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Explosively-Driven Magnetohydrodynamic Generator: Phase II

Manuel G. Vigil

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
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Explosively-Driven Magnetohydrodynamic Generator: Phase II

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Abstract

Phase II work for this Laboratory Directed Research and Development project is presented. Historically, high velocity, solid, electrically conducting armatures or projectiles have been utilized to generate or magnify existing electric fields in magnetohydrodynamic (MHD) devices. Useful power can be extracted from high velocity ionized, electrically conductive plasma jets. The MHD device current output can be switched to power other devices. The purpose of this project is to investigate the use of an Explosively-Driven Ionized Plasma Jet Generator (EDMG) to more efficiently obtain velocities much higher than can be achieved with solid armatures or projectiles. The armature velocity is one of the more important parameters in the electric field magnification process. The ionized plasma jet is generated by explosively collapsing a gas (neon, argon, xenon, hydrogen) filled cavity and directing the jet through a shocktube or core of an MHD device.

Data are presented for two different size and configuration explosive drivers, one explosive (COMP-C4), one gas (argon), different driver pressures (90 - 200 psia), different shocktube or test section pressures (0.01 - 11.7 psia), and for two different shocktube inside dimensions.

Measured time-of-arrival, current, voltage, resistance, power and energy data are presented for tests conducted. Measured time-of-arrival and plasma flow velocity data are compared to the predicted CTH hydrocode data. CTH code calculations are also presented to compare EDMG performance of various test gases and various explosive liner materials.

Acknowledgments

Thanks to Ben Duggins and especially to Ron Kaye for a very thorough review of this report. Ron Kaye designed the electromagnets for these tests and performed the analyses for the predicted performance. Ed Ratliff provided support for Ron Kaye in the electromagnet and capacitor bank hardware installation (operation also) and recording system instrumentation and recording.

John Gaudet, Phillips Lab (PL), coordinated the Sandia, DOE, Air Force, Maxwell Labs, and Phillips Lab team efforts throughout the project this year. Mark Lehr (PL) and Dan Schiffler (PL) designed and fabricated the electronic circuits for the loads attached to the electromagnets. Wayne Summers (Maxwell Lab) was responsible for moving, preparation, and operation of No. 1.5 megajoule capacitor bank system used on the HERTF test.

Donnie Marchi was responsible for interfacing with the Design Definition Department, purchasing of hardware, and scheduling of test site.

John Lanoue, Marc Hagan (Ktech) and Jerry Brock conducted all tests at the Area II, Building 907 test site, wrote the Operating Procedure, which was an addendum to the existing Safe Operating Procedure for the site, and also wrote the extensive checklist for the explosive tests. John and Jerry also were responsible for assembly of the pressure/vacuum hardware, for procuring all plumbing, vacuum pumps, gages, valves, etc.

Ed Mulligan provided the fabrication of the diagnostic sensors, execution of the calibration tests, installation of the instrumentation into the shocktube, and in the data reduction.

Bruce Berry coordinated the test schedules, safety procedure documentation, and provided the interface for communication with range safety activities within and outside Sandia (DOE, Air Force, ECF contractors, etc.).

Theresa Broyles (Ktech) fabricated the required instrumentation system cables and, together with Rick Saxton (Ktech) and Marc Hagan, assisted with test site safety surveillance at test time.

Explosive loading at Sandia was conducted by the Building 9960 team comprised of Ray Cooper, Doug Cox, and Gene Haynes.

Note: Use of trade names (Lexan, Mylar, etc.) implies no endorsement.

CONTENTS

Figures

Table

Nomenclature

MHD	magnetohydrodynamic
EDMG	explosively-driven magnetohydrodynamic generator
EMP	electromagnetic pulse
CTH	"C to the third power" hydrodynamic code
OCVP	open circuit voltage probe
PRP	plasma resistance probe
PCP	plasma current probe
di/dt	current differential
LED	light emitting diodes
VT	voltage-time constant
COMP-C4	explosive
MACH2	MHD code
MDF	mild detonating fuse

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Explosively-Driven Magnetohydrodynamic Generator: Phase II

I. Introduction

Phase II work for this Laboratory Directed Research and Development project is presented. Phase I of this work was published in Reference 1. One of the various ways to characterize explosively-driven magnetohydrodynamic (MHD) Faraday generators is by the power output and ionized flow (plasma flow) duration time as described in Reference 1. Explosively-driven MHD generators (EDMG) are usually classified as pulsed plasma devices and can also be characterized as described in Reference 1. The EDMG consists of an explosive driver, a shocktube or channel test section, and electromagnet coils as shown in Figure 1. Permanent magnets can be substituted for the electromagnet for lower power output requirements.

Historically, high velocity, solid, electrically conducting armatures or projectiles have been utilized to generate or magnify existing electric fields in MHD devices. Useful power can also be extracted from high velocity ionized, electrically conductive plasma flow. The MHD device current output can be used to power other devices or be rapidly switched to produce an Electro-Magnetic Pulse (EMP). The purpose of this project is to investigate an Explosively-Driven Magnetohydrodynamic Generator (EDMG)[1-2] which can more efficiently obtain velocities much higher than can be achieved with solid armatures or projectiles. The plasma or armature velocity is one of the more important parameters in the electric field magnification process. The plasma jet is generated by explosively collapsing a gas (neon, argon, xenon, hydrogen) filled cavity (similar to shaped explosive charge technology) and directing the flow through a shocktube or core of an MHD device as shown in the conceptual configuration of Figure 1.

This technology could have the following significant applications:

(1) MHD generator to drive Electromagnetic Source pulsed power devices;
(2) MHD generator to produce an Electromagnetic Pulse (EMP) for a mine clearing device in conventional warfare;
(3) EMP devices can also be incorporated in land-fired or space-launched terminal defense weapon systems; and
(4) Stun gun using the EMP to temporarily disable personnel in conventional war, terrorist related scenarios, and riot (prison) situations.

The goals of this project are to:

(1) Optimize the explosive driver geometry and materials;
(2) Validate CTH hydrocode (used to design optimized explosive driver) models to predict the flow parameters;

(3) Develop diagnostic instrumentation system to measure the MHD device output parameters;
(4) Validate the MHD code models to predict plasma and MHD device output parameters;
(5) Design an MHD device for one application; and
(6) Demonstrate subsystem application.

The five tests conducted in this Phase II study are listed in Table I. Data are presented for three different size and configuration explosive drivers, one explosive (COMP-C4), one driver gas (argon), different driver pressures (90 - 200 psia), different shocktube or test section pressures (0.01 - 11.7 psia), and for two different shocktube maximum inside dimensions (2.0 and 12.0 inches).

Measured time-of-arrival, current, voltage, resistance, power, and energy data are presented for some of the tests conducted. Measured time-of-arrival and plasma flow velocity data are compared to the predicted CTH hydrocode calculations. CTH code predictions are also presented to compare EDMG performance of various test gases and various explosive liner materials.

II. Explosive Driver Hardware

Three different designs for the EDMG were completed and tested in Phase II of this project. Three EDMG designs were completed and tested in Phase I of this project. The three designs for Phase II are shown in Figures 2 through 4. The three different size and geometry devices contained 1.7, 2.0, and 35.0 pounds of explosives respectively.

EDMG Design 5

The EDMG Design 5 hardware is shown in Figure 2. This design features an eight-point (eight-line) mild detonating fuse (MDF) line to achieve simultaneous initiation of the COMP-C4 cylindrical explosive charge as shown. A single RP-2 detonator initiated the eight each, 2 grain/foot, PETN explosive, aluminum sheathed MDF lines. A 0.05 inch thick, cylindrical, aluminum liner is used to initially separate the ionized noble gas or plasma from the detonation gas products. An aluminum nozzle was used to reduce the plasma flow from 4.5 inch diameter to the 0.5 x 2.0 inch inside dimensions of the rectangular Lexan shocktube. The 0.015 inch Mylar diaphragm for this design was located at the entrance of the shocktube. Argon gas was used in the driver section cavity. Design 5 hardware was loaded with COMP-C4 explosive at Sandia's explosive machining site.

EDMG Design 6

The EDMG Design 6 hardware is shown in Figure 3. This design features a single-point (RP-1 detonator) initiation of the COMP-C4, cylindrical explosive charge. A 0.05 inch thick, cylindrical, aluminum liner is used to initially separate the ionized noble gas or plasma from the detonation gas products. An aluminum nozzle was used to reduce the plasma flow from 4.4 inch diameter to the 0.5 x 2.0 inch inside dimension of the rectangular Lexan shocktube. The 0.015 inch thick

Mylar diaphragm for this design was located at the entrance of the shocktube. Argon gas was used in the driver section cavity. Design 6 hardware was loaded with COMP-C4 explosive at Sandia's explosive machining site.

EDMG Design 7

The EDMG Design 7 hardware is shown in Figure 4. This design features a four-point (RP-1 detonator) initiation of the COMP-C4, explosive charge as shown in Figure 4. A 0.05 inch thick, cylindrical, aluminum liner is used to initially separate the ionized noble gas or plasma from the detonation gas products. An aluminum nozzle was used to reduce the plasma flow from 18.0 inch diameter to the 0.5 x 12.0 inch inside dimension of the Lexan shocktube. The Mylar diaphragm for this design was located at the entrance of the shocktube. Argon gas was used in the driver section cavity. Design 7 hardware was loaded with COMP-C4 explosive at Sandia's explosive machining site.

III. Magnetic Field Sources

Permanent magnets or electromagnets were used on Tests 2 through 5 as listed in Table I to generate the magnetic fields required for MHD operation. Electromagnet coil designs and performance information are documented in References 3 and 4 and Appendices D-G.

Permanent Magnets

Permanent magnets (0.60 Tesla) were used on Test 1 for EDMG driver Design 5 and are shown in Figure A1 of Appendix A. The dimensions of these magnets are 2 x 2 x 0.5 inches each.

9.4 Tesla Electromagnet

The coils deliver 9.4 Tesla on axis in the shocktube. The electromagnet coils used in the Area II tests with the EDMG Design 6 are shown in Figures A2 through A3. The coil drawing is shown in Figure A2. One actual coil is shown in Figure A3. The equivalent circuit for the capacitor bank and coils for EDMG Design 6 tests is shown in Figure A4.

11.2 Tesla Electromagnet

The 11.2 electromagnet coils used in the HERTF test with the EDMG Design 7 are shown in Figures A5 through A7. The coil drawing is shown in Figure A5. Actual coils are shown in Figures A6 and A7. When energized with 1.5 mJ, the coils deliver 11.2 Tesla on axis in the shocktube.

Capacitor Bank Systems

The capacitor bank system used on the EDMG Design 6 tests is shown in Figure A8. The 519 microfarad capacitor banks were charged to 10 kilovolts. The Maxwell Laboratories' 1.5 megajoule capacitor system used on the EDMG Design 7 test is shown in Figure A9. The 41.5 millifarad capacitor banks were charged to 8.39 kilovolts. The 48 cables from the capacitor bank system were reduced to 12 cables connected to the electromagnet coils by the connector-junction interface shown in Figure A10.

Electrical Conducting Probes

The electrical probes were constructed from 1/4 inch threaded brass rods which were screwed into the top and bottom sides of the Lexan shocktube flush with the inside of the tube. Epoxy was used to seal the threads to ensure minimal leakage. Connections to the probes were made using brass nuts and washers. The electrical cables, which were attached to the probes, were fitted with ring lugs to further ensure the integrity of the connections.

IV. Load

EDMG Design 5/Test 1

A resistive load of 0.040 Ohms was used on EDMG Design 5, Test 1 listed in Table I. A resistive load of 0.025 Ohms was used on EDMG Design 6, Test 2 listed in Table I.

EDMG Design 6/Tests 3 and 4

The inductive/capacitive (L/C) load circuit used for EDMG Design 6, Tests 3 and 4 is shown in Figure B1 in Appendix B. The actual L/C load configuration is shown in Figure B2. The load capacitors are shown in Figure B3 after Test 3.

EDMG Design 7/HERTF Test

The inductive/capacitive (L/C) load circuit used for EDMG Design 7, Test 5 is shown in Figure B4 in Appendix B. The actual L/C load configuration is shown in Figure B5.

V. CTH Code Modeling/Simulation

The CTH[6] hydrocode was utilized to model the EDMG Designs 5 and 6 geometries and materials. The CTH code can predict the plasma parameters (at any radius for a given position and at any position in the explosive driver), including flow velocity, pressure, temperature, density, and time-of-arrival. Currently the CTH code can not predict the boundary layer in the shocktube section. The more-expensive- to-run three dimensional modeling is required for rectangular shocktube configurations. Currently, this code can predict only the flow (no MFD parameters) parameters for the ionized plasma in the shocktube. These calculations can be presented graphically in several ways. The plasma flow velocity and time-of-arrival data have been compared to the measured values from development tests.

The CTH code models have been updated to obtain satisfactory agreement with the experimental data. The CTH code was used to help formulate the EDMG Design 7 explosive driver configuration.

Typical CTH code calculations are presented in Appendix C for EDMG Design 5, Test 1. Table C1 lists ionized plasma density, pressure, temperature, velocity, and arrival time for distances from the shocktube entrance(diaphragm location) of 4 to 22 inches. Table C2 in Appendix C lists plasma arrival times at distances between 1.75 through 22.75 inches from the shocktube entrance.

The measured arrival times are compared to the CTH predicted times for Test 1, Design 5 in Table C2 in Appendix C. CTH predicted density, pressure, temperature and velocity versus time and distance from the shocktube entrance data are presented in Figures C1 through C4 in Appendix C. These data are for locations along the surface of the shocktube wall. CTH calculations or predictions are also available but not presented for locations along the shocktube centerline.

The measured plasma arrival time versus distance from the shocktube entrance data are compared to the predicted CTH data in Figure C5 in Appendix C. The measured plasma velocity versus distance from the shocktube entrance data are compared to the CTH predicted data in Figure C6 in Appendix C.

VI. MHD Code Modeling/Simulation

The MACH2[6] MHD two dimensional code is being upgraded by the Phillips Laboratory to a three dimensional code called MACH3 and will be validated using the measured MHD data from these Phase I and II studies. The MACH3 code models will be modified to obtain agreement with the test data. The code will then be used to optimize the design of the MHD device for future work.

VII. Diagnostics

A diagnostic instrumentation system[2] was designed, procured, fabricated, and set up to measure the EDMG plasma parameters. The following six types of plasma diagnostics were measured:

1. Open Circuit Voltage Probe (OCVP), (Vo)

a. The plasma flow velocity (Uf) can be calculated from this measured voltage, the known shocktube diameter (d), and the magnetic field strength (B) as follows:

$$Uf = Vo/Bd \qquad (1)$$

b. The time of arrival of the ionized flow is measured and used to calculate plasma flow velocity.

c. This open circuit voltage can be compared to a voltage across a known load resistance to determine the ionized plasma resistance (Rp). Equation (2) can be used to relate the plasma internal resistance (Rp) to conductivity (σ).

d. Plasma flow duration time is obtained from this measurement.

2. Plasma Resistance Probe (PRP) Voltage, (Vr)

a. PRP voltage is compared to the open circuit voltage to determine the plasma resistance and conductivity. The voltage across the load resistance (Rl) will be half the open circuit voltage if Rl matches the plasma resistance (Rp). Plasma current (I) is calculated as follows:

$$I = (Vr/Rl), \text{ for } R >> (wL + 1/wC) \qquad (2)$$

where,

w = Frequency
L = Inductance
C = Capacitance

b. Plasma electrical conductivity is calculated as follows:

$$\sigma = (G/Rp) \quad (3)$$

where,

G is the gage factor determined from known fluid conductivity calibration tests for the PRP probes (details in Reference 1).

c. Arrival times are used to calculate plasma flow velocity.
d. Plasma flow duration time is obtained from this measurement.

3. Eddy Current Probe Voltage Measurement (Ve)

Electrical coils were fabricated using 36-gage magnet wire. The coils consisted of 40 turns wound on a one-inch form. The coil was then pushed off the form and mounted near the plasma channel. The center of the coil was physically located one inch from the end of a magnet. These coils were used to measure the Eddy currents induced into the plasma as the plasma moved through the magnetic field.

a. The integral of this voltage measurement is proportional to the magnetic Reynolds number for the plasma.
b. The integrated voltage measurement can also used to calculate the plasma electrical conductivity.

4. Plasma Current Probe (PCP)

a. A Ragowski loop is used to make this current measurement.

5. Current Differential (di/dt) of Eddy Current and PCP

a. The PCP current differential can be software integrated to obtain the plasma current. The Eddy current differential can be software integrated to determine the electrical conductivity.

6. Ionization Pins

Velocity measurements were made using ionization pins as the plasma flow time-of-arrival detectors. Inconsistent time data from some of these pins led to using small, inexpensive magnets in an open circuit voltage measurement mode to detect the arrival of the ionized plasma. The arrival times using these gages seem to be much more consistent and additional information is obtained using duration and amplitude data. Ionization pins were used on most electromagnet type tests.

a. These sensors measure the arrival of the ionized flow.
b. Arrival times are used to calculate plasma flow velocity.

VIII. Review Of Data

The five tests conducted are listed in Table I. A Mylar diaphragm was used to separate the high pressure argon gas in the explosive driver from the low pressure air in the shocktube or test section. The argon gas initial pressures varied between 90 and 200 psi. The shocktube pressures varied from 0.01 to 11.7 psia (ambient). The explosive weights were 1.7, 2.0, and 35.0 pounds for EDMG Designs 5, 6 and 7, respectively. COMP-C4 explosive was used on all tests. Argon gas was used in the driver on all tests.

Typical pre-test EDMG photos, including the MHD(permanent magnet or electromagnet coils) hardware, are shown in Figures 5 through 7 for Designs 5, 6, and 7, respectively. Kevlar reinforced blankets, layered sheets of plywood, and sandbags were used to catch or slow down the high velocity metal fragments from the explosive driver.

Test 1/Design 5

The Test 1, Design 5 configuration is shown in Figure 5. The explosive driver and Mild Detonating Fuse (MDF) line, and detonator configuration are shown in Figure D1 in Appendix D. The plasma arrival time data, velocity, type measurement, and magnet strength data are listed in Table D1. The open circuit voltage versus time data are shown in Figure D2. The resistive load voltage versus time data are shown in Figure D3. The plasma current versus time data are shown in Figure D4. The load power versus time data are shown in Figure D5. The energy versus time data are shown in Figure D6.

Test 2/Design 6

The Test 2, Design 6 configuration is shown in Figures E1 and E2 in Appendix E. The resistive load voltage, plasma current, load power, energy, Eddy coil current, and arrival time probe voltage versus time data are shown in Figures E3 through E8.

Test 3/Design 6

The Test 3, Design 6 configuration is shown in Figures F1 in Appendix F. The open circuit voltage, resistive load voltage, and load current versus time data are shown in Figures F2 through F4. The electromagnet charge current versus time data are shown in Figure F5. The plasma arrival time versus distance from the shocktube entrance data are shown in Figure F6 for EDMG Design 6, Tests 2 through 4. These are the only tests that were repeated for this project. These data show that the plasma flow in the shocktube section is very reproducible for this EDMG design configuration. An estimate of the generator source impedance was obtained by matching the experimental voltage traces to a circuit model. The impedance obtained in this manner was 140 milliOhms.

Test 4/Design 6

The plasma arrival time, ionization pin voltage versus time data are presented in Figure G1 in Appendix G for the five different locations in the shocktube. The open circuit voltage, (L/C) load voltage, and (L/C) load current versus time data are shown in Figures G2 through G4.

Test 5/Design 7/HERTF Test

The High Energy Research Technology Facility (HERTF) floor plan, screen room recording location, cable bundle routing, and test pad are shown in Figure H1 in Appendix H. The EDMG Design 7, Test 5 explosive driver configuration is shown in Figures H2 through H4. The plasma arrival time ionization pins (6 each, upper row), plasma detection fiber-optic sensors (4 each, second row), and argon gas sensors (2 each, bottom row) are shown installed in the Lexan shocktube in Figure H5. The instrumentation/recording room hardware are shown in Figure H6. The Design 7 explosive driver, shocktube, electromagnet coils, wooden stand, and Mylar diaphragm are shown in Figures H7 through H10.

The HERTF site pre-test configuration is shown in Figures H11 and H12. The two eight-foot inside diameter concrete culverts used to protect the (L/C) load, firing sets, and vacuum pump hardware are shown in Figures H11 and H12. The stacked concrete blocks (2'x2'x4'), layered plywood roof, armor blankets, and sandbags are also shown in these figures. The photograph shown in Figure H13 was taken during this test. The aluminum, diaphragm holder ring of the shocktube is shown in Figure H13.

The (L/C) load voltages (Voltage #1 and Voltage #2) and current versus time data are shown in Figure H14. The electromagnet (EM) magnetic field strength and EM coil charge current versus time data are shown in Figures H15 and H16, respectively.

IX. DATA ANALYSES

Power Output

The power calculated from the measured voltage and current is listed in Table I for the five EDMG tests. The actual power delivered to the load, calculated from the PCP measured current ([$P = V_l I$] or [$P = I^2 R$]) or (depending on whether a good current measurement was obtained) calculated from the voltage (V_l) across the load resistor ($P = V_l^2/R$), is listed in Table I.
The following analytical algorithm[11] has been used to predict the peak power output (P_m) from other measured MHD parameters:

$$P_m = AB^2 Uf^2 d\sigma/4 \qquad (4)$$

where,

A	=	Electrode area (m^2)
B	=	Magnetic field strength (T)
Uf	=	Plasma flow velocity (m/s)
d	=	Electrode spacing (m)
σ	=	Electrical conductivity (S/m)
P_m	=	Peak power output (w)

For high magnetic Reynolds numbers, the power output can be calculated as follows:

$$P = 2B^2 Ufbd \tag{5}$$

where,

b = Shock tube or channel inside width (m)

At high Reynolds number, the power output is highly dependent primarily on plasma flow velocity (Uf) (to the first power only) and magnetic field strength (B) for fixed MHD generator geometries. The peak power output is independent of electrical conductivity and length of ionized slug.

Magnetic Reynolds Number

The permeability of free space (μ) is $4\pi \times 10^{-7}$ (s/S-m). The magnetic Reynolds number (Rm) is defined as follows:

$$Rm = \mu\sigma Ud \tag{6}$$

The Reynolds number for Test 3 was calculated to be 30. The plasma, electrical conductivity was estimated to be about 18,400 Siemens/m.

X. Summary

Three explosive drivers were designed and tested for magnetohydrodynamic devices. The CTH hydrocode has successfully predicted the plasma arrival times and flow velocities for these different size explosively-driven magnetohydrodynamic generators (Figures 1-3). The CTH code models have been modified to obtain agreement (validation) with the test data. The CTH code is currently being utilized to design a more optimized explosive driver.

A diagnostic instrumentation system has been successfully developed to measure the magnetohydrodynamic (MHD) device output parameters. Fourteen channels of data were successfully measured and recorded for each of the five tests. Data are presented for three different size and configuration explosive drivers, one explosive (COMP-C4), one gas (argon), different driver pressures (90 to 200 psi), and different shocktube or test section pressures (0.01-11.7 psi).

Measured time-of-arrival, current, voltage, resistance, power, and energy data are presented for one of the five tests conducted. Measured time-of-arrival and plasma flow velocity data were compared to the values predicted by the CTH hydrocode.

Analytical methods were presented for calculating the power output for an explosively-driven magnetohydrodynamic generator. The explosive driver, shocktube, electromagnet, and load parameters for the five tests are summarized in Table I.

The details of the CTH code modeling/simulation, electromagnet coil design analyses, electrical circuit/load analyses, and MHD parameter analyses were not presented in this report. Each one of these analyses would require a separate report. Some of this work will be presented at a later date. A primary goal for the report was to present a final status for this three-year funded program.

The accomplishments of this project will allow us to design a more optimized explosive driver which will be utilized to produce the high velocity ionized flow for optimizing an MHD device for a specific application. The MACH2 magnetohydrodynamic code models will be validated with the MHD data from the five tests. The code will then be used to aid in the design of optimized permanent magnet and electromagnet MHD devices for future work. The CTH and MACH2 codes can be used to design explosively-driven plasma generators and MHD devices for future customer-specific applications.

