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ELECTRICAL DESIGN OF A 110-FT LONG MUON PIPE WITH AUTOMATIC DEGAUSSING

A. T. Visser

November 1985

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1. Brief Subject Description

This memo describes a magnetized cylindrical pipe made from tape wound grain oriented low carbon steel rolls. Grain oriented steel yields much higher magnetic fields at low ampereturns than cast iron or other steel pipes. This is especially important when only a few small windings are allowed in the inner bore. The power supply and operating cost are also much lower. The pipe has a high (~9kG) remnant field, but is automatically degaussed upon shutdown of the DC excitation power supply. A remnant field detector senses whether degaussing was successful. The pipe is used in the muon beam line (E665). Its magnetic field deflects unwanted halo muons. Tests need to be conducted with and without pipe field. It is therefore desirable that the pipe field automatically returns to zero when the DC excitation is shut off. This can be rather easily accomplished.

2. Selection of the Muon Pipe Steel

The muon beam line requires a circular DC magnetic field in steel with a wall thickness of 1.25" at 4.5" to 5" inner diameter having a total length of 110'. The field strength should be in the order of 15kG and the excitation winding should only occupy a few percent of the inner bore area. The initial reaction is to use an iron pipe for this purpose. However the magnetic properties of iron pipe are not very good. To obtain 15kG requires about 50 Oersteds, or an excitation of 1600 ampereturns at 5" pipe diameter. This can be predicted from the DC magnetization curves for hot rolled steel plates (see fig. 1).

The pipe steel is most likely worse than these curves indicate. Figure 2 shows the measured B-H curve of a pipe sample. It is not practical to run that many ampere turns in the limited available bore space. We need a better magnetic material. 12 Mill thick, grain oriented steel, commonly used for power transformer construction, has much better magnetic properties, and is relatively inexpensive. Various manufacturers can wind this material to the desired wall thickness and diameter with a stacking factor of 0.95. The material can only be supplied in 6" long pieces, which seems to be a maximum industrial rolling width. Longer rolls can be supplied at a much higher tooling cost. The material used for the muon pipe is 12 mill, grain oriented, 3% silicon steel (Arnold Engineering-Silectron). It was supplied in 6" long rolls (cores), which were annealed and impregnated. The inner diameter was kept to a tolerance of ±1/64". The B-H curves of several cores was measured up to 5 Oersteds. (see Fig. 3 through 10). The total cost for all cores, including all tooling, annealing, measurements, etc. was about $16,000 or $1.90/lbs. A common (?) steel pipe was estimated to cost about $1.30/lbs.

The measured B-H curves show that we are now in a much better magnetic shape compared to an iron pipe.

To obtain 15kG at 5" diameter requires 2 Oersteds or 64 ampere turns compared to 1600 ampereturns for the iron pipe. The remnant field is in the order of 9KG. It is possible to degauss the cores with 60Hz housepower, since they are made from 12 mill steel.

3. Muon Pipe Construction, Excitation, and Degaussing

The complete muon pipe consists of 220 cores, 6" long each, with 1.25" wall. 160 cores have 5" I.D. and 60 cores have 4.5" I.D. They are installed in four groups, located in four different enclosures, spanning a total beam length of about 600 feet. The power supply is 200' away. The excitation winding for all muon pipe cores are wired in series and consist of one turn made from 4 AWG#10 wires in parallel. They are operated at 100 ADC. Cores excited with 100 ampere turns (3.1 Oersteds at 5") yield about 1.6kG. Fig. 11 shows the μ-pipe field as a function of the diameter at 100 ampere turns.

The B-H curve of the cores is not linear and the inductance of the muon pipe depends therefore strongly on the value of the excitation current.

In general we can write:

$$L_{pipe} = \frac{N\Phi}{I} \text{ Henry}$$

or

$$L_{pipe} = \frac{NAB}{I} \text{ Henry}$$

N - number of turns, N=1

B - field in Wb/m^2.

A - cross section of 220 cores in m^2. $A=1.06\ m^2$

I - operating current in A

Using the measured B-H curves of fig. 3 to 10 we can find B for various operating currents and make the following table:

I AMP	L_{pipe} Henry
100	17×10^{-3}
15	94×10^{-3}
10	140×10^{-3}
5	2.3

The remnant field in the cores can be removed (degaussed) by exciting the cores up to the non-linear region of the B-H curve and gradually reducing this degaussing current to zero using alternate polarities. We can use 60Hz housepower and a variable transformer for degaussing since the cores are laminated. The maximum required current for reaching the non-linear B-H region is about 10 ATRMS or 14AT peak. The required degaussing voltage with 1 turn is:

$$V_{Degauss} \sim 2\pi fLI$$

$$V_{Degauss} \sim 2\pi 60\times0.094 \times 10$$

$$V_{Degauss} \sim 350V$$

From field tests we found that 10A degaussing current can be obtained at 250VAC, using the one turn excitation winding of the cores. With four turns (originally installed) we would have needed 2.5A at about 1000VAC. That is not practical.

Degaussing could have also been obtained from the DC excitation power supply and a reversing switch. The output needs than alternately be programmed down to zero. This is a somewhat tedious and time consuming process. The biggest problem is around zero. It is very hard to control the output of a 100A power supply to within 100mA, while switching it on and off. A solid state reversing switch would also be hard to control at these levels. If we do not control the lower current values very well, then we can easily leave a remnant field of several kGauss, as can be seen from the B-H curves of Fig. 3 through 10. AC degaussing with a variac solves all these problems economically and fast for this type of steel.

An 82μF capacitor (Fig. 12) connected in parallel with the muon pipe draws about 8A at 250VAC. This leading capacitor current compensates the lagging degaussing current through the muon pipe. The variac current is now in the order of 2 to 4Amp with 10Amp degaussing current in the muon pipe. High current variacs are expensive. The capacitor also reduces the effect of variac switching steps at the low end. It can also absorb some leftover stored energy in the cores when the load contactor switches, but there should be none. The μ-pipe time constant was measured to be about 0.1 sec. It is short, because a lot of remnant field is left in the cores.

4. Muon Pipe Electrical Schematic and Remnant Field Detector

Schematic

Fig. 12 shows the control schematic for the muon pipe.

A mechanically held contactor, controlled by a timer transfers the load from the DC power supply to the degaussing variac, when the power supply is shut down. The variac runs up and down, after which the load is returned to the DC run supply.

A mechanically held contactor and timer are used because they will not change state upon loss of control power. Uncontrolled switching in the inductive DC load circuit can therefore not take place.

Two remnant field detector cores share the same DC excitation/degaussing winding as the muon pipe cores. Let us first understand the timer contact functions.

Description of the Timer Contact Functions

Refer to Fig. 12. The sequence of events listed below starts when the μ-pipe power supply is shut off. Power supply shut off starts a timer motor, which rotates at 3^{o}/sec. This motor drives a shaft to which 9 cam driven switches M1 through M9 are mounted. The cam positions are adjustable.

Sequence of Events

1. M2

The DC power supply is running and the timer sits at $360^{o}(0^{o})$. K1 is picked up. The contactor is in the F position.

2. M1

Shut the DC power supply off. K1 drops and the timer runs from 0^{o} to 300^{o} via K1 and M1.

3. M3,M5

M5 removes the DC power supply on permit at 10°. None of the other cam switches change state, when the timer runs from 0 to 180°. The DC load current decays to 0 during this period which lasts about 60 seconds. M3 closes at 180° and transfers the contactor to the degaussing variac. (R position)

4. M6

The timer keeps running until M6 reaches 200° and drives the variac up. Driving the variac up takes about 15° (5 sec.) The variac starts going down at 220° and the cores are degaussed when the variac reaches zero again.

5. M8

M8 enables the remnant field detector from 240° to 260°. This detector is disabled at all other times, so that load current changes during normal running and degaussing do not give any false indications.

6. M7

M7 applies a "remnant field detector power pulse" at windings D at 250°. Note that the detector is enabled at that moment. This power pulse will activate K3 if the detector cores have a remnant field, which is the result of improper degaussing. Proper degaussing should have removed the remnant field from the detector cores and the μ-pipe cores.

7. M7, M8

Check winding D is disconnected and the detector disabled at 260°.

8. M4

All degaussing and checking is complete. The load is transferred back to the DC power supply (contactor F position) at 270°.

9. M5

This DC power supply interlock permits the supply to come on when the timer is between 280° and 10°.

10. M1

All is ready. The timer runs to 300° and stops until the power supply is switched on.

11. M2

The timer runs from 300° to 360° after starting the DC power supply.

12. M9

It is meaningless to indicate the presence of a remnant field from the previous check after the DC power supply has been restarted, M9 resets the degaussing failure indication, if there was any, at 350°.

13. M1, M2

The DC power supply is on. The timer stops at 360° via K1 and M2. Note that M1 and M2 contacts overlap, so that the motor can always receive power when K1 changes state.

