AIIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

MANUFACTURED TO AIIM STANDARDS

BY APPLIED IMAGE, INC.

SAND94-1715C

Modeling of Transformers using Circuit Simulators

Abstract

Transformers of two different designs; an unencapsulated pot core and an encapsulated toroidal core have been modeled for circuit analysis with circuit simulation tools. We selected MicroSim's PSPICE and Anology's SABER as the simulation tools and used experimental BH Loop and network analyzer measurements to generate the needed input data. The models are compared for accuracy and convergence using the circuit simulators. Results are presented which demonstrate the effects on circuit performance from magnetic core losses, eddy currents, and mechanical stress on the magnetic cores.

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

Modeling of Transformers using Circuit Simulators

W. E. Archer, M. F. Deveney, R. L. Nagel

Sandia National Labs

Introduction

Several transformers have been modeled using two different circuit simulators, PSPICE and Saber. These simulators were selected because they model non-linear magnetics and hysteresis. Two types of transformers were modeled: pulse and power which had toroidal encapsulated and pot ferrite unencapsulated cores, respectively. It should be noted that Sandia applications often require encapsulating the cores which is not standard industry practice. For transformers with gapped cores, a linear model is usually sufficient since the cores are not driven into saturation, however actual inductance and BH Loop measurements are required for encapsulated parts with gapped cores to extract the actual permeability. The stresses on the core can change the gap and the intrinsic material permeability. The effect of stress on permeability is discussed in references 1 & 8. For encapsulated ungapped cores that are driven into saturation, actual BH Loop data is necessary for accuracy since the BH Loop data are substantially changed. The measured BH Loop data for unencapsulated transformers are generally sufficiently close to published and supplier data that one can use these data. Parasitic parameters, i.e., capacitive coupling, leakage inductance, and winding losses are needed for higher frequency simulations. Actual passive components are added to the circuit to simulate these effects. The frequencies that require the parasitic parameters depend primarily on the transformer geometries. The primary and secondary coil proximity and geometry are very significant. The effects of eddy currents depends on the core material characteristics, the conductivity of the core materials, and the core configuration, e.g. laminations.

Extraction of BH Loop Data

We used an OS Walker Hysteresis system, AMH-400, to extract the BH loop data. We measured the BH Loops at frequencies from 60 Hz to 200K Hz using sine and square wave. All of the cores were ferrite materials. We had one encapsulated gapped core which had a linear characteristic with some hysteresis, one pot core with no gap which was unencapsulated, and one toroid that was encapsulated. The most interesting effects are shown in Figure 1 for the pulse transformer with the toroidal core that was encapsulated. The BH Loop for Magnetics Inc core, R40603, which was encapsulated for this part, is quite different from the unencapsulated one. The basic shape of the BH Loop for both parts has been modified, and each of the two parts have different saturation values. Since we only have data on two parts, we can only speculate on the reasons for the different saturation values between the 2 samples. There should be no difference in the saturation values. There could be variations in the core cross sectional areas which would make our plotted results look different, since we inputted this parameter into the hysteresis system. No physical measurements were made on the cores before they were encapsulated to substantiate this hypothesis. For the unencapsulated power transformer core, Ferroxcube Core, Part No. 1811PL00-3B7, the BH Loop data for a bare core and the actual part are almost identical as shown in Figure 2. The width of the BH Loops, i.e., the apparent coercive force does increase for higher frequencies. Little difference was seen for square waves versus sine waves for driving the BH Loops, Figure 3.

Input of BH Loop data into the Simulator

Both simulators use the Jiles-Atherton model for analytical representation of BH loops. Reference 3 goes into some detail on how to match actual data with the Jiles-Atherton model. Some of the parameters are related to reality, e.g., the Ms parameter directly affects the saturate value and little else. The BH loop with the Jiles-Atherton model cannot be adjusted to match actual BH Loop data for the encapsulated toroidal part that we have with the pulse transformer. A piece-wise linear approximation to the BH Loop is possible with the SABER simulator, but has not been tried as of yet. For unencapsulated parts with no gap, the Jiles-Atherton Model can be adjusted to give a close enough approximation to actual data. For the power transformer an approximation to the actual BH loop is shown in Figure 4.

PSPICE has a technique to handle core loss. There is a parameter, Gamma, which increases the apparent coercive force.

Simulation: Accuracy

Figure 5 shows an oscillator circuit which has a center tapped transformer with two primaries and two secondaries. Figure 6 shows the operating region of the core BH Loop for this circuit. Figure 7 shows the simulation results compared to actual data. The PSPICE simulator gives reasonably accurate results. However, one problem is apparent. There is a start up problem with the PSPICE simulator. It does not allow the core to start from a saturated value. Therefore, one must disregard the first pulse unless the core starts from a demagnetized state.

Figure 8 shows the same circuit with parasitic parameters, i.e., capacitors for capacitive coupling between the primary and secondary. There is also a resistor added to simulate core loss. The parasitic parameters were measured with a HP4194 Impedance Analyzer. The coupling capacitances were measured at 10K Hz, which is close to the frequency of operation. Figure 9 shows a histogram which shows the effects of variations (manufacturing permutations like the spacing within and between the primary and secondary coils) in these parasitic parameters on the pulse amplitude. The parameters were allowed to have a 100% deviation in the Monte Carlo simulation. The simulator can also look at these effects on pulse height, frequency, rise time, etc. The effects of winding eddy currents, more commonly called "skin effect" and "proximity effect", are neglected since the circuit frequency is about 10K Hz, and small wire gauges are used. If the capacitive coupling became too large (approximately 2 orders of magnitude higher), then the circuit wave forms are like those shown in Figure 10. Estimates to the capacitive coupling can be calculated for new designs using formula given in references 5 and 6.

The parameters that can be varied in the Monte Carlo simulation are limited in PSPICE to resistors, capacitors, inductors, etc. With SABER one can also look at the effects of BH Loop variations. This is useful, since core properties can have fairly large variations in coercive force, permeabilities, etc.

Simulation: Convergence

Convergence is a troublesome problem with PSPICE for transformers with significant losses (high Gamma in the Jiles-Atherton model), and highly non-linear BH shapes. Saber improves convergence for these conditions.