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FIGURES

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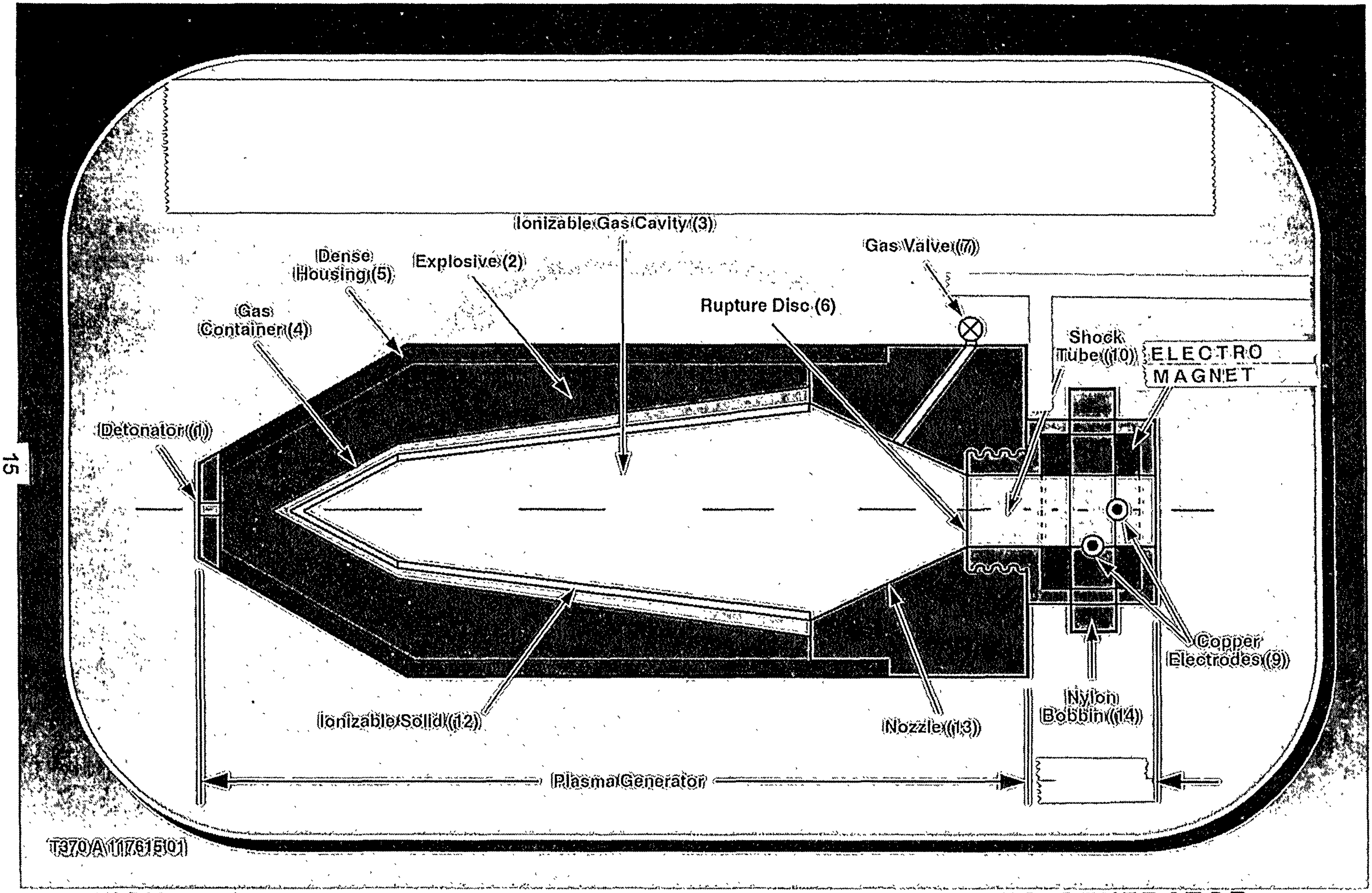

FIGURE 1. EXPLOSIVELY-DRIVEN MAGNETOHYDRODYNAMIC GENERATOR

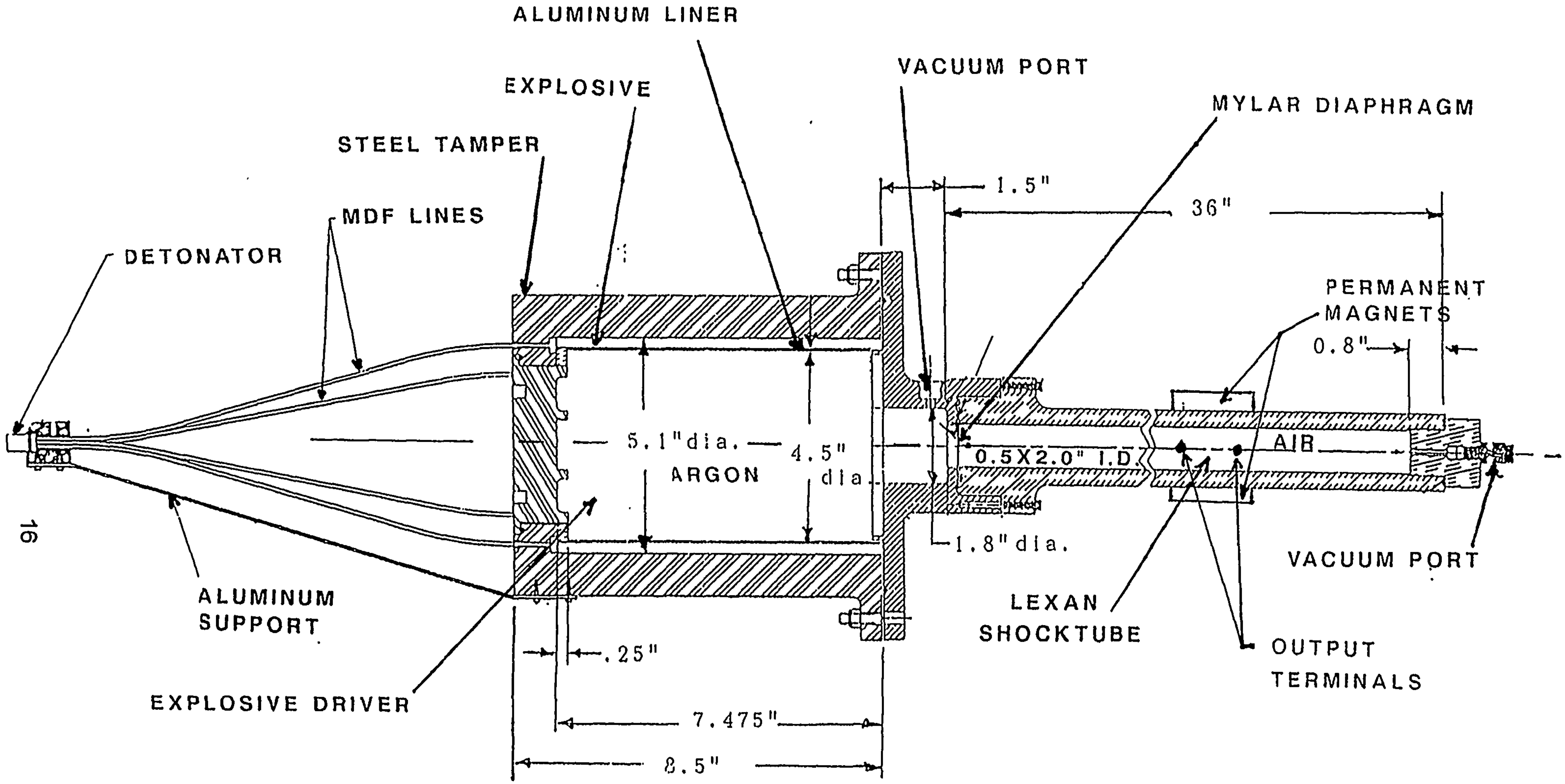

FIGURE 2. EXPLOSIVELY-DRIVEN MHD GENERATOR/DESIGN # 5

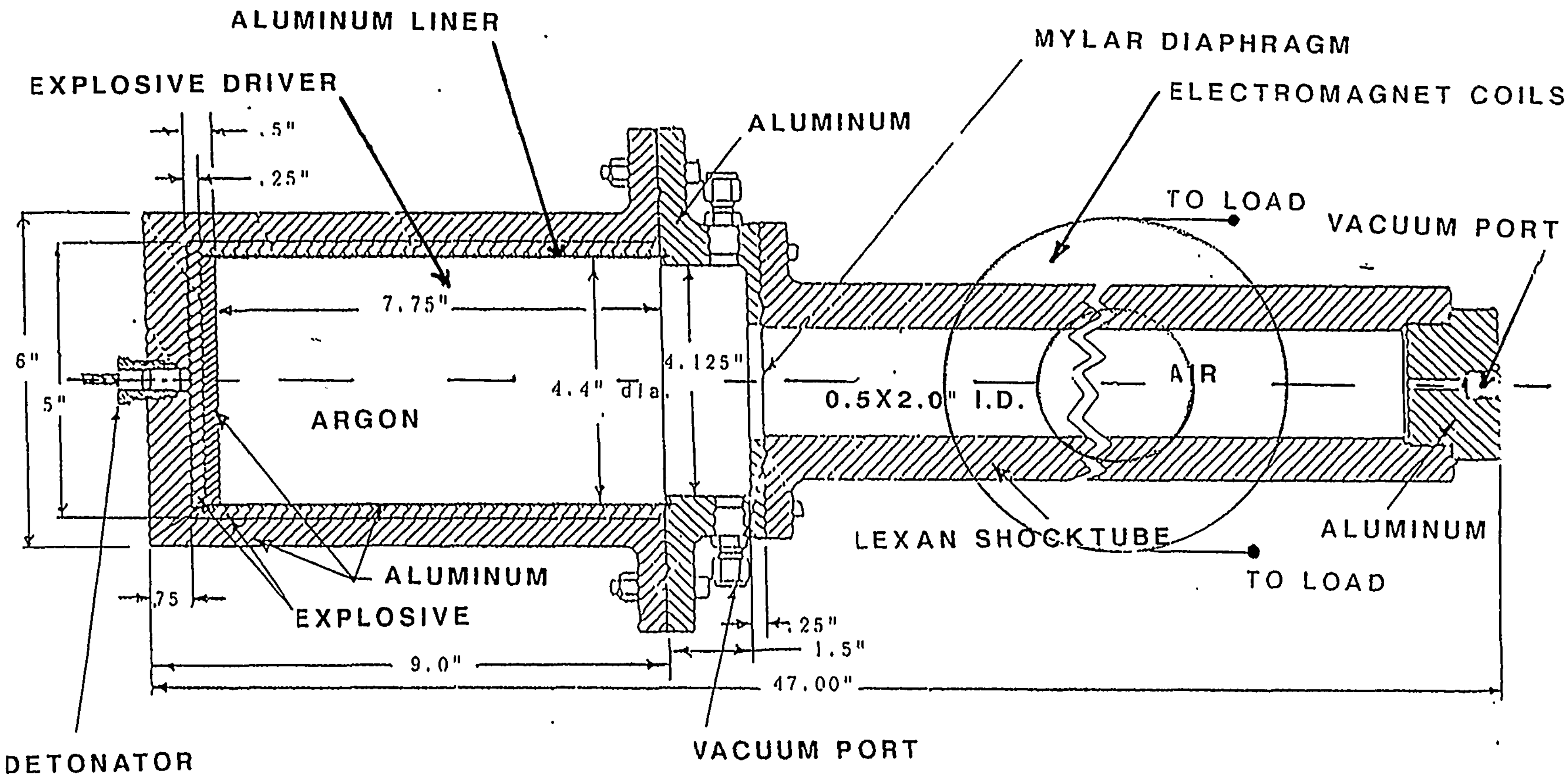

FIGURE 3 EXPLOSIVELY-DRIVEN MHD GENERATOR/DESIGN # 6

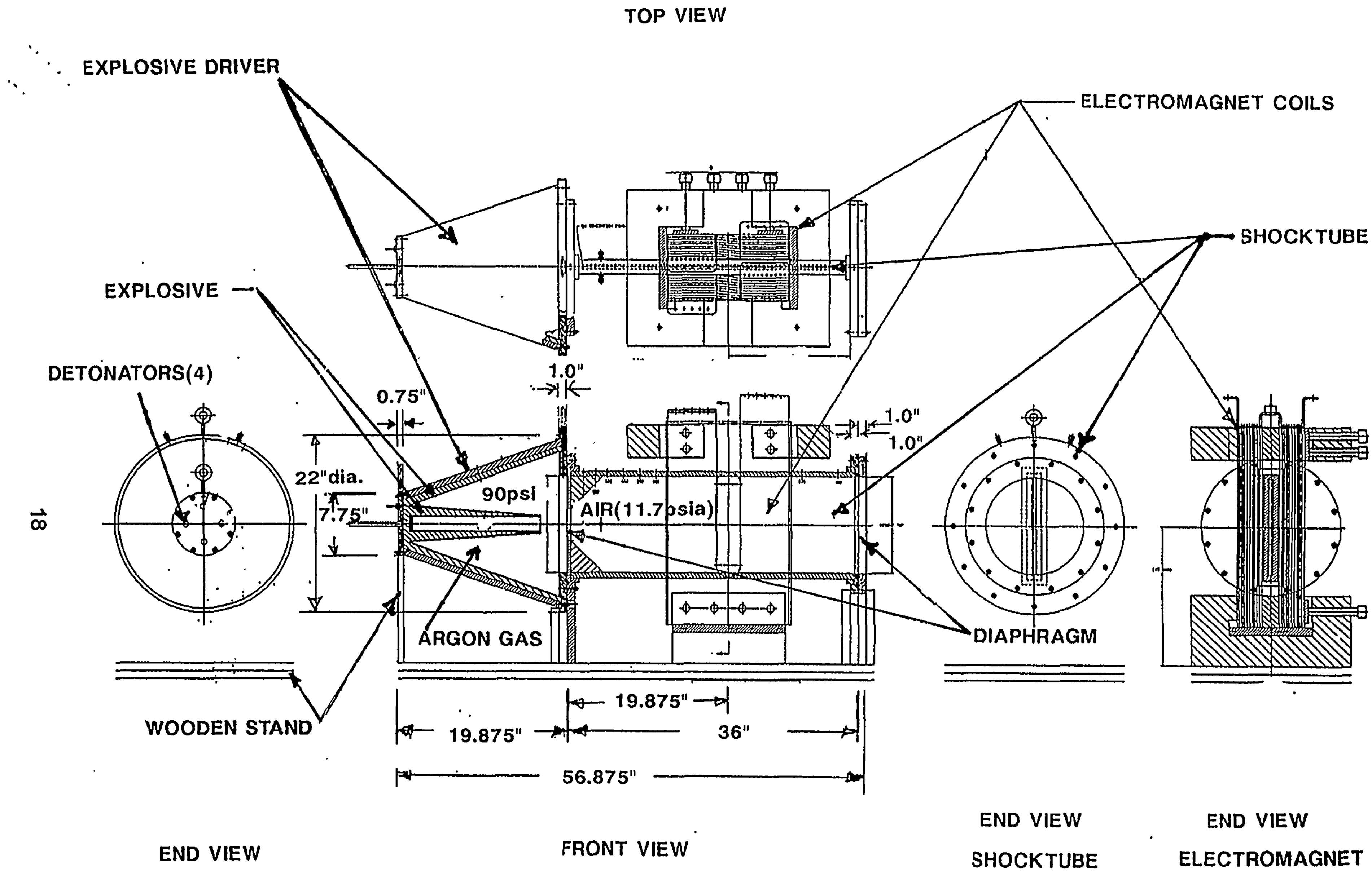

FIGURE 4. EXPLOSIVE-DRIVEN MHD GENERATOR/SHOCKTUBE/ELECTROMAGNET/DESIGN # 7/HERTF TEST

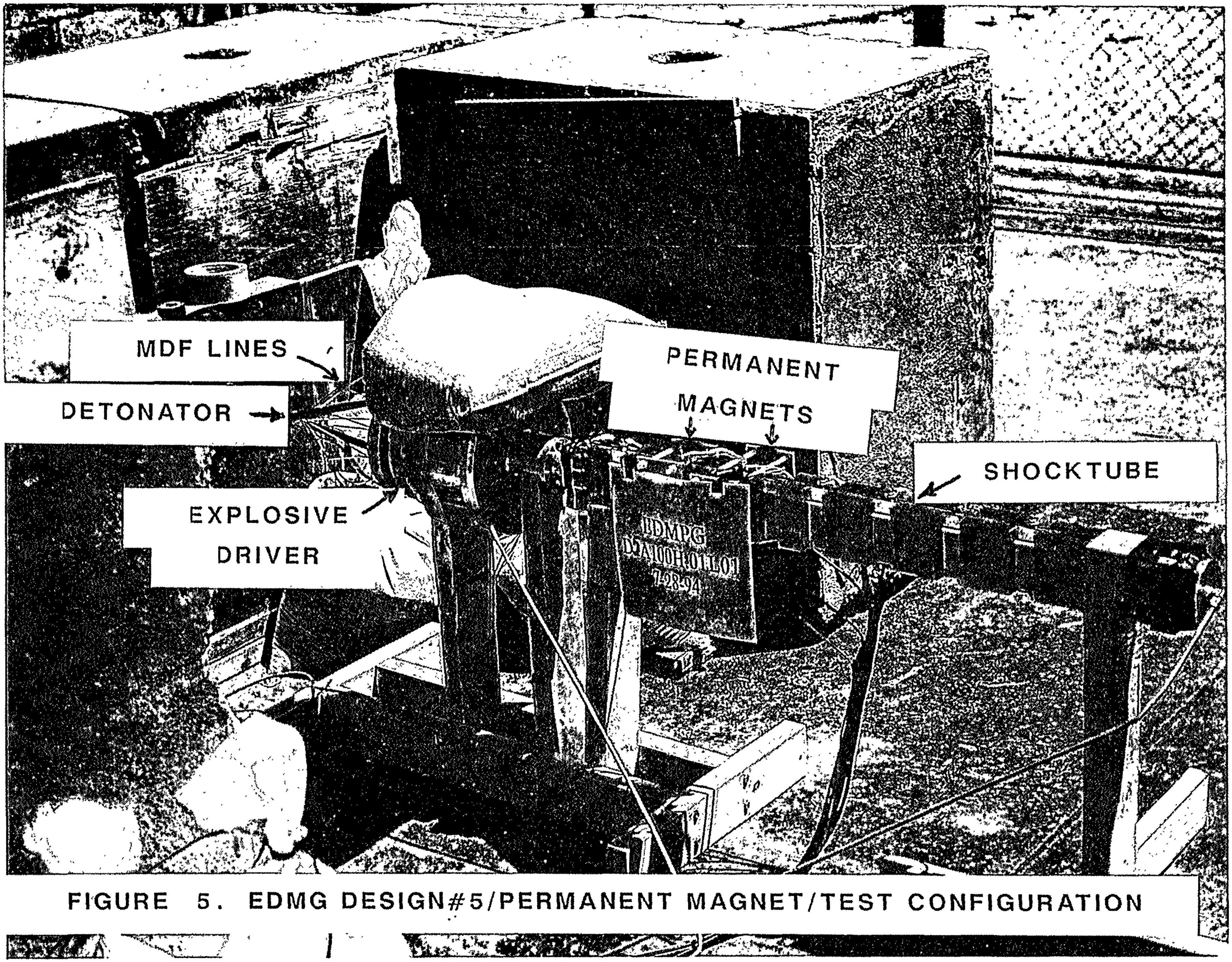

FIGURE 5. EDMG DESIGN#5/PERMANENT MAGNET/TEST CONFIGURATION

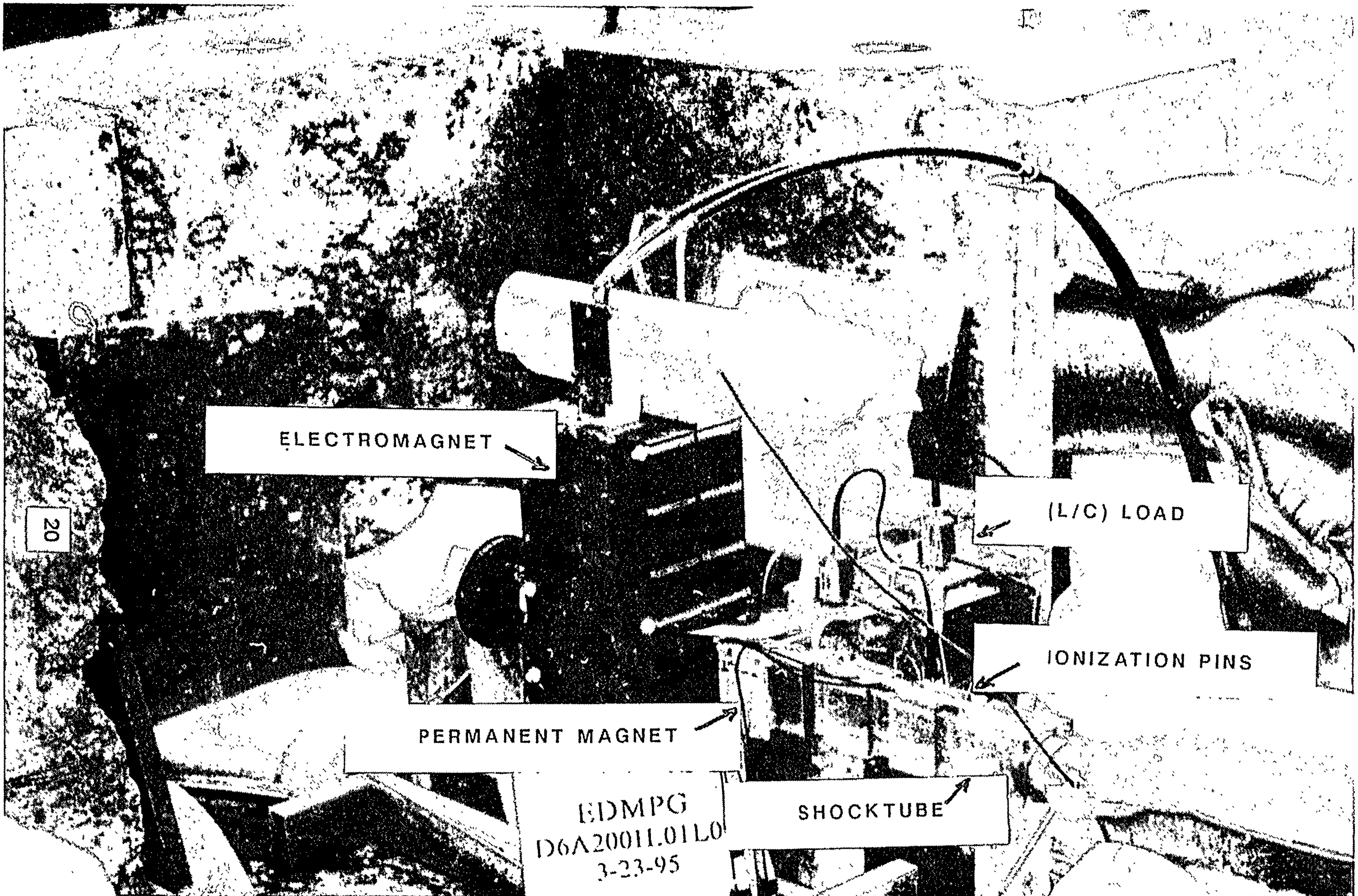

FIGURE 6. SHOCKTUBE/ELECTROMAGNET/(L/C) LOAD/EDMG DESIGN # 6 TESTS

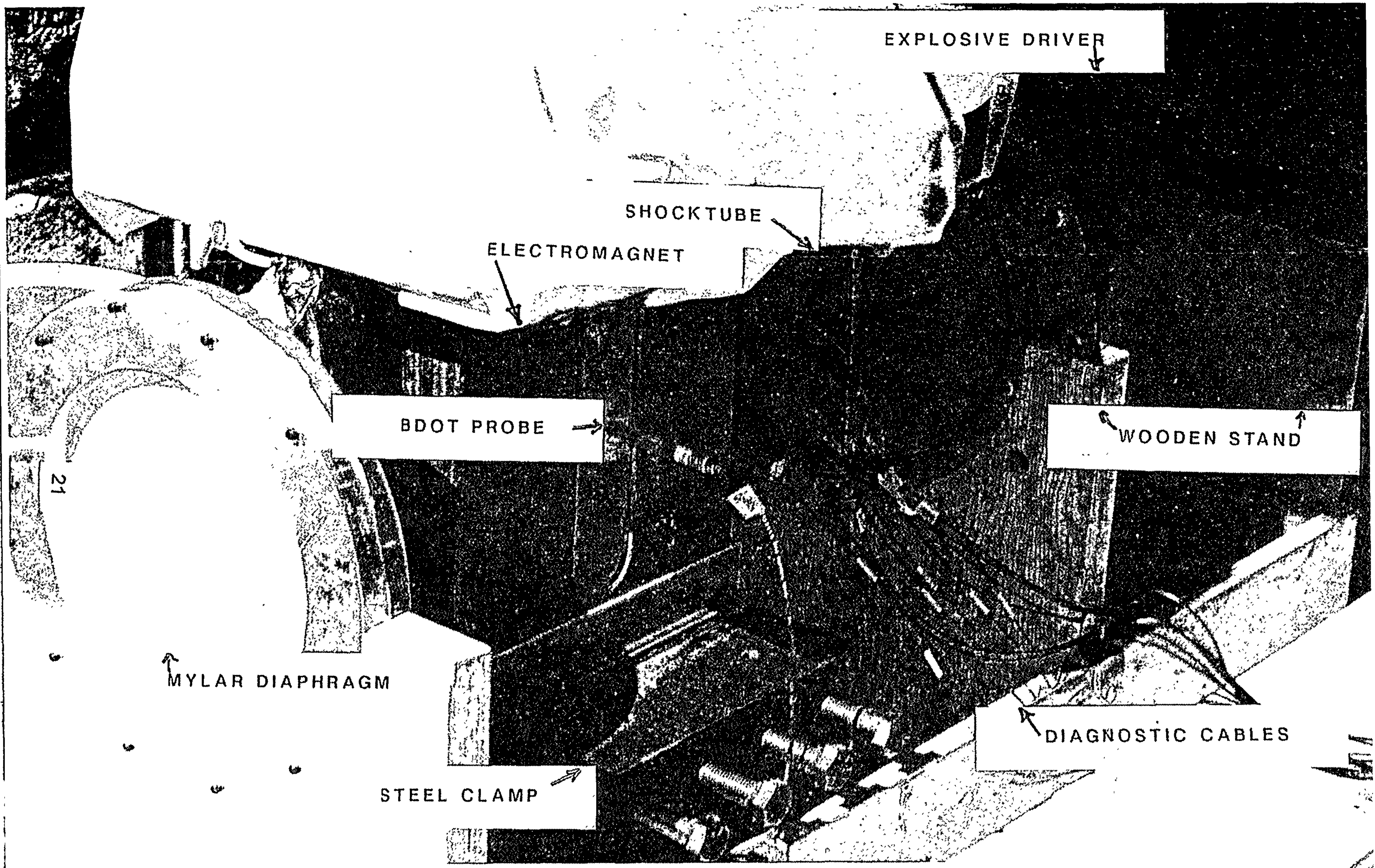

FIGURE 7. EXPLOSIVELY-DRIVEN MHD GENERATOR/SHOCKTUBE/ELECTROMAGNET CONFIGURATION

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TABLE

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Table I. Explosively Driven MHD Generator/Electromagnet/(L/C) Load Data
MYLAR Diaphragm at Shocktube Entrance (0.015" thick)

		Driver			Shocktube		Electromagnet			(L/C) Load			
Test No.	Date	P_d (psia)	Gas	W (lb)	P_s psia	U_f (Km/s)	B (T)	I_e (KA)	V_e (KV)	V_o (KV)	V_l (KV)	I_l (KA)	P_l (GW)
1.[1]	7-26-94	200	A	1.7	0.01	25.5	0.40	NA	NA	0.35	0.139**	5.7**	0.001
2.[2]	8-24-94	200	A	2.0	0.01	23.4	9.40	39.2	9.95	18.0	9.0**	115.0**	1.04**
3.[2]	3-17-95	200	A	2.0	0.01	21.0	9.40	39.4	9.92	30.5	14.0	12.2	0.17
4.[2]	3-29-95	200	A	2.0	0.08	23.0	9.95	41.8	10.43	21.8	4.7	13.9	0.07
5.[3]	9-31-95	100	A	35.0	11.7*	7.0	11.2	154.0	8.50	ND	15.0	40.0	0.60

A = Argon
P_d = Driver gas pressure
W = Driver explosive weight, COMP-C4 explosive, 1.6 g/cc
P_s = Shocktube pressure, gas: Air
U_f = Flow velocity at electromagnet test station
B = Magnetic field strength
I_d = Electromagnet charge current
V_e = Electromagnet charge voltage
(1) = Driver design #5
(2) = Driver design #6
(3) = Driver design #7

* = Ambient pressure, air, 6300 foot altitude, HERTF
** = Resistive load, FY94 test
V_o = Open circuit voltage near electromagnet center
V_l = (L/C) load voltage
I_l = (L/C) load current
P_o = Power = V_oI_l, open circuit voltage
P_l = Power = V_lI_l, load voltage and current
ND = No data/not measured
NA = Not applicable//permanent magnets only

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Appendix A

Permanent Magnets And Electromagnet Coils Configurations

Figures

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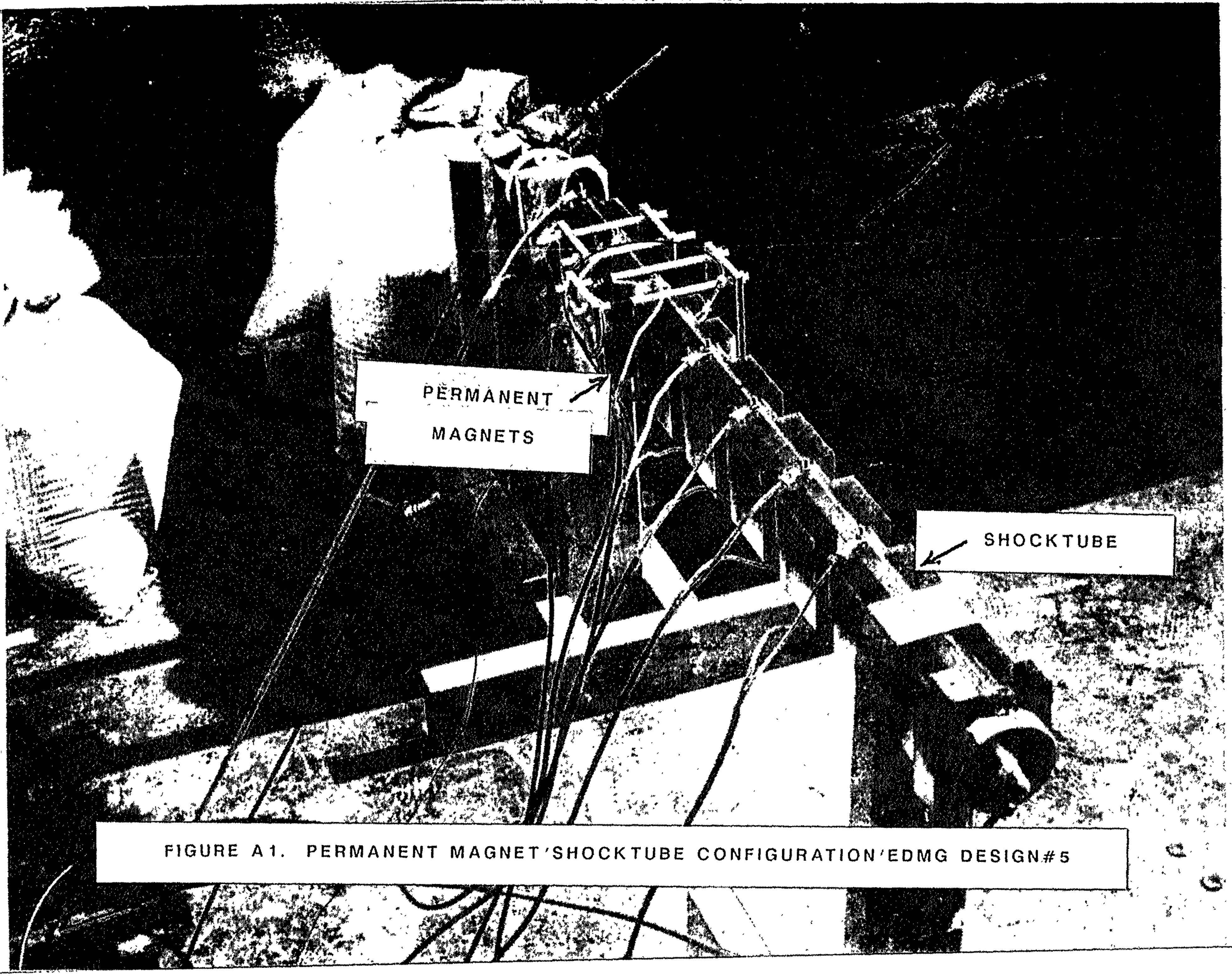