14. Initial Startup

After assembly the contactor and timer could be in any arbitrary position. For instance the contactor could be in R with the timer between 280° and 360°. The DC power supply could start, but the load circuit is open. No DC current will flow. The power supply should be shut off and the system should complete one degaussing cycle. This will remove this out of synch condition. It is also possible to manually push the contactor to F and set the timer at 0° after initial assembly.

The Remnant Field Detector

The μ-pipe and the remnant field detector cores are identical, except for length. The remnant field detector consists of two identical 5" I.D. cores with three windings each. The run/degaussing winding L puts both cores in the same magnetic state as the muon pipe cores. The test windings D are identical and connected in series, but in opposite direction. A power pulse at D will drive one core up and the other down. The series connected sense winding senses the $d\phi/dt$ in each core and each produces a proportional induced voltage. These voltages are equal but opposite when the cores are perfectly degaussed since the B-H curves are symmetrical around zero. The bridge output is then zero volt.

Refer to Fig. 13. Now let us assume that cores 1 and 2 both have the same remnant field. The power pulse at D drives one core in the same direction as the remnant field and the other core in the opposite direction. One core will saturate faster and can only support a small $d\phi/dt$ compared to the other.

This unequal $d\phi/dt$ will induce unequal voltages in windings S. Windings S produce now a net bridge output voltage to the comparitor. The comparitor can be set to trip at a preset level and thus indicate the presence of a remnant field.

Selection of Component Values for the Remnant Field Detector

1. The detector test winding D should be able to drive the test cores up to about 2 Oersteds (80AT).

2. The test cores are made from 1" wide, 1.25" thick pieces, cut from a leftover core. The test cores were electrochemically etched to remove shorts at the cut.

3. The current through the timer contact switches must not exceed 10Amp peak (rating).

4. The resonant frequency of the test winding and the discharge capacitor should be less than about 100Hz, since the steel is 12 mill thick (60Hz material). From these requirements we can select the values for L_{test}, C and the charging voltage for C.

Choose 20 turns for each test winding with $\hat{i}=4A$.

$$L_{test} = \frac{20x1x2.54x2.54x10^{-4}x1.6}{4} \times 2 \text{ (cores)}$$

$$L_{test} = 13x10^{-3}H$$

The remnant frequency of L_{test} and C has to be about 100Hz.

$$f = \frac{1}{2\pi\sqrt{LC}} < 100$$

$$C > 195\mu F$$

We choose $C = 250\mu F$.

The peak current $\hat{i}$ depends on the charging voltage of C.

$$4<\hat{i}<10$$

If we neglect all losses in the LC resonant circuit, we can write:

$$1/2\ L\hat{i}^2 = 1/2\ C\hat{v}^2$$

$$\hat{v} = \hat{i}\sqrt{\frac{L}{C}}$$

$$\hat{v} = 7.2\ \hat{i}$$

thus:

$$29v<\hat{v}<72v$$

Choose v = 30v since that is easily available.

Summary:

$L_{test} = 13x10^{-3}H$

$C = 250\mu F$

$\hat{V} = 30V$

$\hat{i} = 4A$

$f = 100Hz$

The sense winding has 40 turns. The detector has proven to be extremely handy during testing, in order to check, whether the peak degaussing current was high enough or not. Fig. 14 shows some pictures of the bridge output voltage for cores with and without remnant field. This detector is not too practical for toroids operating at several 1000A, but a scaled-down version, which mirrors the toroid steel and current at the same ratio, could be used.

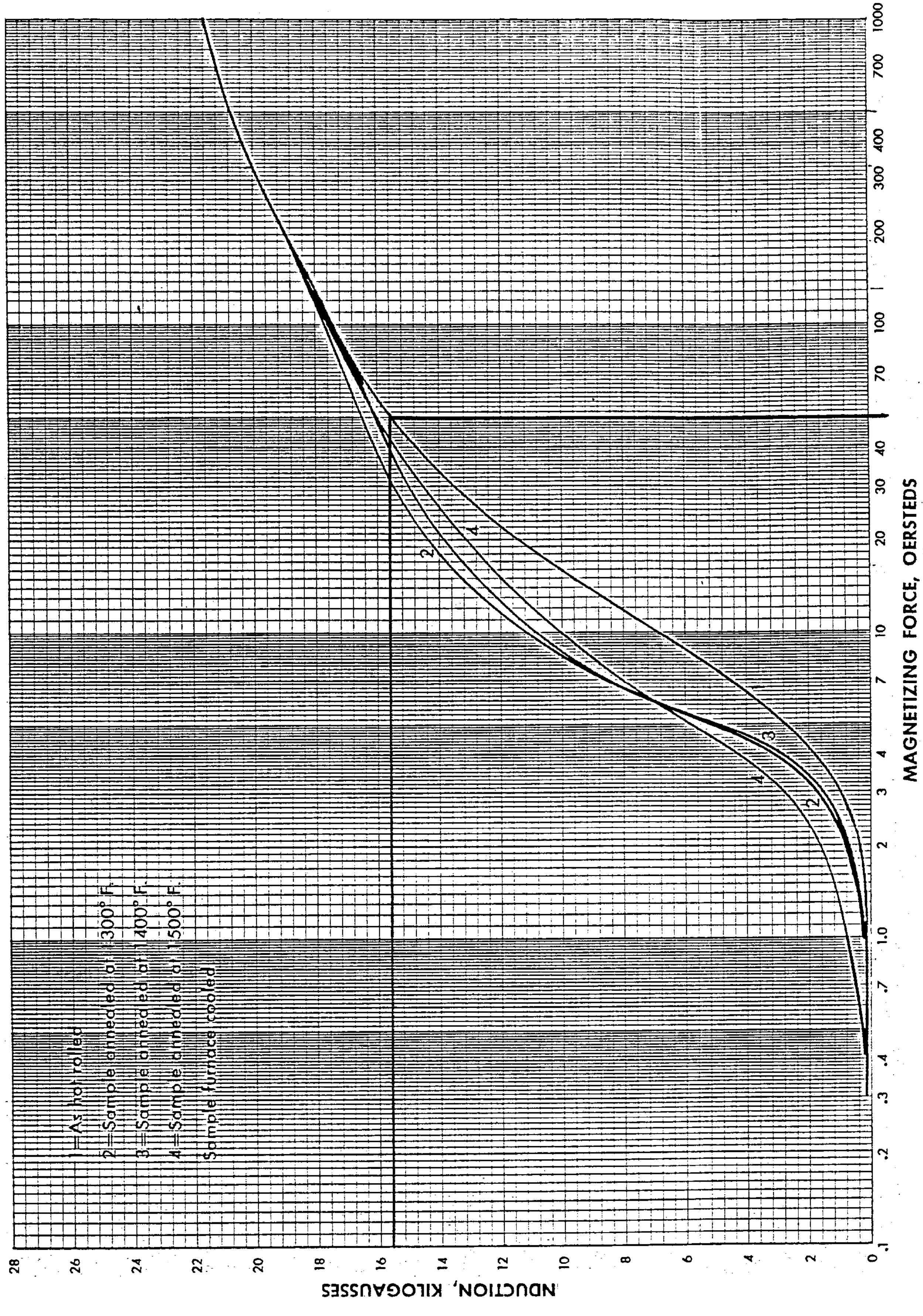
5. Acknowledgements

I am grateful to J. Lentz. He made quite a few preliminary measurements and became almost magnetized with this job.

The degaussing equipment was built from left over materials on hand, but the variac was purchased ($512).

ATV:plm

USS HOT ROLLED LOW CARBON STEEL PLATES
C1030 — OVER .250 INCHES
DC MAGNETIZATION



Test Conditions: Lenghtwise samples tested in Fahy Permeameter.

