\lvert\mu\epsilon\rvert - 4.0$)	$\sigma_1 = .075\lvert\mu\epsilon\rvert - 8.13$	+17.4	+7.8	+39.1
CH 4	$\sigma_4 = .045\lvert\mu\epsilon\rvert - .75$	$\sigma_4 = .053\lvert\mu\epsilon\rvert - 5.9$	$\sigma_4\uparrow = .058\lvert\mu\epsilon\rvert - 1.3$ ($\sigma_4\downarrow = .056\lvert\mu\epsilon\rvert - 6.4$)	$\sigma_4 = .068\lvert\mu\epsilon\rvert - 6.45$	+17.7	+5.2	+28.9
AVG (THEORY)	$\sigma_I = .0455\lvert\mu\epsilon\rvert - .73$ ($\sigma_{IC} = .039\lvert\mu\epsilon\rvert$)				$+17.0^{\pm 0.9}$	$+6.5^{\pm 1.8}$	$+34.0^{\pm 7.2}$
OUTER COILS CH 2	$\sigma_2 = .056\lvert\mu\epsilon\rvert + 3.0$	$\sigma_2 = .060\lvert\mu\epsilon\rvert - 5.1$	$\sigma_2\uparrow = .055\lvert\mu\epsilon\rvert - 1.9$ ($\sigma_2\downarrow = .053\lvert\mu\epsilon\rvert - 11.1$)	$\sigma_2 = .059\lvert\mu\epsilon\rvert - 10.0$	+7.3	+8.1	-1.8
CH 3	$\sigma_3 = .057\lvert\mu\epsilon\rvert + 2.1$	$\sigma_3 = .063\lvert\mu\epsilon\rvert - 3.1$	$\sigma_3\uparrow = .067\lvert\mu\epsilon\rvert + .34$ ($\sigma_3\downarrow = .064\lvert\mu\epsilon\rvert - 10.4$)	$\sigma_3 = .074\lvert\mu\epsilon\rvert - 4.86$	+11.0	+5.2	+17.5
CH 5	$\sigma_5 = .056\lvert\mu\epsilon\rvert + 3.0$	$\sigma_5 = .061\lvert\mu\epsilon\rvert - 4.5$	$\sigma_5\uparrow = .077\lvert\mu\epsilon\rvert + 6.3$ ($\sigma_5\downarrow = .073\lvert\mu\epsilon\rvert - 4.7$)	$\sigma_5 = .084\lvert\mu\epsilon\rvert - 1.2$	+7.8	+7.5	+37.5
CH 6	$\sigma_6 = .056\lvert\mu\epsilon\rvert + 6.0$	$\sigma_6 = .060\lvert\mu\epsilon\rvert - 2.3$	$\sigma_6\uparrow = .060\lvert\mu\epsilon\rvert - 4.4$ ($\sigma_6\downarrow = .061\lvert\mu\epsilon\rvert - 20.1$)	$\sigma_6 = .064\lvert\mu\epsilon\rvert - 12.7$	+8.5	+8.3	+7.1
AVG (THEORY)	$\sigma_O = .0562\lvert\mu\epsilon\rvert + 3.5$ ($\sigma_{OC} = .036\lvert\mu\epsilon\rvert$)				$+8.65^{\pm 1.6}$	$+7.3^{\pm 1.4}$	$+15.1^{\pm 16.9}$

NOTES 1. All values for coil stress found by these formulas are in N/mm^2.

TABLE II

APPENDIX A

HERA Inner Coil Transducer



$$A_{\substack{\text{cross-}\\\text{section}}} = (29.083-6.350) \times 6.350 + \pi\,(6.350)^2/4$$
$$= 176.024\ \text{mm}^2\ (.2728\ \text{in}^2)$$

$$E_{7075-T6} = 10.4 \times 10^6\ \text{psi} = 7.17 \times 10^4\ \text{N/mm}^2$$

$$\text{Uniaxial Strain} = \varepsilon_a = \frac{\sigma_A}{E} = \frac{P}{(176.024)(7.17\text{x}10^4)}$$

$$= \varepsilon_a = (7.923\text{x}10^{-8})P$$

$$\text{Microstrain} = \mu\varepsilon_a = (7.923\text{x}10^{-2})P$$

$$A_{\substack{\text{inner coil}\\\text{under load}}} = 10.16 \times 31.75 = 322.58\ \text{mm}^2\ (0.500\ \text{in}^2)$$

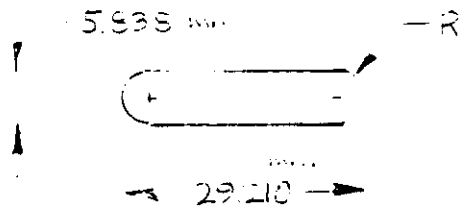
$$\therefore \sigma_{\substack{\text{inner}\\\text{coil}}} = \frac{P}{(322.58)}$$

$$\Rightarrow \mu\varepsilon_a = (7.923\text{x}10^{-2})(322.58).\sigma_{IC}$$

$$= 25.559\ \sigma_{IC}$$

$$\boxed{\begin{aligned} \therefore \sigma_{\substack{IC\\\text{Theory}}} &= 0.039\ \mu\varepsilon\ (\text{N/mm}^2) \\ &= 5.7\mu\varepsilon\ (\text{psi}) \end{aligned}}$$

HERA Outer Coil Transducer



$$A_{\text{cross-section}} = (29.21-5.838) \times 5.838 + \pi\,(5.838)^2/4$$
$$= 163.214\ \text{mm}^2\ (.2530\ \text{in}^2)$$

$$E_{7075-T6} = 10.4 \times 10^6\ \text{psi} = 7.17 \times 10^4\ \text{N/mm}^2$$

$$\text{Uniaxial Strain} = \varepsilon_a = \frac{\sigma_A}{E} = \frac{P}{(163.214)(7.17\text{x}10^4)}$$

$$= \varepsilon_a = (8.545\text{x}10^{-8}).P$$

$$\text{Microstrain} = \mu\varepsilon_a = (8.545\text{x}10^{-2}).P$$

$$A_{\text{outer coil under load}} = 10.3\ \text{mm} \times 31.75\ \text{mm} = 327.05\ \text{mm}^2\ (0.507\ \text{in}^2)$$

$$\therefore \sigma_{\text{outer coil}} = \frac{P}{(327.05)}$$

$$\Rightarrow \mu\varepsilon_a = (8.545\text{x}10^{-2})(327.05).\sigma_{OC}$$

$$= 27.947\ \sigma_{OC}$$

$$\boxed{\begin{aligned} \therefore \sigma_{OC\ \text{Theory}} &= 0.036\ \mu\varepsilon\ (\text{N/mm}^2) \\ &= 5.2\ \mu\varepsilon\ (\text{psi}) \end{aligned}}$$

HERA Magnet Transducer Calibration - Individual in Press

GAGE: WK-13-062TT-350, G.F.: 1.95, IC: 339

INNER 7/7/87 R.M.J.

Coil Stress	PSI	KG	No. 1 295°K	No. 1 4.7°K		No. 4 295°K	No. 4 4.7°K
N/mm²		0	0	-137		0	-104
15.2	2206	500	-354	-48[illegible]		-359	-2[illegible]
30.4	4412	1000	-679	-733		-699	-697
45.6	6618	1500	-1000	-1019		-1028	-978
60.8	8824	2000	-1325	-1301		-1360	-1266
76.0	11030	2500	-1657	-1576		-1699	-1[illegible]
91.2	13236	3000	-1939	-1851		-2040	[illegible]
106.4	15442	3500	-2320	-2110		-2370	-2100
		0	0	-137		0	-104
		500	-360	-437		-365	-388
		1000	-683	-731		-706	-688
		1500	-1005	-1021		-1035	-979
		2000	-1330	-1298		-1367	-1264
		2500	-1650	-1575		-1701	-1547
		3000	-1980	1850		-2040	-1827
		3500	-2310	-2110		-2370	-2100
		0	0	-138		0	-104

CH 1

$\sigma_{1,295K} = 6.72\,|\mu\epsilon| - 103$ PSI
$= .046\,|\mu\epsilon| - .71$ N/mm²

CORR = .99994

$\sigma_{1,4.7K} = 7.82\,|\mu\epsilon| - 1230$ PSI
$= .054\,|\mu\epsilon| - 8.5$ N/mm²

CORR = .9998

$\Delta E = \frac{E_4 - E_{295}}{E_{295}} \times 100\ (\%)$

$\Delta E_1 = +16.4\%$

Corr .9999

CH 4

$\sigma_{4,295K} = .55\,|\mu\epsilon| - 1[illegible]$
$= .045\,|\mu\epsilon| - .75$

CORR = .99994

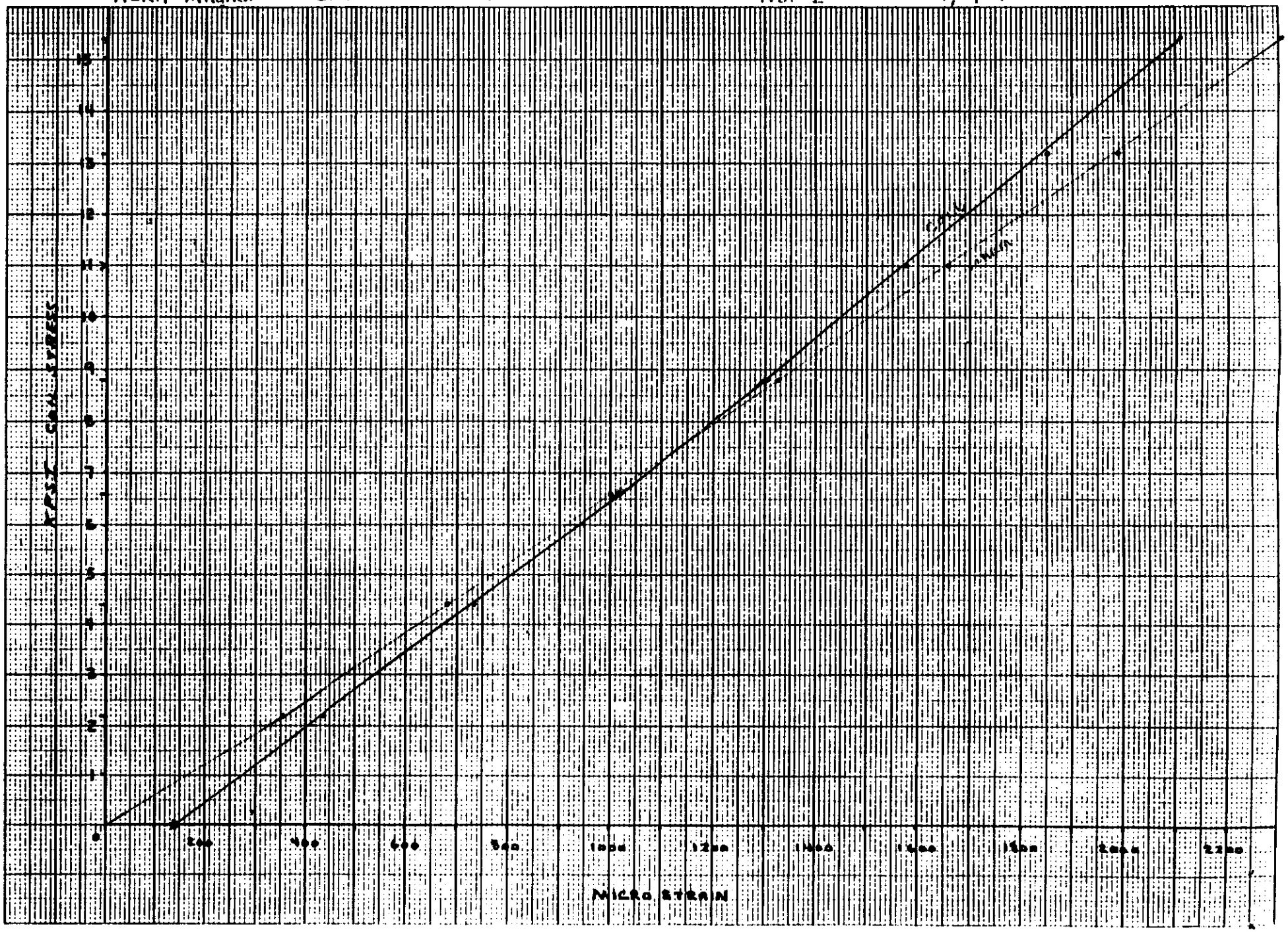
$\sigma_{4,4.7K} = 7.71\,|\mu\epsilon| - 359$
$= .053\,|\mu\epsilon| - 5.91$