FIGURE A1. PERMANENT MAGNET/SHOCKTUBE CONFIGURATION/EDMG DESIGN#5

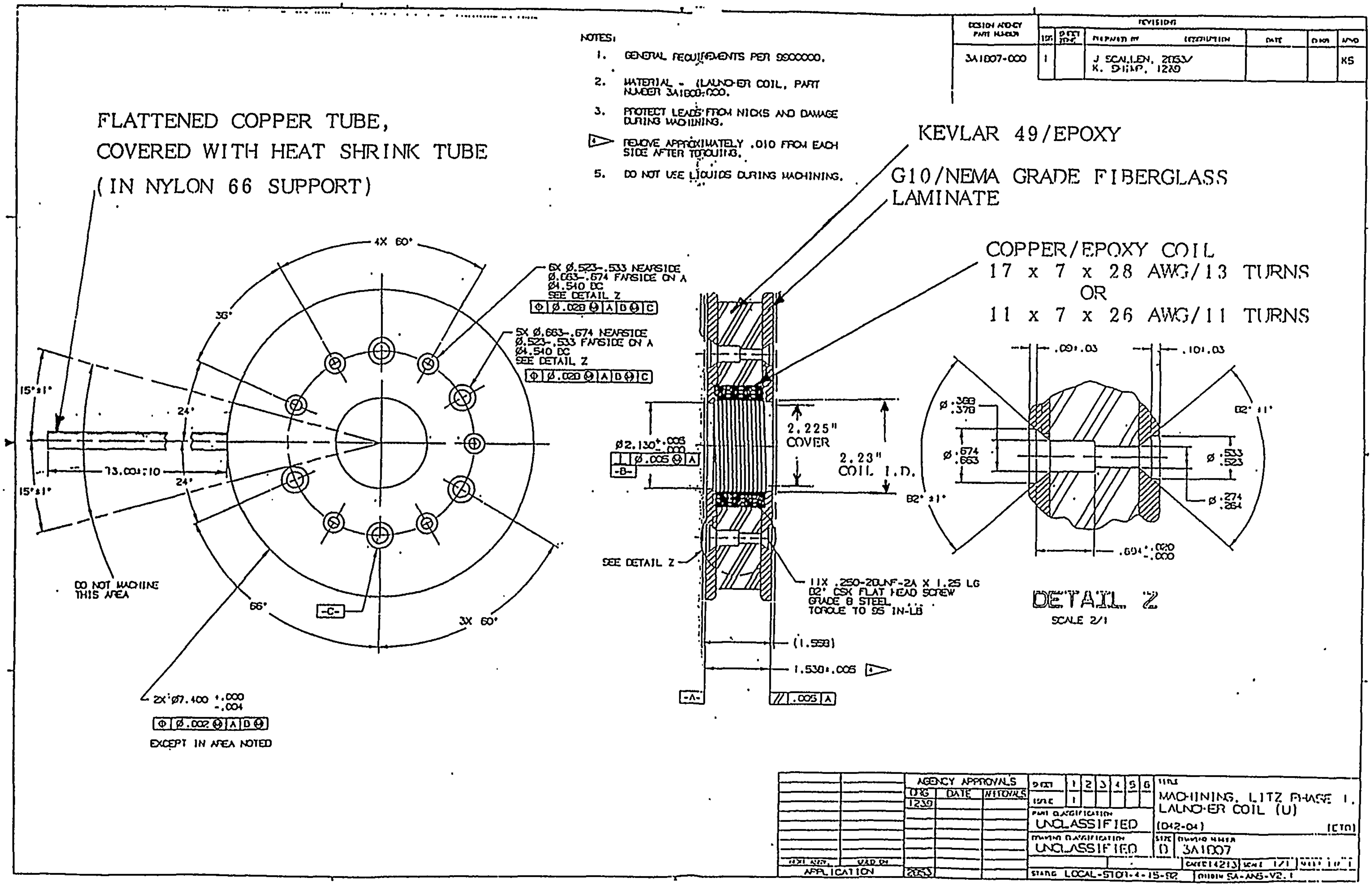

FIGURE A2. ELECTROMAGNET COIL DRAWING/EDMG DESIGN#6 TESTS

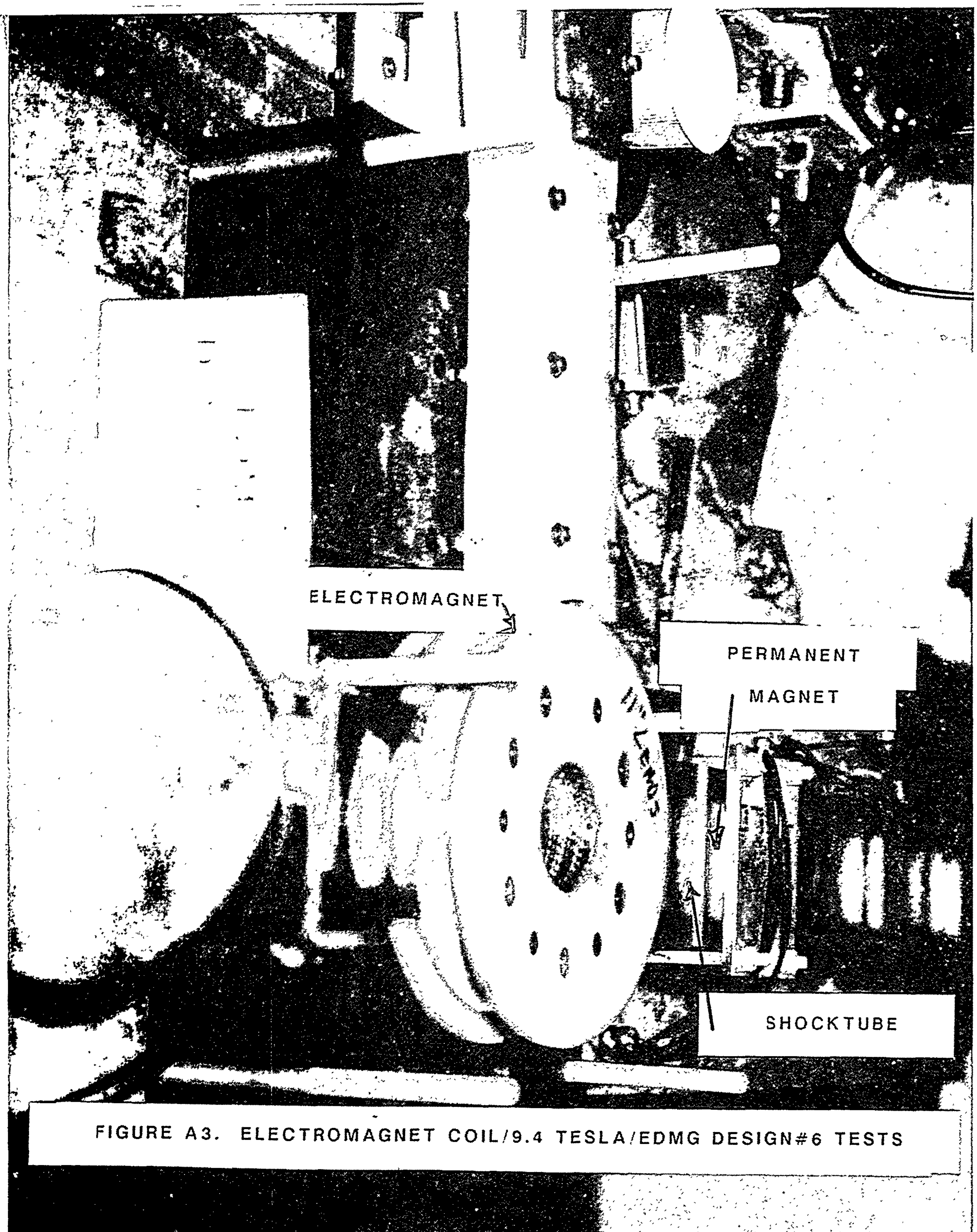

FIGURE A3. ELECTROMAGNET COIL/9.4 TESLA/EDMG DESIGN#6 TESTS

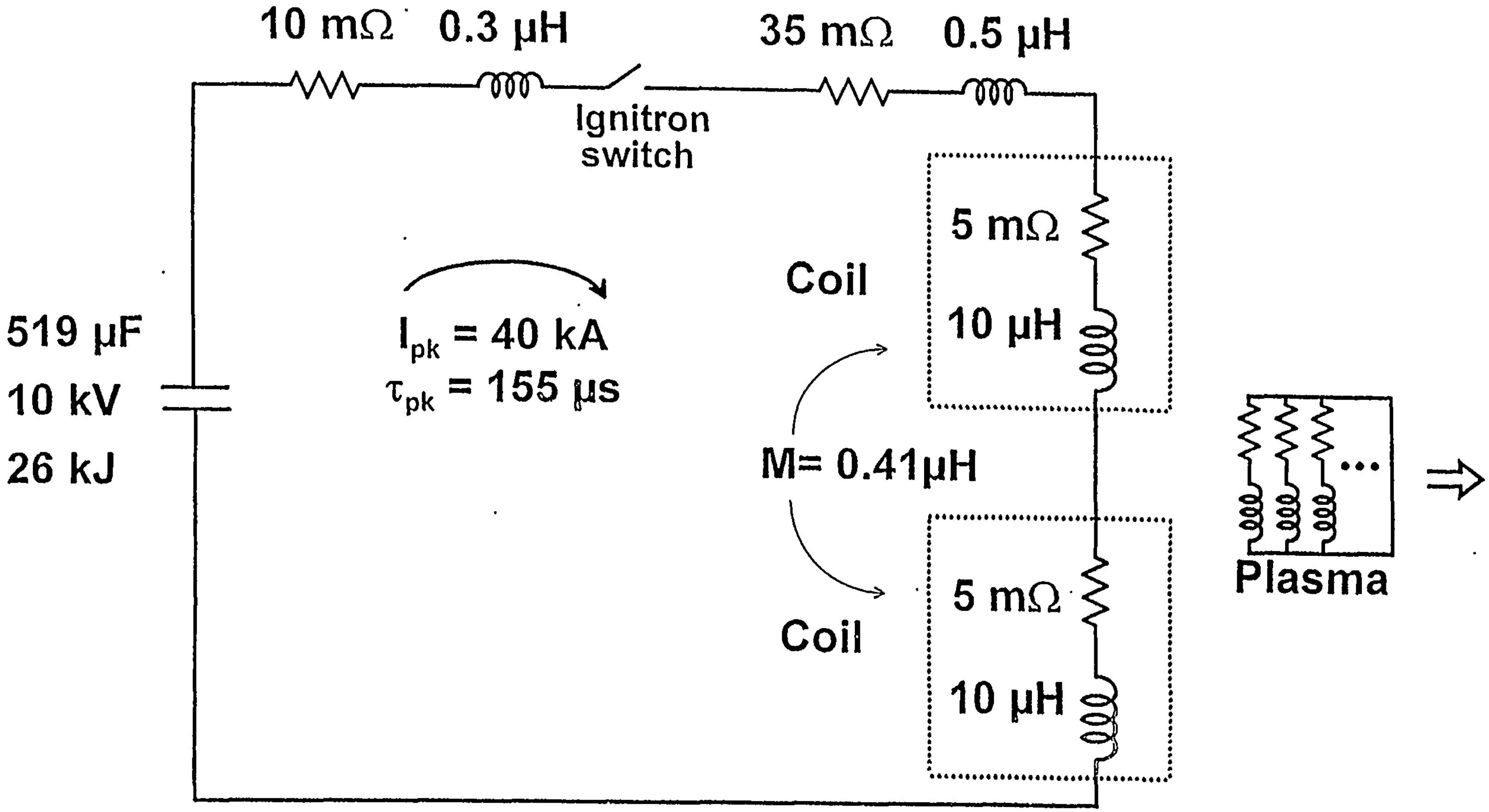

FIGURE A4. ELECTROMAGNET COILS CIRCUIT/EDMG DESIGN#6 TESTS

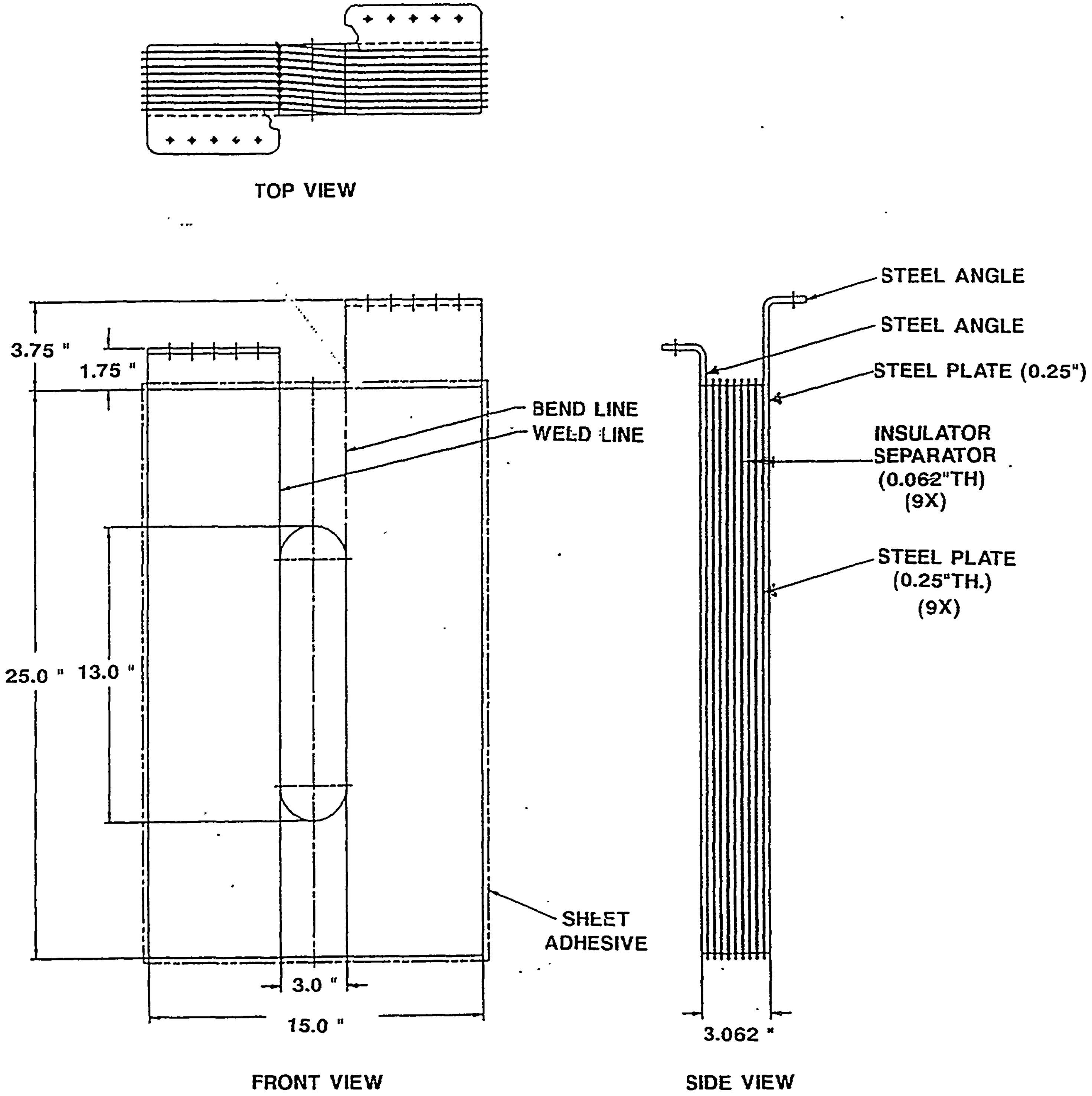

FIGURE A5. ELECTROMAGNET CONFIGURATION/HERTF TEST

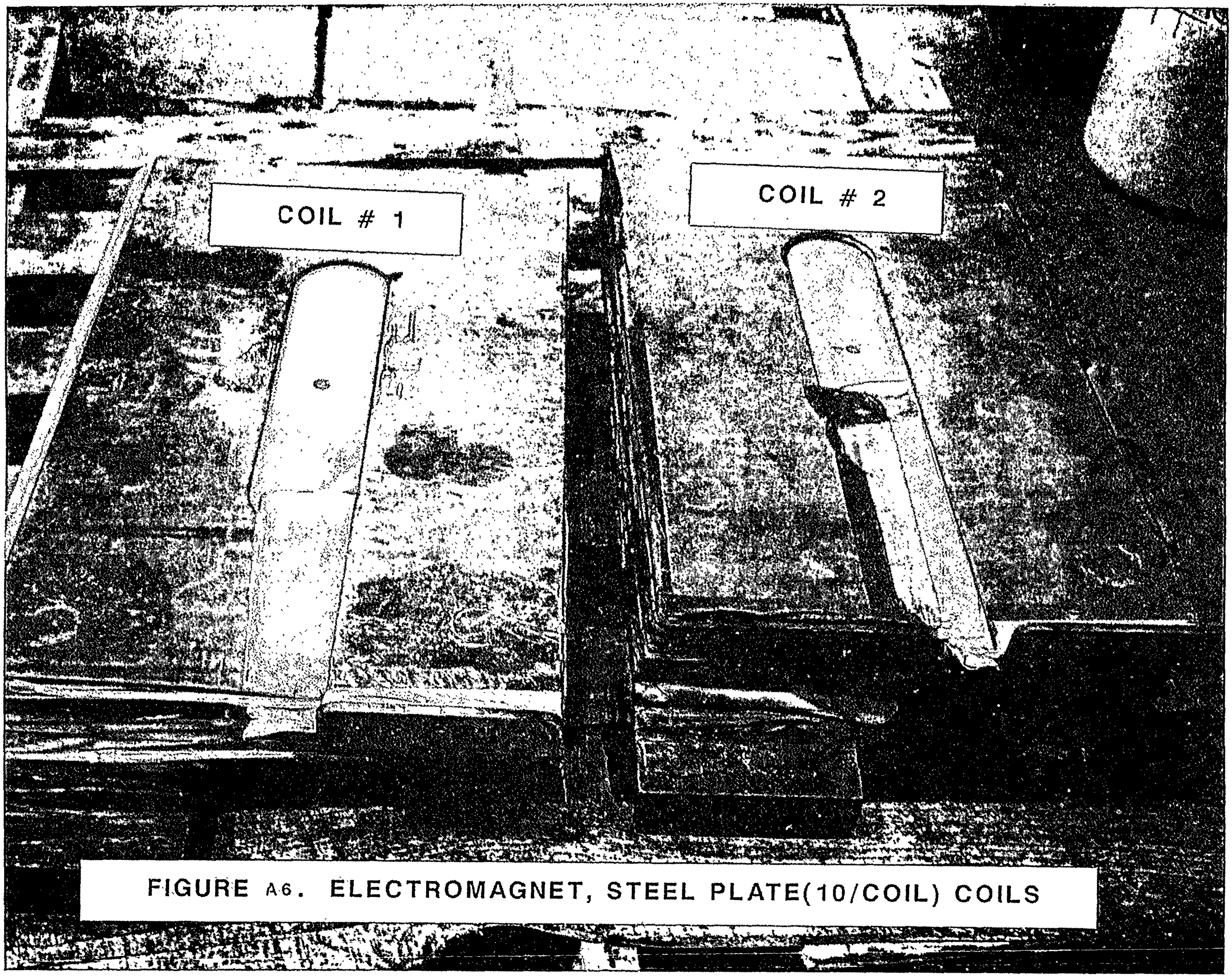

FIGURE A6. ELECTROMAGNET, STEEL PLATE(10/COIL) COILS

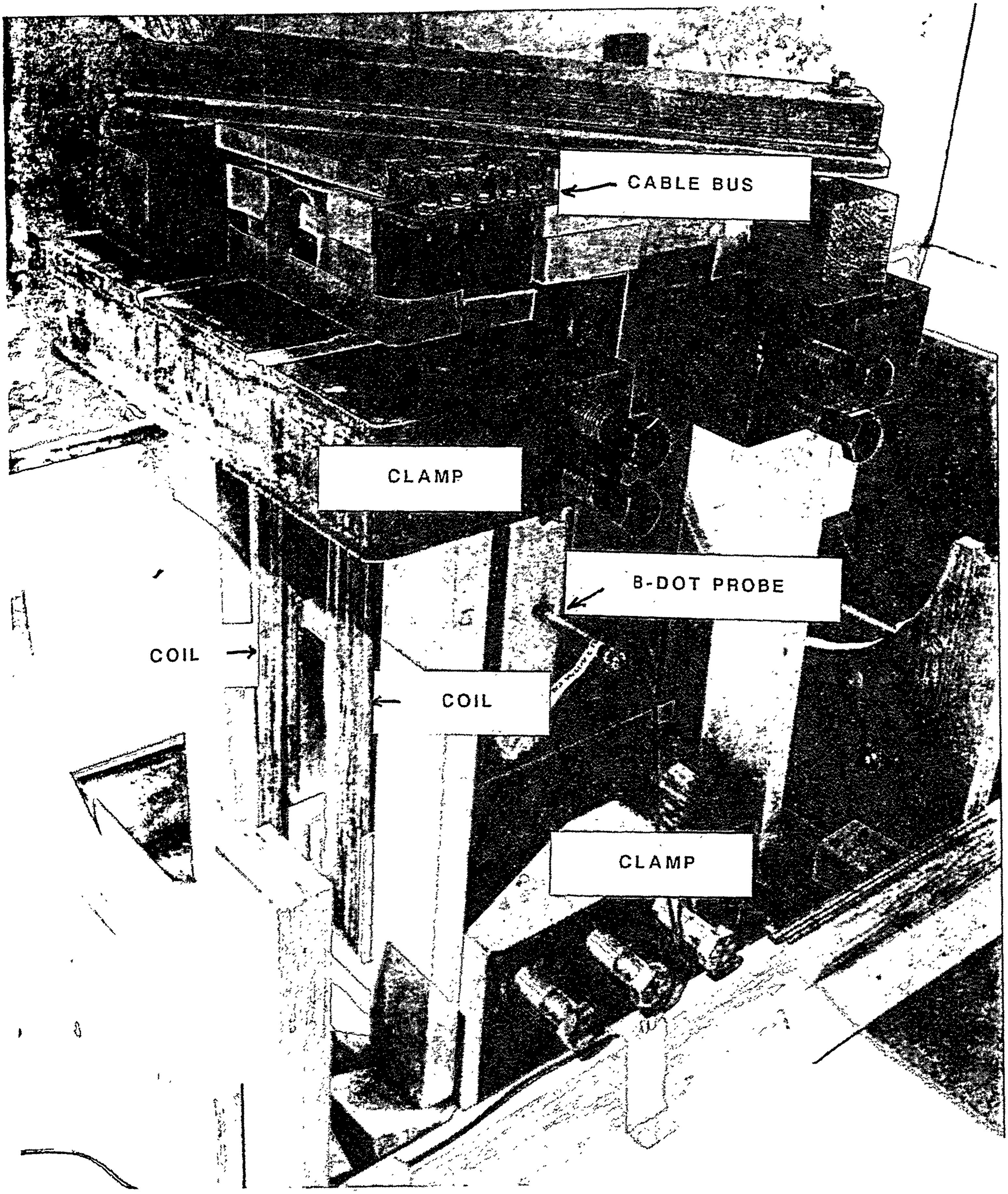

FIGURE A7. HERTF TEST ELECTROMAGNET COILS

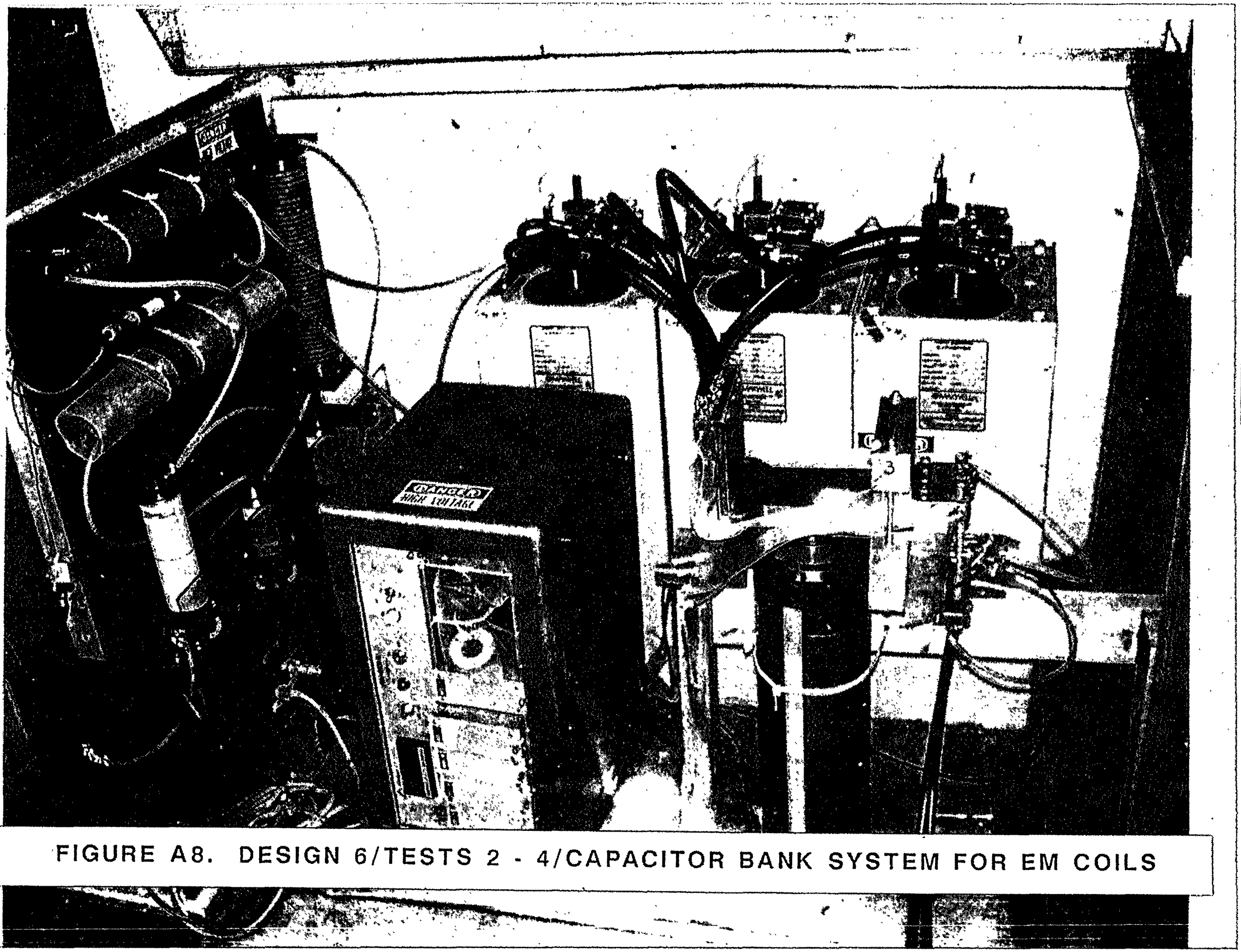

FIGURE A8. DESIGN 6/TESTS 2 - 4/CAPACITOR BANK SYSTEM FOR EM COILS

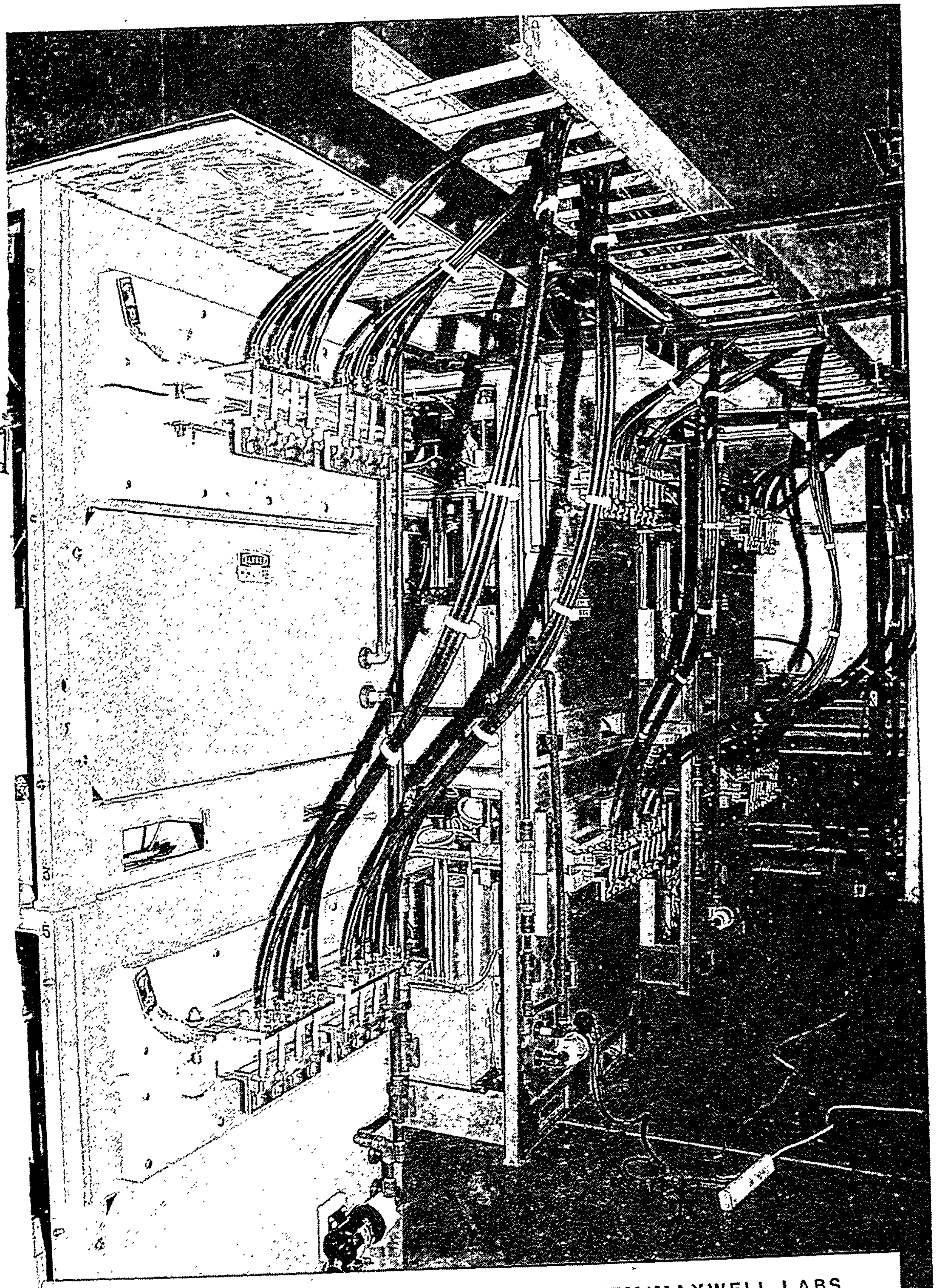

FIGURE A9. 3 MJ CAPACITOR BANK SYSTEM/MAXWELL LABS

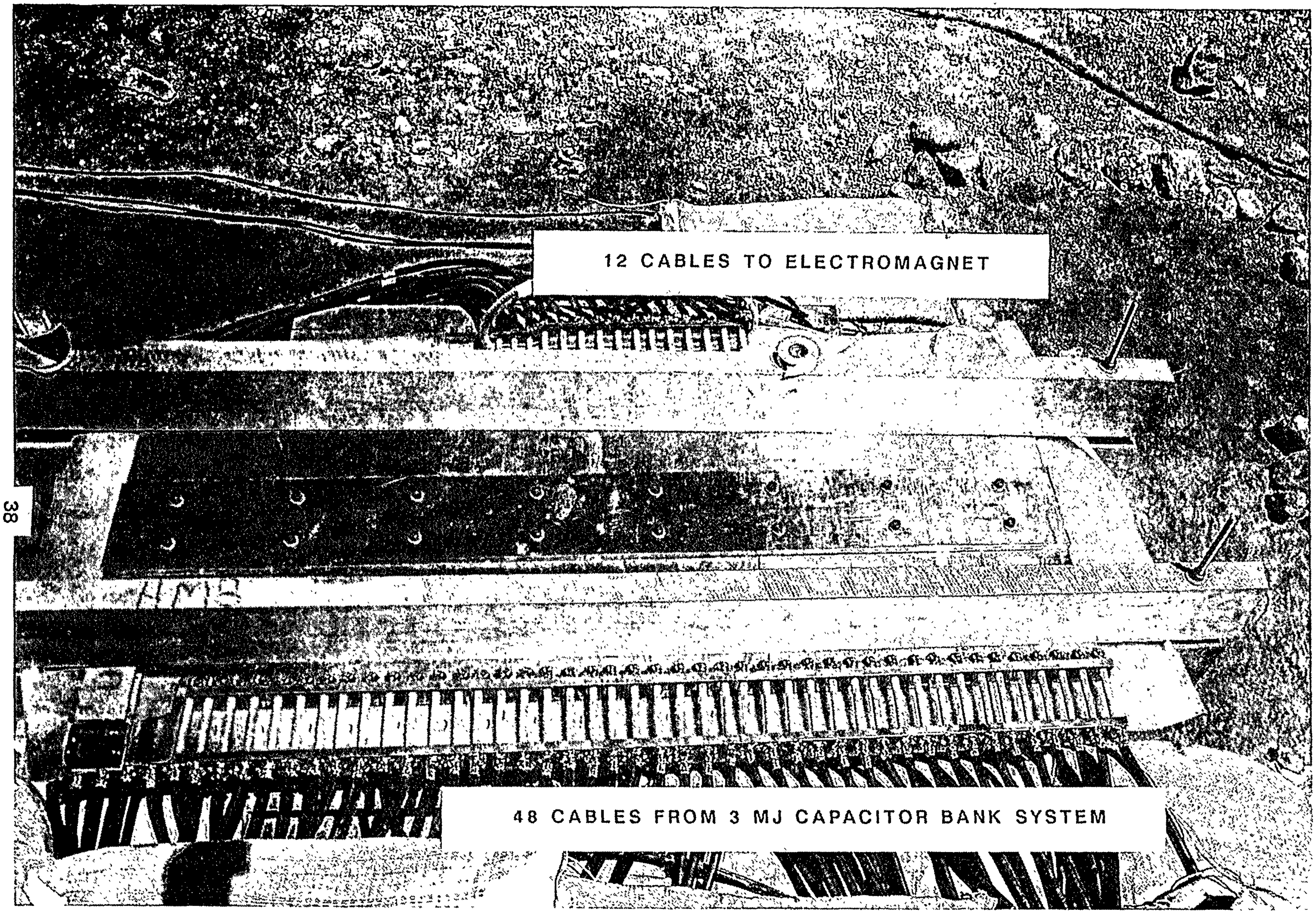