The test circuits used for simulation comparisons required modification of convergence criteria, i.e., delta V & delta I, in order to obtain convergence. This is acceptable, since the voltages and currents in the circuits were several orders of magnitude greater than obtained in typical IC circuits for which most simulators are optimized. Also in PSPICE, for transient solutions one can control the number of iterations at a given time interval, reference 7. For the power transformer circuit, a study was done to examine the effects of this parameter. Fifty Monte Carlo runs were made varying the parasitic parameters. Using the default number for iterations ITL4=10, 16 of the solutions did not converge. By increasing ITL4 to 40, only 6 did not converge. Increasing ITL4 to 400 provided convergence for all 50 Monte Carlo runs and did not increase the run time.

For the higher frequency simulation with the test circuits (50-200KHz), Saber allows additional parameters to correct the BH Loop for eddy currents and core losses. For example, this will show the effect of applying a single square wave pulse for a pulse transformer. The higher frequency components will produce eddy current effects in the core of the transformer. With PSPICE, one has to select the frequency of operation and use the corresponding BH Loop. A simple way to simulate core losses in PSPICE is to add a resistor in parallel with the primary coil, as was done in the Monte Carlo simulations. Another way is to add the Gamma parameter; this increases the apparent hysteresis of the BH Loop which can simulate eddy current losses. The Saber approach can improve the accuracy for simulation of circuit with higher frequency components because one does not need to select a single frequency.

Conclusion

Nonlinear transformers require real data for accurate simulation. The effects of stress can substantially change the BH Loops for ferrite cores and encapsulated cores with gaps. These effects have to be built into the BH Loop that is used by the circuit simulators. Accurate modeling of these stress effects is not always possible with the standard Jiles-Atherton Model. The equations used for this model do not allow for accurate representation for stressed components. However, the errors introduced because of inaccurate BH Loops are hard to estimate without accurate simulation. Both simulators, PSPICE and SABER, provide accurate results for the low frequency oscillator circuit that was modeled. However for higher frequency simulations, additional parasitic parameters must be added for accurate simulation with PSPICE. The SABER simulator has built in modeling capability for core losses and eddy current effects, but one does need to add passive components to simulate coil coupling effects.

References:

(1) F. N. Bradley, **Materials for Magnetic Functions**, Hayden Book Company, 1971, pgs 41ff

(2) D. C. Jiles and D. L. Atherton, " Theory of Ferromagnetic Hysteresis," J. Magnetism and Magnetic Materials, vol. 61, pp. 48-60, 1986

(3) Stephen Prigozy, " PSPICE Computer Modeling of Hysteresis Effects", IEEE Transactions on Education, vol. 36, no. 1, Feb 1993

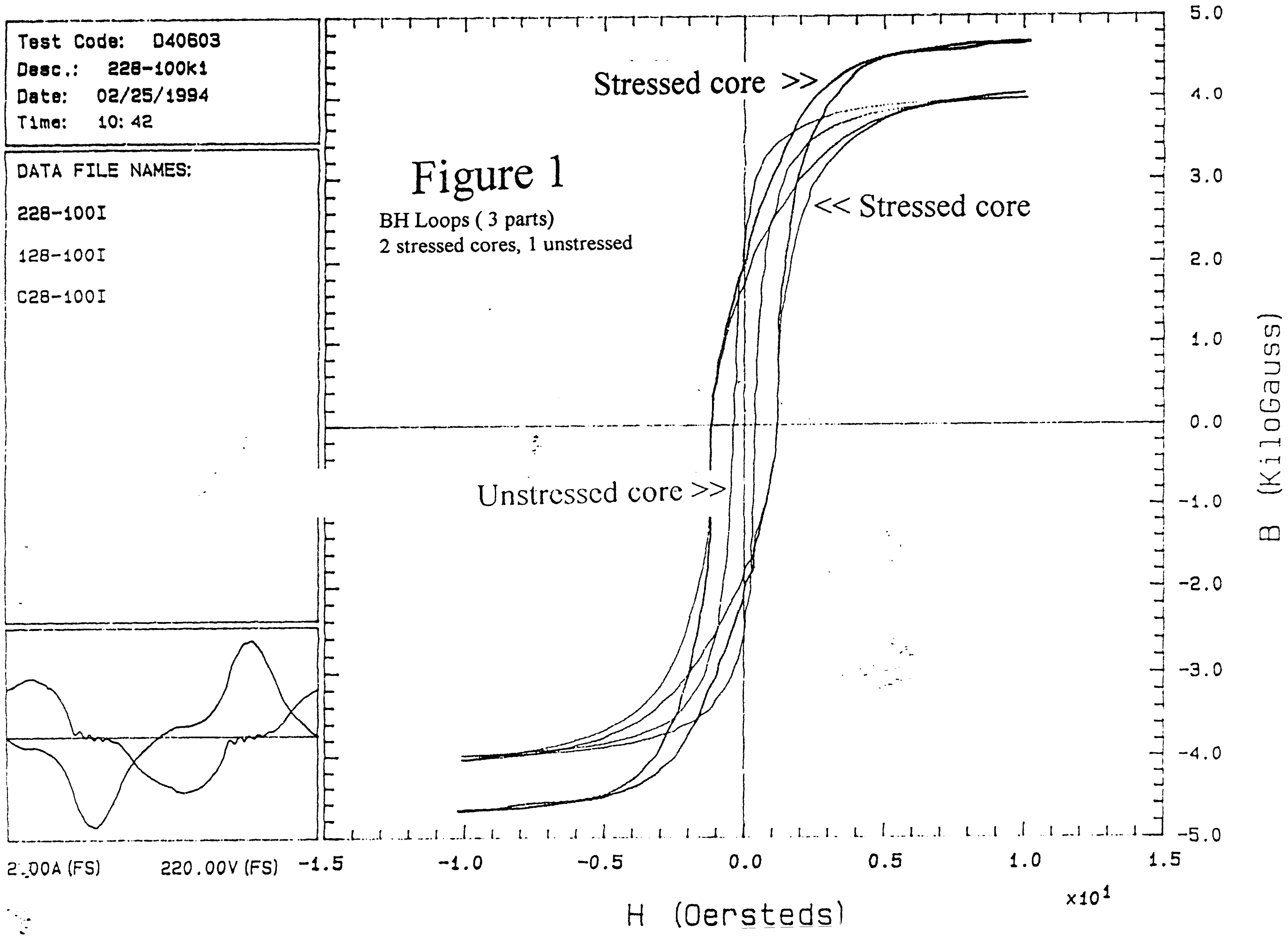
(4) J. H. Chan, et al, "Transformer Modeling Model for Circuit Simulation", IEEE Transactions on Computer Aided Design , vol. 10, no. 4, April 1994