CORR = [illegible]

$\Delta E_4 = +17.7\%$

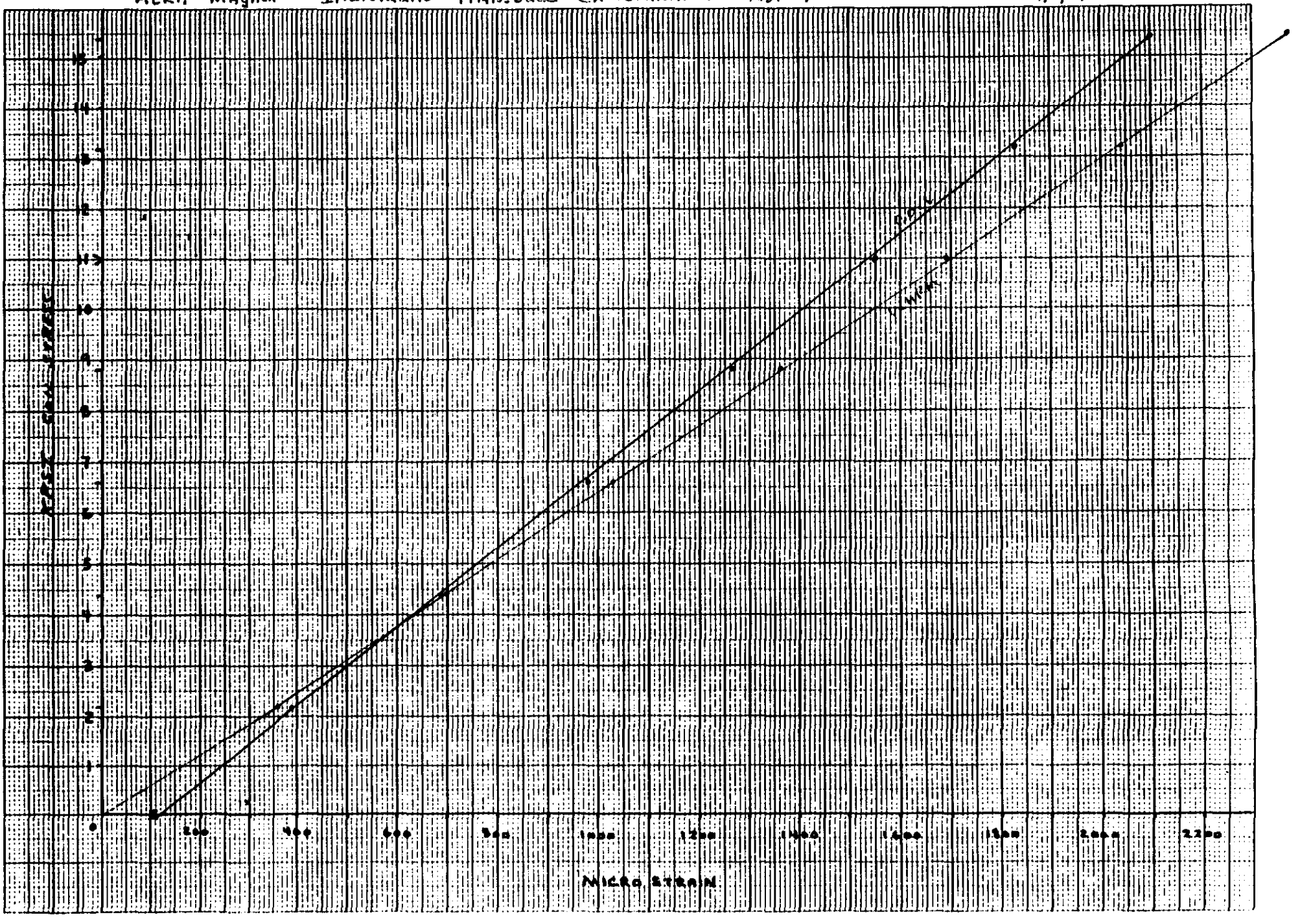
SQUARE 10 X 10 TO THE CENTIMETER AS-8014-60

HERA Magnet - Individual Transducer Calibration : No. 1 7/1/77



GRAPHPAPER GRAPHIC CONTROLS CORPORATION Buffalo, New York
SQUARE 10 X 10 TO THE CENTIMETER AS-8014-GB

HERA Magnet - Individual Transducer Calibration : No. 4 7/7/71



HERA MAGNET TRANSDUCER CALIBRATION - Inner coil in Collar Pack

Gage factor : 1.95 , IC 339

7/14/87 RMJ

T = 295°K

N/mm²	LOAD: N	PSI	LBS	No. 1	No. 4
			0	0	0
14.6	44.5	2114	10K	230 με*	273 με*
29.2	89.0	4227	20	462	537
43.8	133.4	6341	30	692	791
58.4	177.9	8455	40	923	1043
72.9	222.4	10569	50	1150	1287
87.5	266.9	12682	60	1377	1531
102.1	311.4	14796	70	1601	1768
87.5		12682	60	1462	1624
72.9		10569	50	1281	1433
58.4		8455	40	1058	1193
43.8		6341	30	810	927
29.2		4227	20	548	640
14.6		2114	10	277	340
			0	0	0
2nd cycle			10	236	276
			20	468	541
			30	698	795
			40	927	1044
			50	1151	1289
			60	1376	1531
			70	1595	1766
			60	1460	1622
			50	1279	1430
			40	1055	1192
			30	810	923
			20	549	640
			10	280	338
			0	0	0

* : ALL VALUES NEGATIVE

CH 1

$\sigma_1 \uparrow$ = [illegible] PSI
$\sigma_1 \uparrow$ = .064 |με| - 34 N/mm²
CORR = [illegible]

$\sigma_1 \downarrow$ = 8.81 |με| - 582 PSI
$\sigma_1 \downarrow$ = .061 |με| - 4.0 N/mm²
CORR = .998

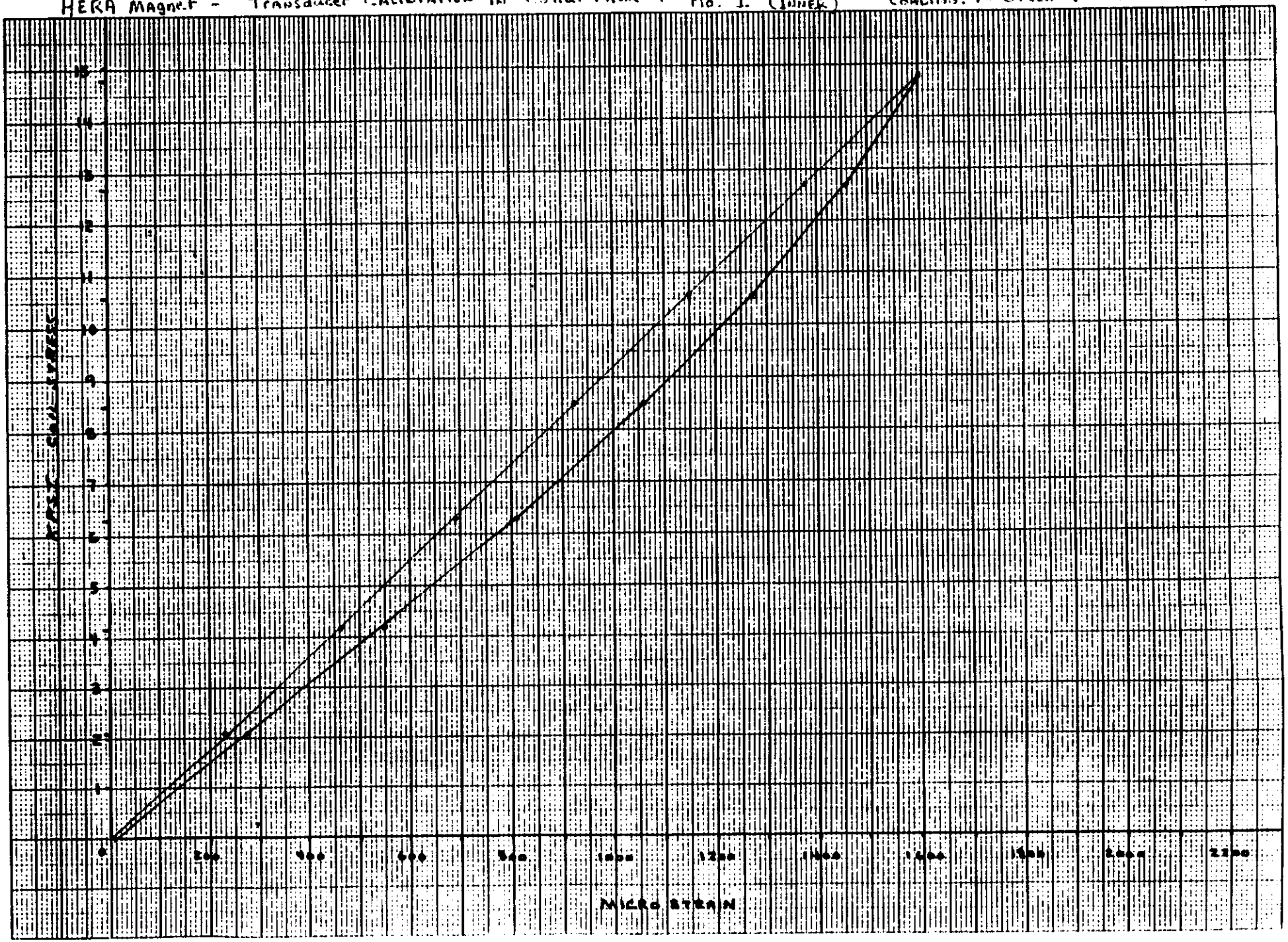
CH 4

$\sigma_4 \uparrow$ = 8.39 |με| - 190 PSI
$\sigma_4 \uparrow$ = .058 |με| - 1.3 N/mm²
CORR = .9997