FIGURE A10 3 MJ CAPACITOR BANK/ELECTROMAGNET CABLE CONNECTION INTERFACE CONFIGURATION

Appendix B

Load Circuits and Configurations

Figures

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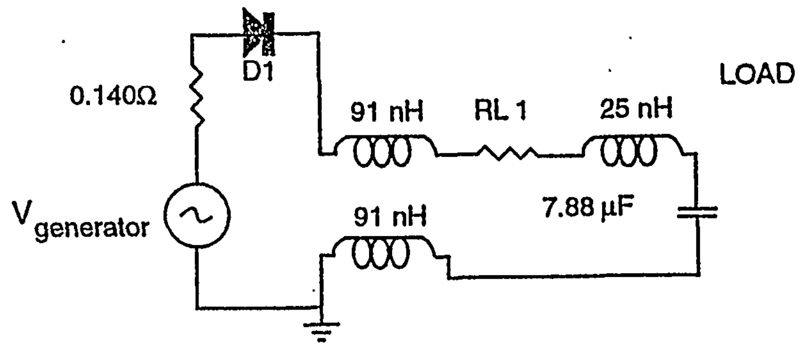

FIGURE B1. (L/C) LOAD CIRCUIT/EDMG DESIGN # 6/A-II TESTS

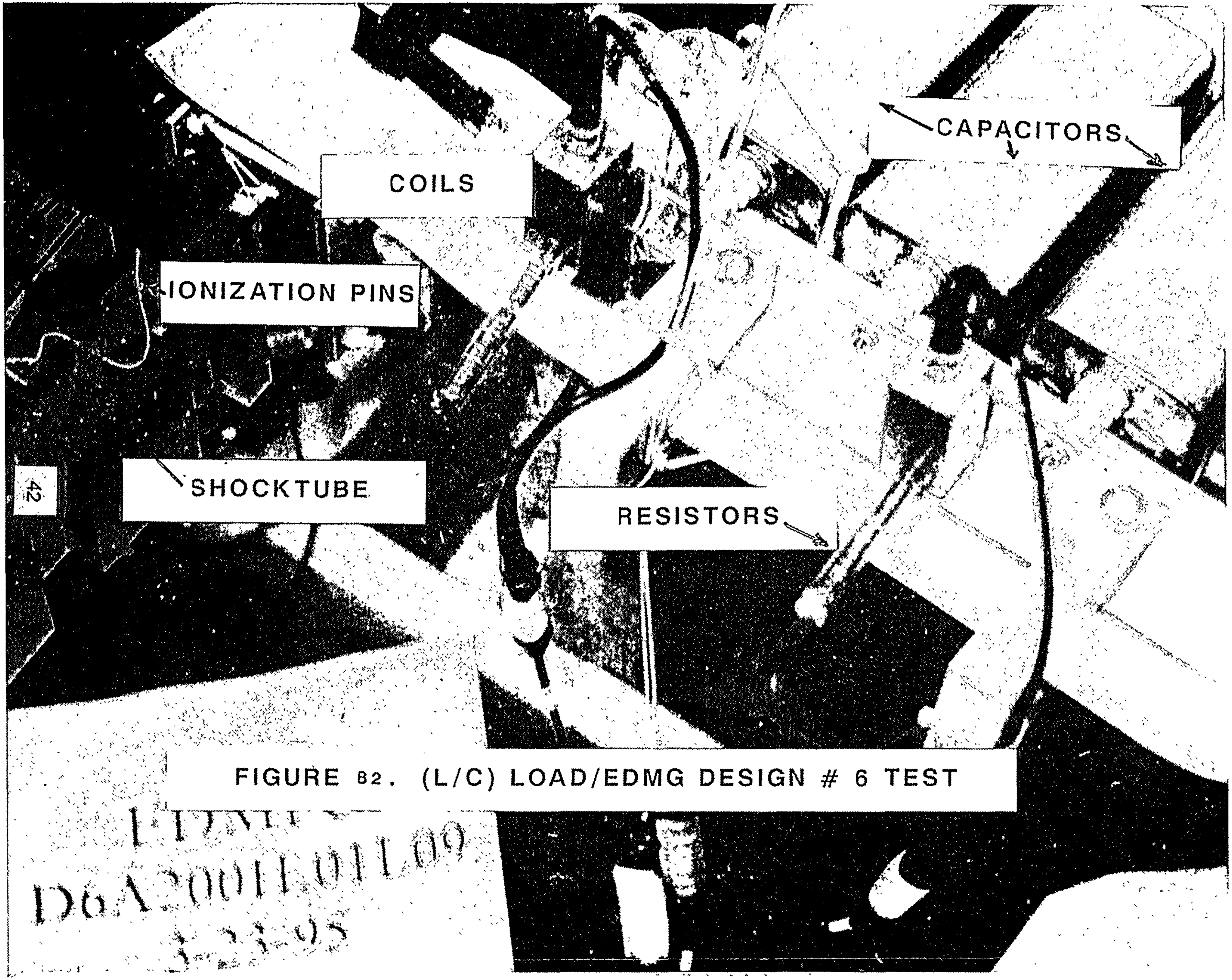

FIGURE B2. (L/C) LOAD/EDMG DESIGN # 6 TEST

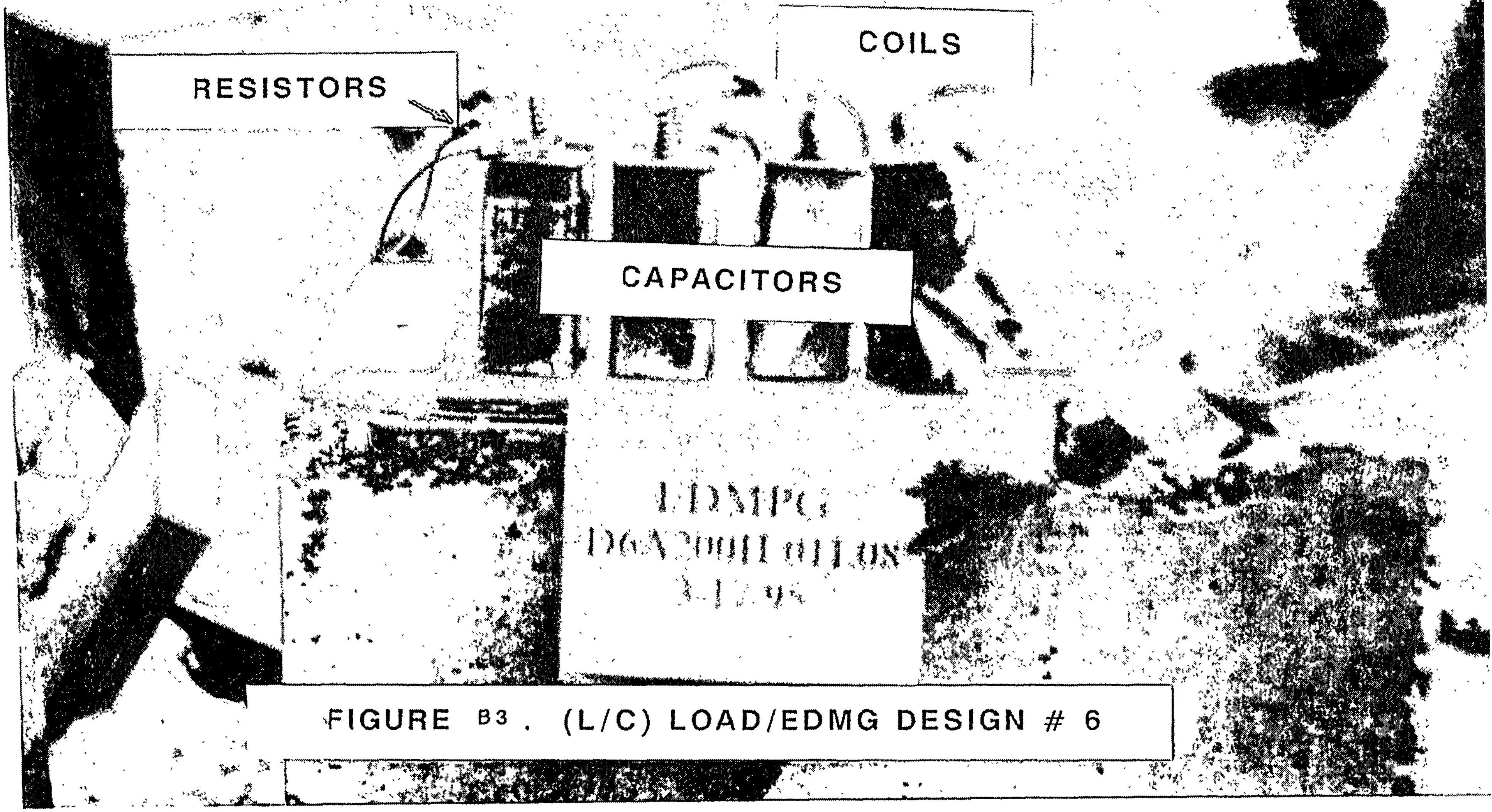

FIGURE B3. (L/C) LOAD/EDMG DESIGN # 6

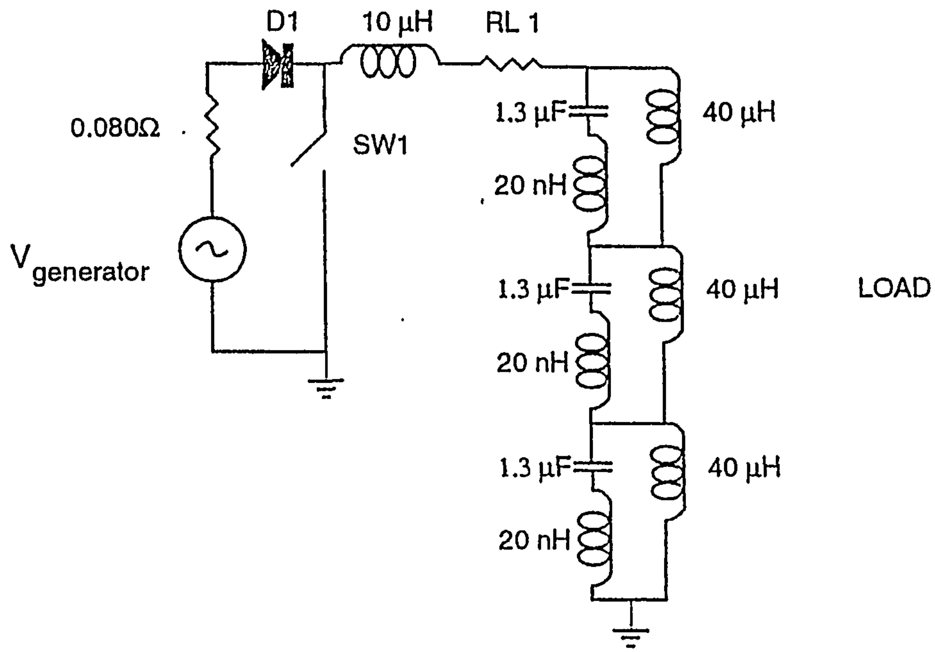

FIGURE B4. (L/C) LOAD CIRCUIT/EDMG DESIGN # 7/HERTF TEST

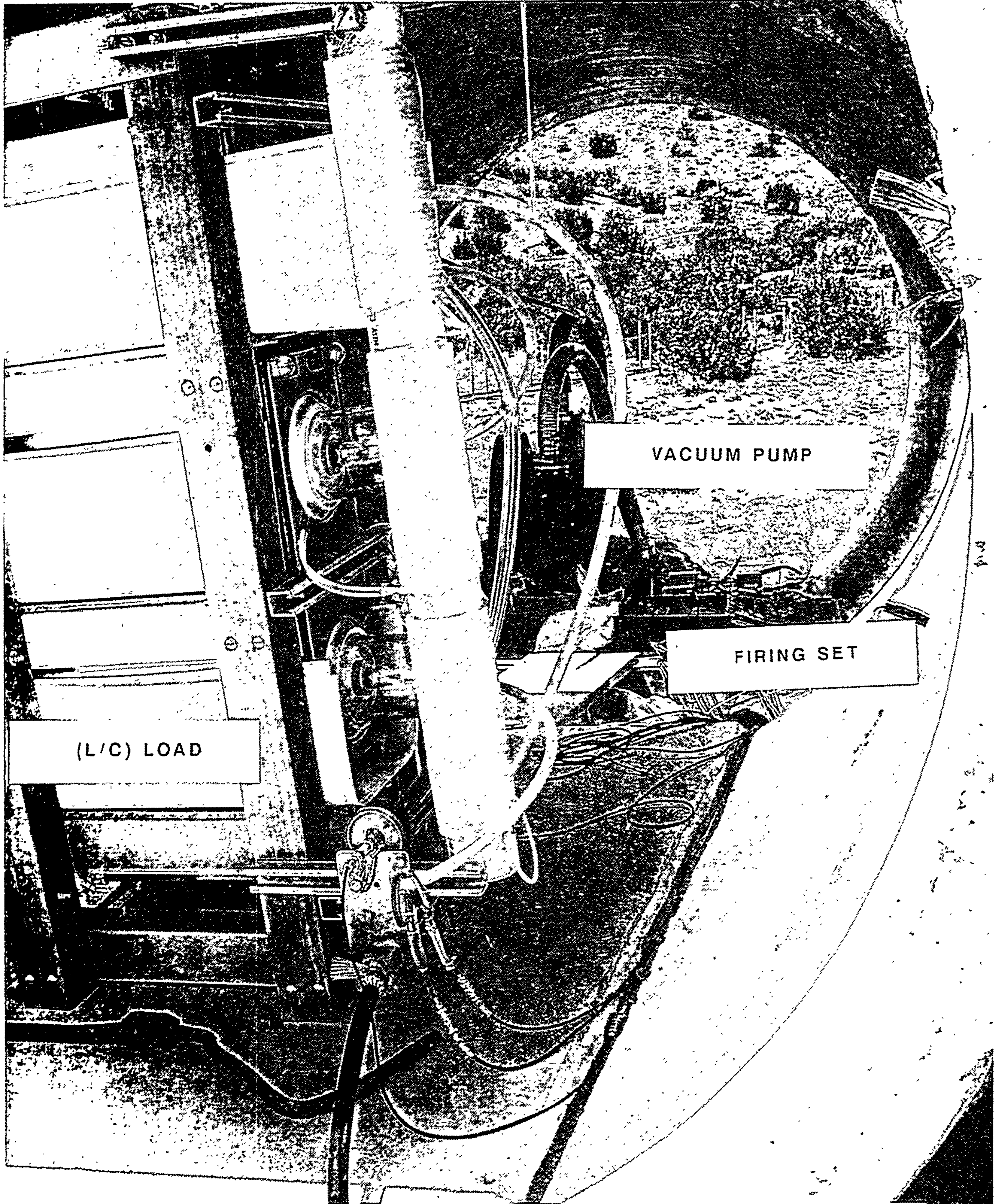

FIGURE B5. HERTF TEST/(L/C) LOAD, FIRING SET & VACUUM PUMP

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Appendix C

CTH Code Predicted Data

Figures

Table

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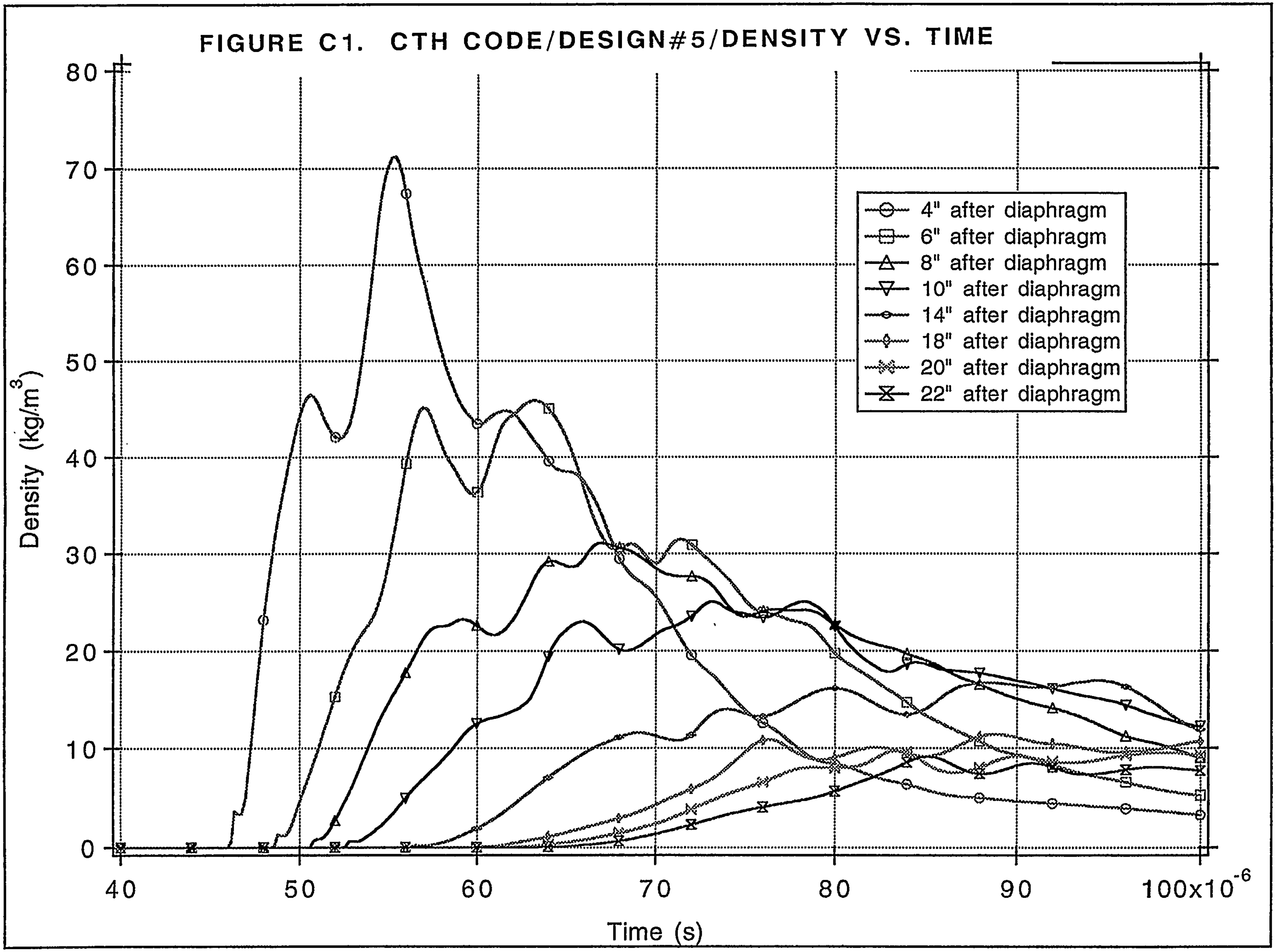
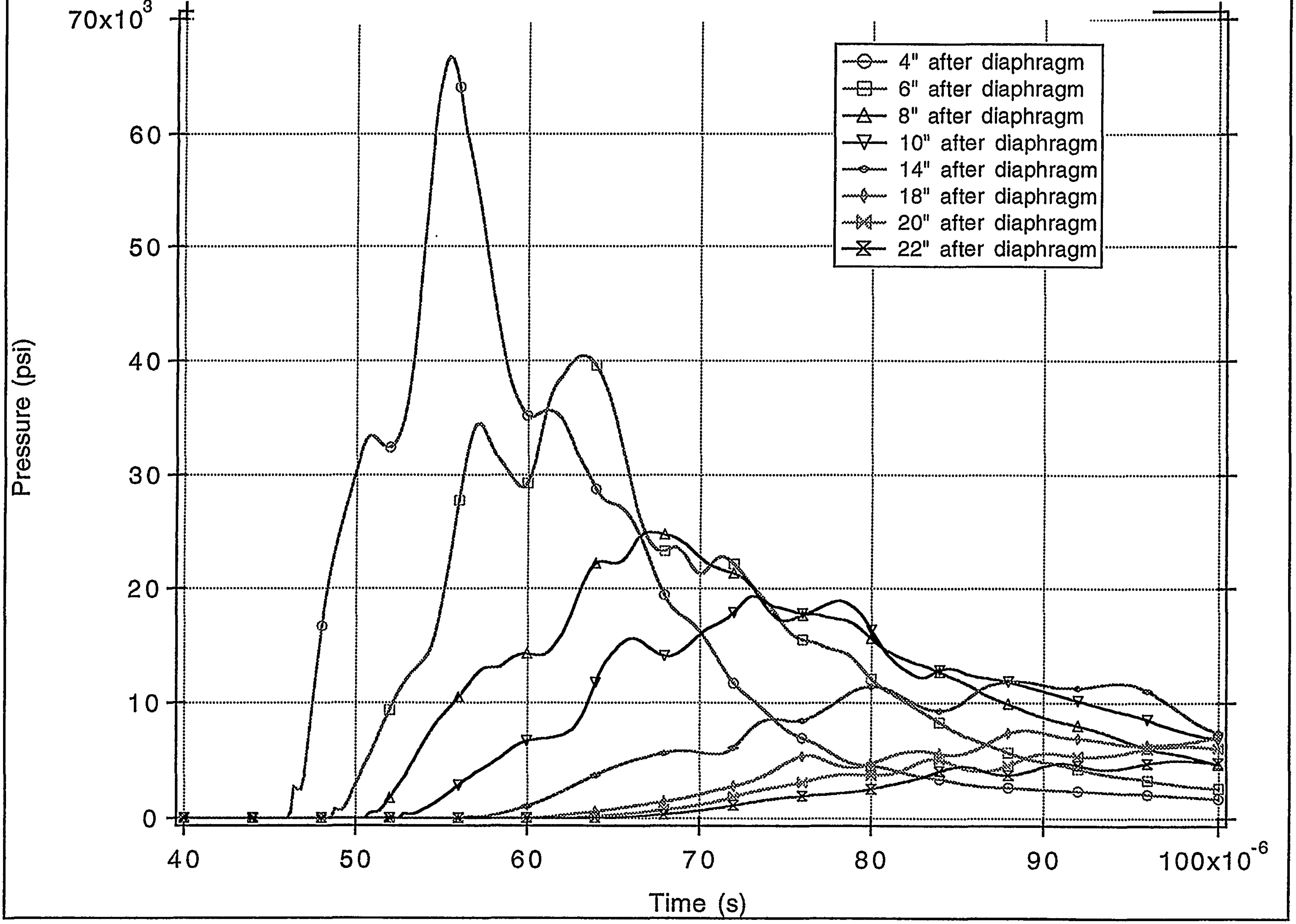