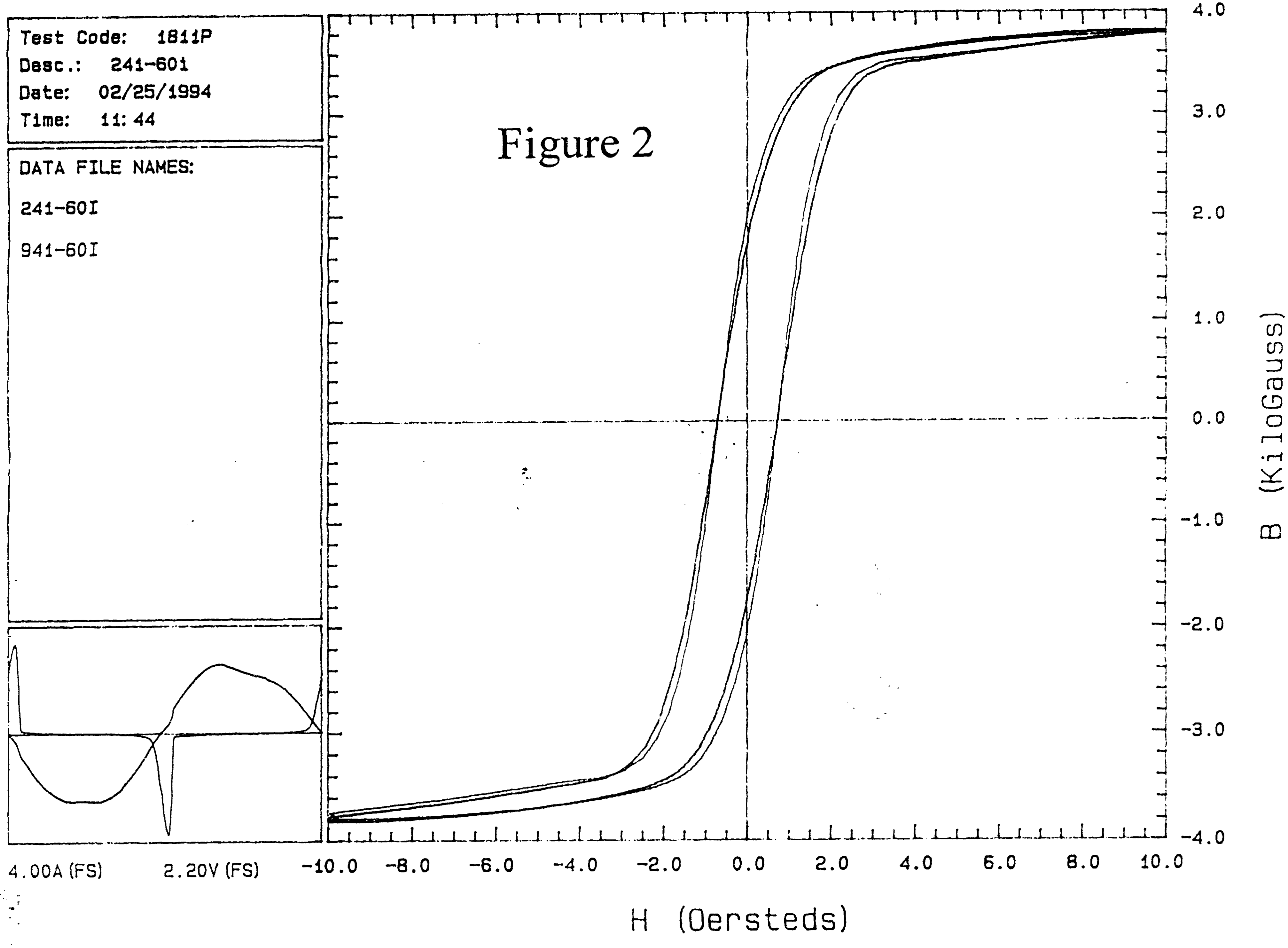
(5) E. C. Snelling, **Soft Ferrites**, Iliffe Books, 1969, pgs 350ff

(6) W. T Duerdoth, "Equivalent capacitances of transformer windings", Wireless Engr, 23, 161, (1946)

(7) R. M. Kielkowski, **Inside Spice** , McGraw-Hill Inc., 1994, pgs 60ff

(8) R. M. Bozorth, **Ferromagnetism**, D. Van Nostrand, 1951, pgs 585ff


Test Code: D40603
Desc.: 228-100k1
Date: 02/25/1994
Time: 10: 42
DATA FILE NAMES:
228-100I
128-100I
C28-100I
Figure 1
BH Loops (3 parts)
2 stressed cores, 1 unstressed
Stressed core >>
<< Stressed core
Unstressed core >>
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
B (KiloGauss)
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
x10^1
H (Oersteds)
2.00A (FS)
220.00V (FS)



Test Code: 1811P
Desc.: 241-601
Date: 02/25/1994
Time: 11:44
DATA FILE NAMES:
241-60I
941-60I
4.00A (FS)
2.20V (FS)
-10.0 -8.0 -6.0 -4.0 -2.0 0.0 2.0 4.0 6.0 8.0 10.0
H (Oersteds)
4.0 3.0 2.0 1.0 0.0 -1.0 -2.0 -3.0 -4.0
B (KiloGauss)
WALKER SCIENTIFIC INC.