$\sigma_4 \downarrow$ = 8.12 |με| - 923 PSI
$\sigma_4 \downarrow$ = .056 |με| - 6.4 N/mm²
CORR = .997

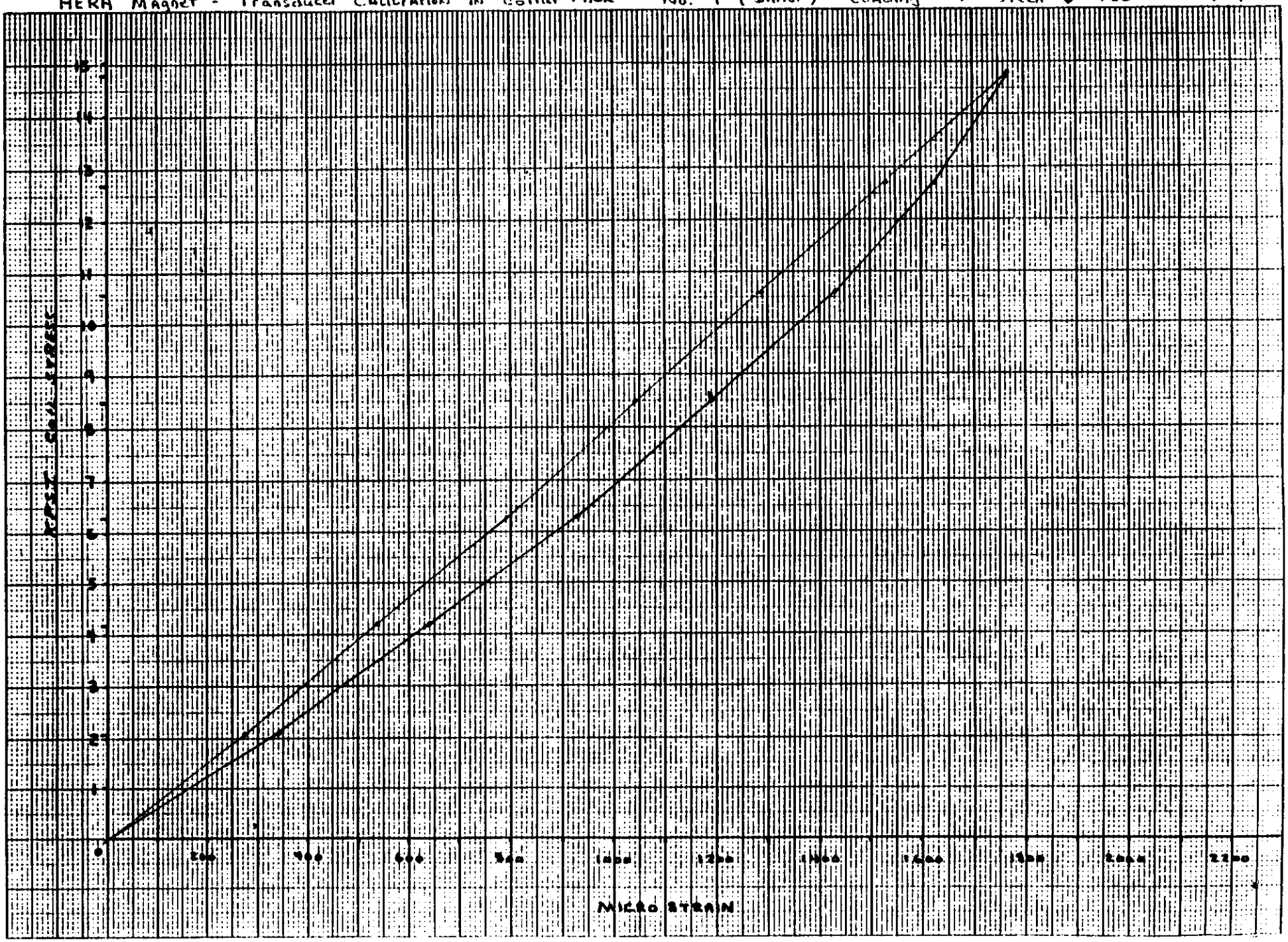
SQUARE 10 X 10 TO THE CENTIMETER AS-8014-60

HERA Magnet - Transducer Calibration in Collar Pack : No. 1. (Inner) Loading: ↑ = Green ↓ = red 7/14/87



SQUARE 10 X 10 TO THE CENTIMETER AS 8014-60

HERA Magnet - Transducer Calibration in collar Pack : No. 4 (Inner) Loading : ↑ = Green ↓ = red 7/14/81



HERA Magnet Transducer Calibration - Individual in Press

Gauge: WK-13-062TM-350, G.F. 1.95, LC: 339

7/7/97 R.M.J.

OUTER

Micro strain:

Load:

N/mm²	Coil stress PSI	Press KG	No. 2 295°K	No. 2 4.7°K	No. 3 295°K	No. 3 4.7°K	No. 5 295°K	No. 5 4.7°K	No. 6 295°K	No. 6 4.7°K
		0	0	-138	0	-127	0	-145	* (0)	-132
15.0	2172	500	-192	-332	-215	-295	-194	-320	-173	-274
30.0	4343	1000	-458	-554	-469	-470	-452	-524	-424	-473
45.0	6515	1500	-732	-806	-735	-711	-722	-774	-695	-733
60.0	8686	2000	-1007	-1072	-1004	-966	-995	-1037	-963	-1002
75.0	10858	2500	-1285	-1336	-1276	-1227	-1268	-1301	-1232	-1269
90.0	13029	3000	-1566	-1599	-1546	-1488	-1542	-1564	-1502	-1536
105.0	15201	3500	-1845	-1858	-1819	-1744	-1821	-1824	-1778	-1803
		0	0	-138	0	-126	0	-146	* (0)	-132
		500	-193	-331	-216	-295	-191	-315	-173	-273
		1000	-460	-551	-468	-474	-452	-516	-425	-478
		1500	-724	-806	-737	-715	-721	-767	-693	-739
		2000	-1009	-1069	-1006	-971	-992	-1034	-961	-1002
		2500	-1284	-1333	-1275	-1228	-1265	-1301	-1230	-1270
		3000	-1567	-1597	-1548	-1489	-1543	-1561	-1504	-1536
		3500	-1843	-1858	-1820	-1742	-1818	-1818	-1720	-1800
		0	0	-138	0	-126	0	-145	0	-132

CH2

$\sigma_{2,295K} = 8.08\,\mu\epsilon + 440$ PSI
$= .056\,\mu\epsilon + 3.0$ N/mm²
CORR = .9992

$\sigma_{2,4.7K} = 8.67\,\mu\epsilon - 737$ PSI
$= .060\,\mu\epsilon - 5.1$ N/mm²
CORR = .9989

$\Delta E_2 = +7.3\%$

CH3

$\sigma_{3,295K} = 8.25\,\mu\epsilon + 310$ PSI
$= .0571\,\mu\epsilon + 2.1$ N/mm²
CORR = .9995

$\sigma_{3,4.7K} = 9.16\,\mu\epsilon - 450$ PSI
$= .063\,\mu\epsilon - 3.1$ N/mm²
CORR = .997

$\Delta E_3 = +11.0\%$

CH5

$\sigma_{5,295K} = 8.20\,\mu\epsilon + 426$ PSI
$= .056\,\mu\epsilon + 3.0$ N/mm²
CORR = .9992

$\sigma_{5,4.7K} = 8.84\,\mu\epsilon - 657$ PSI
$= .061\,\mu\epsilon - 4.5$ N/mm²
CORR = .9990

$\Delta E_5 = +7.8\%$

CH6

*(2000 lbs. 1.6)

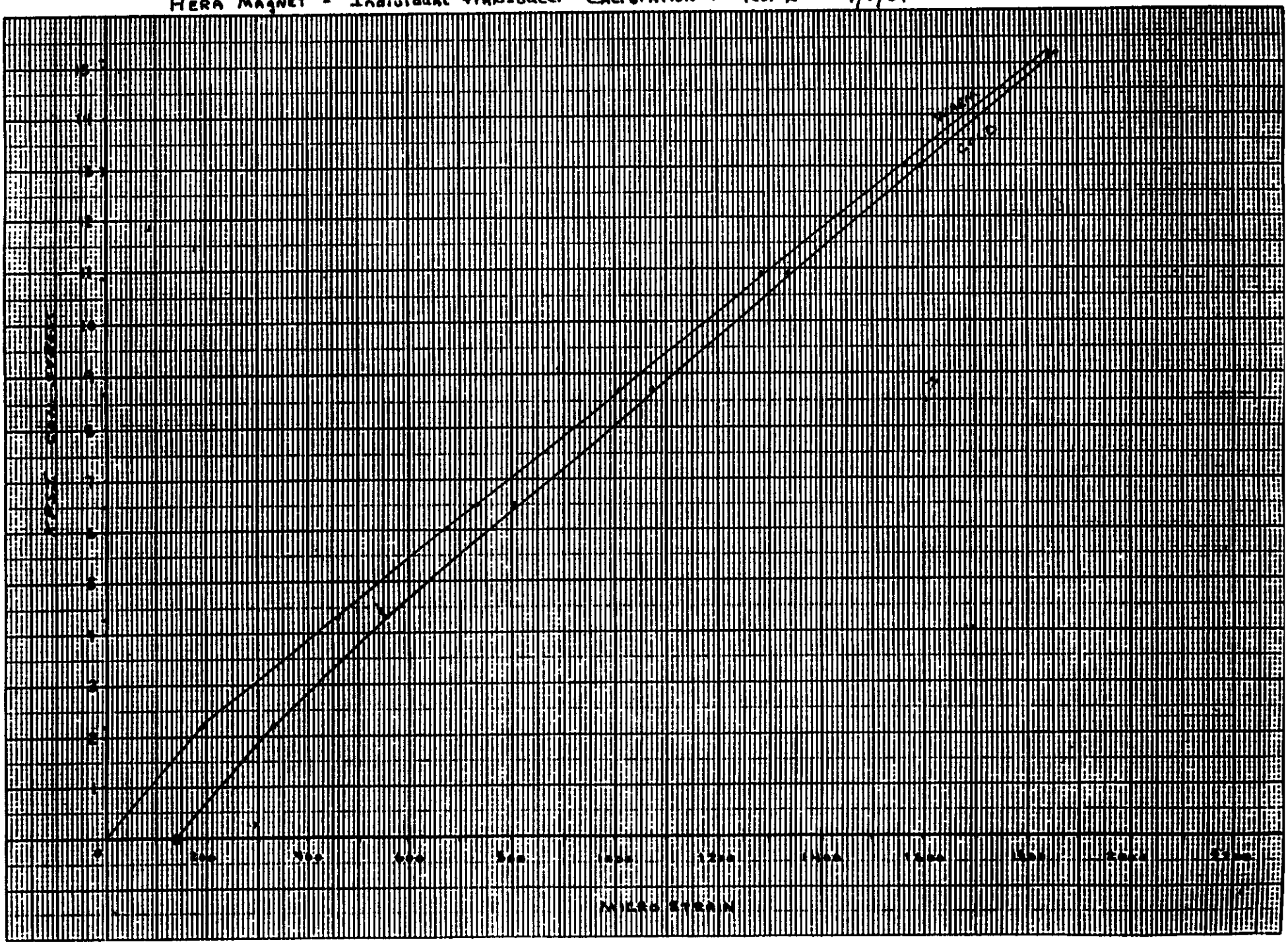
$\sigma_{6,295K} = 8.07\,\mu\epsilon + 865$ PSI
$= .056\,\mu\epsilon + 6.0$ N/mm²
CORR = .99993