FIG 1

6/7/83

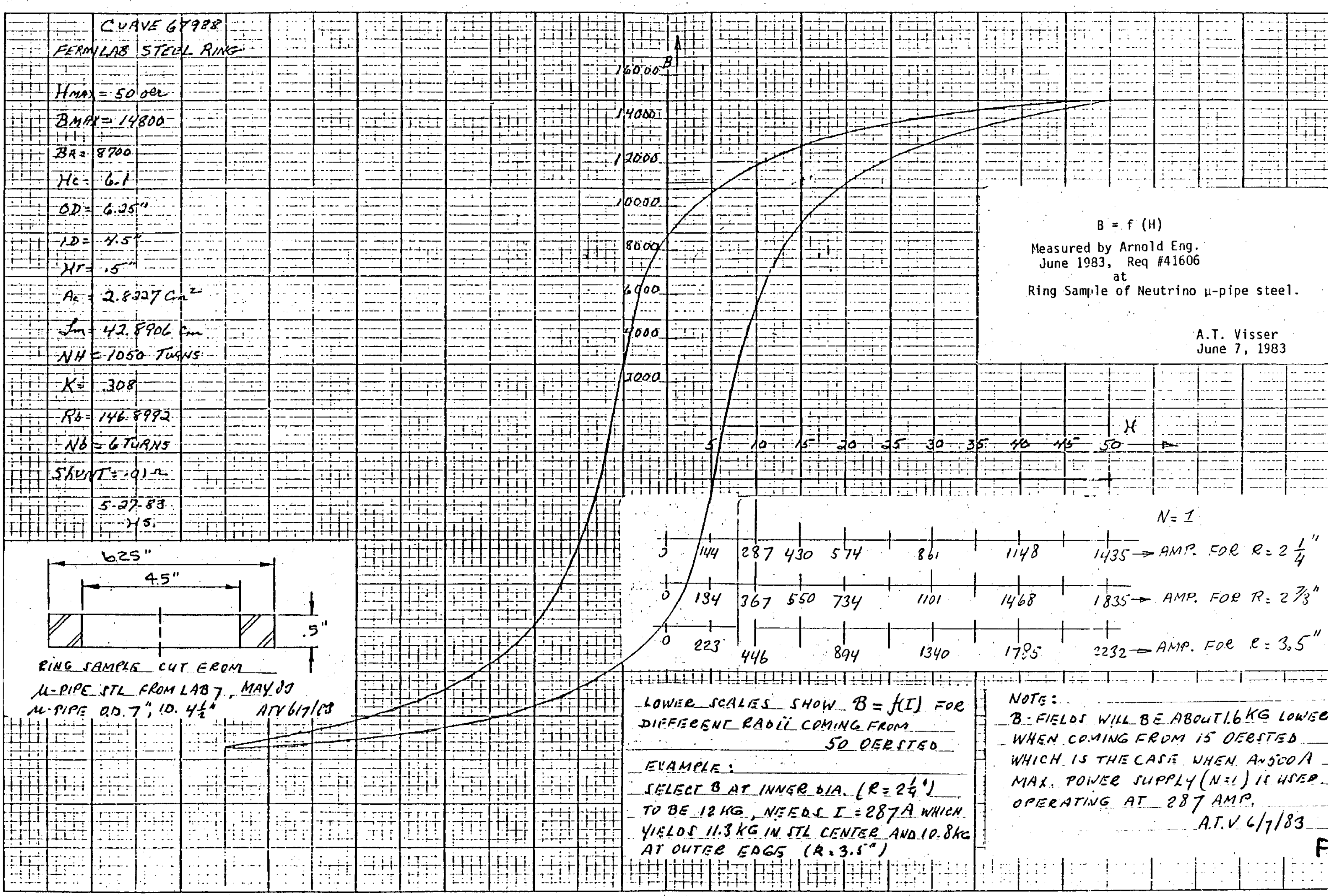
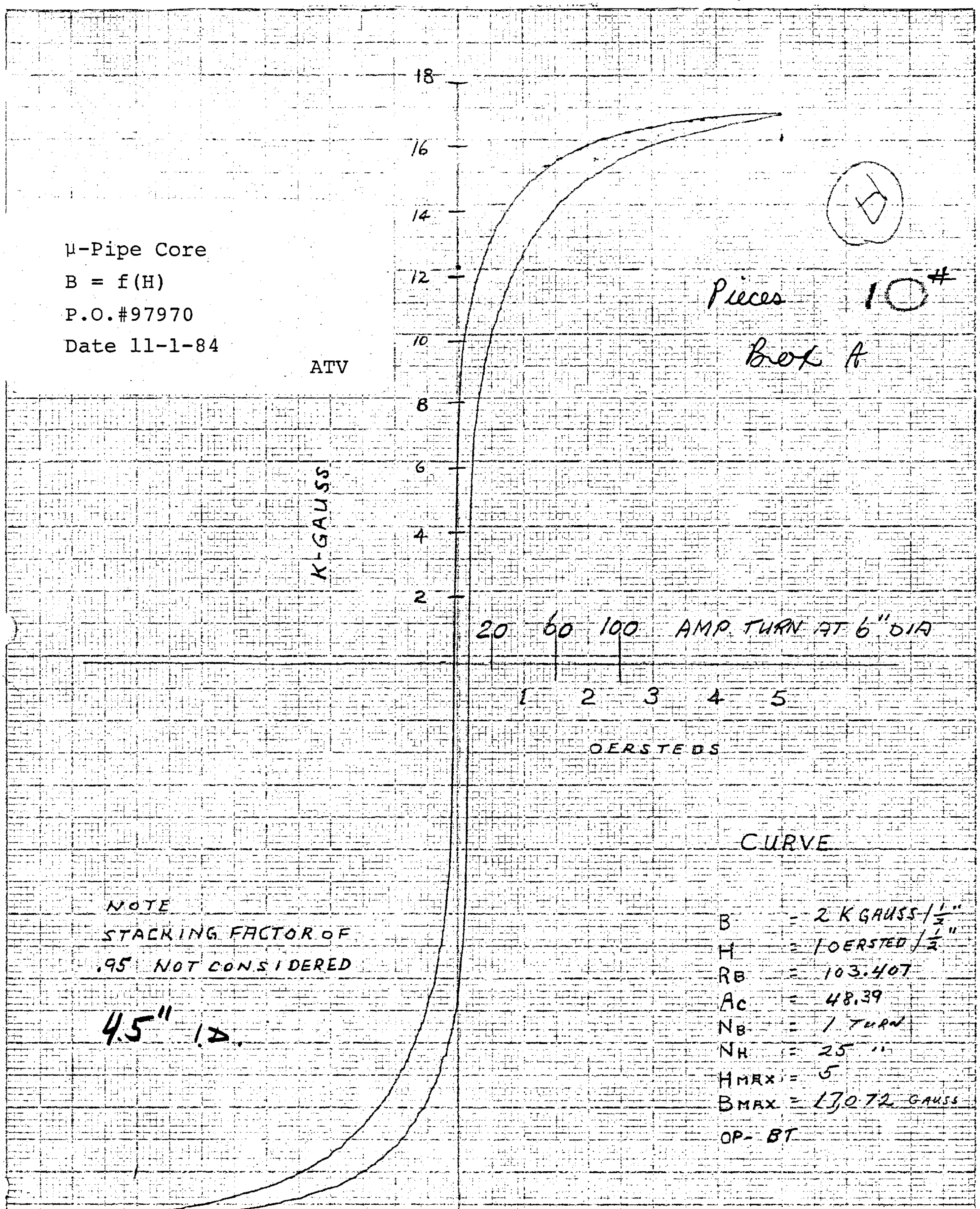

CURVE 67988
FERMILAB STEEL RING
HMAX = 50 oer
BMAX = 14800
BR = 8700
Hc = 6.1
OD = 6.25"
ID = 4.5"
Ht = .5"
Ac = 2.8227 Cm²
lm = 42.8906 Cm
NH = 1050 TURNS
K = .308
Rb = 146.8992
Nb = 6 TURNS
SHUNT = .01 Ω
5-27-83
HS.
6.25"
4.5"
.5"
RING SAMPLE CUT FROM
μ-PIPE STL FROM LAB 7, MAY 83
μ-PIPE O.D. 7", I.D. 4½"
ATV 6/7/83
B
16000
14000
12000
10000
8000
6000
4000
2000
H
5 10 15 20 25 30 35 40 45 50
B = f (H)
Measured by Arnold Eng.
June 1983, Req #41606
at
Ring Sample of Neutrino μ-pipe steel.
A.T. Visser
June 7, 1983
N = 1
0 144 287 430 574 861 1148 1435 → AMP. FOR R = 2 1/4"
0 184 367 550 734 1101 1468 1835 → AMP. FOR R = 2 ⅔"
0 223 446 894 1340 1785 2232 → AMP. FOR R = 3.5"
LOWER SCALES SHOW B = f(I) FOR
DIFFERENT RADII COMING FROM
50 OERSTED
EXAMPLE:
SELECT B AT INNER DIA. (R = 2¼")
TO BE 12 KG, NEEDS I = 287 A WHICH
YIELDS 11.3 KG IN STL CENTER AND 10.8 KG
AT OUTER EDGE (R = 3.5")
NOTE:
B-FIELDS WILL BE ABOUT 1.6 KG LOWER
WHEN COMING FROM 15 OERSTED
WHICH IS THE CASE WHEN AN 500 A
MAX. POWER SUPPLY (N=1) IS USED
OPERATING AT 287 AMP.
A.T.V. 6/7/83