Figure 2

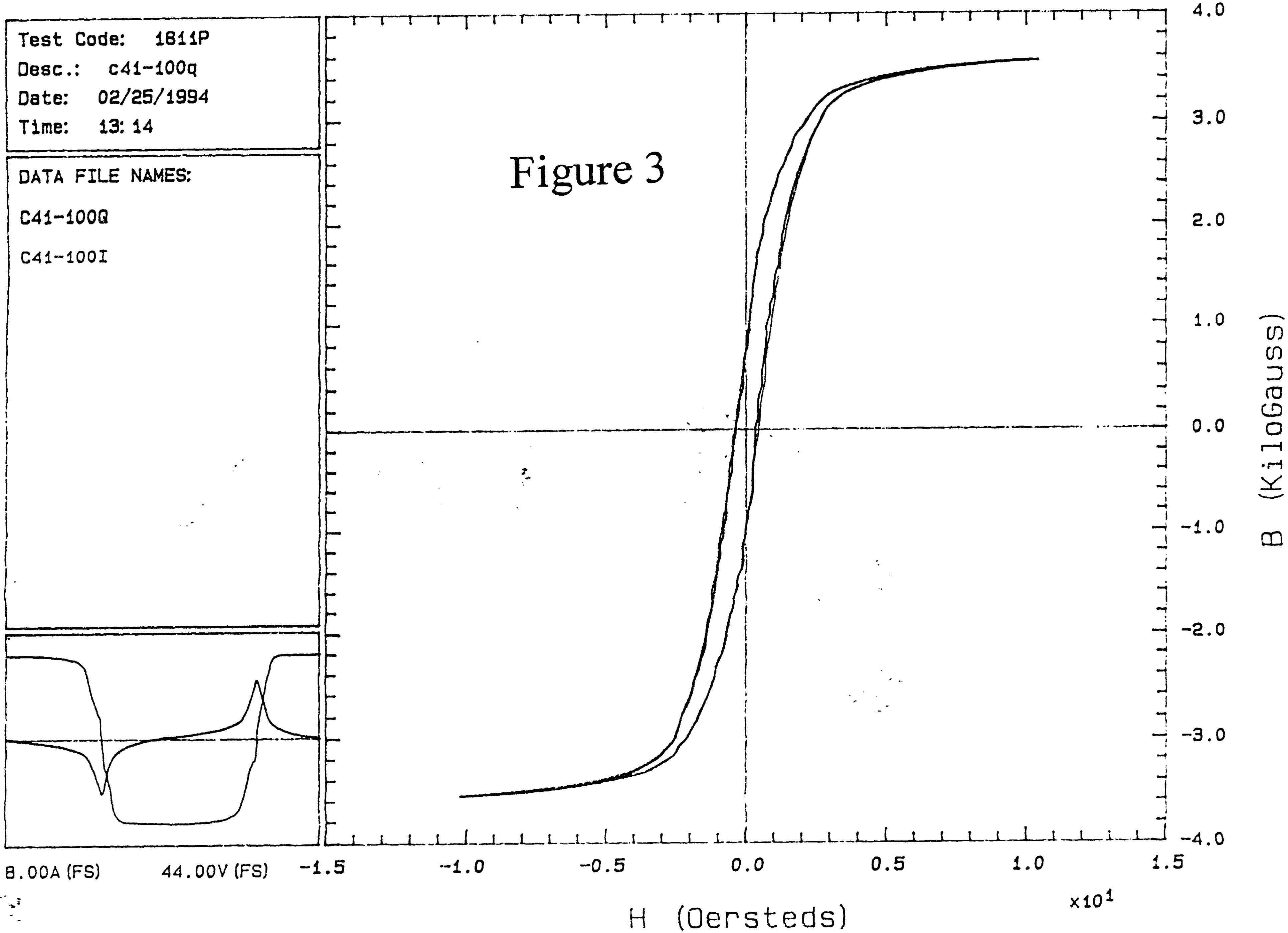


Figure 3

WALKER SCIENTIFIC INC

* C:\MSIM54\bhloop.sch

Date/Time run: 03/01/94 13:07:26 Temperature: 27.0