FIGURE C1. CTH CODE/DESIGN#5/DENSITY VS. TIME
Density (kg/m3)
Time (s)
0
10
20
30
40
50
60
70
80
40
50
60
70
80
90
100x10-6
4" after diaphragm
6" after diaphragm
8" after diaphragm
10" after diaphragm
14" after diaphragm
18" after diaphragm
20" after diaphragm
22" after diaphragm

FIGURE C2. CTH CODE/DESIGN#5/PRESSURE VS. TIME



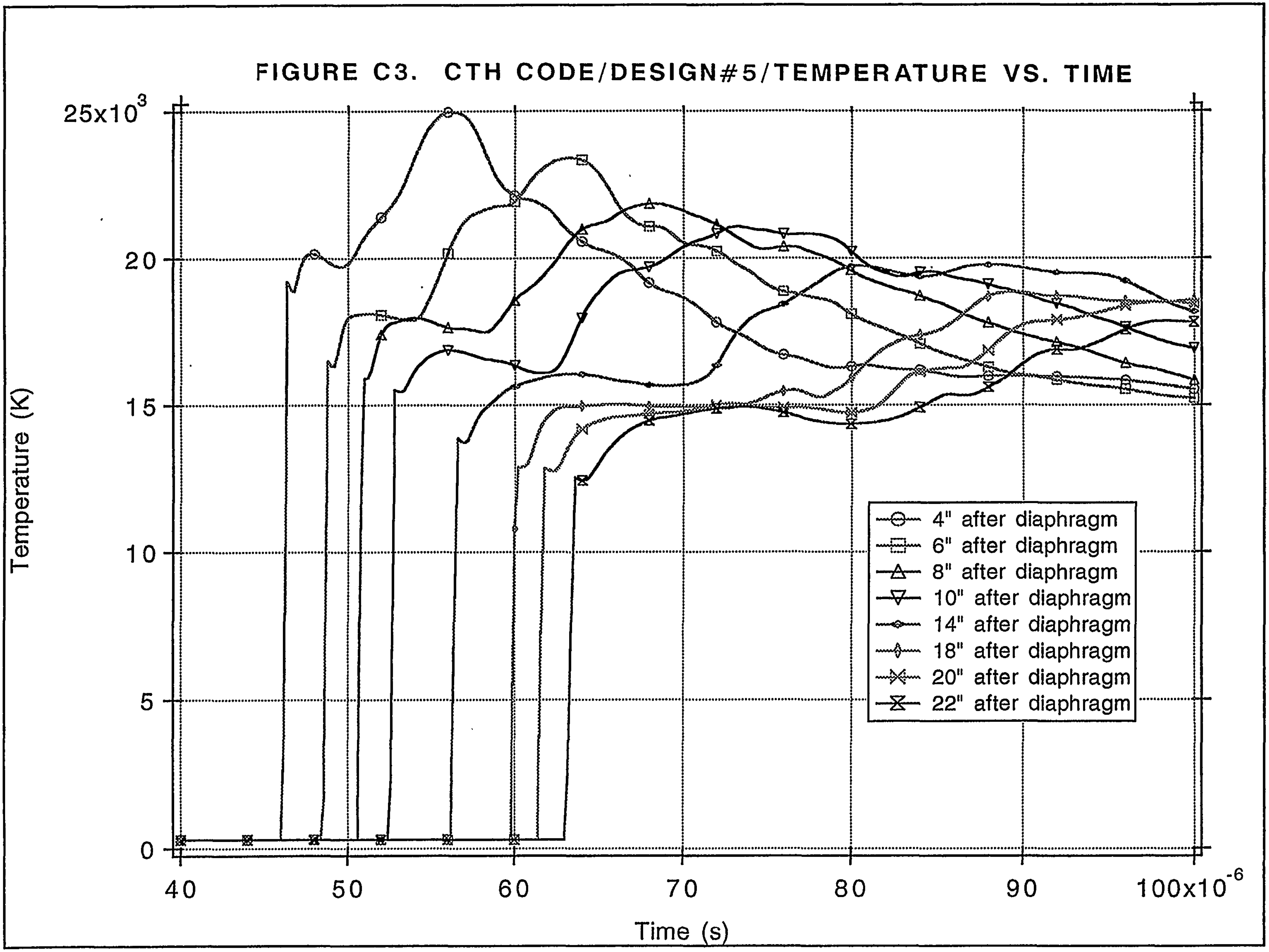


FIGURE C3. CTH CODE/DESIGN#5/TEMPERATURE VS. TIME
Temperature (K)
25x10^3
20
15
10
5
0
40
50
60
70
80
90
100x10^-6
Time (s)
4" after diaphragm
6" after diaphragm
8" after diaphragm
10" after diaphragm
14" after diaphragm
18" after diaphragm
20" after diaphragm
22" after diaphragm

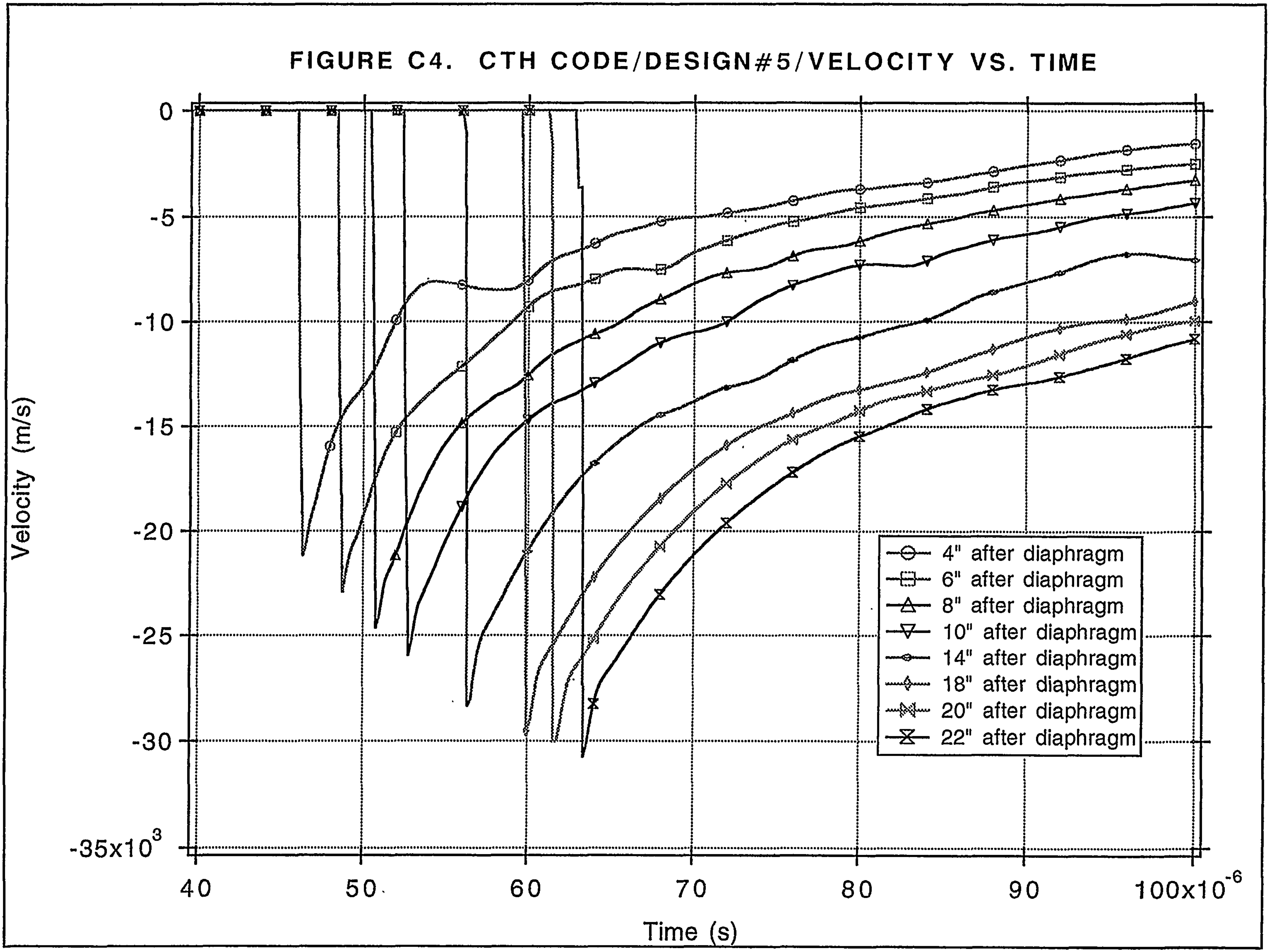


FIGURE C4. CTH CODE/DESIGN#5/VELOCITY VS. TIME
Velocity (m/s)
0
-5
-10
-15
-20
-25
-30
-35x10^3
40
50
60
70
80
90
100x10^-6
Time (s)
4" after diaphragm
6" after diaphragm
8" after diaphragm
10" after diaphragm
14" after diaphragm
18" after diaphragm
20" after diaphragm
22" after diaphragm

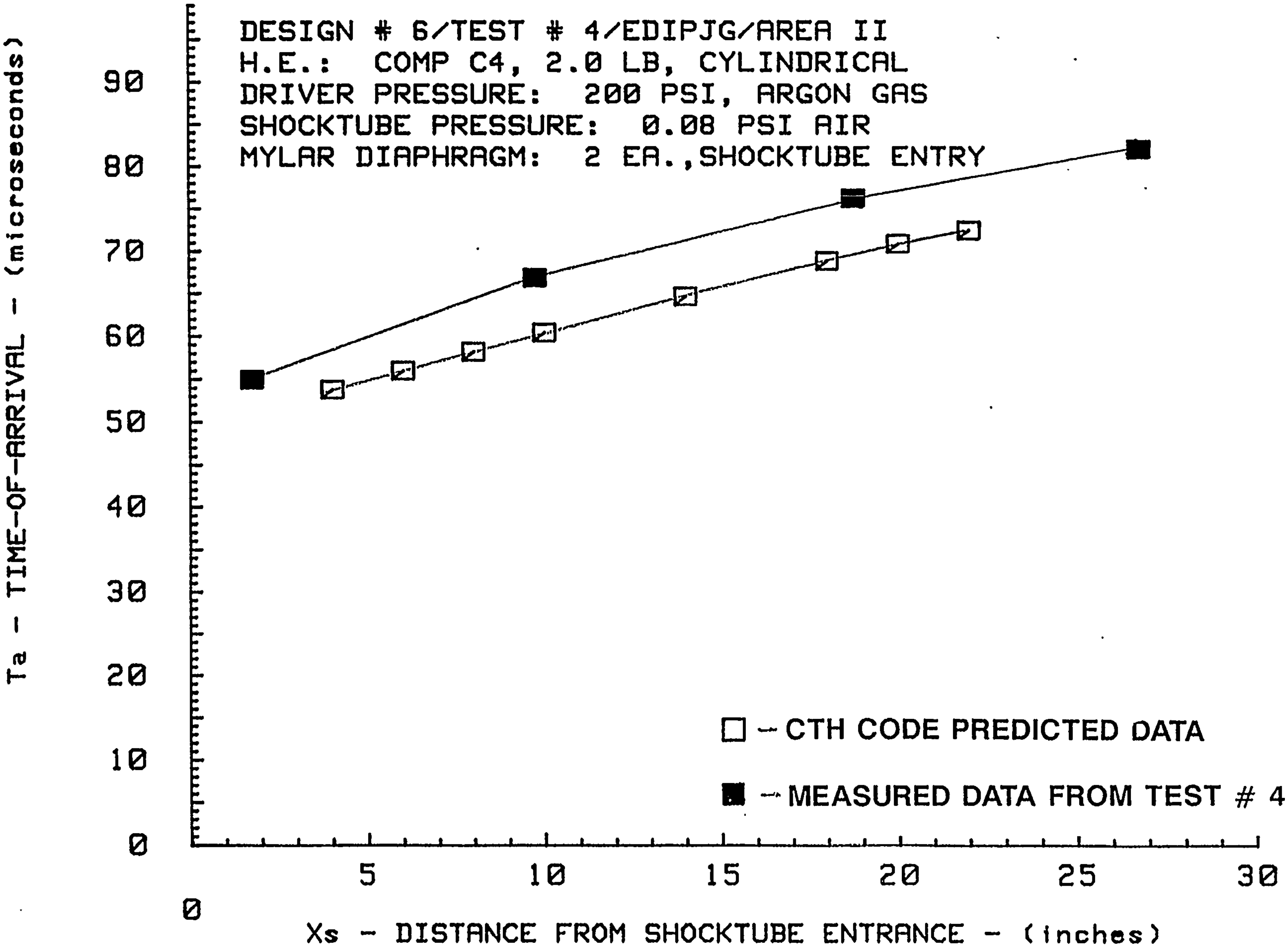


FIGURE C5. CTH CODE PREDICTED PLASMA FLOW TIME-OF-ARRIVAL VERSUS DISTANCE FROM SHOCKTUBE ENTRANCE COMPARED TO MEASURED DATA FOR TEST 4

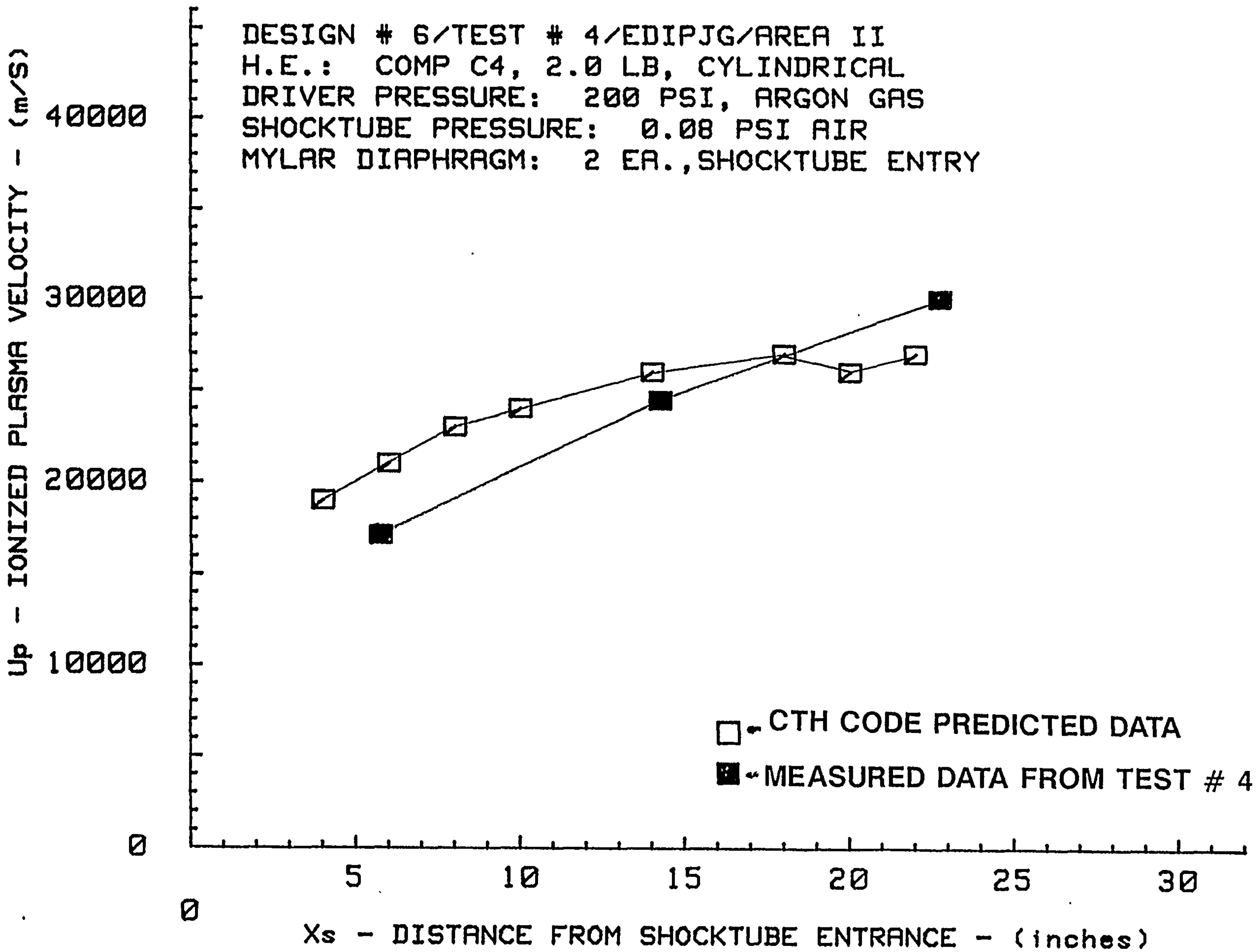


FIGURE C6. CTH CODE PREDICTED PLASMA FLOW VELOCITY VERSUS DISTANCE FROM SHOCKTUBE ENTRANCE COMPARED TO MEASURED DATA FOR TEST 4

TABLE C1. CTH CODE PREDICTED DATA/EDMG DESIGN#5

CTH run d5-2a200h.01					
Location (in) relative to diaphragm	Density (kg/m^3)	Pressure (10^3 psi)	Temperature (10^3 K)	Velocity† (10^3 m/s) (instantaneous)	Arrival Time* (μs)
4" after	71	67	25	21	46
6" after	46	40	23	23	48.4
8" after	31	25	22	25	50.4
10" after	25	19	21	26	52.4
14" after	17	12	20	28	56.2
18" after	11	8	19	30	59.6
20" after	10	6	19	30	61.4
22" after	8	5	18	31	62.8

* Arrival times were determined from the velocity histories.

+ Velocities listed above are termed instantaneous to differentiate them from the velocities obtained from the experiments, which are determined by a $V = \Delta x/\Delta t$ calculation.

TABLE C2. CTH CODE PREDICTED DATA'EDMG DESIGN#5

Comparison of arrival times for run d5-2a200h.01 and test D3A200H.01L02			
Distance from shock tube inlet (in)	Arrival time, experiment◊ (μs)	Arrival time, analysis‡(μs)	Difference (μs)
1.75	53.1	43.3	9.9
5.75	56.7	48.1	8.6
9.75	61.0	52.2	8.8
18.75	69.7	60.3	9.4
22.75	73. 7	63.3	10.4

◊ Experiment arrival times listed were calculated by subracting 48.3 μs from experimental results to account for MDF lines.

‡ Arrival times for comaprison with test results are interpolated from stations listed in the first table above.

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APPENDIX D

Test 1/Design 5/Configurations and Experimental Data

Figures

Tables

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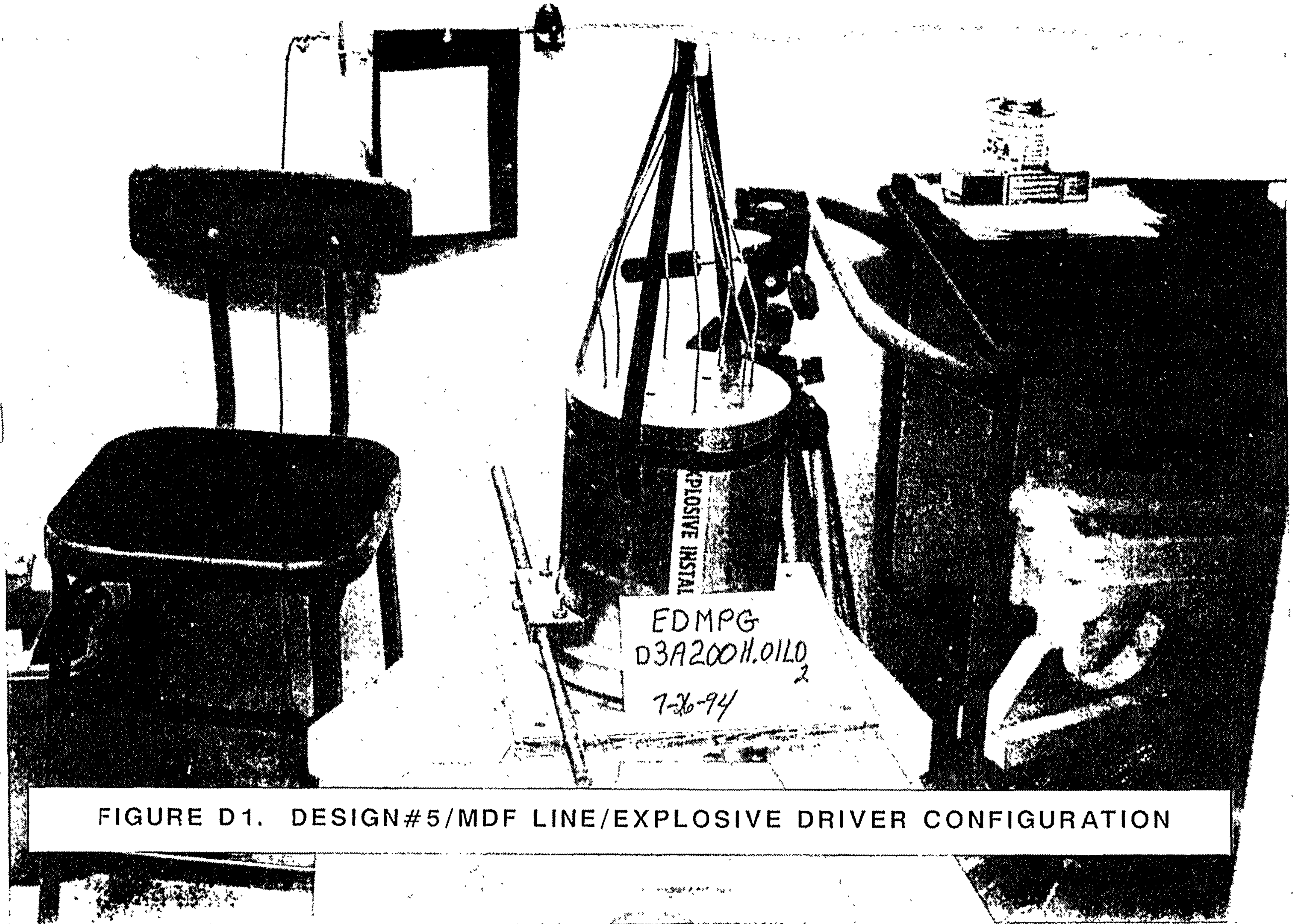