$\sigma_{6,4.7K} = 8.78\,\mu\epsilon - 331$ PSI
$= .060\,\mu\epsilon - 2.3$ N/mm²
CORR = .9969

$\Delta E_6 = +8.5\%$

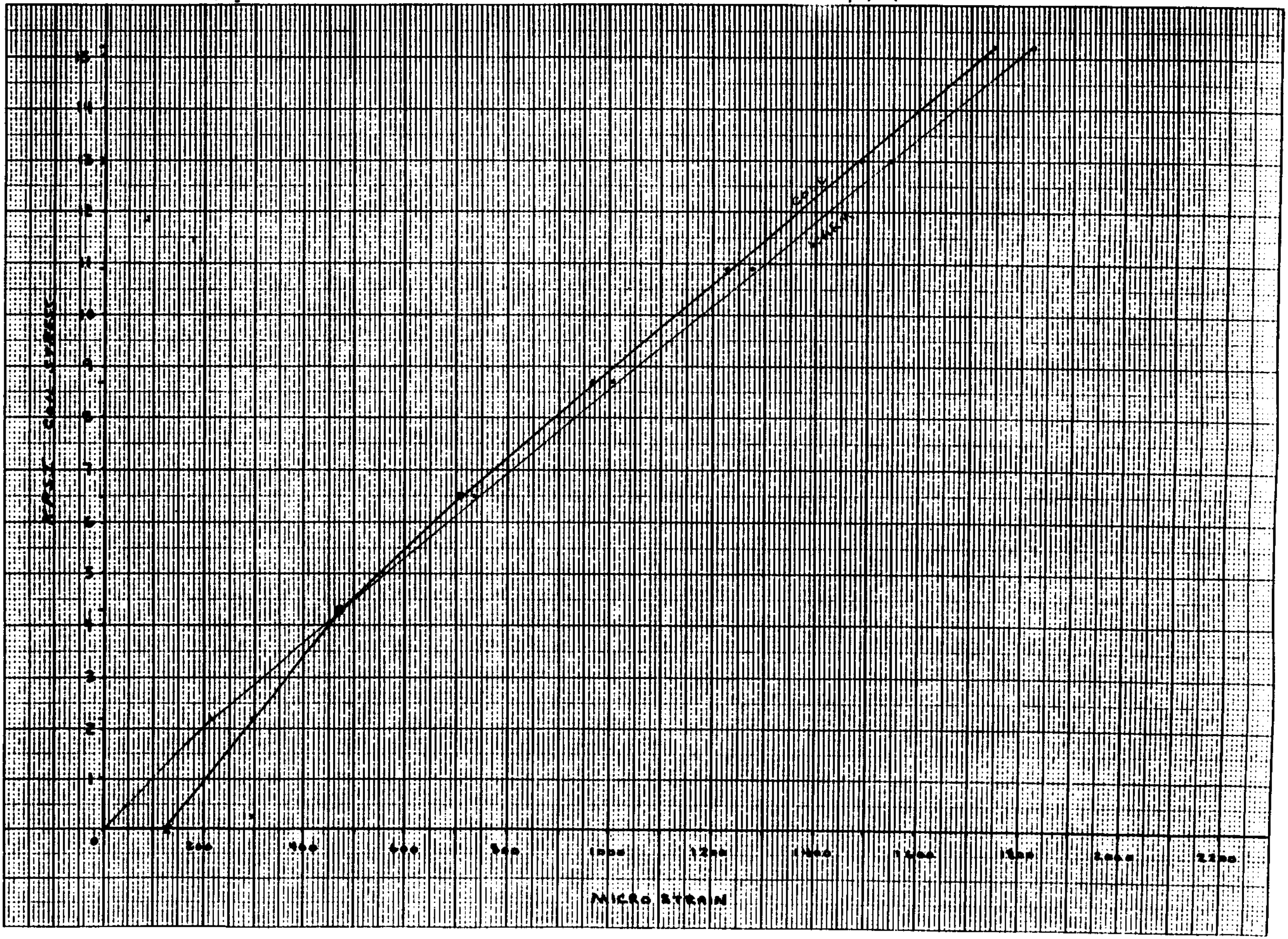
SQUARE 10 X 10 TO THE CENTIMETER AS-8014 -60

HERA MAGNET - Individual transducer CALIBRATION : No. 2 7/7/87



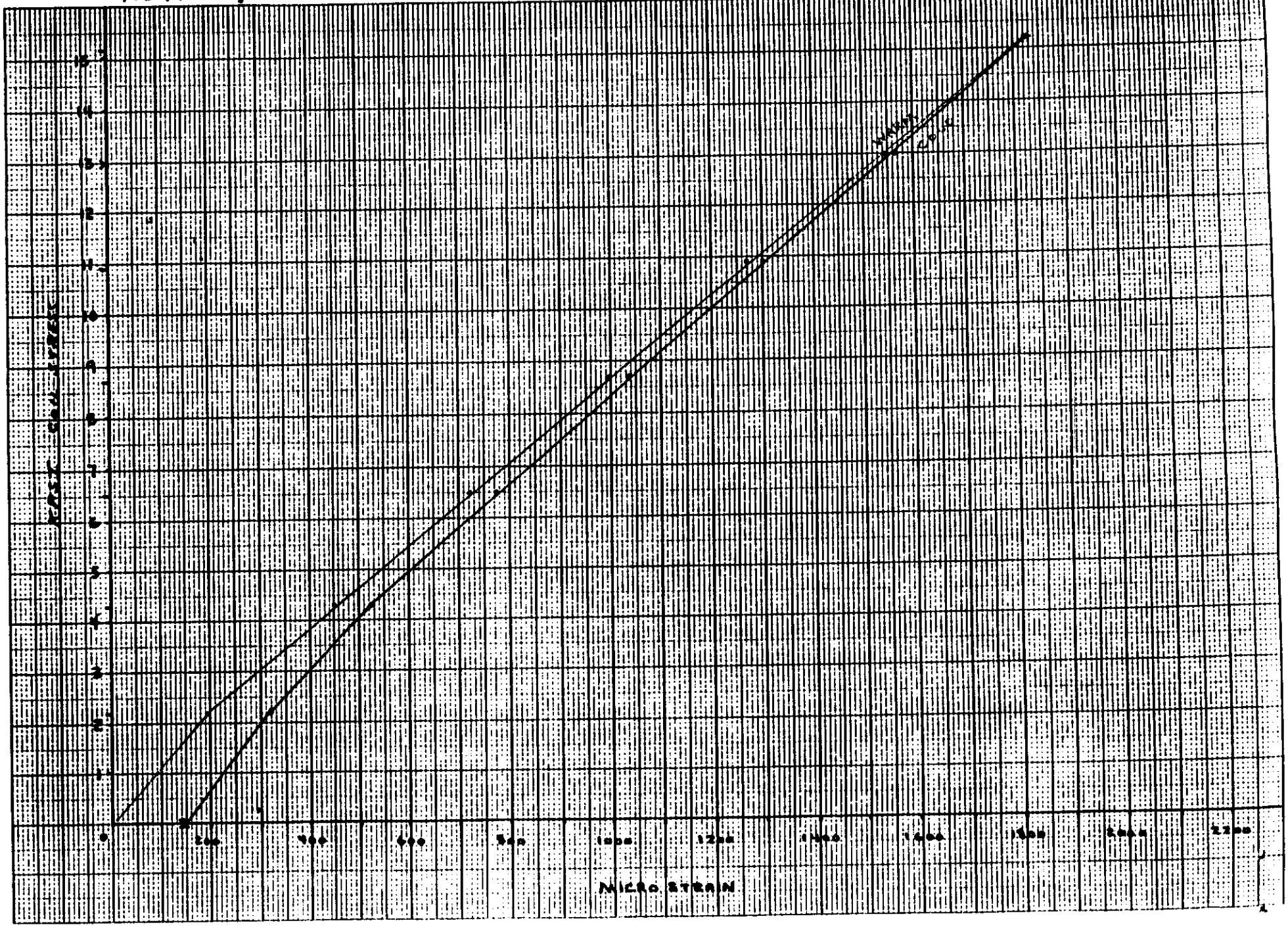
SQUARE 10 X 10 TO THE CENTIMETER AS-8014-60

HERA Magnet - Individual transducer Calibration : No. 3 7/7/87



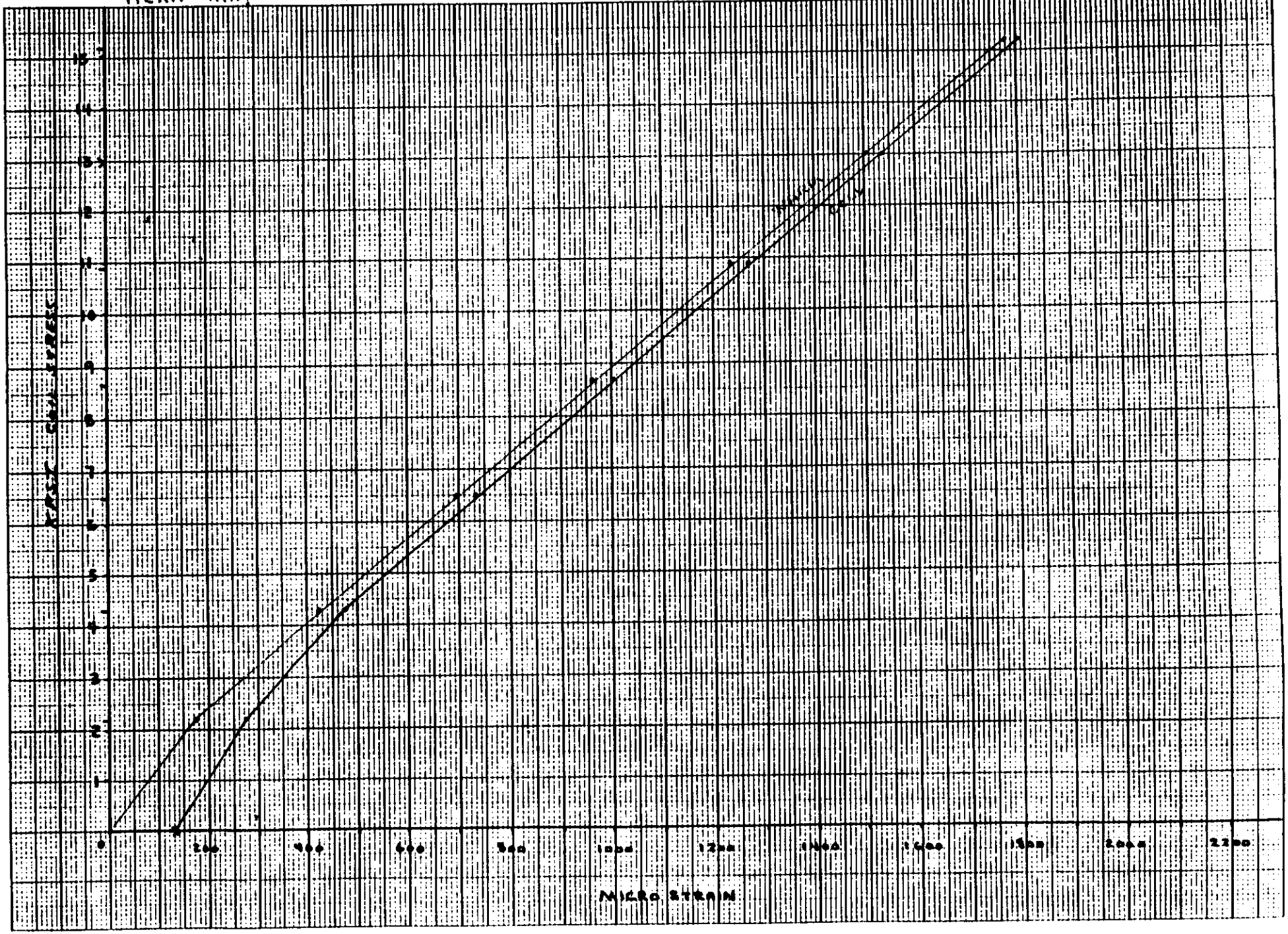
SQUARE 10 X 10 TO THE CENTIMETER AS-0014-60