FIG. 2



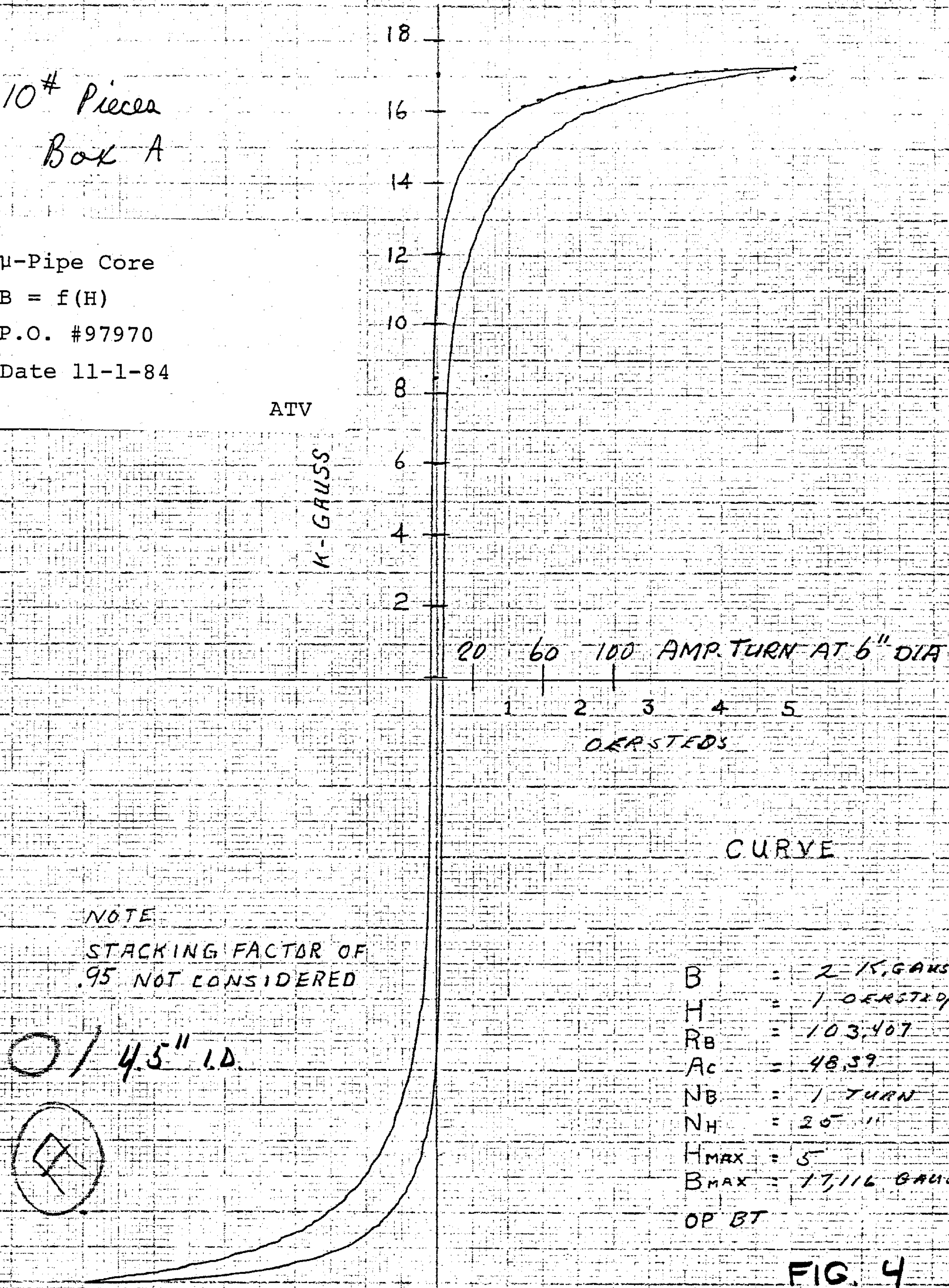
μ-Pipe Core
B = f(H)
P.O.#97970
Date 11-1-84
ATV
18
16
14
12
10
8
6
4
2
K-GAUSS
20 60 100 AMP TURN AT 6" DIA
1 2 3 4 5
OERSTEDS
Pieces 10#
Box A
CURVE
B = 2 K GAUSS / 1/2"
H = 1 OERSTED / 1/2"
RB = 103.407
Ac = 48.39
NB = 1 TURN
NH = 25 "
HMAX = 5
BMAX = 17,072 GAUSS
OP- BT
NOTE
STACKING FACTOR OF
.95 NOT CONSIDERED
4.5" I.D.

FIG 3

10# Pieces
Box A

µ-Pipe Core
B = f(H)
P.O. #97970
Date 11-1-84

ATV



CURVE

NOTE
STACKING FACTOR OF .95 NOT CONSIDERED

O/ 4.5" I.D.

B = 2 K GAUSS/½"
H = 1 OERSTED/½"
R_B = 103,407
A_C = 48.39
N_B = 1 TURN
N_H = 20 "
H_{MAX} = 5
B_{MAX} = 17,116 GAUSS

OP BT

FIG. 4

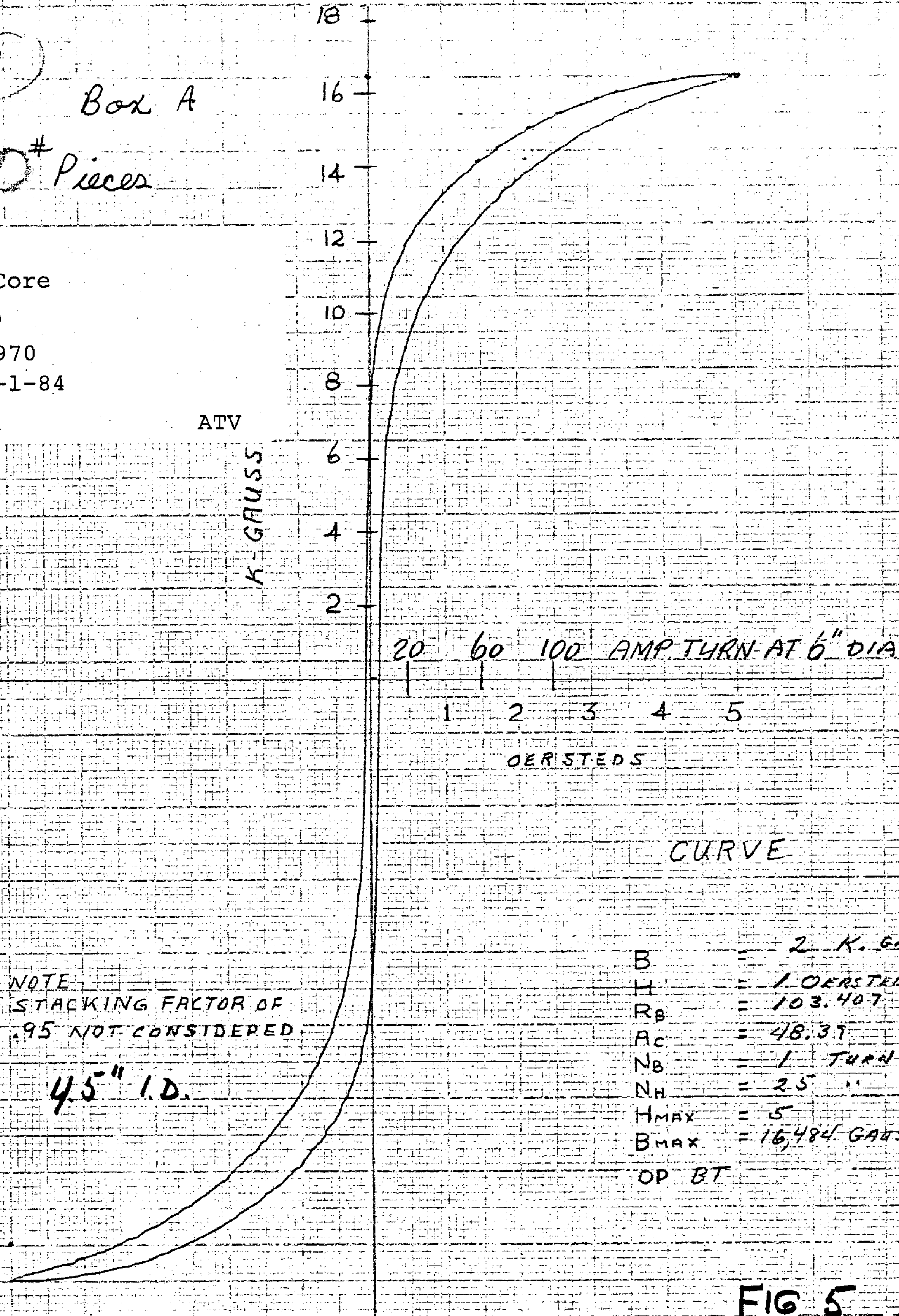
#3

(A) Box A

10# Pieces

μ-Pipe Core
B = f(H)
P.O.#97970
Date 11-1-84

ATV



CURVE

NOTE
STACKING FACTOR OF
.95 NOT CONSIDERED

4.5" I.D.