FIGURE D1. DESIGN#5/MDF LINE/EXPLOSIVE DRIVER CONFIGURATION

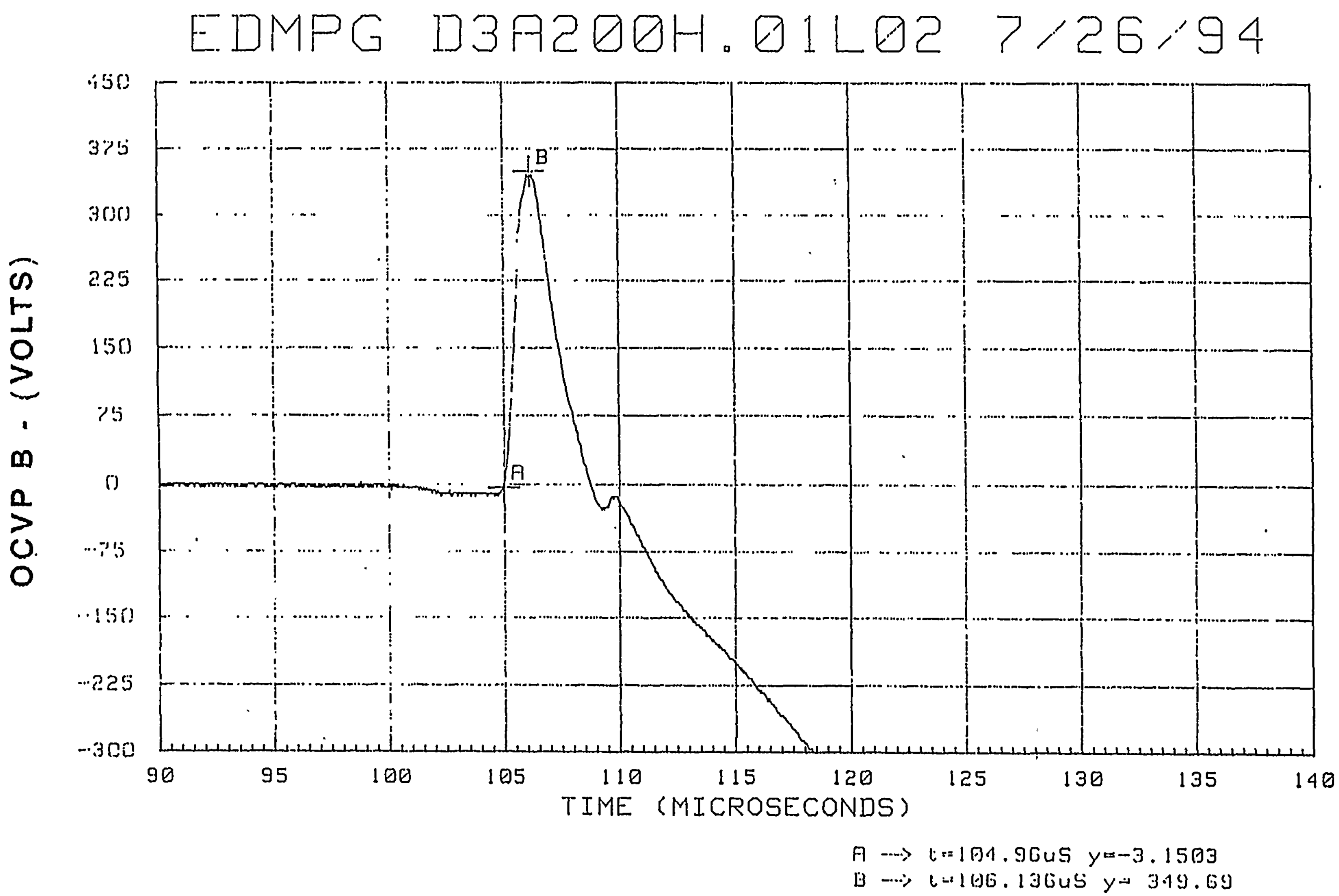

FIGURE D2. DESIGN#5/OPEN CIRCUIT VOLTAGE VS. TIME

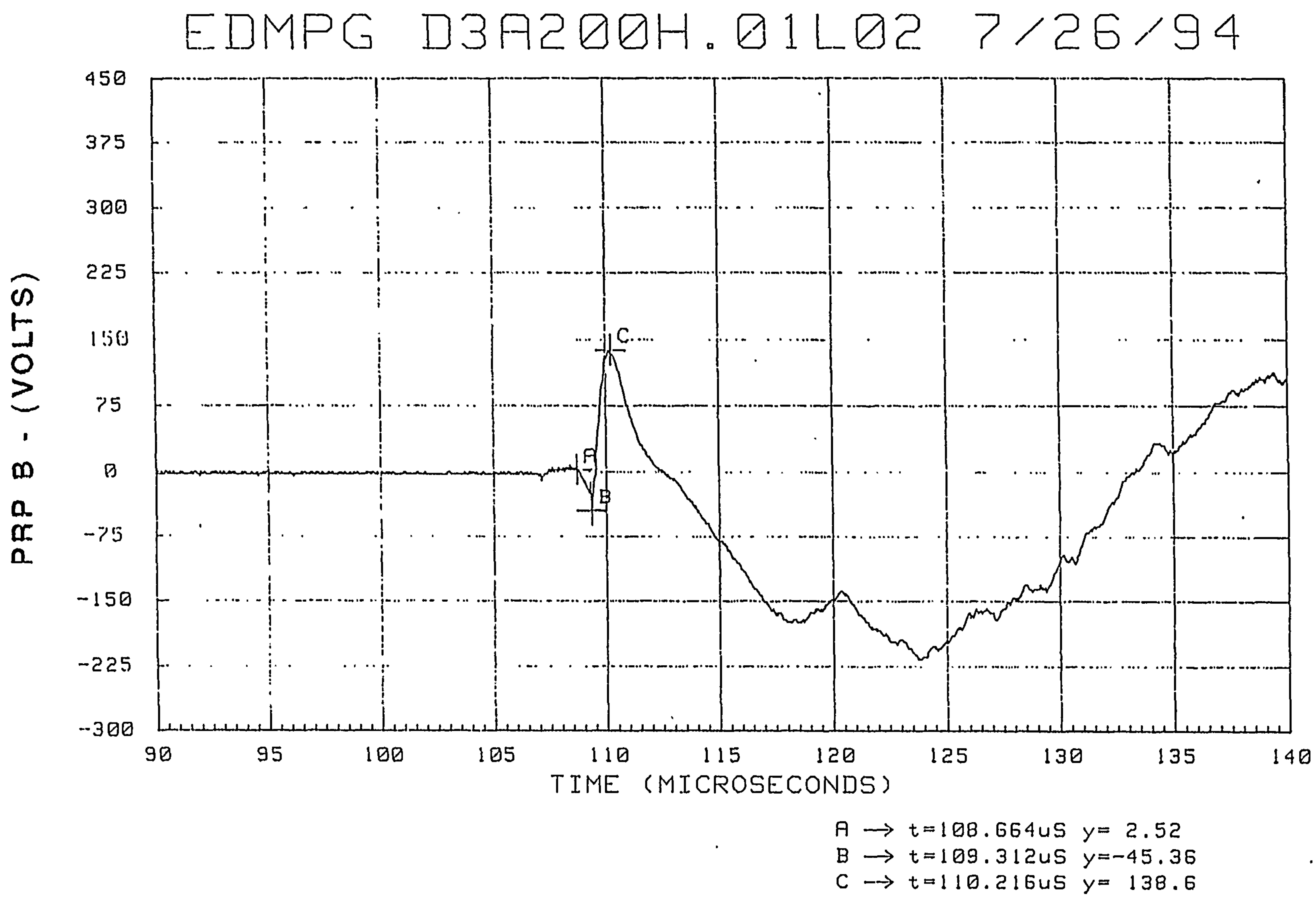

FIGURE D3. DESIGN#5/RESISTIVE LOAD VOLTAGE VS. TIME

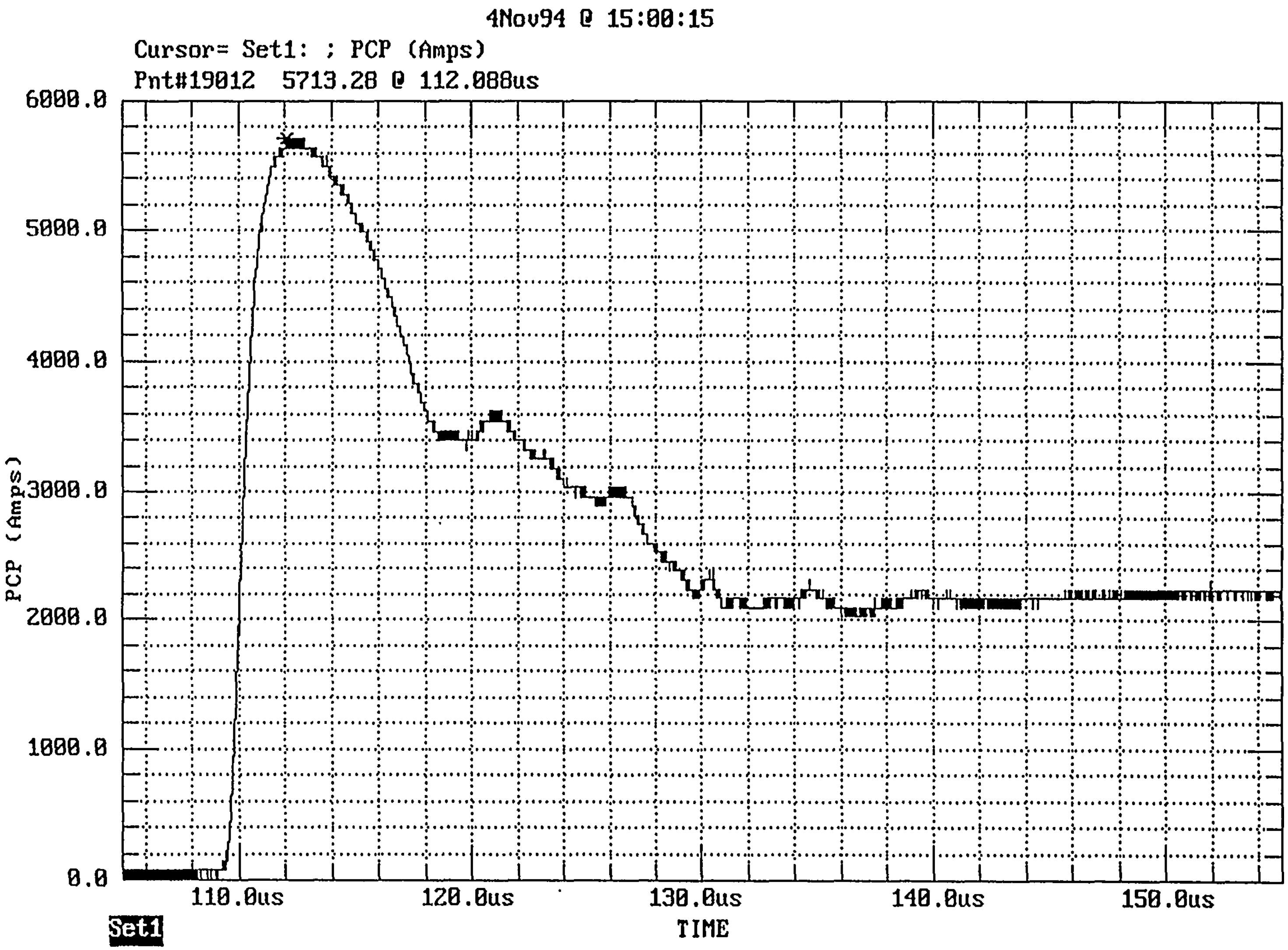

FIGURE D4. DESIGN#5/CURRENT VS. TIME

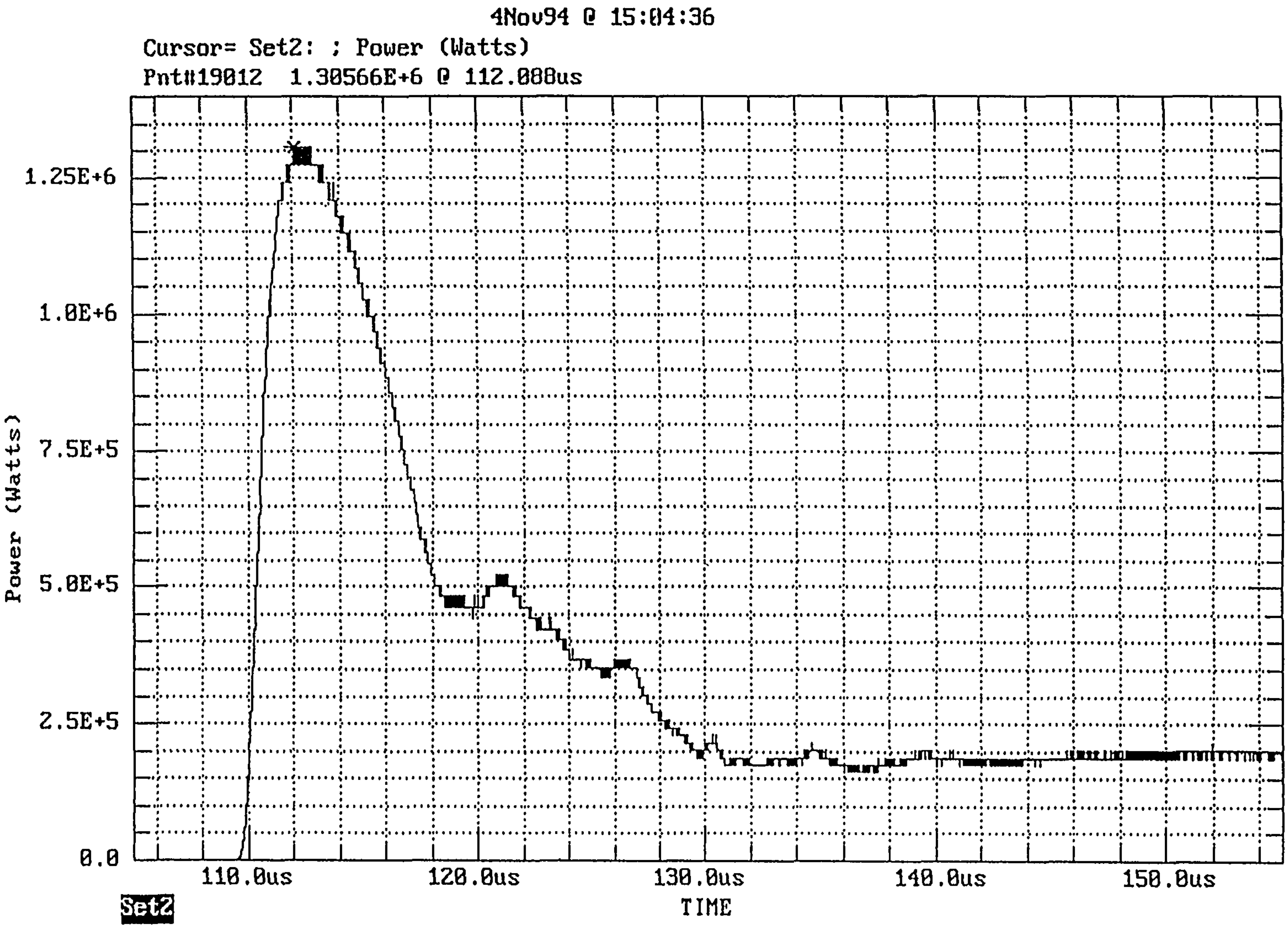

FIGURE D5. DESIGN#5/LOAD POWER VS. TIME/R=0.040 OHMS

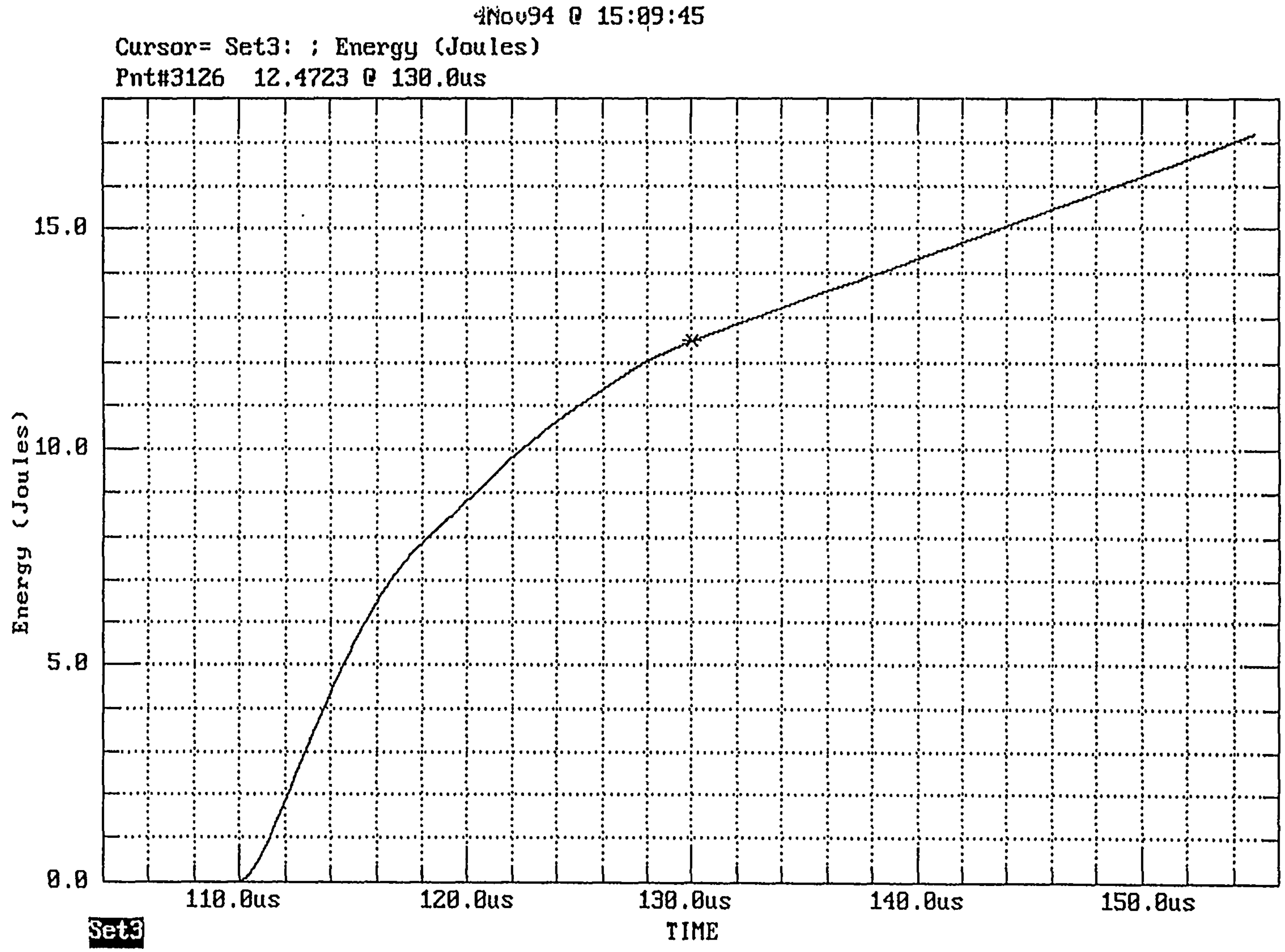

FIGURE D6. DESIGN#5/ENERGY VS. TIME

TABLE D1. EDMG DESIGN#5 PLASMA TIME, DISTANCE, VELOCITY & MAGNET DATA

Test Date: 7/26/94
Pins: None
Diaphragm: Mylar, 0.014" thick, at Shocktube entrance
Shocktube Air Pressure: 0.012psi (600 mT)

Probe No.	t Time (zero fidu) (µs)	Δt (µs)	X Distance fm Shocktube Inlet (in)	ΔX (m)	Uf (m/s)	Type Measurement	Magnet Strength (T)
1	101.352		1.75			VP	.07
		3.624		0.1016	28,042		
2	104.976		5.75			OCVP	.40+
		4.344		0.1016	23,389		
3	109.320		9.75			PRP	.60+
		8.697		0.2286	26,285		
4	118.016		18.75			VP	.07
		3.976		0.1016	25,553		
5	121.992		22.75			VP	.07
		4.136		0.1016	24,565		
6	126.128		26.75			VP	.07

VP - Voltage Probe
Plasma Arrival Time Accuracy: ± 8.0ηs

MGVigil:edipl.doc:7/28/94

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Appendix E

Test 2/Design 6/Configurations And Experimental Data

Figures

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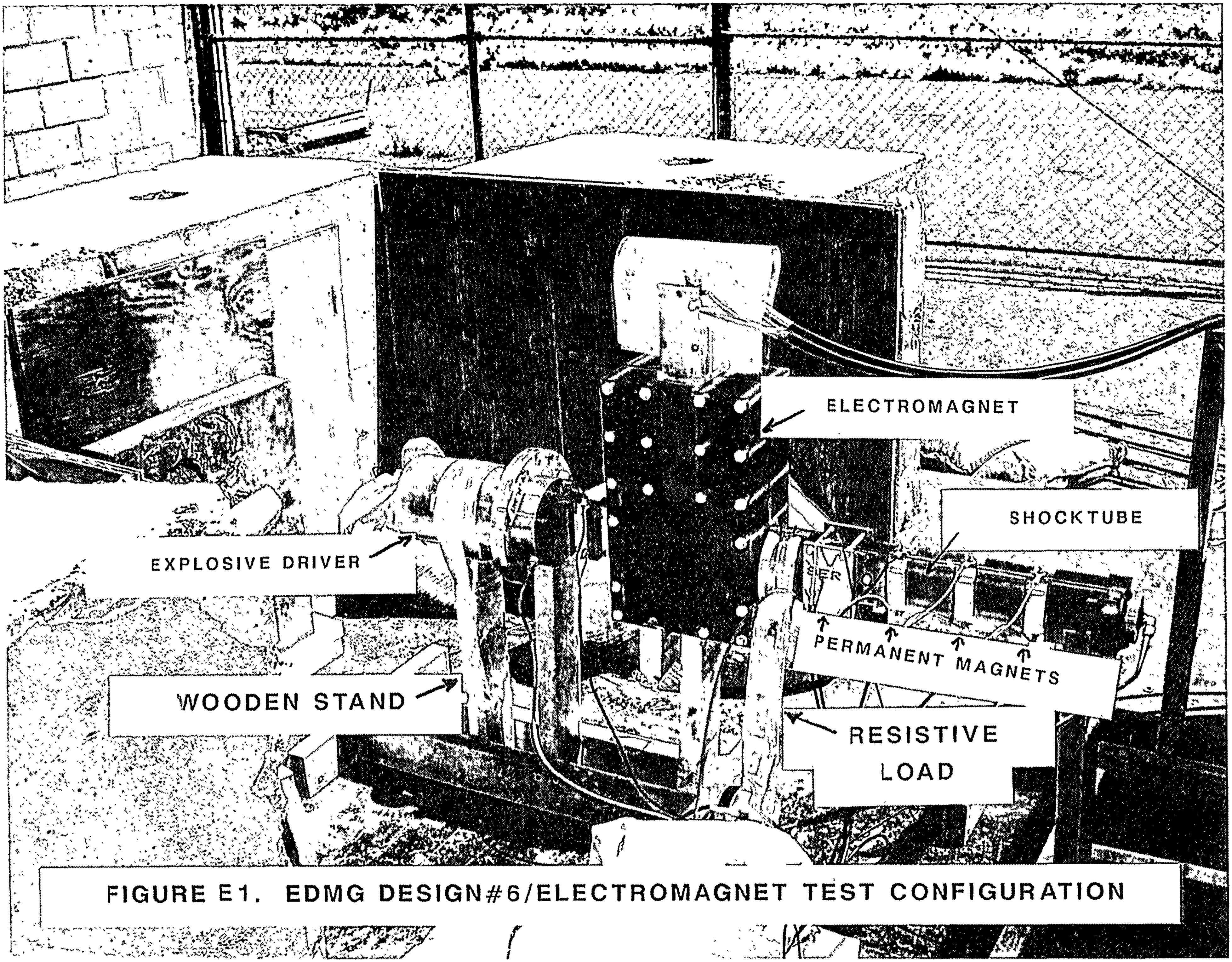