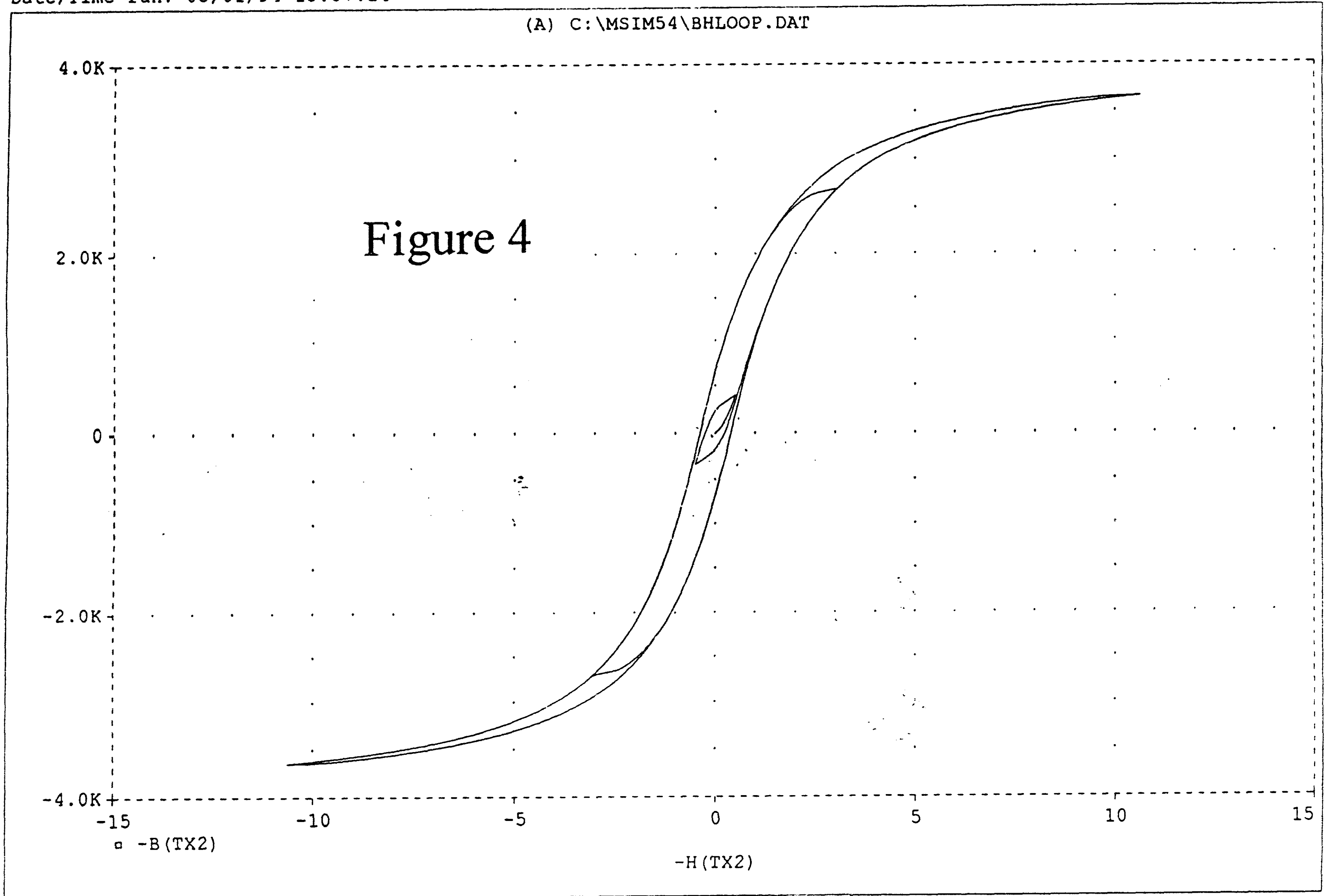


Figure 4

Date: March 01, 1994 Page 1 Time: 13:09:55

Oscillator Circuit

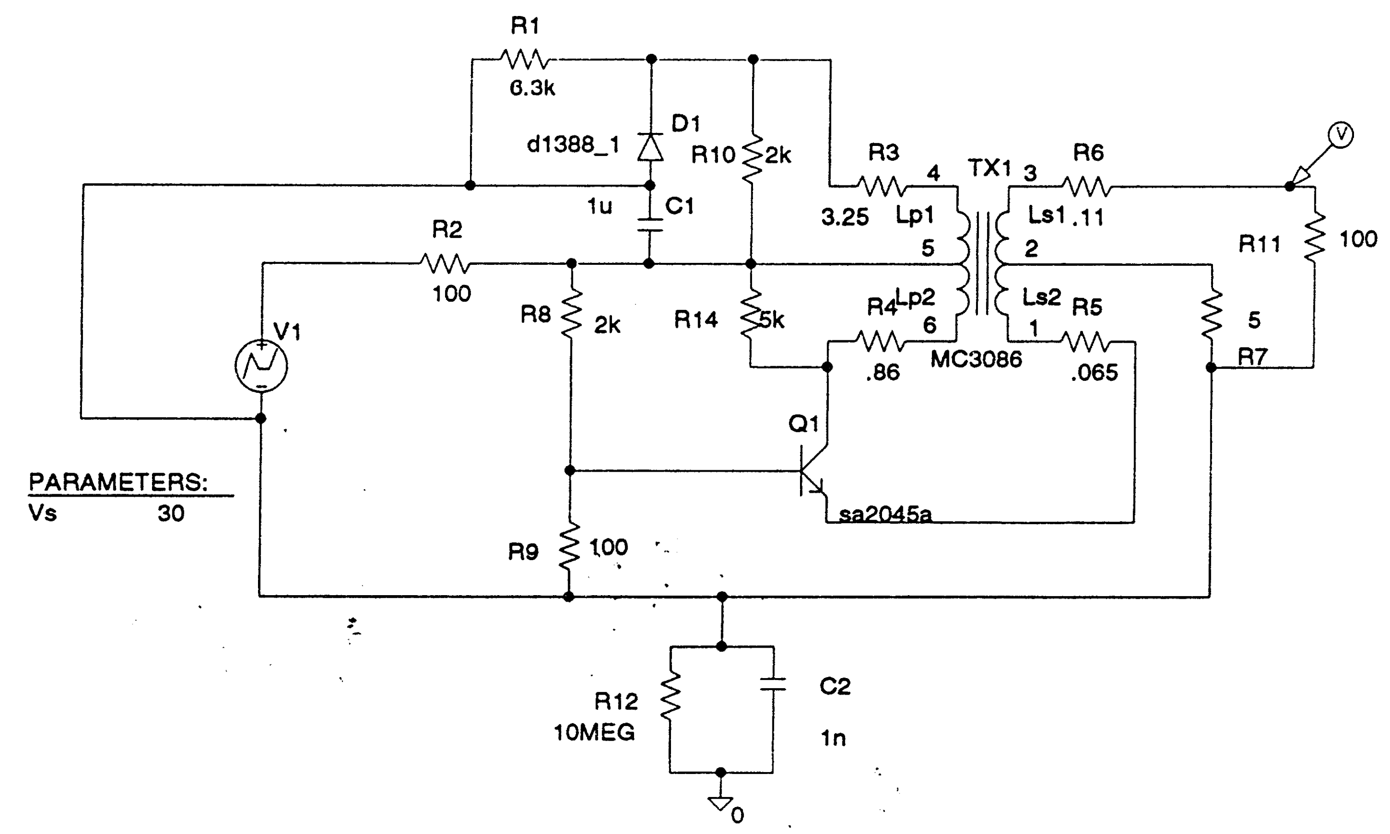