B = 2 K. GAUSS/½"
H = 1 OERSTED/½"
R_B = 103.407
A_C = 48.31
N_B = 1 TURN
N_H = 25 "
H_{MAX} = 5
B_{MAX} = 16,484 GAUSS
OP BT

FIG 5

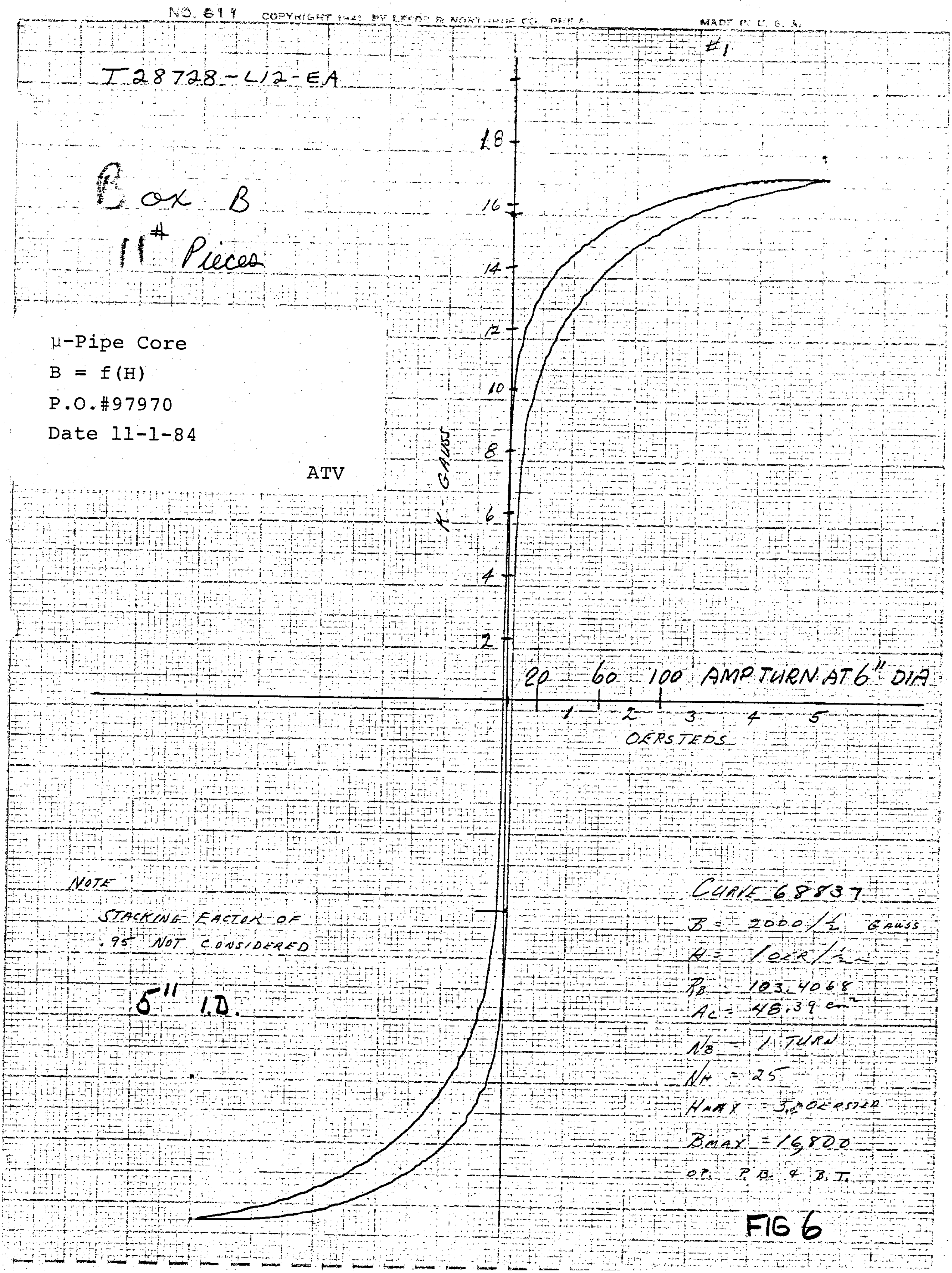

NO. 611 COPYRIGHT 1941 BY LEEDS & NORTHRUP CO. PHILA.
MADE IN U. S. A.
#1
T28728-L12-EA
Box B
11# Pieces
µ-Pipe Core
B = f(H)
P.O.#97970
Date 11-1-84
ATV
K-GAUSS
18
16
14
12
10
8
6
4
2
20 60 100 AMP TURN AT 6" DIA
1 2 3 4 5
OERSTEDS
NOTE
STACKING FACTOR OF .95 NOT CONSIDERED
5" I.D.
CURIE 68837
B = 2000/½ GAUSS
H = 1 OER/½
RB = 103.4068
Ac = 48.39 cm²
NB = 1 TURN
NH = 25
HMAX = 3.0 OERSTED
BMAX = 16,800
OP. P.B. & B.T.

FIG 6

T 28728-L12-EA

Box B
11 Pieces

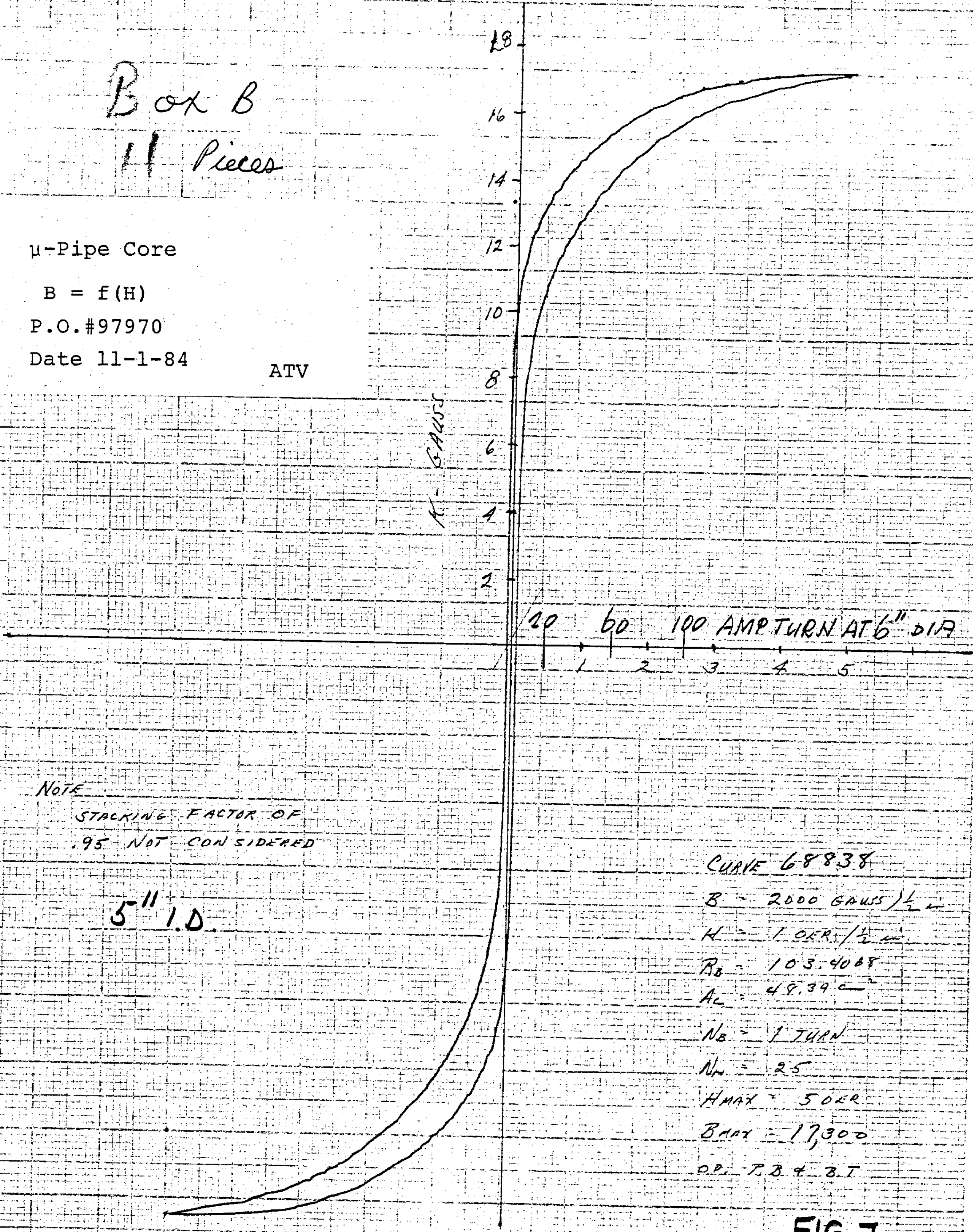
µ-Pipe Core

B = f(H)

P.O.#97970

Date 11-1-84

ATV



NOTE
STACKING FACTOR OF
.95 NOT CONSIDERED

5" I.D.