HERA MAGNET - Individual Transducer Calibration: No. 5 7/7/87



SQUARE 10 X 10 TO THE CENTIMETER AS-8014 GO

HERA Magnet - Individual Transducer Calibration : No. 6 7/1/87



HERA MAGNET TRANSDUCER CALIBRATION - OUTER COIL IN COLLAR

Gage factor : 1.95, IC 339

7·14·87 R.M.J.

T = 295°K

LOAD				MICRO STRAIN						
N/mm²	kN	PSI	LBS	No. 2		No. 3		No. 5		No. 6
			0	0		0		0		
14.4	44.5	2087	10K	289		220		77		
28.8	89.0	4173	20	581		417		253		
43.2	133.4	6260	30	851		619		433		
57.6	177.9	8346	40	1110		826		614		
72.1	222.4	10433	50	1360		1057		810		
86.5	266.9	12519	60	1602		1286		1027		
100.9	311.4	14606	70	1849		1528		1261		
		12519	60	1735		1434		1178		
		10433	50	1585		1318		1063		
		8346	40	1349		1121		879		
		6260	30	1080		898		675		
		4173	20	778		629		458		
		2087	10	412		345		216		
			0	0		0		0		
			10	295		232		93		
			20	585		432		279		
			30	853		639		458		
			40	1112		855		643		
			50	1360		1071		821		
			60	1600		1290		1048		
			70	1842		1519		1276		
			60	1730		1428		1194		
			50	1583		1313		1079		
			40	1346		1113		872		
			30	1081		872		686		
			20	778		620		480		
			10	409		336		227		
			0	0		0		0		

$\sigma_6\uparrow = 8.68|\mu\epsilon| - 638$ PSI

$= .060|\mu\epsilon| - 4.4$ N/mm²

CORR = .9977

$\sigma_6\downarrow = 8.90|\mu\epsilon| - 2923$ PSI

$= .061|\mu\epsilon| - 20.1$ N/mm²

CORR = .991

$\sigma_2\uparrow = 7.93|\mu\epsilon| - 279$ PSI

$= .055|\mu\epsilon| - 1.9$ N/mm²

CORR = .9993

$\sigma_2\downarrow = 7.71|\mu\epsilon| - 1610$ PSI

$= .053|\mu\epsilon| - 11.1$ N/mm²

CORR = .991

$\sigma_3\uparrow = 9.67|\mu\epsilon| + 50$ PSI

$= .067|\mu\epsilon| + .34$ N/mm²

CORR = .9997

$\sigma_3\downarrow = 9.25|\mu\epsilon| - 1506$ PSI

$= .064|\mu\epsilon| - 10.4$ N/mm²

CORR = .991

$\sigma_5\uparrow = 11.2|\mu\epsilon| + 919$ PSI

$= .077|\mu\epsilon| + 6.3$ N/mm²

CORR = .9957

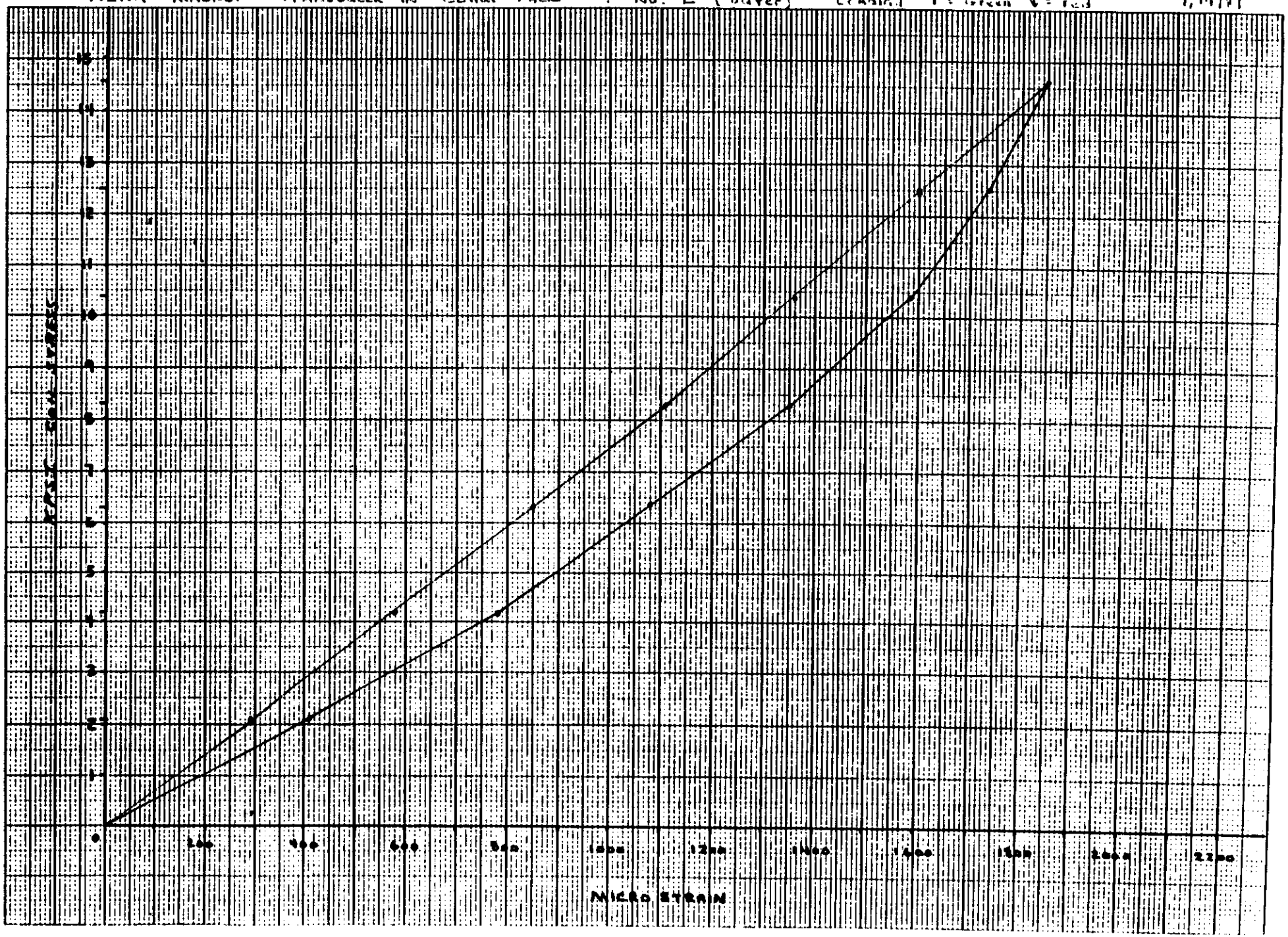
$\sigma_5\downarrow = 10.6|\mu\epsilon| - 677$ PSI

$= .073|\mu\epsilon| - 4.7$ N/mm²

CORR = .994

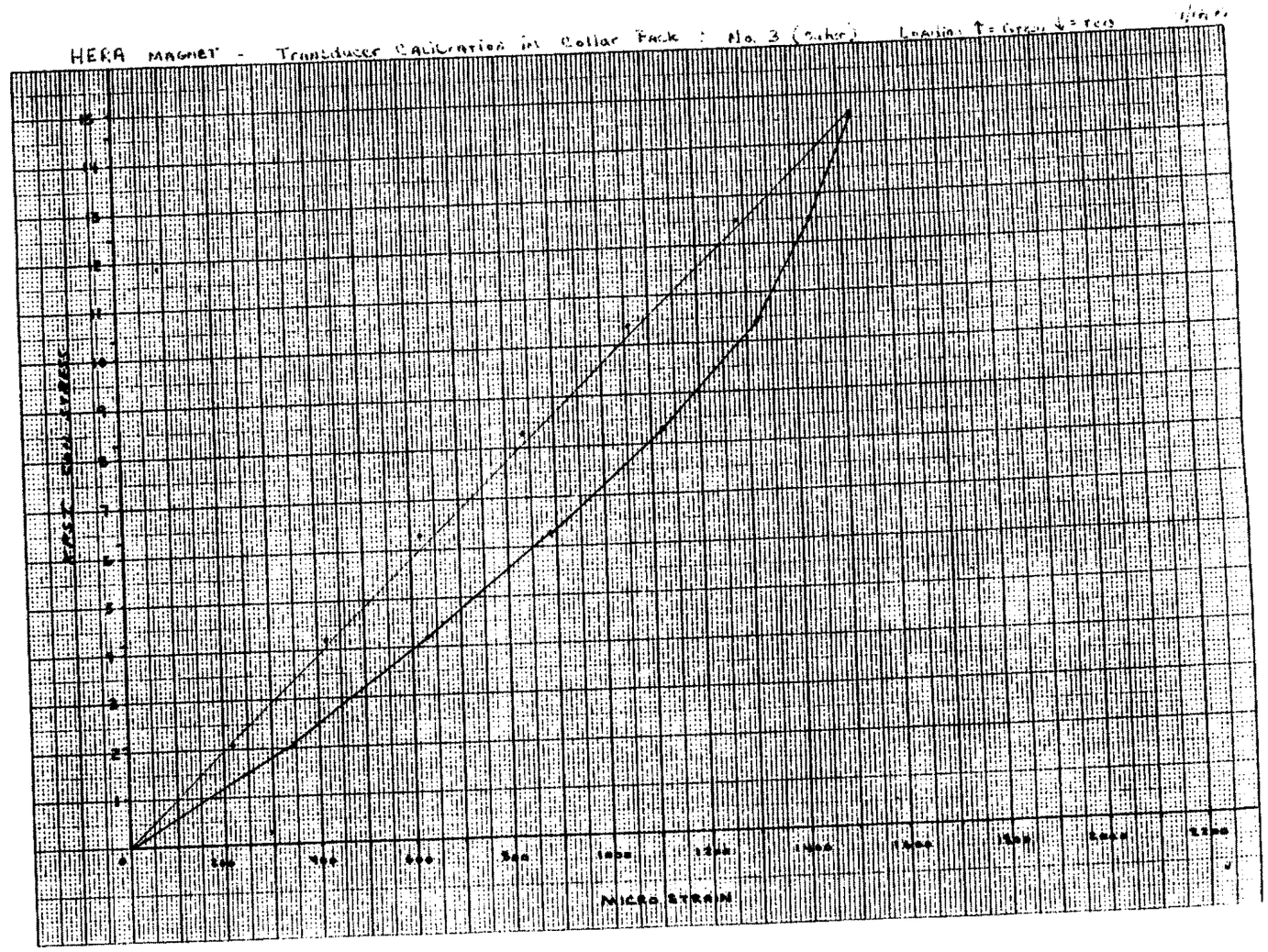
SQUARE 10 X 10 TO THE CENTIMETER AS-8014-60