FIGURE 5

6/1/94

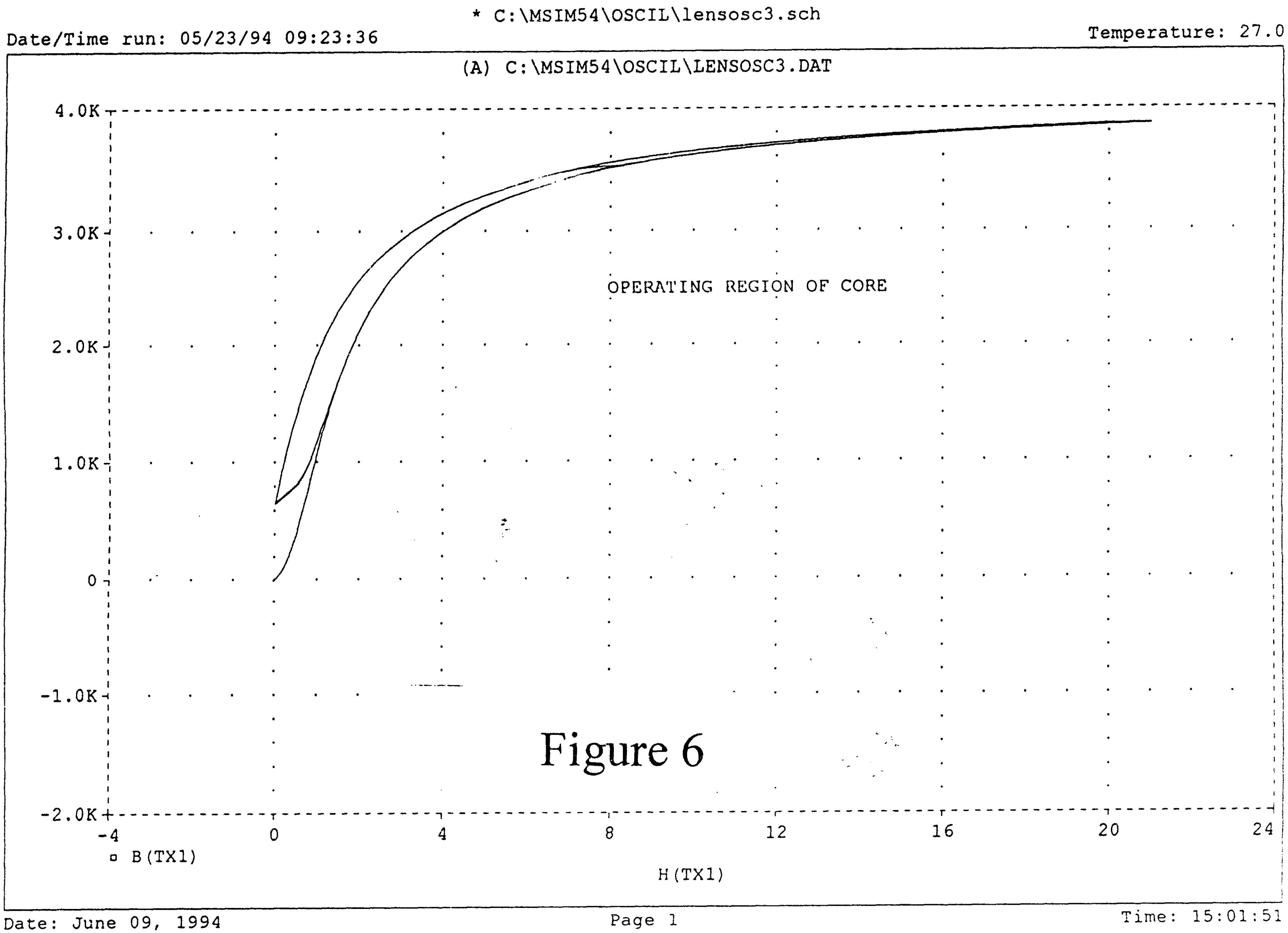
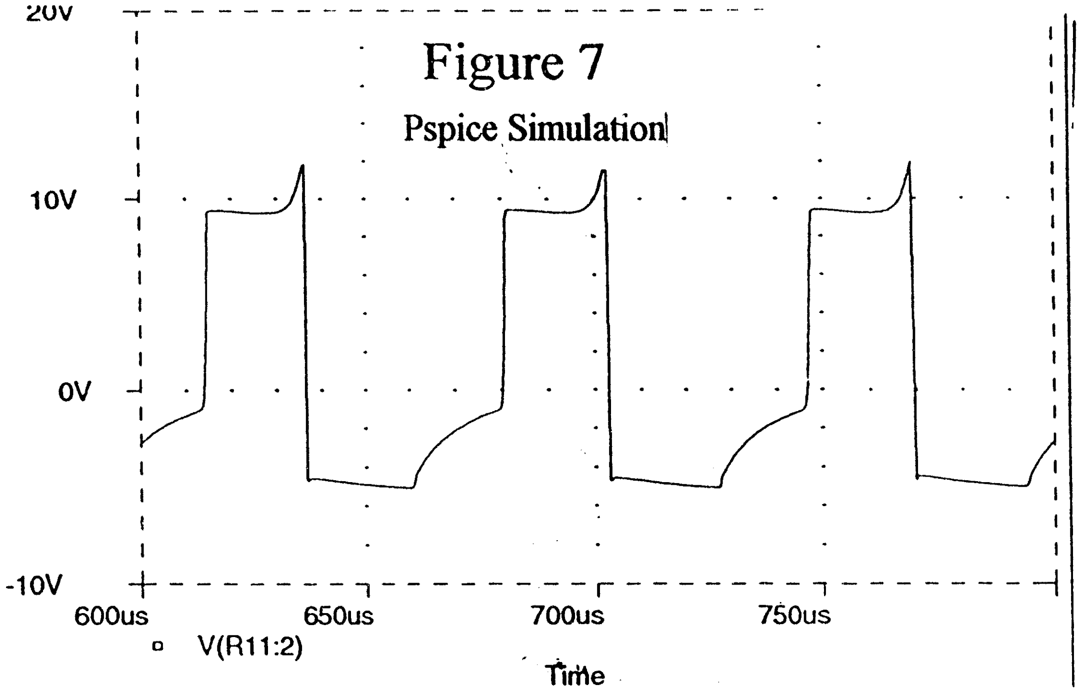
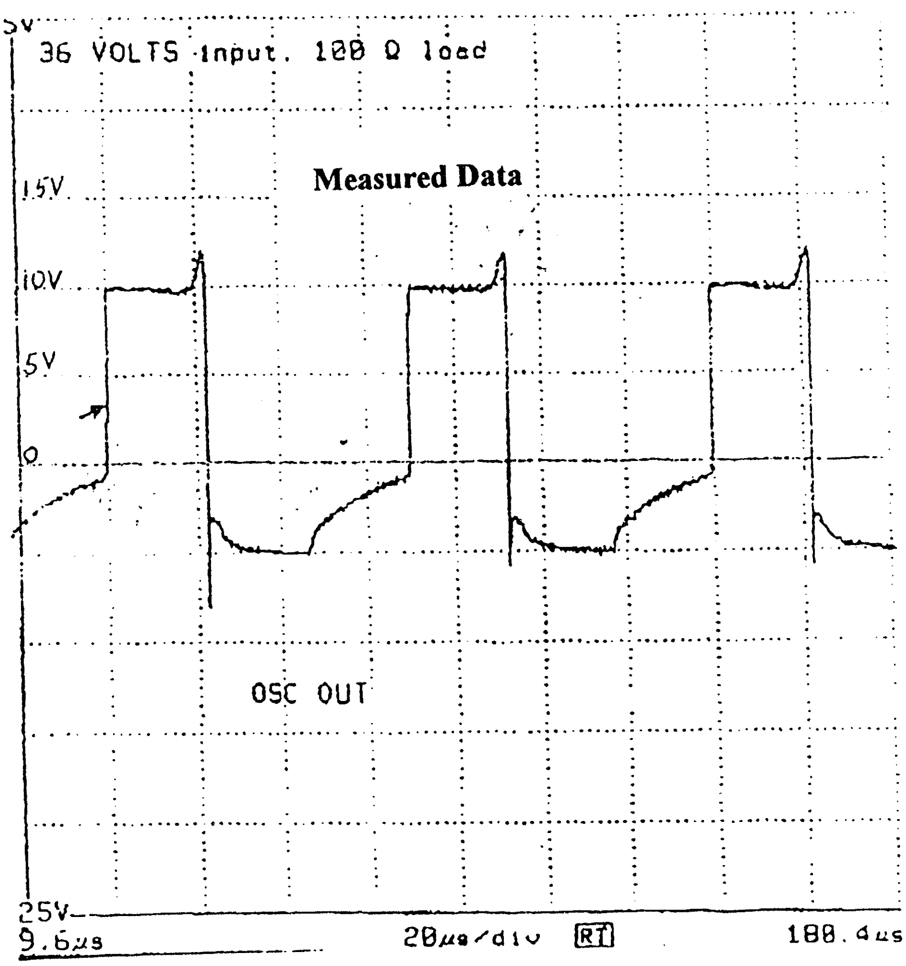