CURVE 68838
B = 2000 GAUSS/½ in
H = 1 OERS/½ in.
R_B = 103.4068
A_C = 48.39 cm^2
N_B = 1 TURN
N_H = 25
HMAX = 5 OER
BMAX = 17,300
OP. P.B. & B.T

FIG 7

μ-Pipe Core

B = f(H)

P.O.#97970

Date 11-1-84

ATV

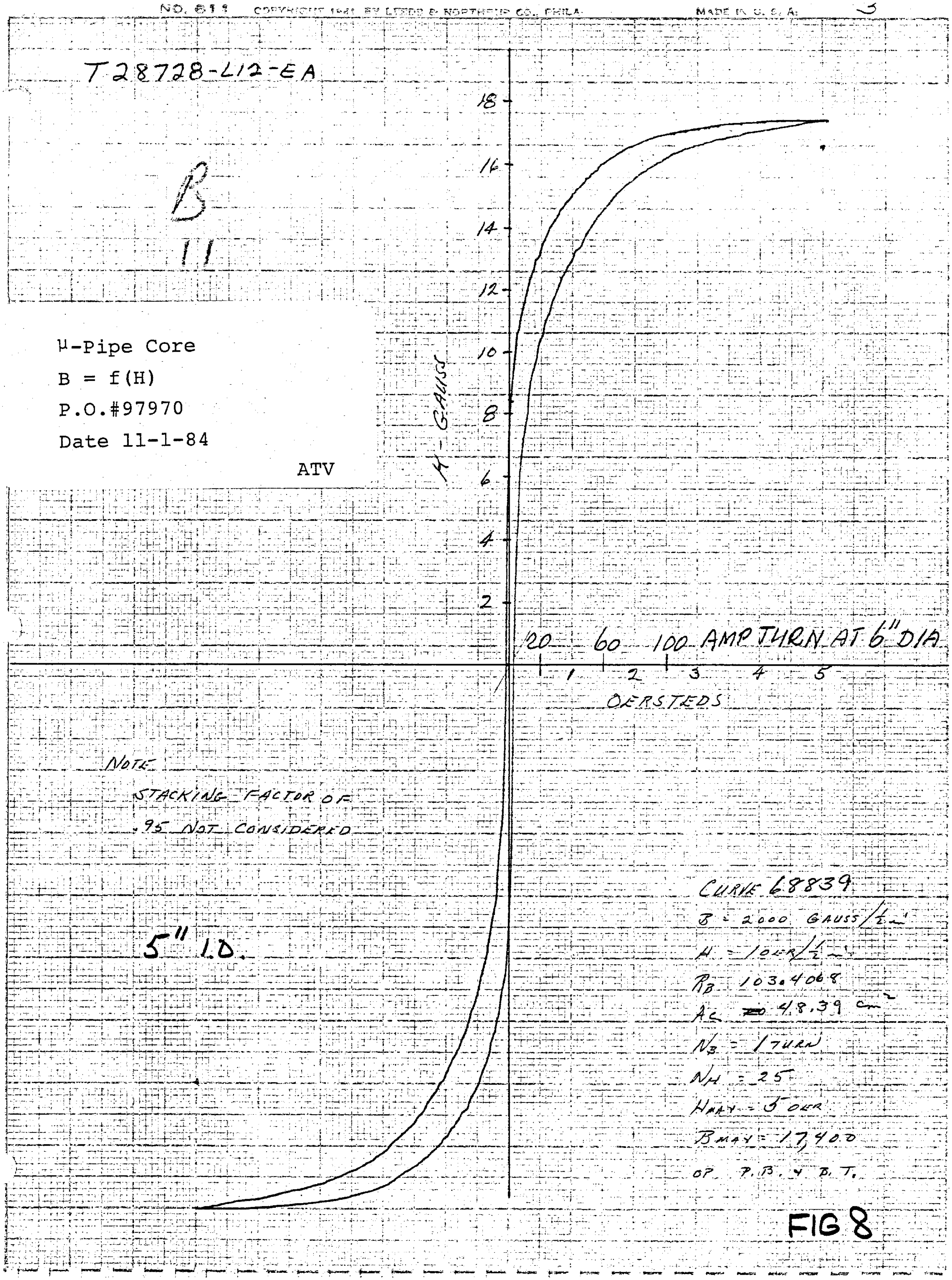


FIG 8

μ-Pipe Core
B = f(H)
P.O.#97970
Date 11-1-84

ATV

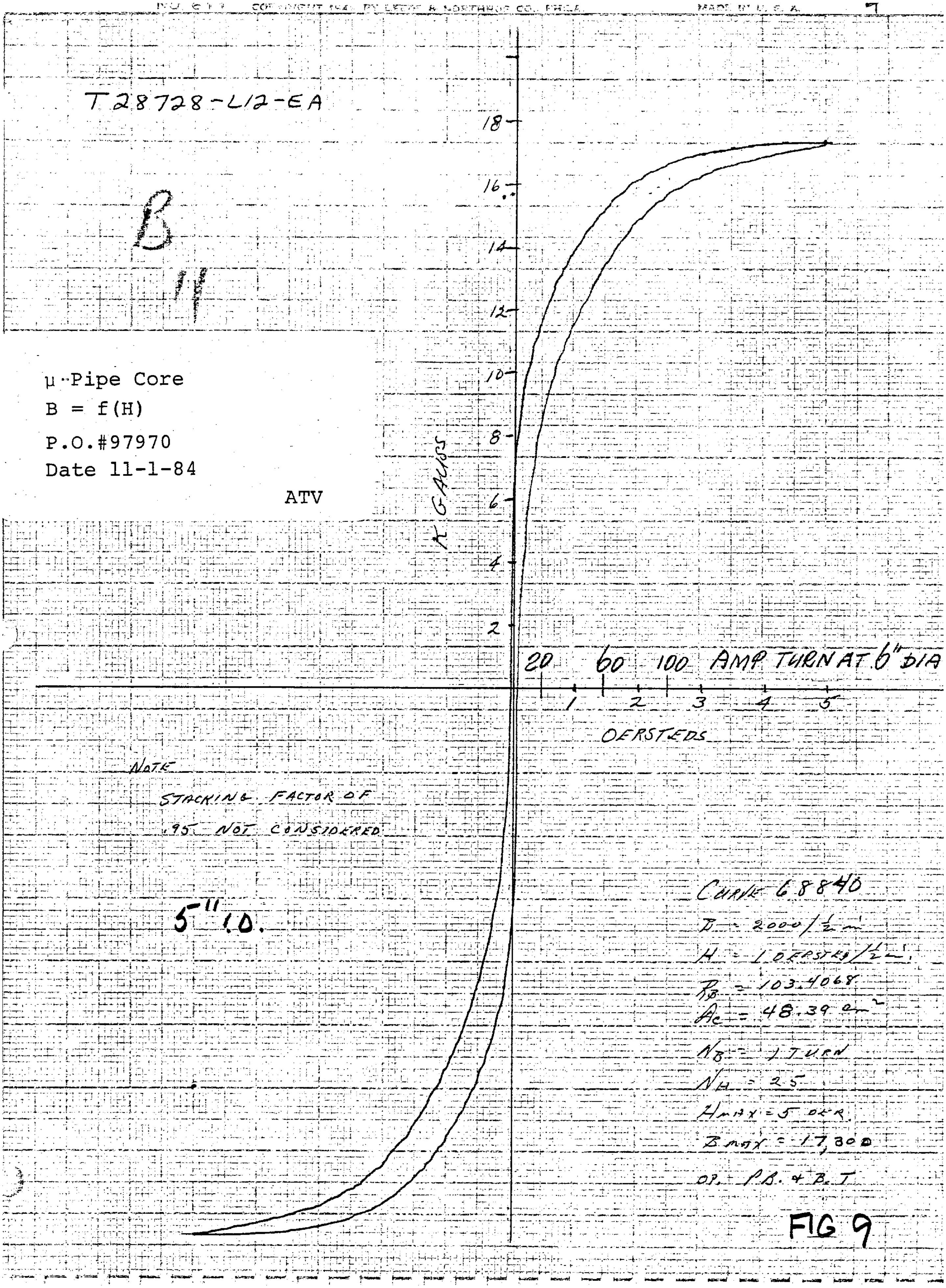


FIG 9

#5

T 28728-L12-EA

Box B

11# Pieces

μ-Pipe Core

B = f(H)