HERA MAGNET - TRANSDUCER IN COLLAR PACK : No. 2 (Outer) Loading ↑ = Green ↓ = Red 7/14/71



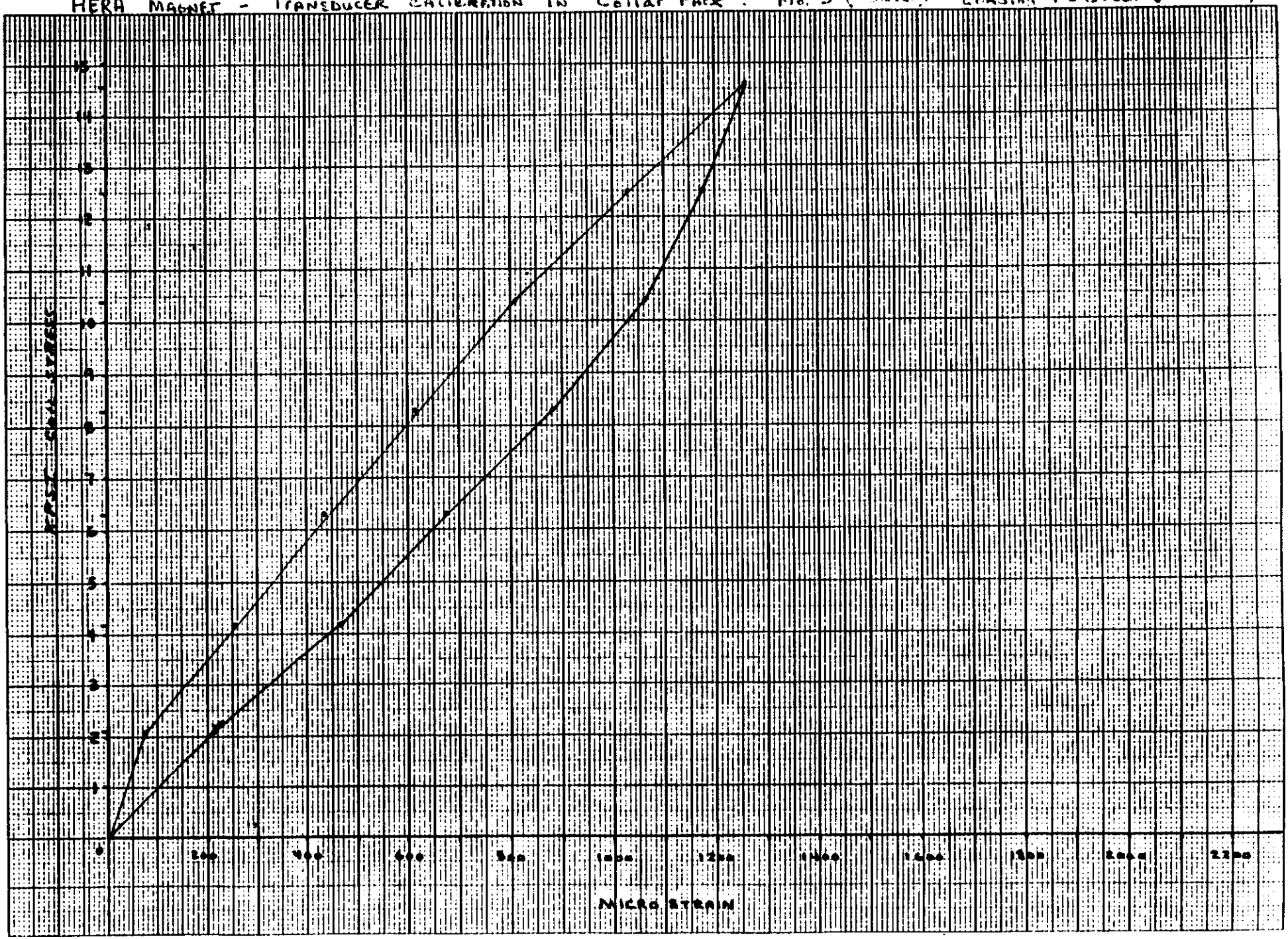
SQUARE 10 X 10 TO THE CENTIMETER AS-8014 SR

HERA MAGNET - Transducer CALIBration in Collar Pack : No. 3 (outer) Loading: ↑ = green, ↓ = red



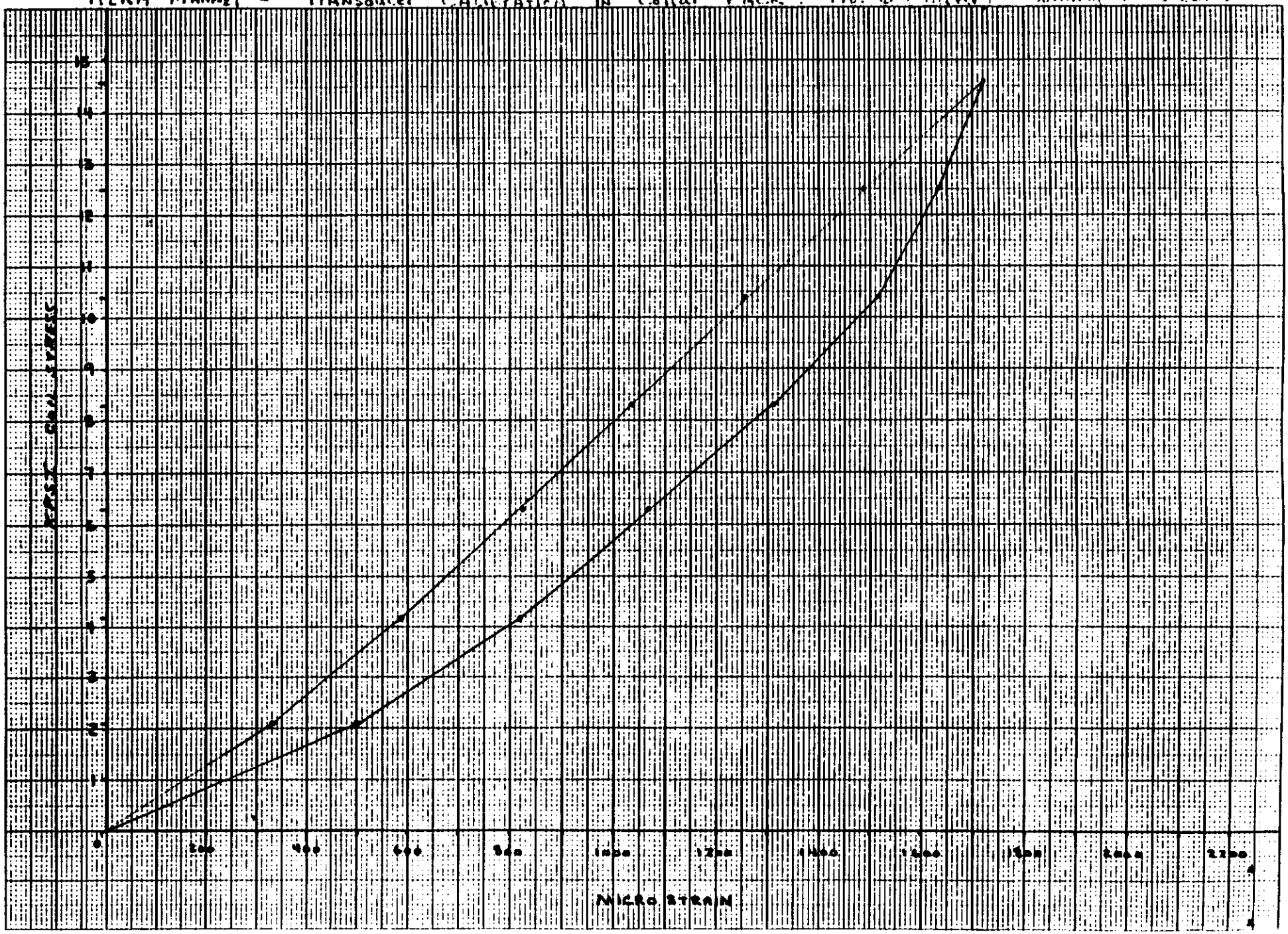
SQUARE 10 X 10 TO THE CENTIMETER AS-8014-60

HERA MAGNET - TRANSDUCER CALIBRATION IN Collar PACK : No. 5 ([illegible]) Loading ↑ = Green ↓ = red [illegible]



SQUARE 10 X 10 TO THE CENTIMETER AS-8014-60

HERA MAGNET - TRANSDUCER CALIBRATION IN COLLAR TRACK : No. 6 (Mister) Loading ↑ = Green ↓ = red



APPENDIX C

HERA Magnet Notes

I) Ref. Data:

1) Outer Coil Width = 58.66 - 48.36 = 10.3 mm (.405 in) (over insulation).

2) Inner Coil Width = 47.86 - 37.7 = 10.16 mm (.400 in) (over insulation).

3) Transducer Length = 31.75 mm (1.25 in).

4) Collar Pack Length = 150 mm (5.905 in).

II) Calibration Load/Coil Stress Conversions

1) Transducer Calibrations - (0-7,500 lb).

A. Inner Coil Transducer

Coil Area Under Load = 10.16 x 31.75.

= 322.58 mm^2 (0.500 in^2).

$\Rightarrow$ 1000 N (224.8 lb_f) = 3.10 N/mm^2 (450. psi).

(1000N÷9.8 m/s^2 = 102 kg).

$\therefore$ 1000 kg = 30.39 N/mm^2 (4412 psi).

B. Outer Coil Transducer

Coil Area Under Load = 10.3 x 31.75.

= 327.05 mm^2 (.507 in^2).

$\Rightarrow$ 1000 N (224.8 lb_f) = 3.06 N/mm^2 (443 psi).

$\Rightarrow$ 1000 kg = 30.0 N/mm^2 (4343 psi).

2. Collar Pack Calibrations

A. Inner Coil Calibrations

Coil Area Under Load

$= 2 \times 10.16 \times 150 = 3048\ mm^2\ (4.72\ in^2)$.