* C:\MSIM54\OSCIL\lensosc3.sch
Date/Time run: 05/23/94 09:23:36
Temperature: 27.0
(A) C:\MSIM54\OSCIL\LENSOSC3.DAT
4.0K
3.0K
2.0K
1.0K
0
-1.0K
-2.0K
OPERATING REGION OF CORE
-4
0
4
8
12
16
20
24
B(TX1)
H(TX1)
Date: June 09, 1994
Page 1
Time: 15:01:51

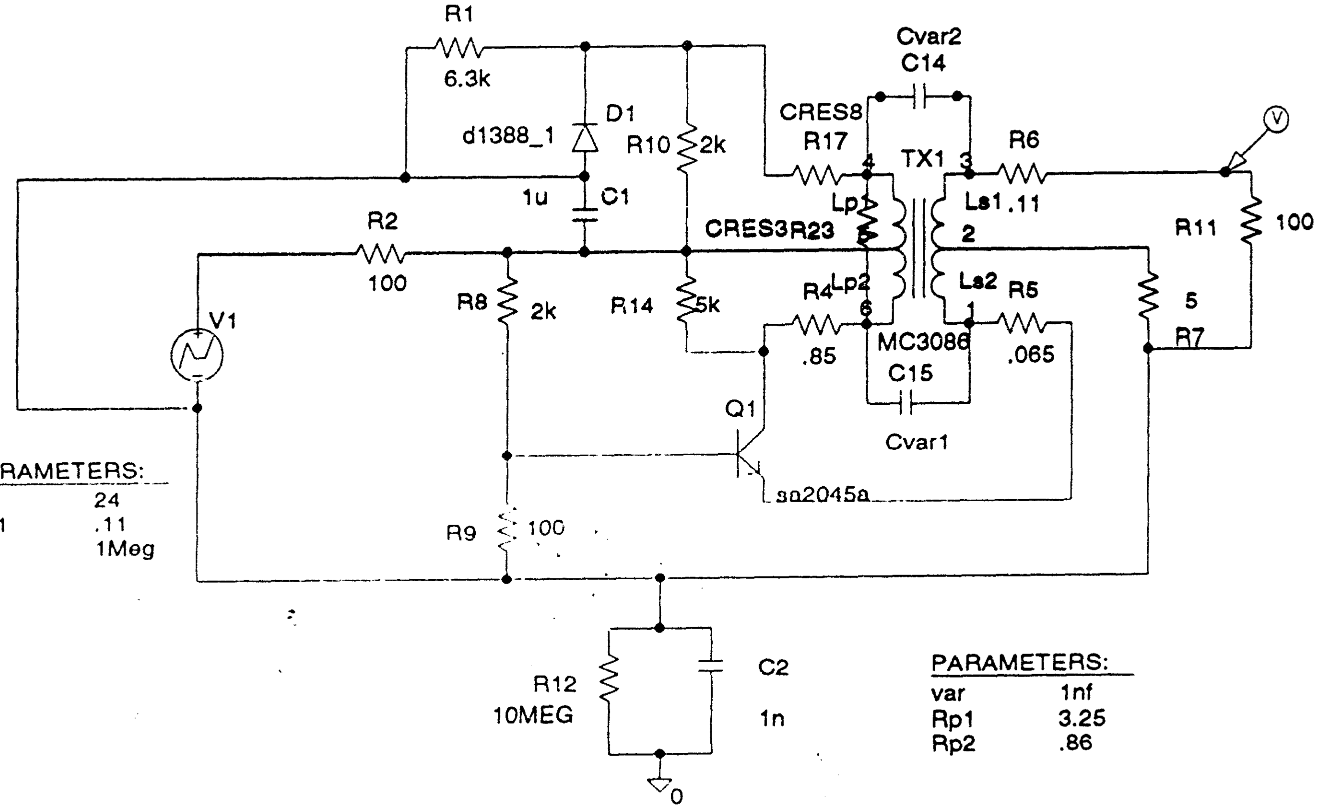
Figure 6

Figure 7


Pspice Simulation
20V
10V
0V
-10V
600us
650us
700us
750us
V(R11:2)
Time


36 VOLTS input. 100 Ω load
Measured Data
15V
10V
5V
0
OSC OUT
25V
9.6µs
20µs/div
RT
180.4µs

OSICILLATOR CIRCUIT WITH PARASITICS



PARAMETERS:	
Vs	24
Rs1	.11