FIGURE E1. EDMG DESIGN#6/ELECTROMAGNET TEST CONFIGURATION

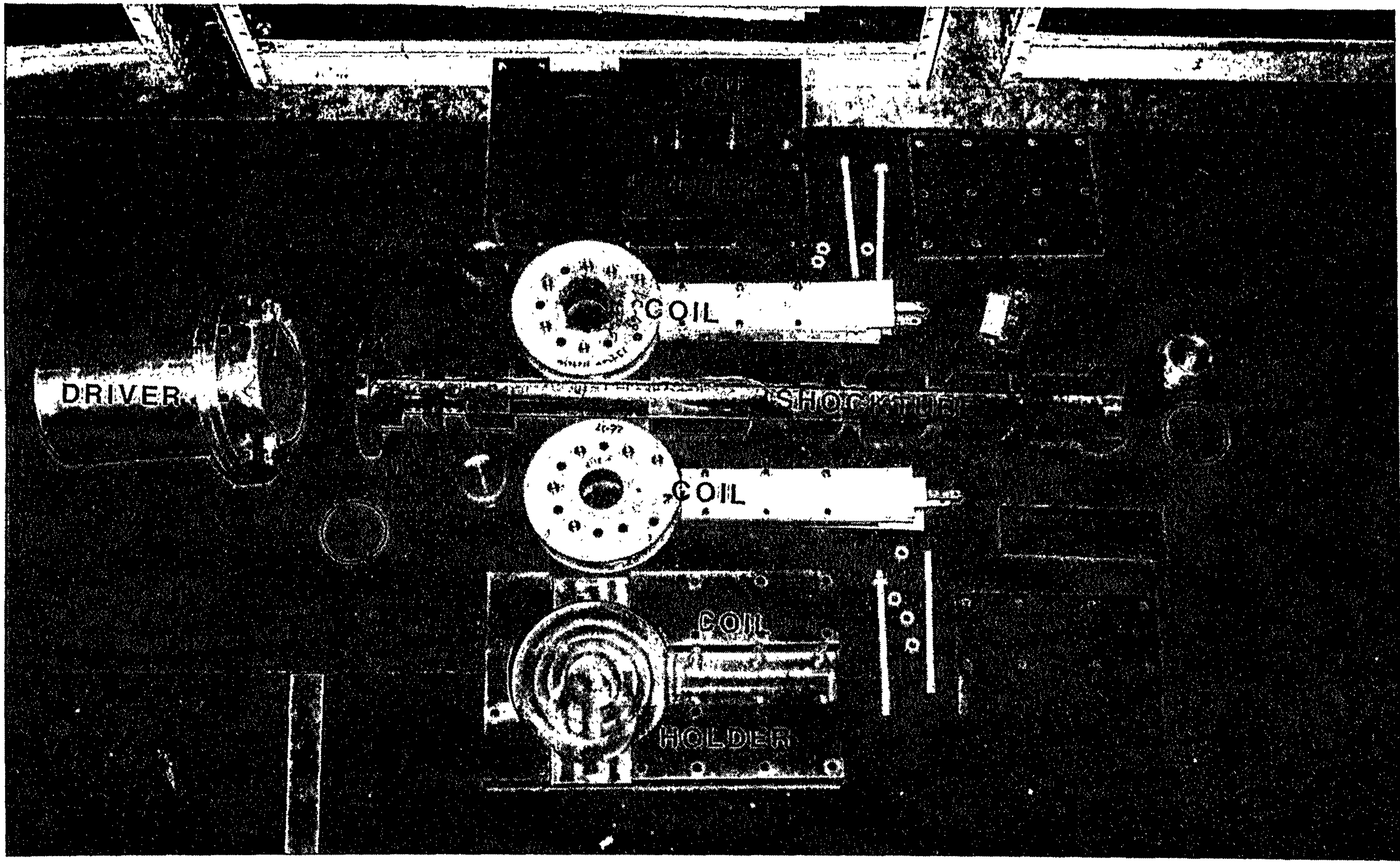

FIGURE E2. EDMG DESIGN#6/ELECTROMAGNET COILS/HARDWARE CONFIGURATION

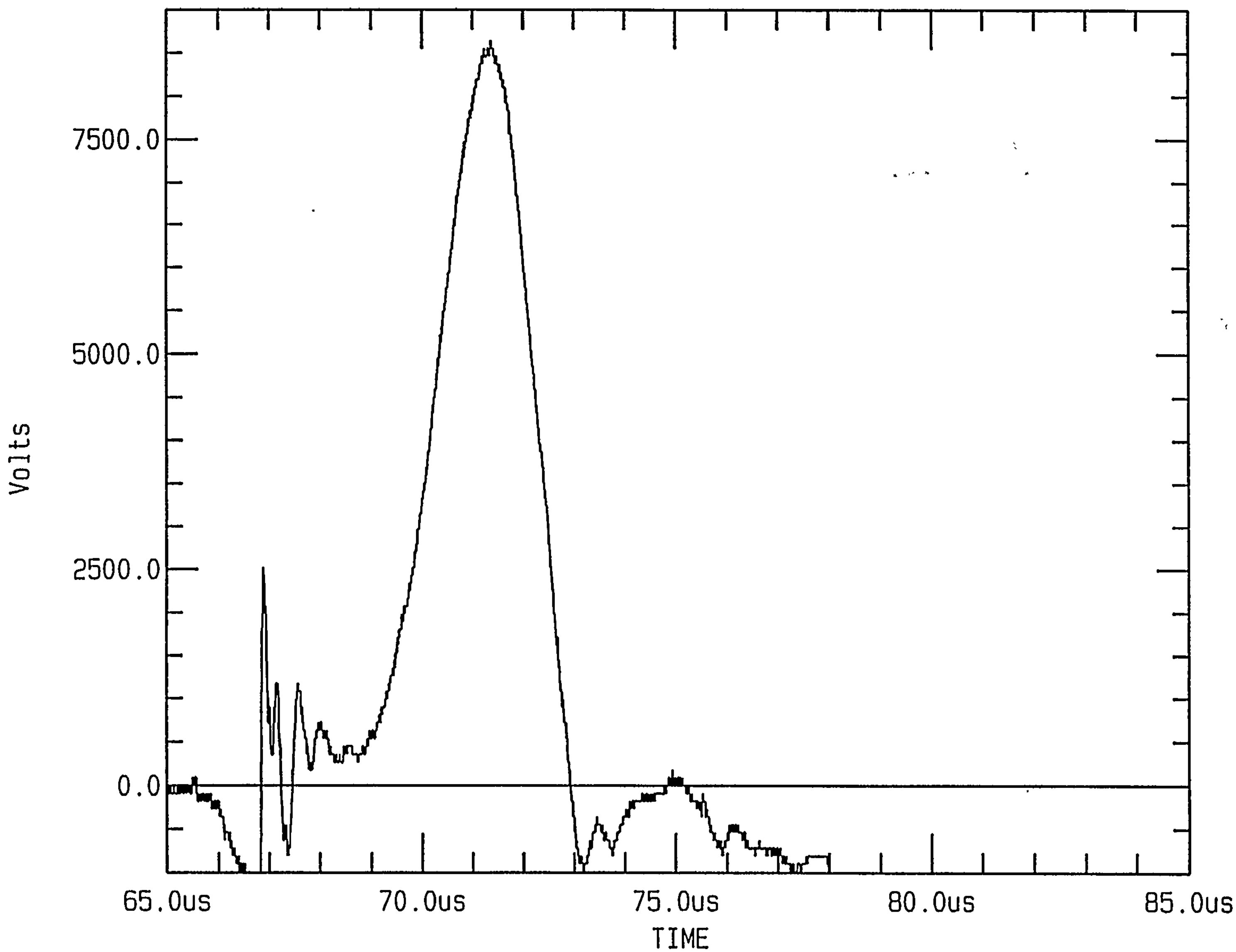

FIGURE E3. DESIGN 6/TEST 2/RESISTIVE LOAD VOLTAGE VS. TIME

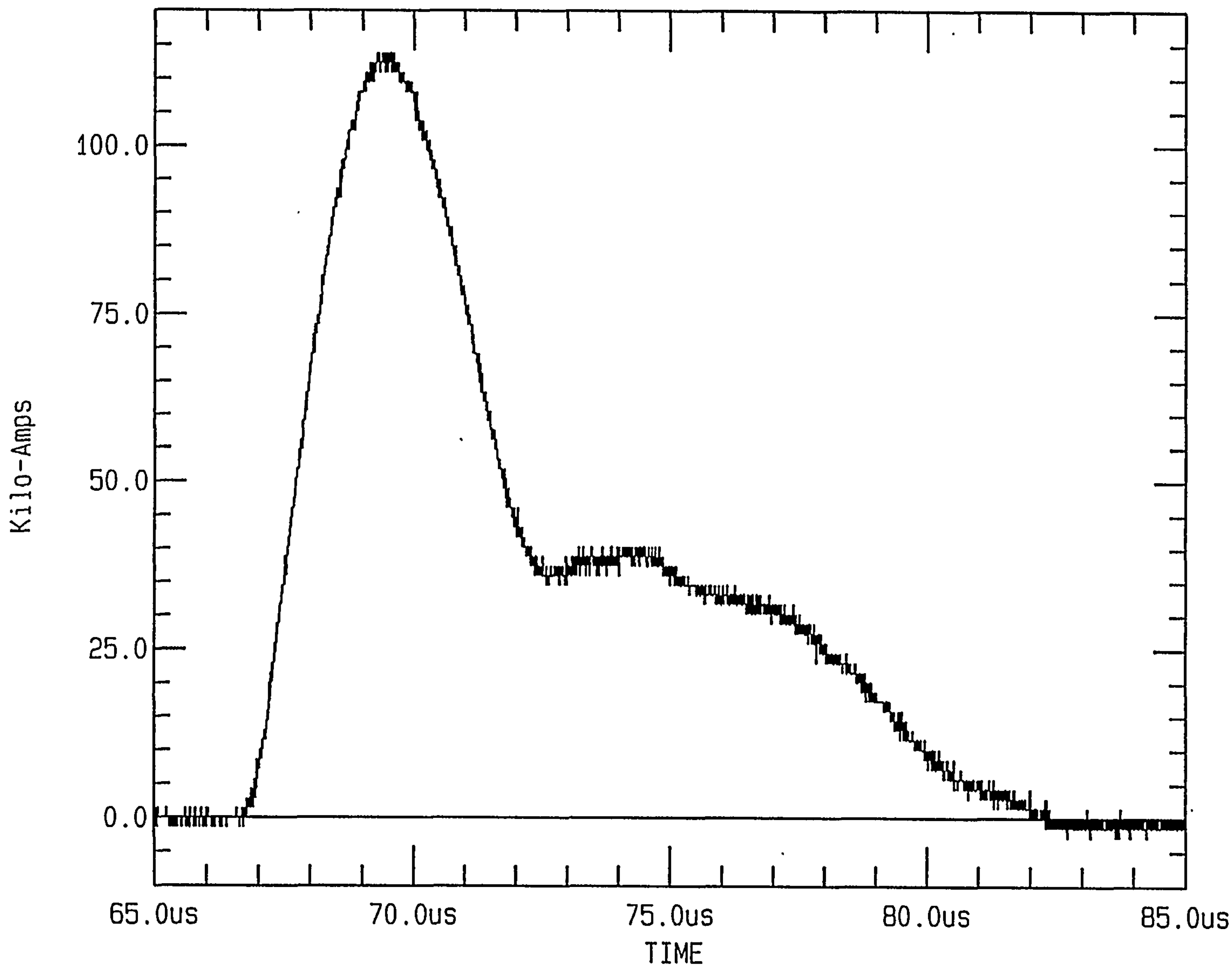

FIGURE E4. DESIGN 6/TEST 2/PLASMA CURRENT VS. TIME

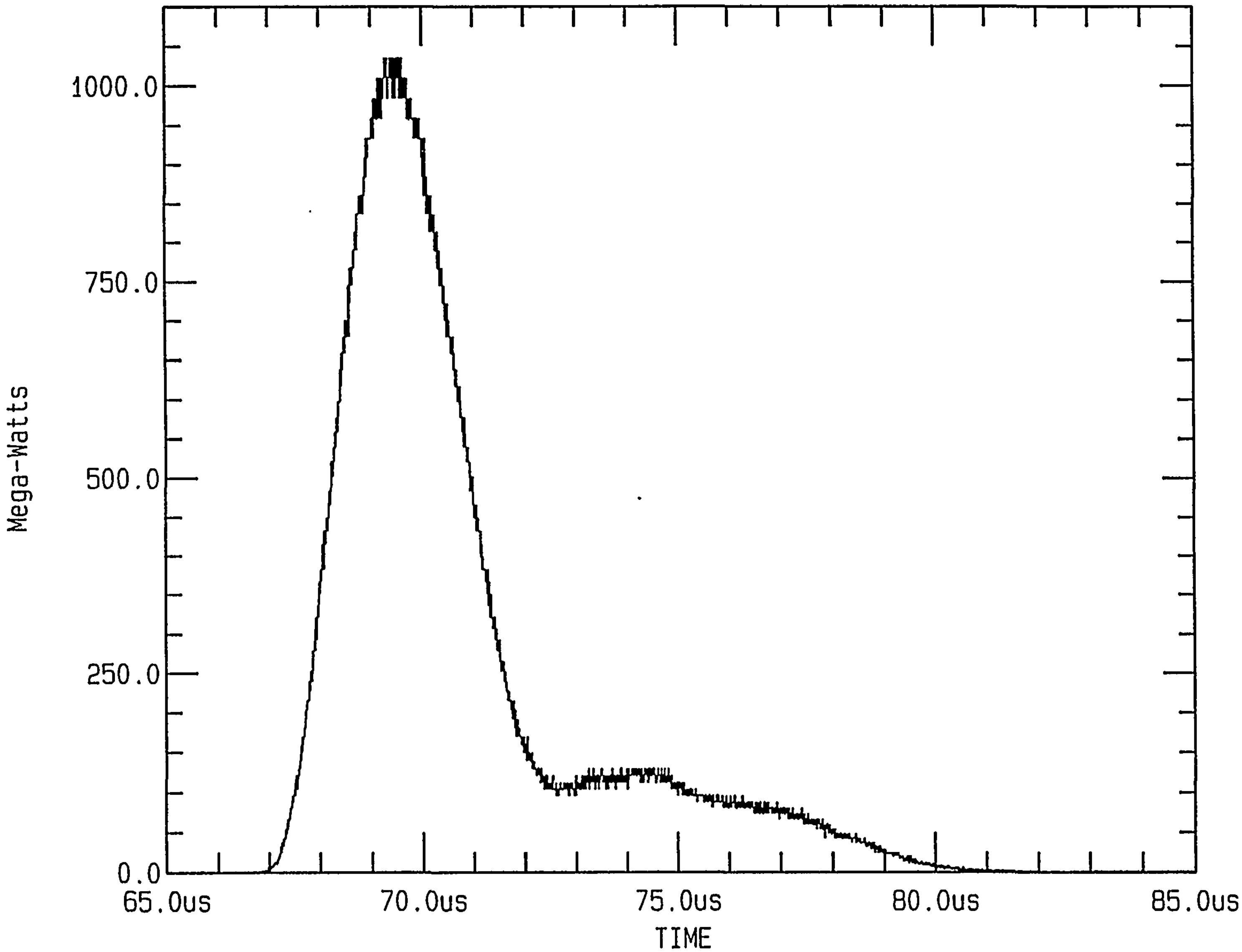

FIGURE E5. DESIGN 6/TEST 2/LOAD POWER VS. TIME

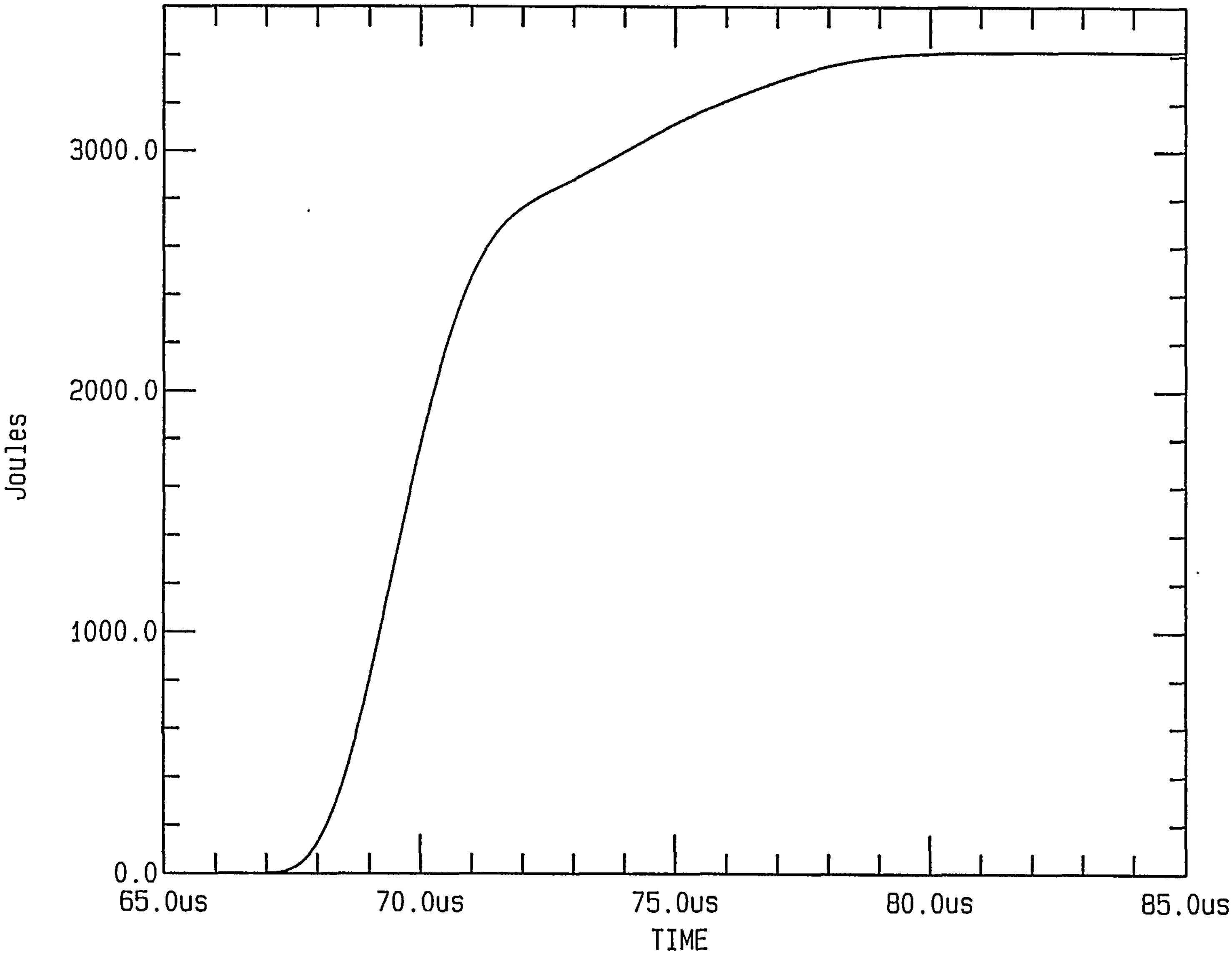

FIGURE E6. DESIGN 6/TEST 2/ENERGY VS. TIME

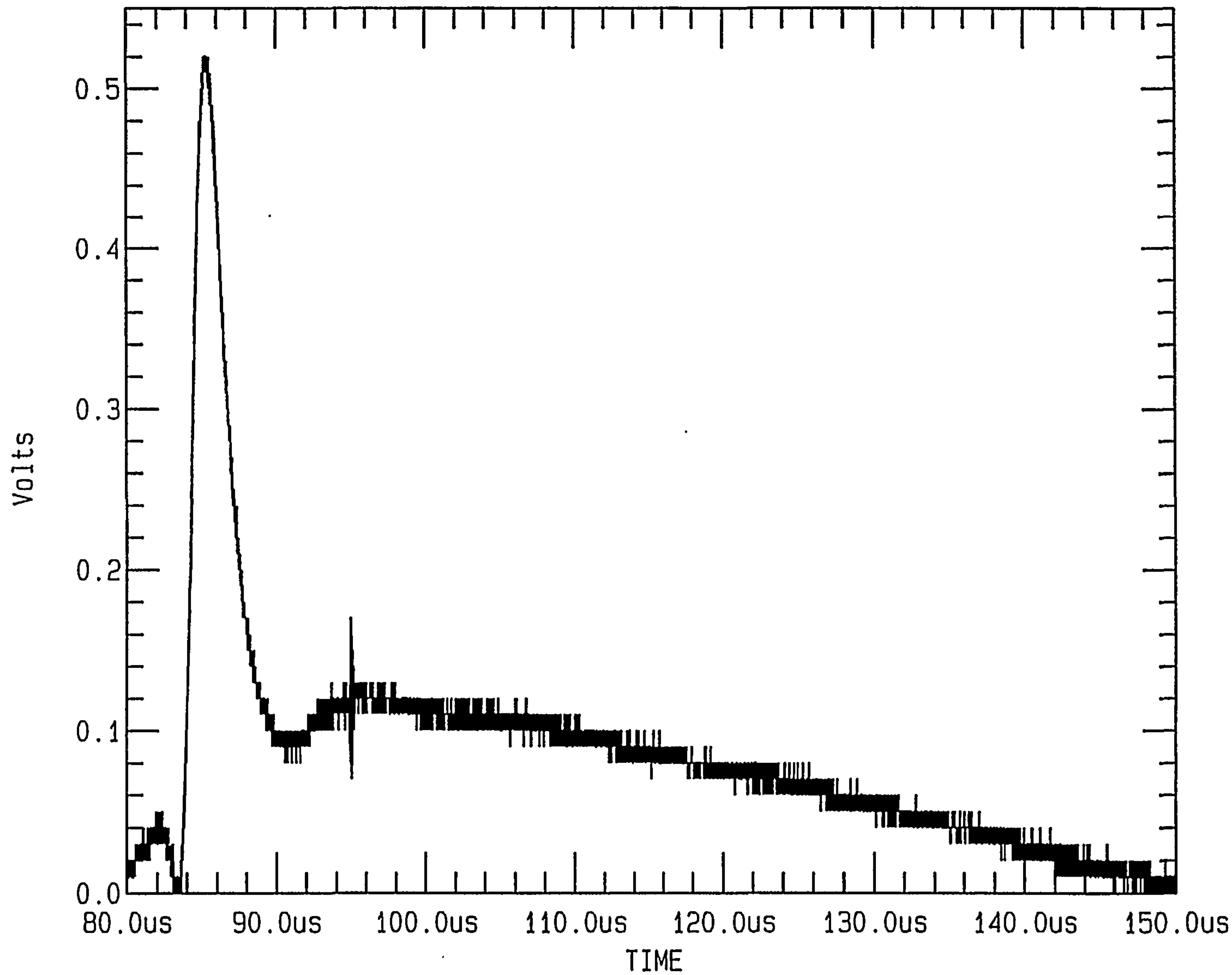

FIGURE E7. DESIGN 6/TEST 2/EDDY COIL CURRENT VOLTAGE VS. TIME

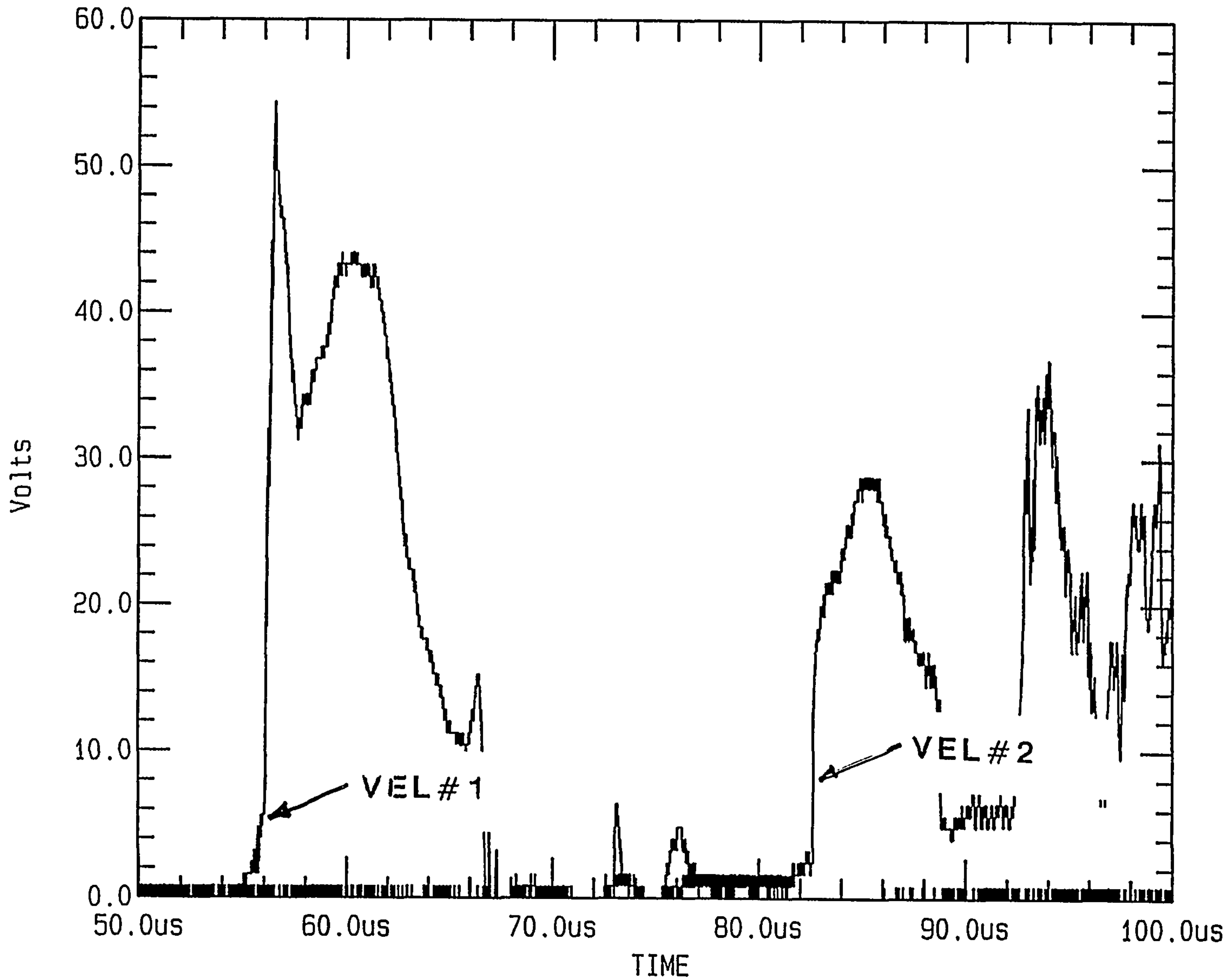

FIGURE E8. VELOCITY PROBE ARRIVAL TIME PROBE VOLTAGE VS. TIME

Appendix F

Test 3/Design 6/Configurations And Experimental Data

Figures

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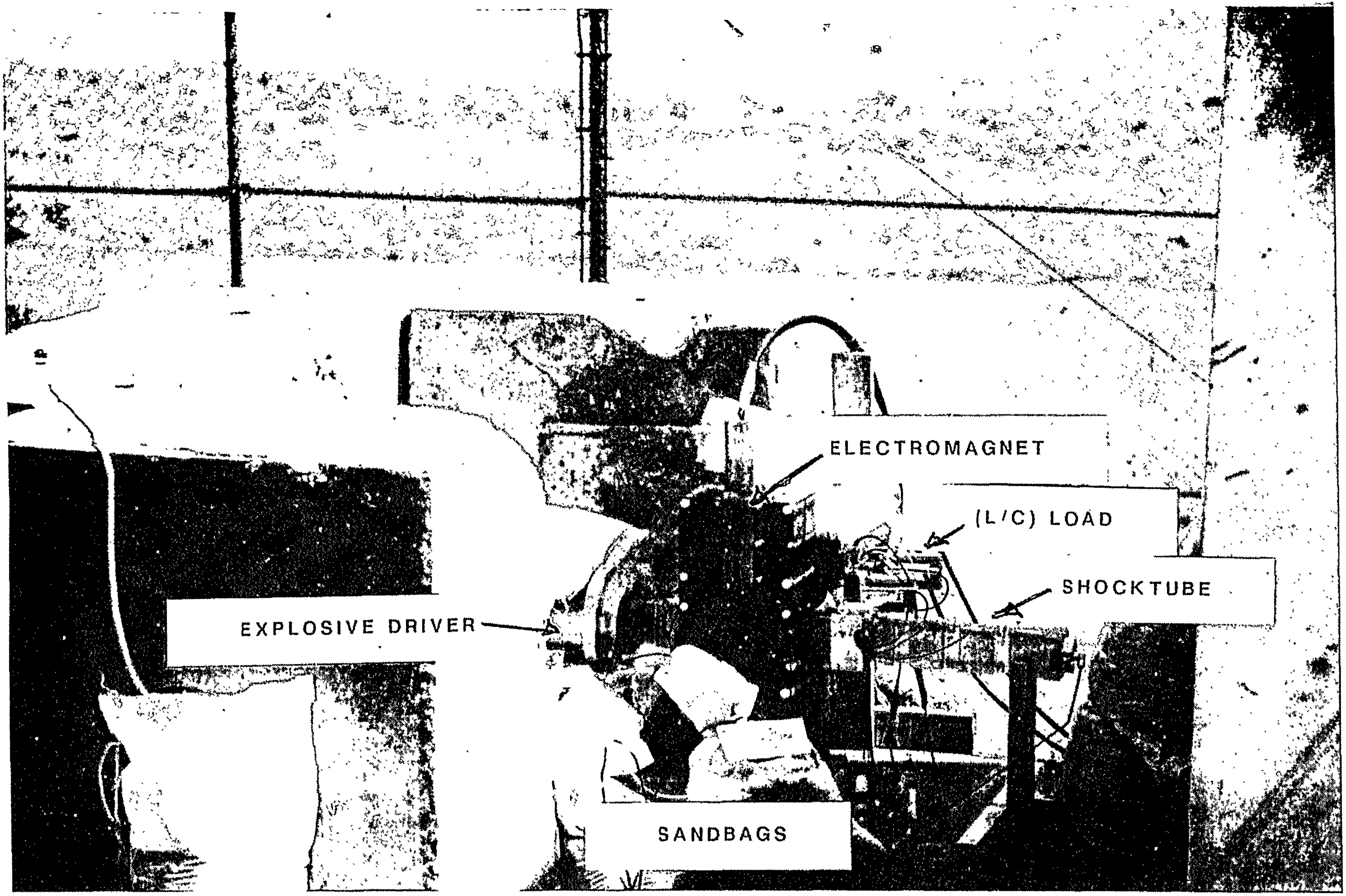
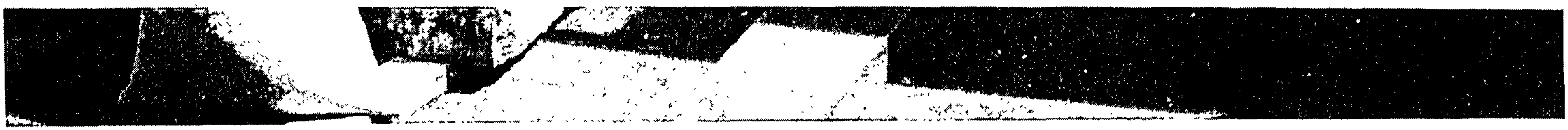