$\Rightarrow 1000\ N = 0.328\ N/mm^2\ (47.6\ psi)$.

$\Rightarrow 1000\ kg = 3.22\ N/mm^2\ (466\ psi)$.

B. Outer Coil Calibrations

Coil Area Under Load

$= 2 \times 10.3 \times 150 = 3090\ mm^2\ (4.79\ in^2)$.

$\Rightarrow 1000\ N = 0.324\ N/mm^2\ (46.9\ psi)$.

$\Rightarrow 1000\ kg = 3.17\ N/mm^2\ (460\ psi)$.

APPENDIX D No. 1

HERA - transducer CALIBRATION - IN COLLAR

1 TON = 1000 KG

Gage factor : 1.95 , I.C. = 339

	LOAD N/mm²	LOAD KG	INNER Ch. 1	MICRO STRAIN Ch. 4
7/27/87		0	0	0
	12.88	4000	151	148
	25.76	8000	326	366
	33.64	12000	526	551
	51.52	16000	739	750
	59.57	18,500 ~~19.6~~	978	879
		0	0	0
		4	146	140
		8	327	329
		12	526	542
		16	740	731
		18.6 ~~19.6~~	867	970
		0	1	0

AT HERA CH 1

$\sigma_1 = 0.067/\mu\epsilon + 2.1\ N/mm^2$

(BNL: $\sigma_1 = .064|\mu\epsilon| - .34$) corr = .9999

$\Delta E = +4.7\%$

AT HERA CH 4

$\sigma_4 = .067/\mu\epsilon| + 1.9\ N/mm^2$

corr = .9996

(BNL: $\sigma_4 = .058|\mu\epsilon| - 1.3$)

$\Delta E = +15\%$

[illegible]

HERA - transducer CALIBRATION - IN COLLAR

Gage factor : 1.95 , I.C. = 339

LOAD N/mm²	KG ~~TON~~	Outer ch 2	MICRO STRAIN 3	5	6
7/27	0	0	0		
12.68	4000	190	103	98	338
25.36	8000	392	260	276	660
[illegible]	12000	586	454	460	933
50.72	16000	778	671	660	1191
62.13	19,600 ~~20~~	972	885	848	1412
	0	0	+1	0	0
	4	198	100	114	368
	8	407	261	300	680
	12	604	457	480	946
	16	779	667	682	1194
	19.6	965	869	851	1403
	0	1	1		

CH2

$\sigma_2 = .064/\mu\epsilon - .035\ N/mm^2$

corr = .9999

(BNL : $\sigma_2 = .055/\mu\epsilon - 1.9$)

$\Delta E = [illegible]$

CH3

$\sigma_3 = .067/\mu\epsilon + 4.4\ N/mm^2$

corr = .9922

(BNL : $\sigma_3 = .067/\mu\epsilon + .30$)

$\Delta E = +3\%$

CH5

$\sigma_5 = .077/\mu\epsilon + 3.3\ N/mm^2$

corr = [illegible]

(BNL : $\sigma_5 = .077/\mu\epsilon + 6.3$)

$\Delta E = -7.8\%$

CH6

$\sigma_6 = [illegible]$

corr = [illegible]

(BNL : $\sigma_6 = [illegible]$)

$\Delta E = [illegible]$

APPENDIX E

8/2/87
MDA

HERA 1M COLLAR ASSEMBLY FORCE BALANCE

REF DATA:

- $1\,\text{BAR} = 1\,\text{kg/cm}^2 \times 9.81\,\text{N/kg} \times \frac{\text{cm}^2}{10^2\,\text{mm}^2} = 0.098\,\text{N/mm}^2$
- COIL LENGTH (OVERALL) = 958.5 mm

  COIL LENGTH UNDER LOAD ≅ ST. SECT. LG. + ½ OF END LG

  $\approx 958.5\,\text{mm} - \frac{1}{2}(2 \times 180\,\text{mm}) = 778.5\,\text{mm}$
- # OF CYLINDERS = 4

  $\phi_{CYL} = 190\,\text{mm}$

→ CYLINDER AREA $= 4 \times \pi(190)^2/4 = 113{,}412\,\text{mm}^2$

INNER COIL AREA $= 2 \times 10.16 \times 778.5 = 15819.12\,\text{mm}^2$

OUTER COIL AREA $= 2 \times 10.3 \times 778.5 = 16037.1\,\text{mm}^2$

① HYDRAULIC PRESSURE (BAR)	② APPLIED FORCE (kN) $\left(① \times .098\,\text{Bar/N/mm}^2 \times \frac{113{,}412\,\text{mm}^2}{1000}\right)$	③ INNER COIL STRESS (N/mm²)	④ INNER COIL FORCE (kN) $\left(③ \times \frac{15819.12\,\text{mm}^2}{1000}\right)$	⑤ OUTER COIL STRESS (N/mm²)	⑥ OUTER COIL FORCE (kN) $\left(⑤ \times \frac{16037.1\,\text{mm}^2}{1000}\right)$	⑦ FORCE EFFICIENCY κ $\left(\frac{④+⑥}{②}\right) \times 1$ (%)
50	555.7	18.8	297.4	14.7	235.7	96 %
100	1111.4	35.1	555.2	35.8	574.1	101 %
150	1667.2	52.4	828.9	60.9	976.6	108 %
200	2222.8	64.8	1025.1	79.2	1270	103 %
250	2778.6	77.0	1218.1	96.1	1541.2	99 %
290	3223.2	84.4	1335.1	106.4	1706.3	94 %
0 (RODS INSTALLED)		46.3		40.2		

MAGNET/PROJECT : [illegible] LOCATION : _____

ASSEMBLY No. : 4 GAGE FACTOR : _____

STRAIN GAGE DATA : (full bridge)

Date:	Status:	INNERS: # 1	~~KPSI~~ N/mm²	# 4	~~KPSI~~ N/mm²	AVE.	OUTERS: # 2	~~KPSI~~ N/mm²	# 3	~~KPSI~~ N/mm²	# 5	~~KPSI~~ N/mm²	# 6	~~KPSI~~ N/mm²	AVE.
7/28/87	0	0		0			0		0		0		0		
	50	348	21.9	303	15.7	18.8	212	9.8	47	3.5	167	19.1	513	26.4	14.7
	100	609	38.6	568	31.6	35.1	555	28.6	237	16.2	492	44.2	974	54.0	35.8
	150	836	56.4	856	48.3	52.4	947	50.2	537	36.3	891	74.9	1441	82.0	60.9
	200	1084	69.0	1067	60.6	64.8	1249	66.8	793	53.5	1180	97.2	1728	99.3	79.2
	250	1277	81.4	1273	72.5	77.0	1531	82.3	1051	70.8	1438	117.0	1980	114.4	96.1
max	290	1396	89.0	1400	79.9	84.4	1711	92.2	1220	82.1	1596	129.2	2110	122.2	106.4
rods	- 0	771	49.0	775	43.6	46.3	534	27.5	322	21.9	491	44.1	1196	67.4	40.2
7/30/87	[illegible]	774	49.2	770	[illegible]	47.5	532	27.4	327	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	27.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	67.4	[illegible]
[illegible]															
8/3/87	4°K	771	49.6	345	51.0	50.3	524	20.9	[illegible]	22.4		41.7	[illegible]	[illegible]	[illegible]
8/3/87 @ 4°K	4.43 0	760	48.9	835	50.3	49.6	520		362		508		1189		
Power	500 A	755	48.5	832	50.1	49.3	520		360		508		1188		
	1000A	742	47.5	819	49.2	48.3	523		359		509		1186		
	1500 A	720	45.9	799	47.9	46.9	522		357		511		1181		
	2000	690	43.6	769	45.8	44.7	524		354		513		1174		
	2500	642	40.0	723	42.7	41.3	526		350		515		1169		
	3000	588	35.6	672	39.2	37.4	528		347		518		1158		
	3500	526	31.3	610	35.0	33.2	531		344		521		1148		
	4000	458	26.2	542	30.4	28.3	534		340		525		1135		
	4500	393	21.3	474	25.8	23.6	538		339		530		1119		
	5000	323	16.1	411	21.5	18.8	542		336		535		1102		
	5500	253	10.8	343	16.9	13.9	546		334		540		1084		
	6000	180	5.4	270	11.9	8.6	549		330		545		1063		
	6500	~~180~~ 112	.3	198	7.0	3.6	55[illegible]		323		549		1036		
Quench	@ 6800 A														
	0	743	47.6	814	48.9	48.2	518		364		483		1198		
	500 A	739		810			518		362		483		1197		
	1000	726		799			519		361		485		1195		
	1500	706		778			520		358		486		1190		

MAGNET/PROJECT : HERA 1m DIPOLE

LOCATION : _____

ASSEMBLY No. : _____

GAGE FACTOR : _____

STRAIN GAGE DATA : (full bridge)

	INNERS :					OUTERS :								
Date: Status:	# 1	KPSI	# 4	KPSI	AVE.	# 2	KPSI	# 3	KPSI	# 5	KPSI	# 6	KPSI	AVE.
8/3/87 (cont.)														
4.33 K° Power 2000A	677	42.6	751	44.6	43.6	522	20.8	355	21.4	441	39.2	1183	63.0	36.1
2500 A	641	40.0	716	42.2	41.1	525	21.0	351	21.1	492	40.1	1174	62.4	36.2
3000	598	36.7	673	39.3	38.0	527	21.1	348	20.9	498	40.6	1164	61.8	36.1
3500	546	32.8	622	35.8	34.3	530	21.3	342	20.5	503	41.1	1151	60.9	36.0
4000	488	28.5	565	32.0	30.3	533	21.4	338	20.2	509	41.6	1137	60.8	35.8
4500	424	23.7	501	27.6	25.7	536	21.6	334	19.9	516	42.1	1120	59.0	35.7
5000	~~317~~	—	~~372~~	—	—	~~543~~	—	~~328~~	—	~~530~~	—	~~1081~~	—	
5500	313	15.3	372	18.9	17.1	543	22.0	328	19.4	536	43.3	1081	56.5	35.3
6000	200	6.9	279	12.5	9.7	547	22.3	324	19.1	539	44.1	1055	54.8	35.1
6500	120	.9	203	7.4	4.2	549	22.4	321	18.9	547	44.7	1028	53.1	34.8
Quench @6750 A														
8/3/87 14:30 0A	745	47.7	816	49.0	48.4	515	30.4	362	22.0	480	39.1	1195	63.8	38.8

MDA 8/3/87

HERA 1M MAGNET

COIL STRESS VS ASSEMBLY PRESSURE (300°K)

&

COIL STRESS VS CURRENT (4°K)