P.O. #97970

Date 11-1-84

ATV

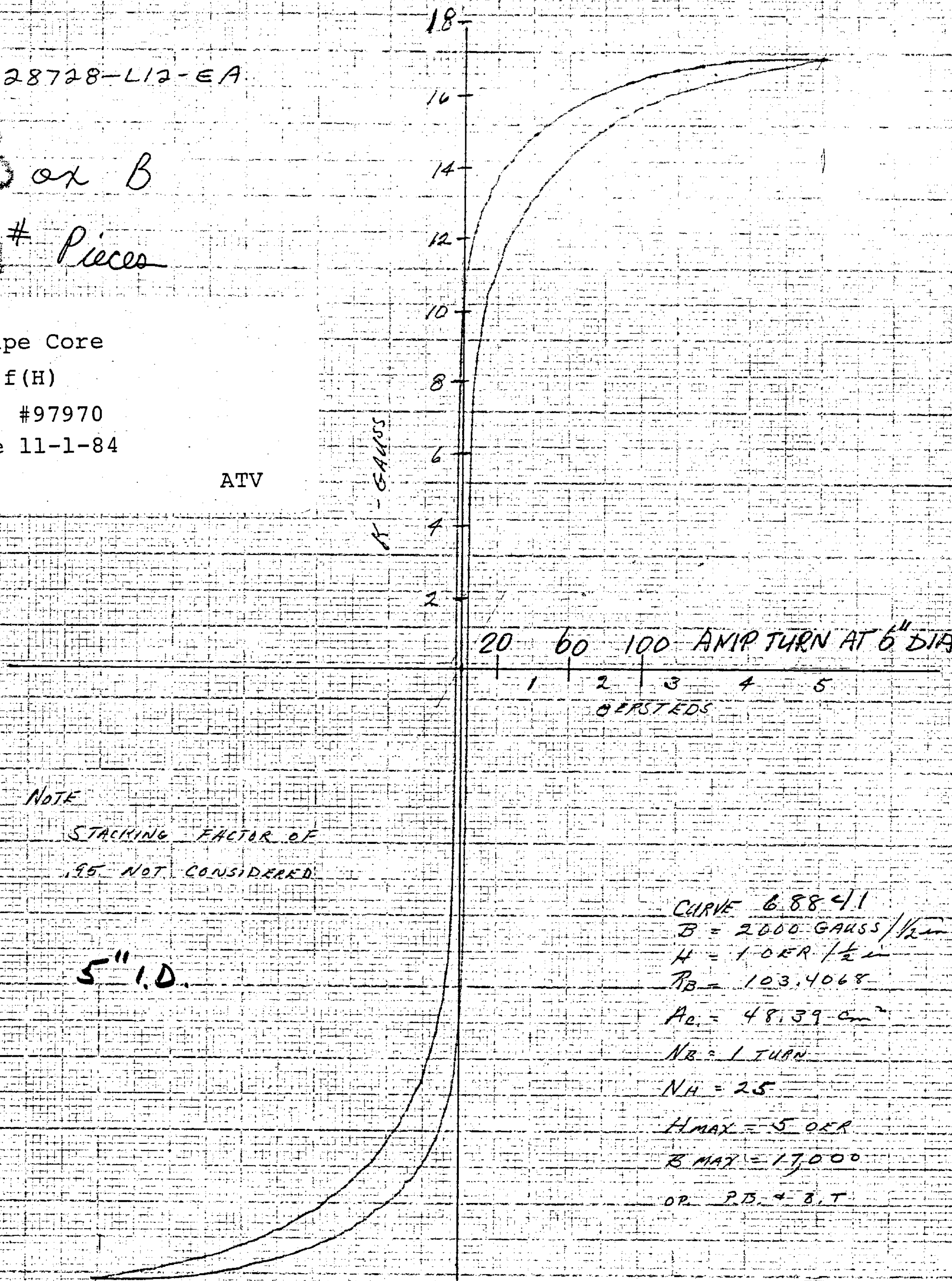


FIG 10

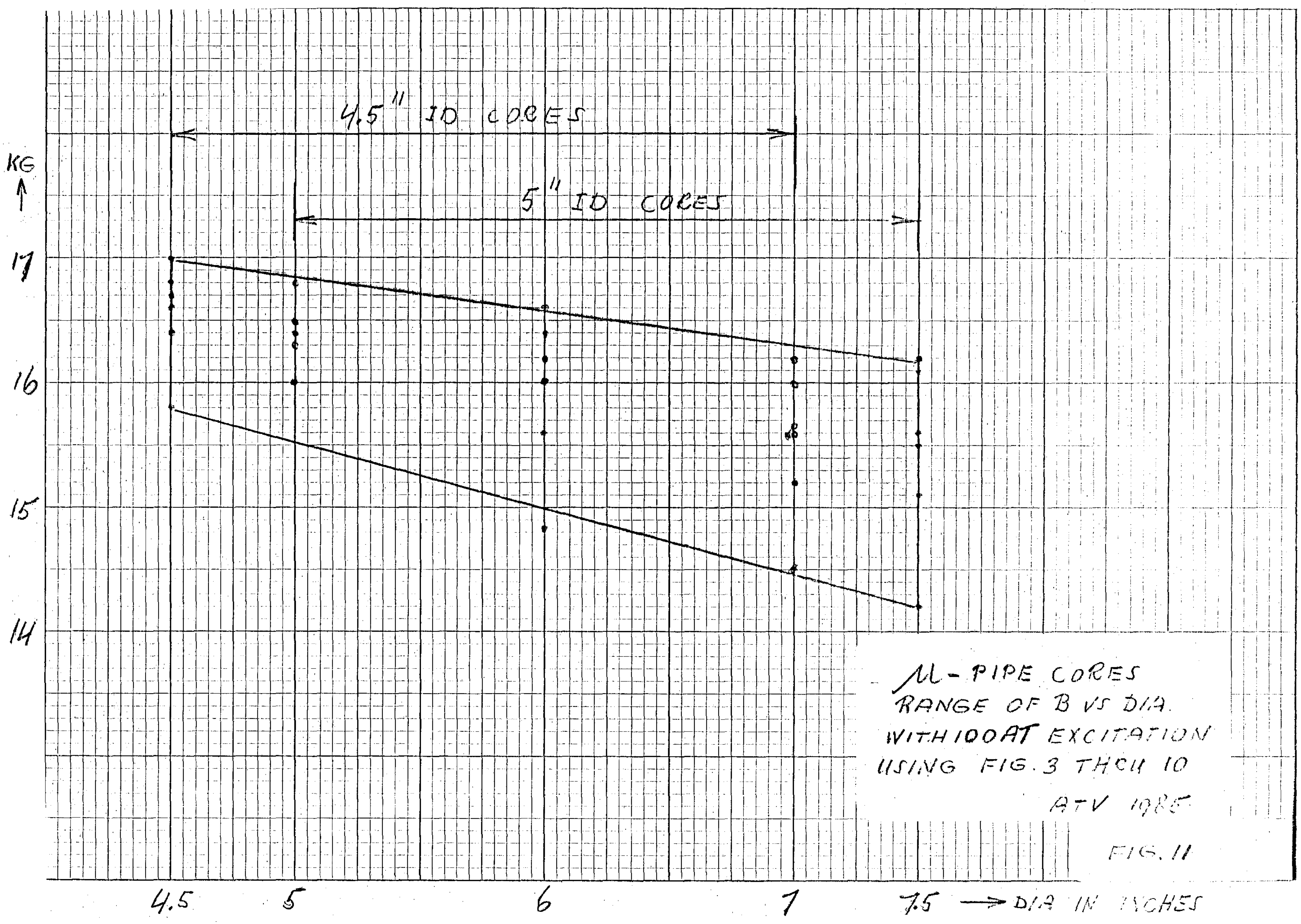

4.5" ID CORES
5" ID CORES
KG
17
16
15
14
4.5
5
6
7
7.5
DIA IN INCHES
M-PIPE CORES
RANGE OF B VS DIA.
WITH 100AT EXCITATION
USING FIG. 3 THRU 10
ATV 1985

FIG. 11

FERMILAB **ENGINEERING NOTE**

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
EED	X665	M-PIPE	1 OF 1

SUBJECT: M-PIPE AUTOMATIC DEGAUSSING AND REMANENT FIELD DETECTOR - SCHEMATIC

NAME: A.T. VISSER

DATE: 10/3/85

REVISION DATE:

DRW# ATV 100385 REV0 11/21

PREL.