RV	1Meg

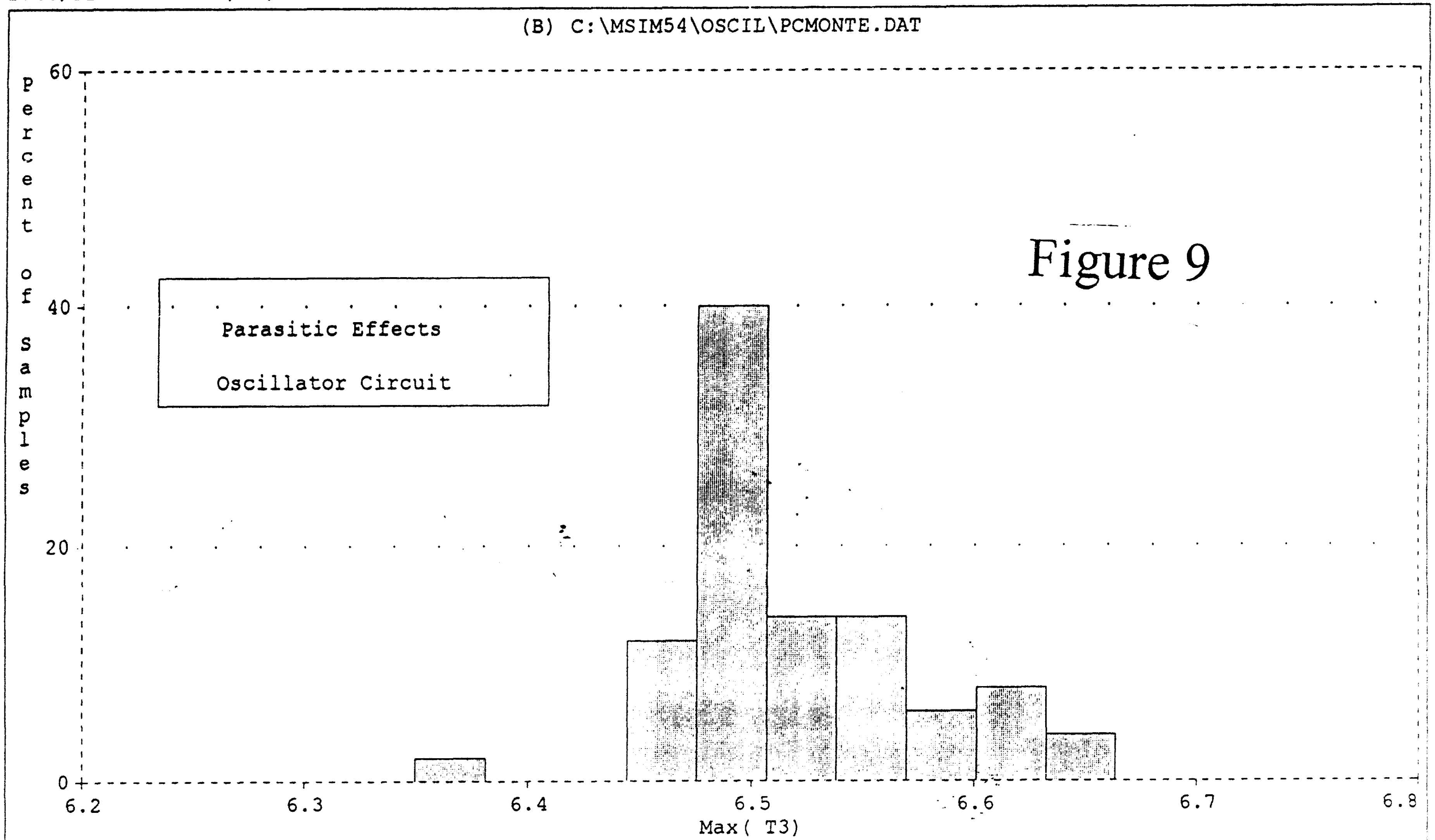
PARAMETERS:	
var	1nf
Rp1	3.25
Rp2	.86

FIGURE 8

* C:\MSIM54\OSCIL\pcmonte.sch

Date/Time run: 06/01/94 09:11:19

Temperature: 27.0



n samples	= 50	sigma	= 0.0590951	median	= 6.50383
n divisions	= 10	minimum	= 6.34972	90th %ile	= 6.61219
mean	= 6.51965	10th %ile	= 6.46569	maximum	= 6.66366

* C:\MSIM54\OSCIL\pcvar.sch

Date/Time run: 06/09/94 16:17:58 Temperature: 27.0

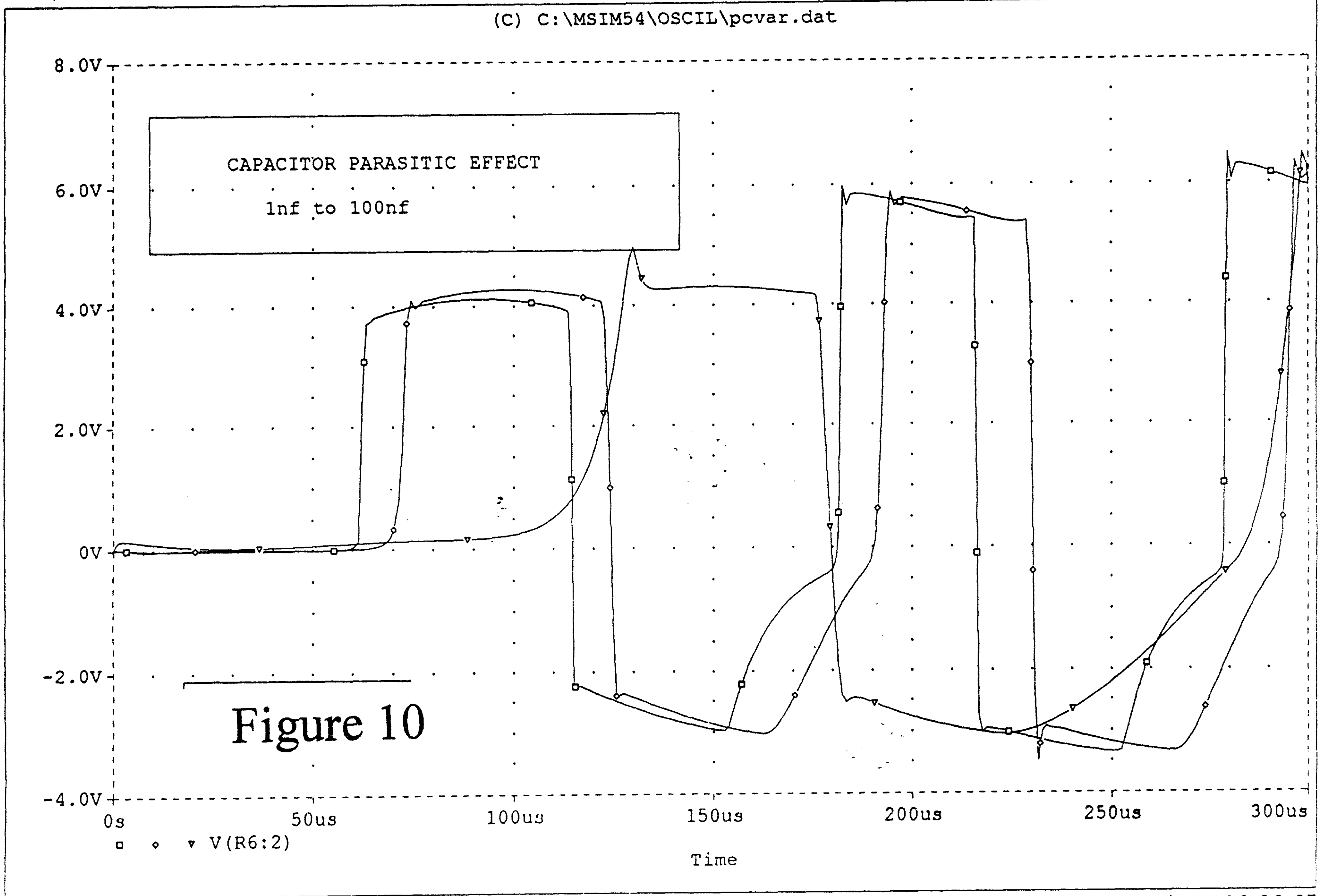


Figure 10

Date: June 09, 1994 Page 1 Time: 16:26:27

II

DATE FILMED

8/23/94

END