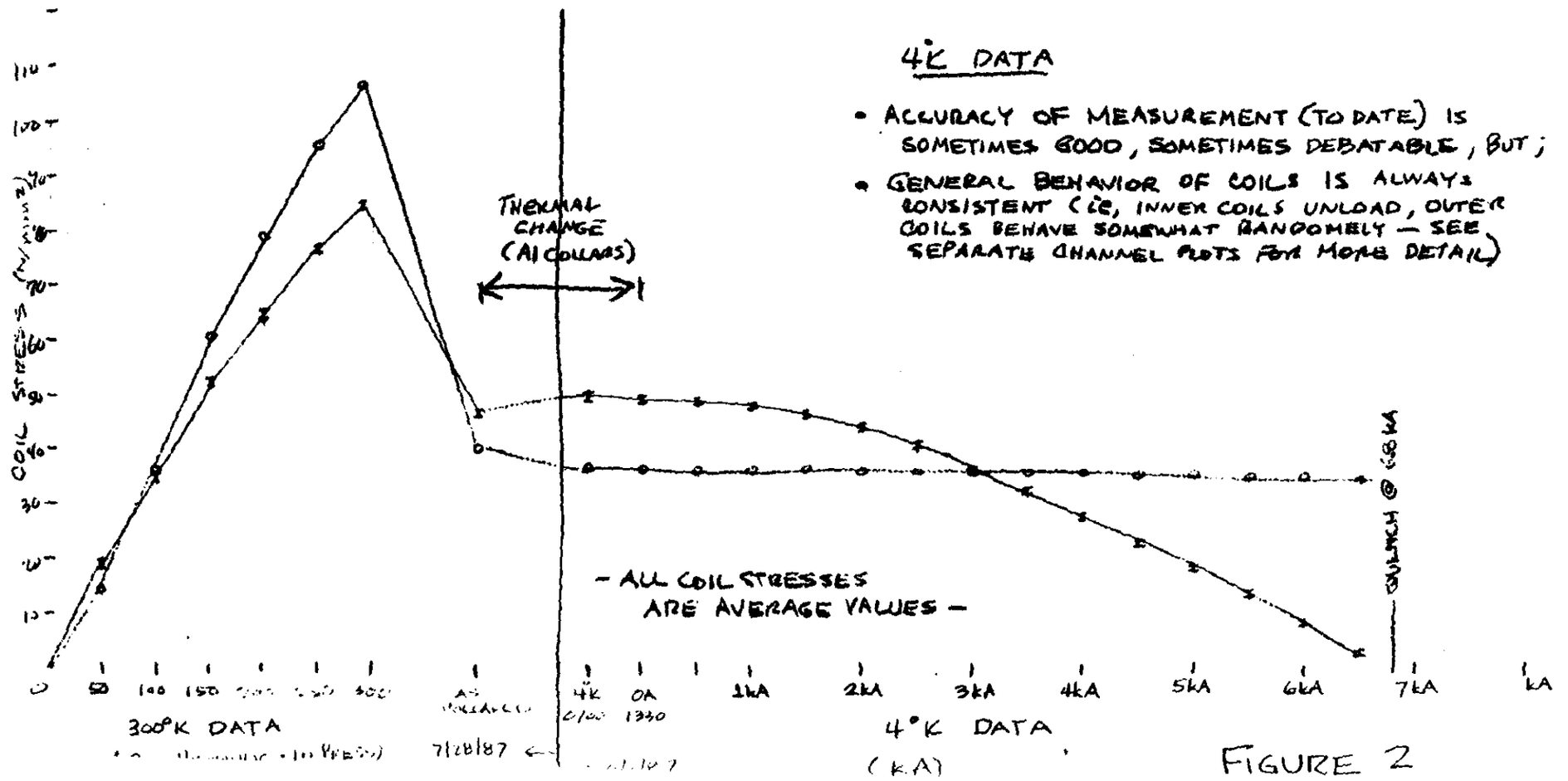
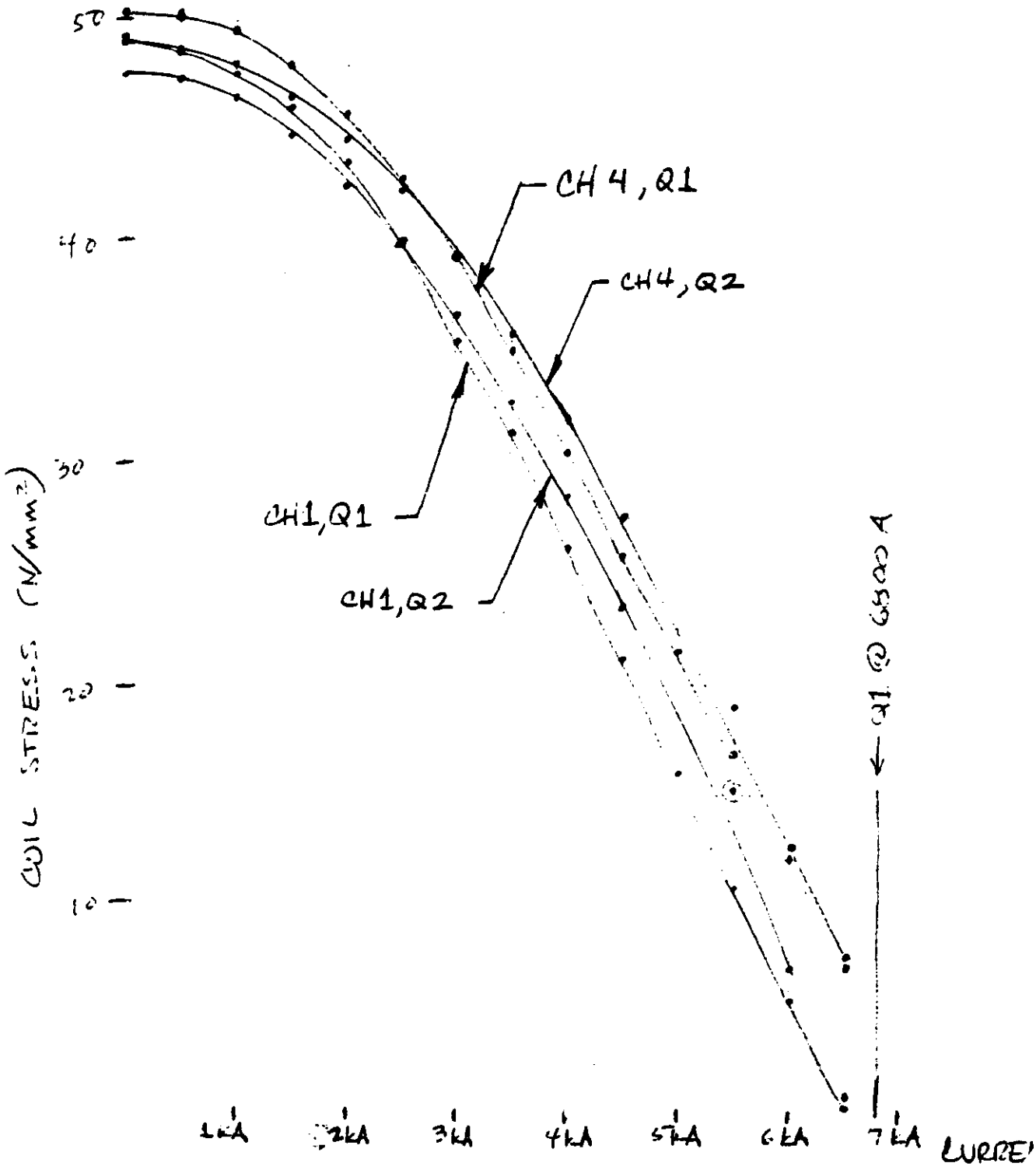


FIGURE 2

HERA 1M MAGNET
INNER COIL STRESS
VS
CURRENT
MDA 8/3/87

FIGURE 3



8/3/8

OUTER COIL STRESS
VS
CURRENT

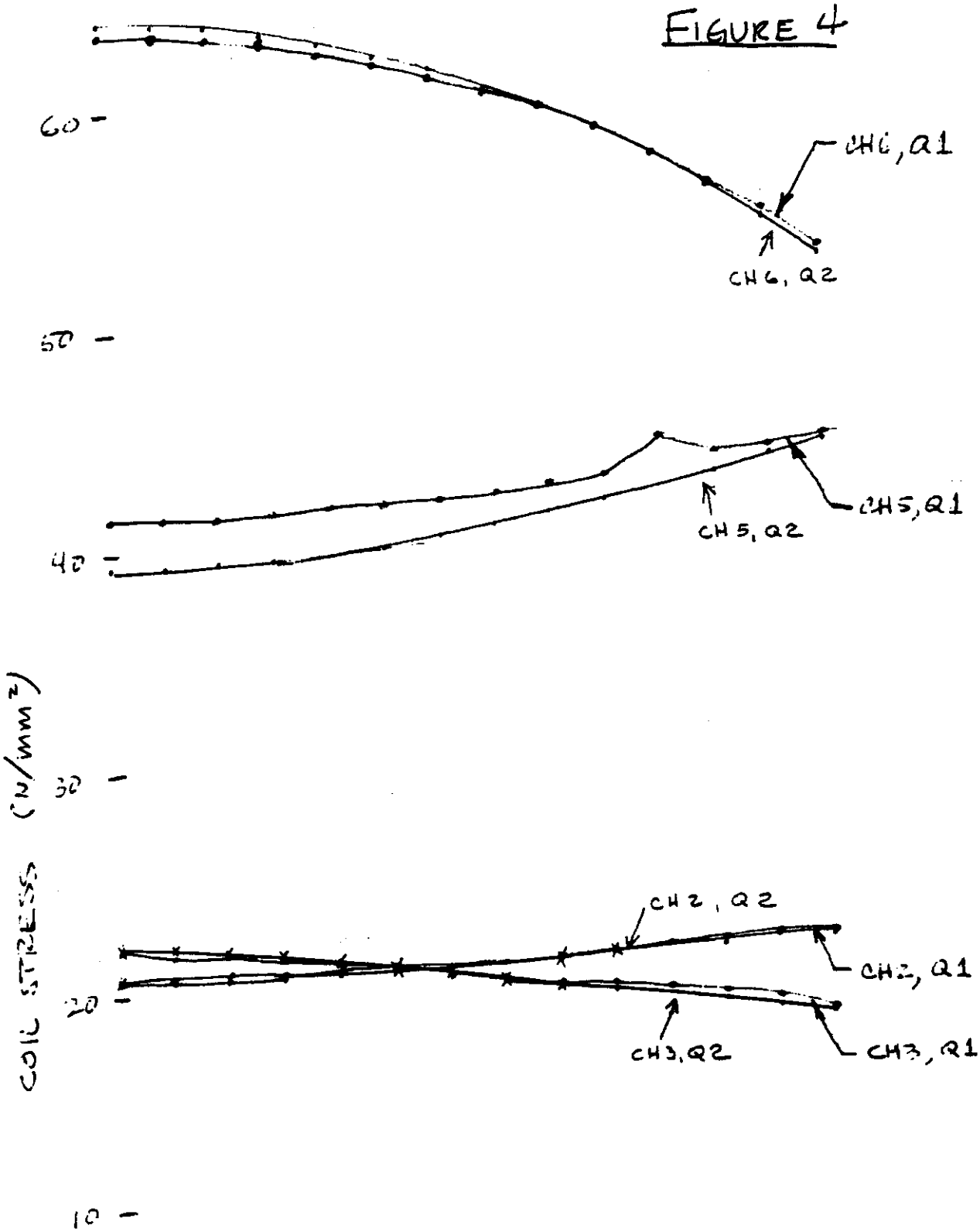



FIGURE 4