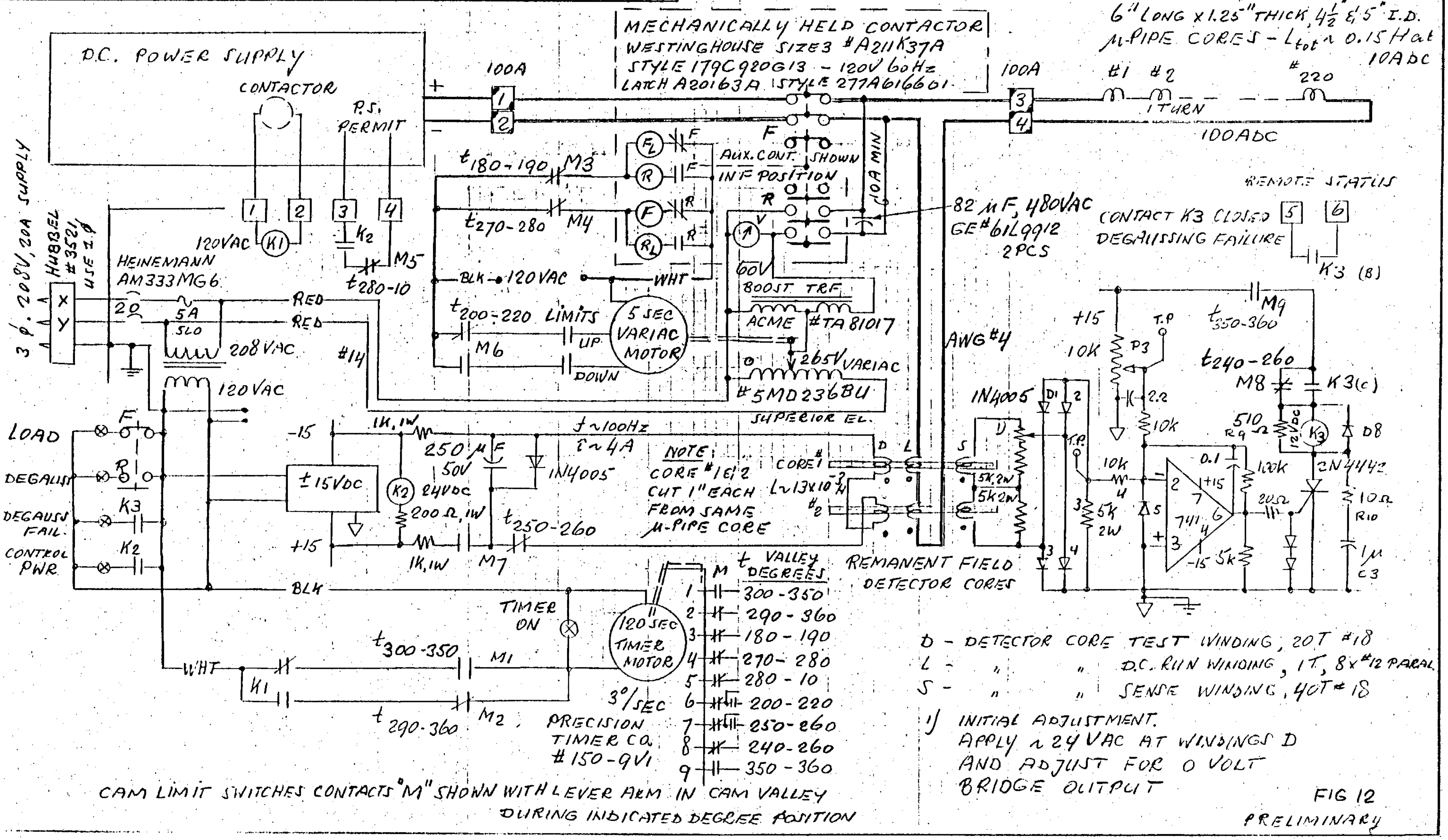


FIG 12
PRELIMINARY

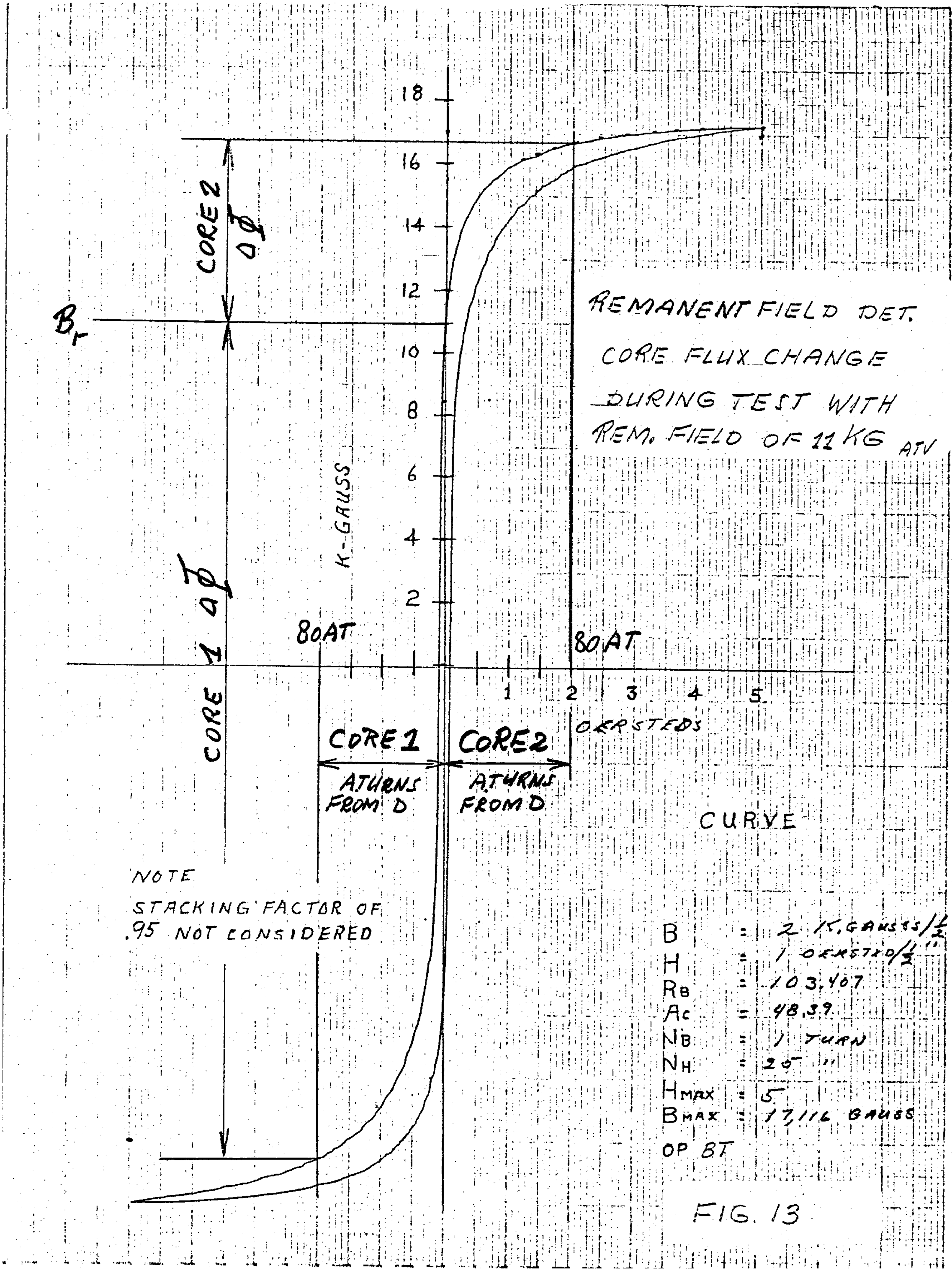
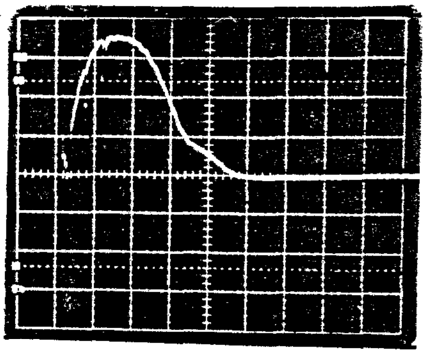

REMANENT FIELD DET.
CORE FLUX CHANGE
DURING TEST WITH
REM. FIELD OF 11 KG ATV
K-GAUSS
18
16
14
12
10
8
6
4
2
B_r
CORE 2 $\Delta\Phi$
CORE 1 $\Delta\Phi$
80AT
80AT
1
2
3
4
5
OERSTEDS
CORE 1
ATURNS FROM D
CORE 2
ATURNS FROM D
CURVE
NOTE
STACKING FACTOR OF .95 NOT CONSIDERED
B : 2 K GAUSS/½"
H : 1 OERSTED/½"
RB : 103,407
Ac : 48.39
NB : 1 TURN
NH : 25 "
HMAX : 5
BMAX : 17,116 GAUSS
OP BT

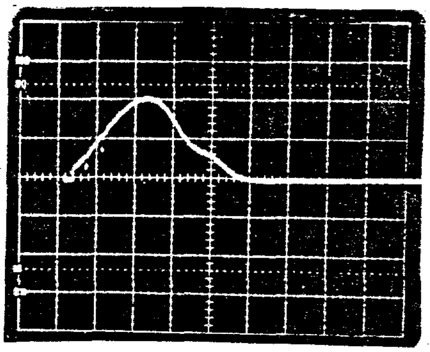
FIG. 13



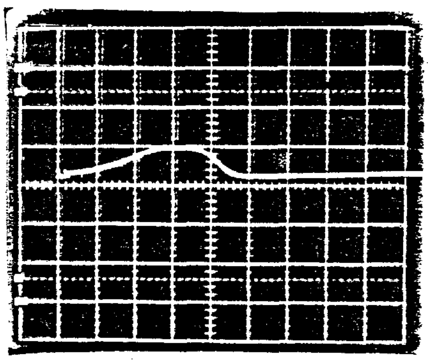
$10V/_{DIV}$ Typical

$0.5msec/_{DIV}$ Typical

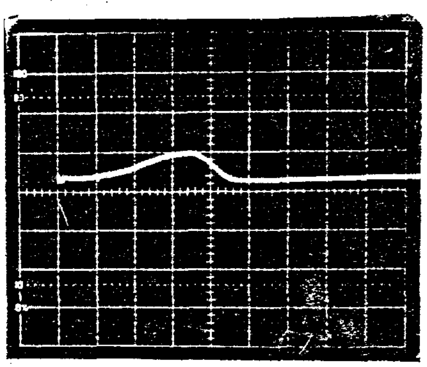
Degauss 0 Ampturn



Degauss 4 Ampturn



Degauss 8 Ampturn



Degauss 10 Ampturn

FIG. 14

Remnant field detector bridge output voltages for different 60Hz degaussing currents from a bench set up