FIGURE F1. EXPLOSIVELY-DRIVEN MHD GENERATOR/SHOCKTUBE/ELECTROMAGNET CONFIGURATION



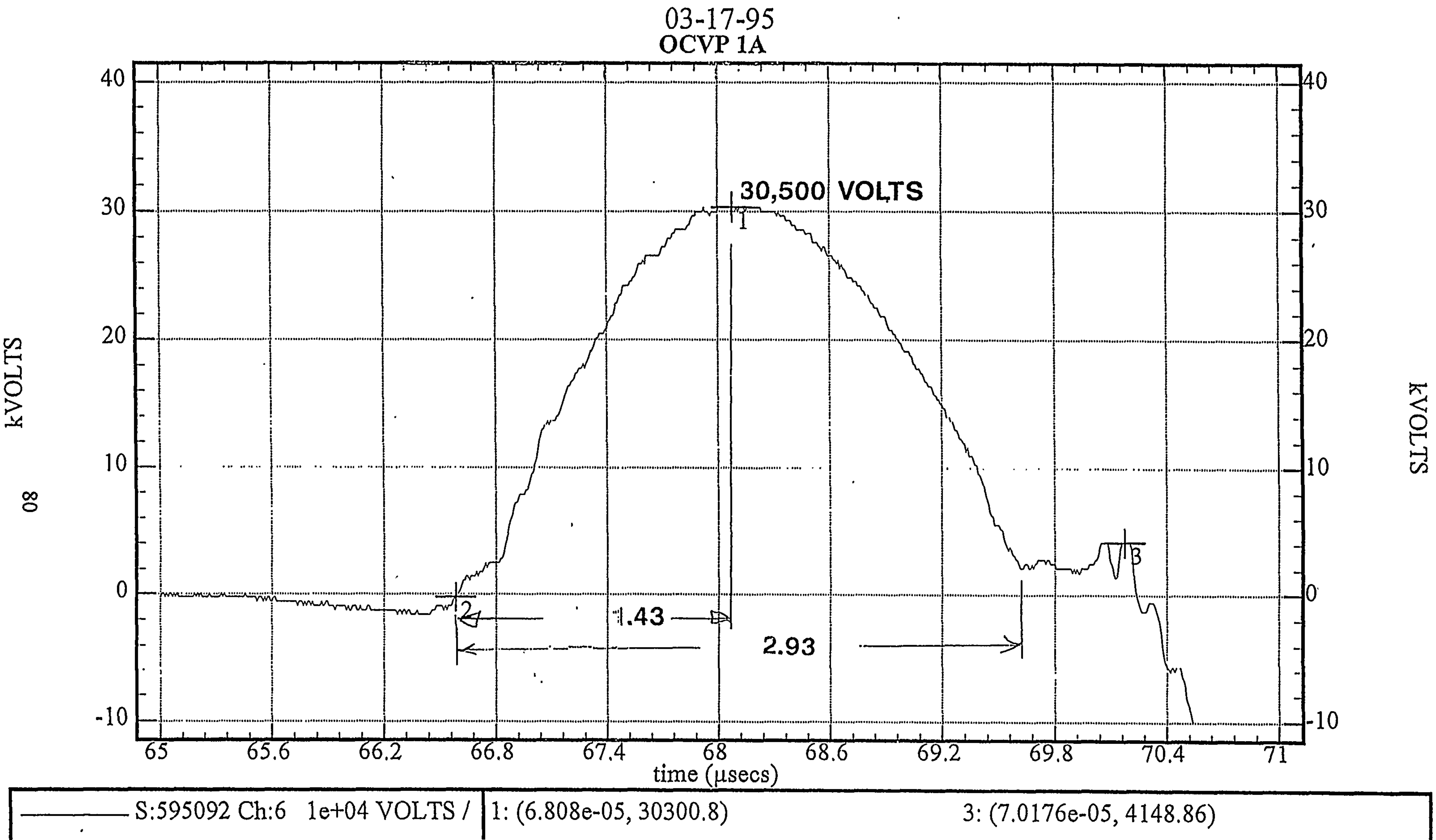


FIGURE F2. OPEN CIRCUIT VOLTAGE VS. TIME

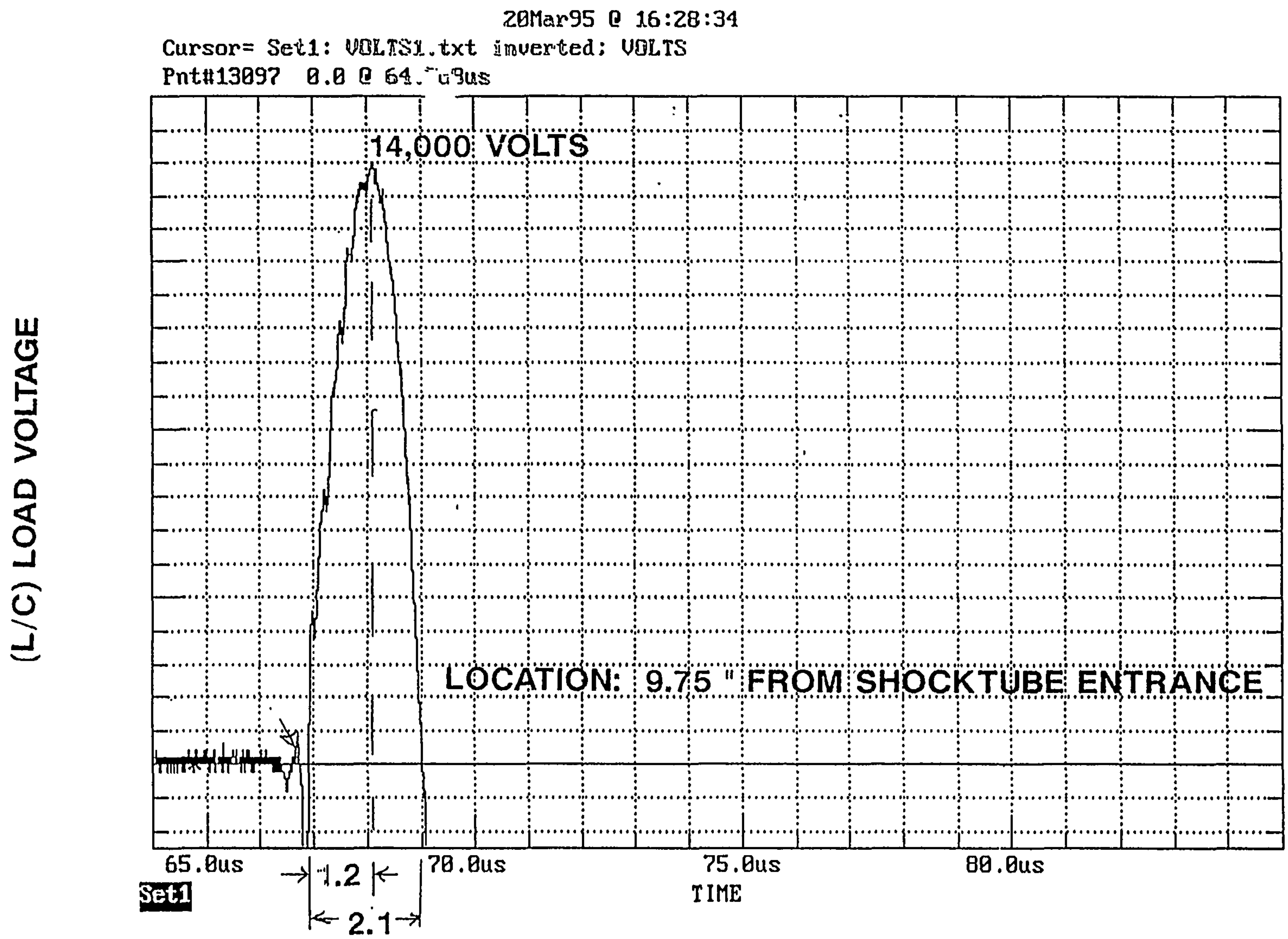


FIGURE F3 (L/C) LOAD VOLTAGE VERSUS TIME/TEST # 1/AREA II/VOLTS1

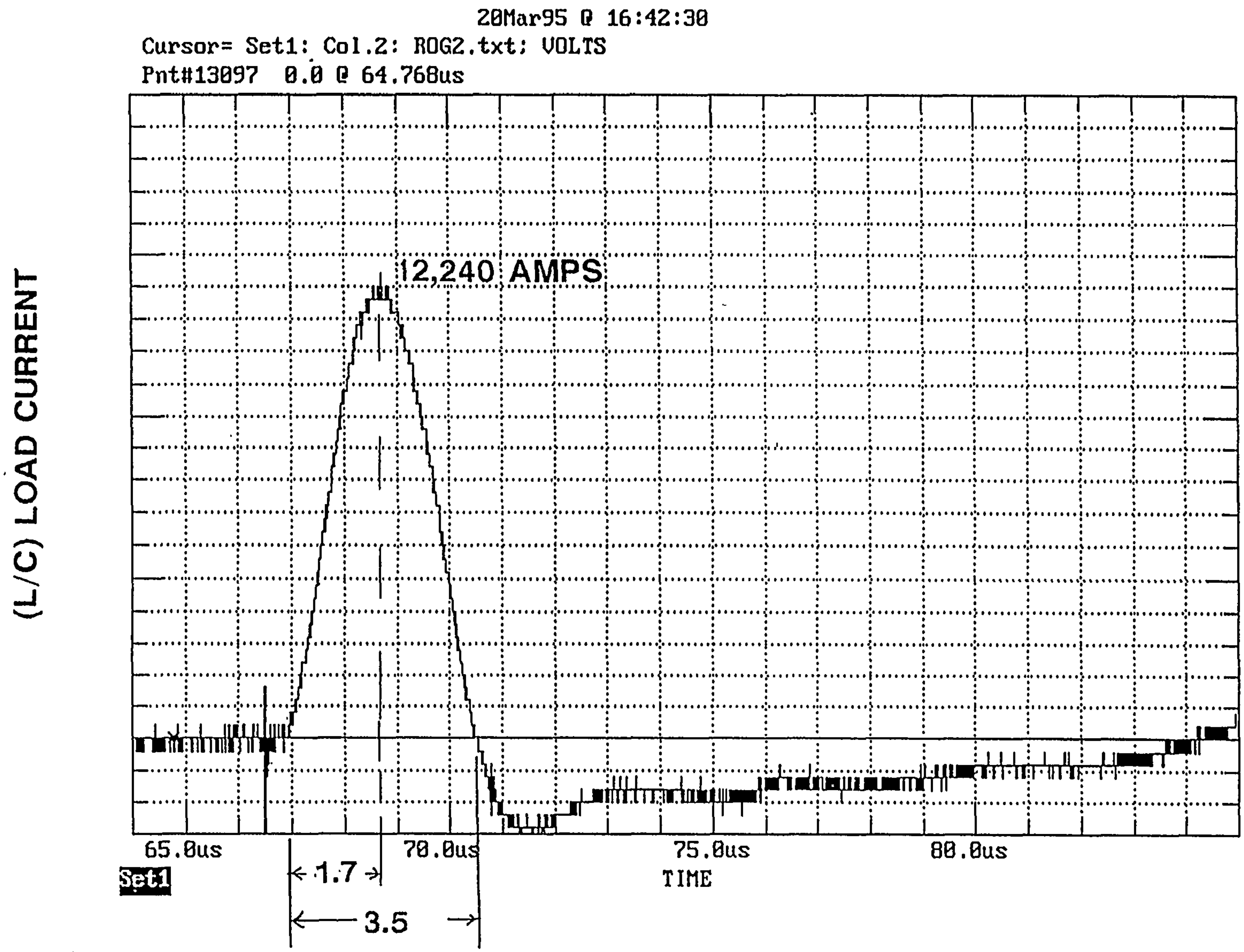


FIGURE F4 (L/C) LOAD CURRENT VERSUS TIME/TEST # 1/AREA II/ROGOWSKI # 2

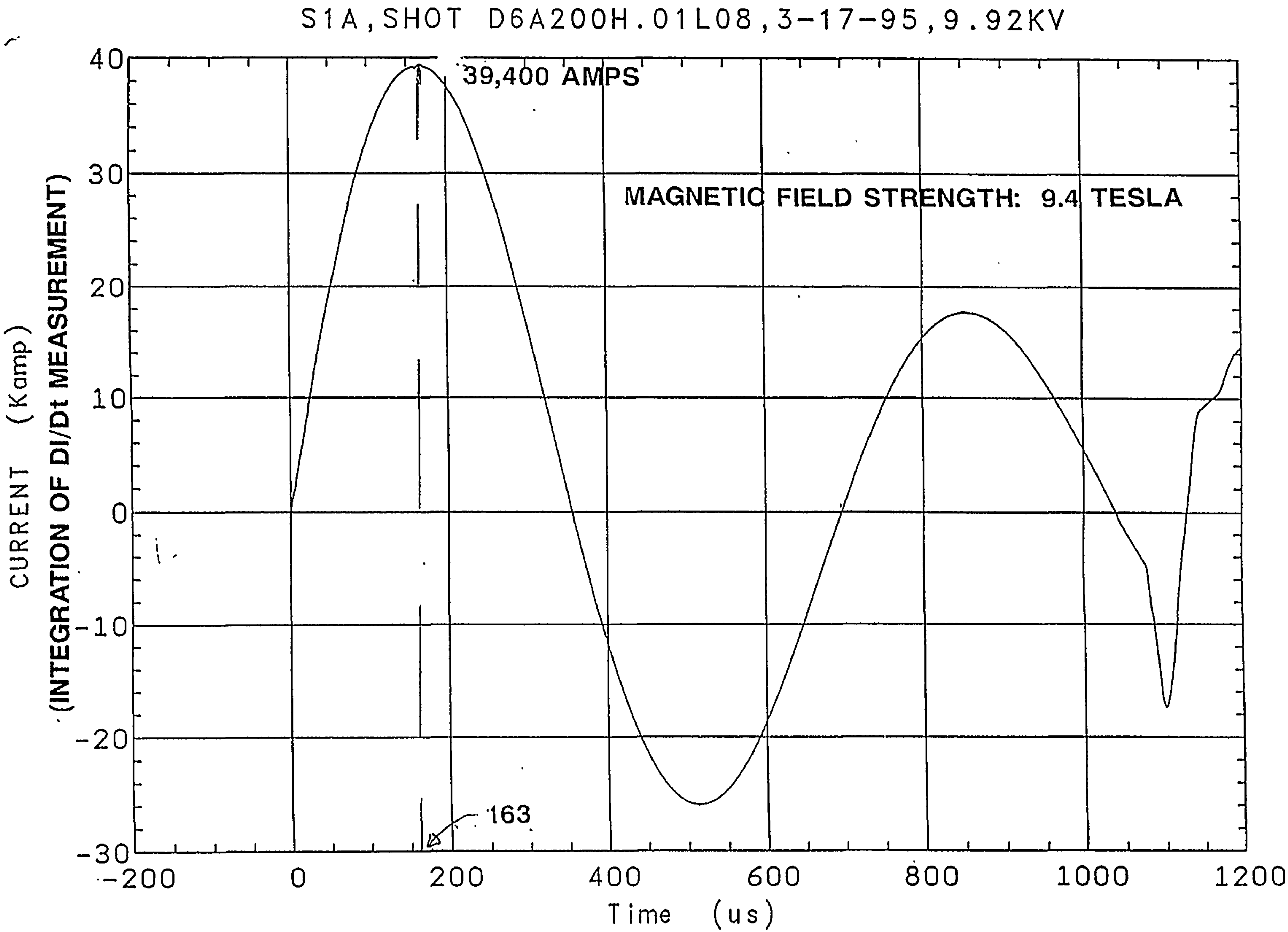


FIGURE F5 ELECTROMAGNET CHARGE CURRENT VERSUS TIME/

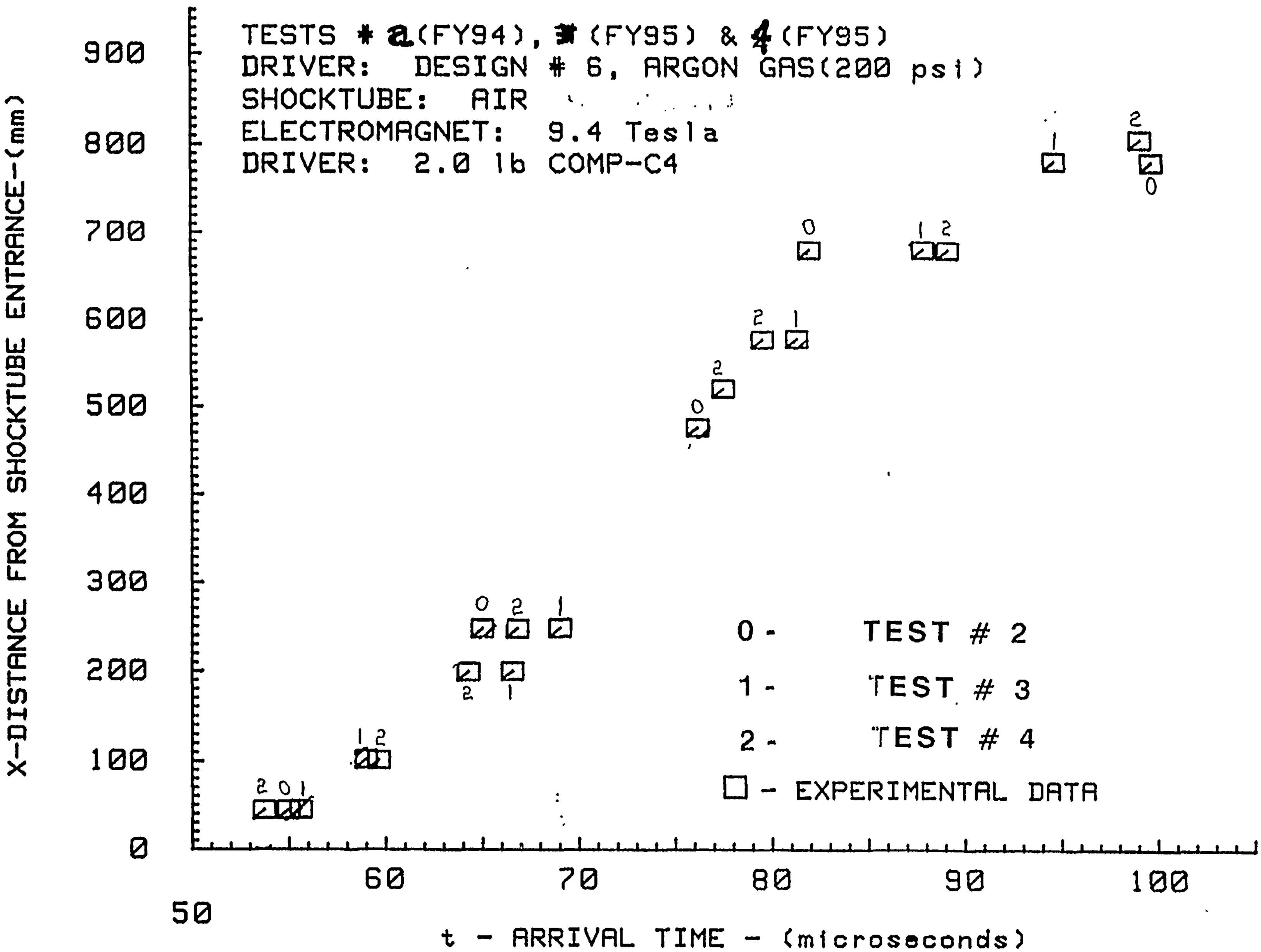


FIGURE F6 DISTANCE FROM SHOCKTUBE ENTRANCE VERSUS PLASMA ARRIVAL TIME/3 TESTS

APPENDIX G

TEST 4/DESIGN 6/CONFIGURATIONS AND EXPERIMENTAL DATA

Figures

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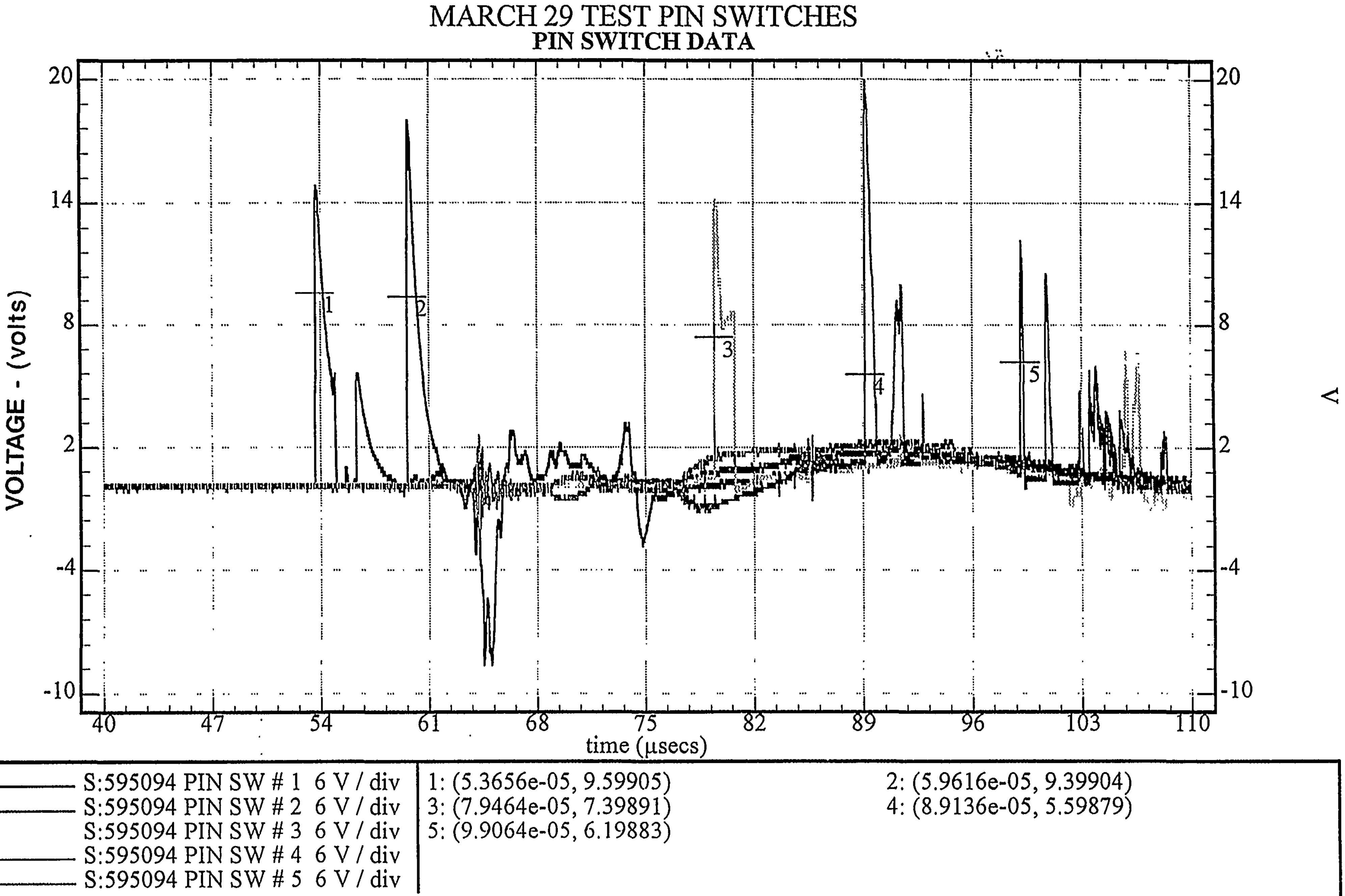

FIGURE G1. IONIZATION PIN SWITCH VOLTAGE VERSUS TIME/TEST # 2/AREA II

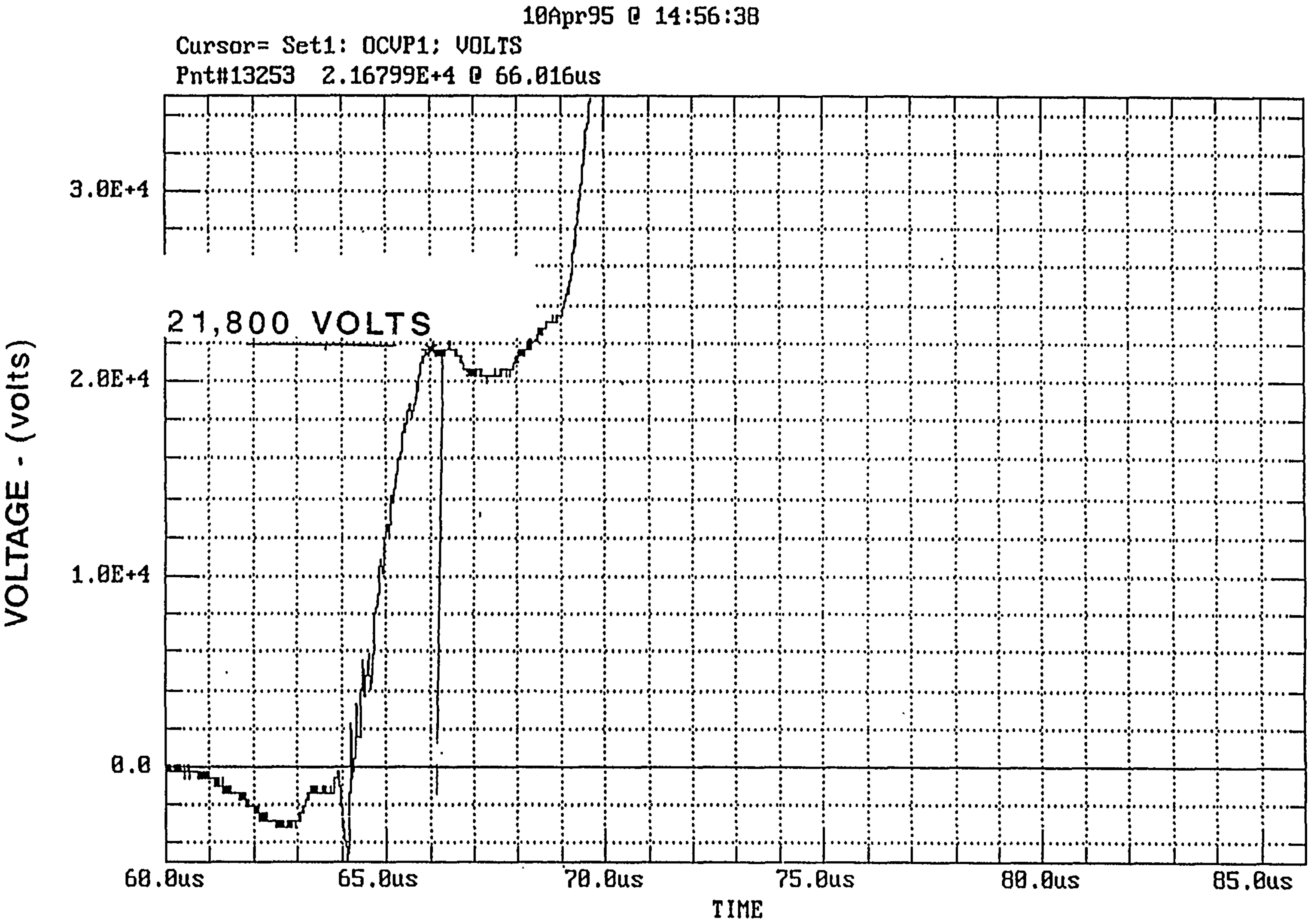

FIGURE G2. OPEN CIRCUIT VOLTAGE VERSUS TIME/TEST # 2/AREA II/OCVP1

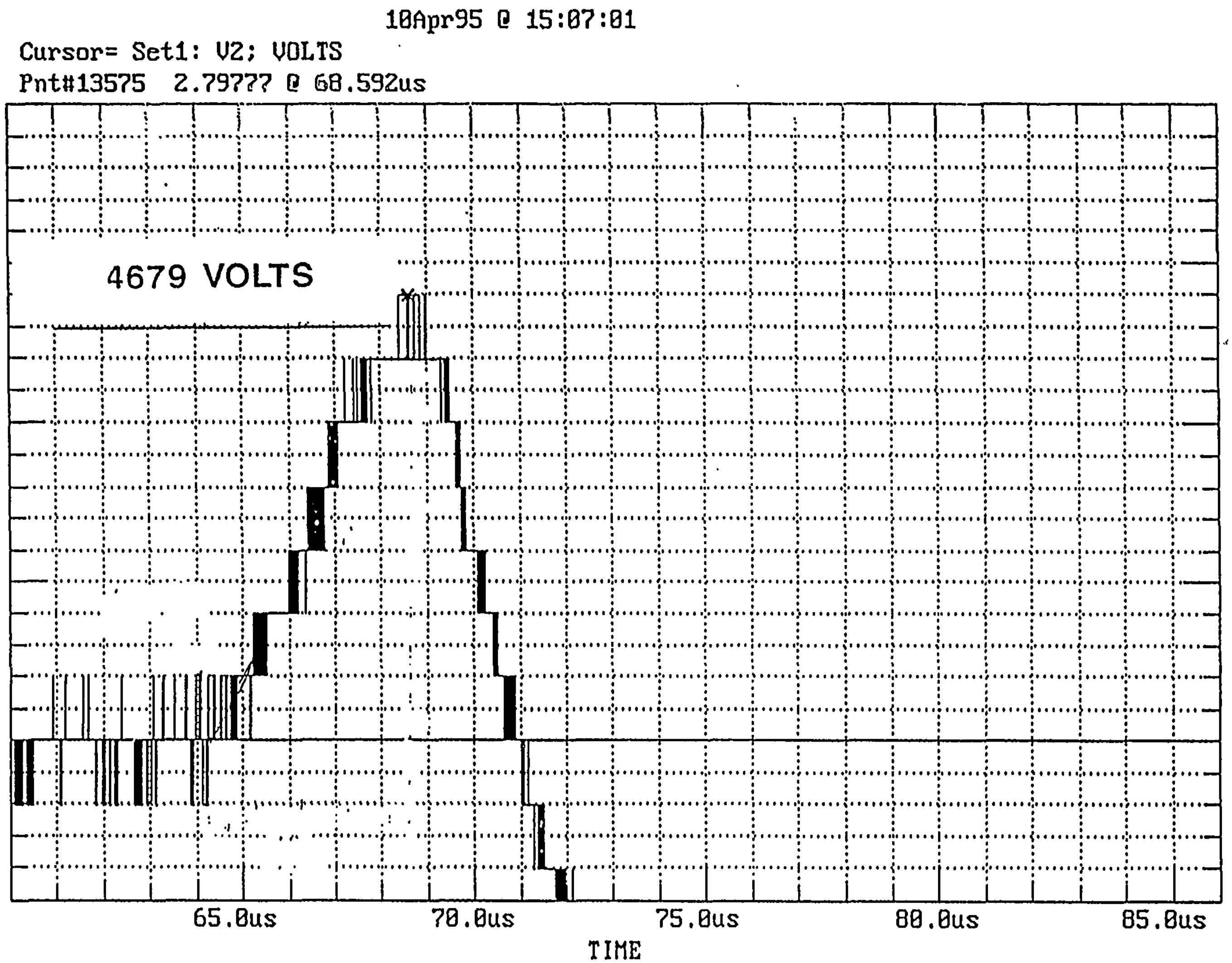

FIGURE G3. (L/C) LOAD VOLTAGE VERSUS TIME/TEST # 2/AREA II/V2

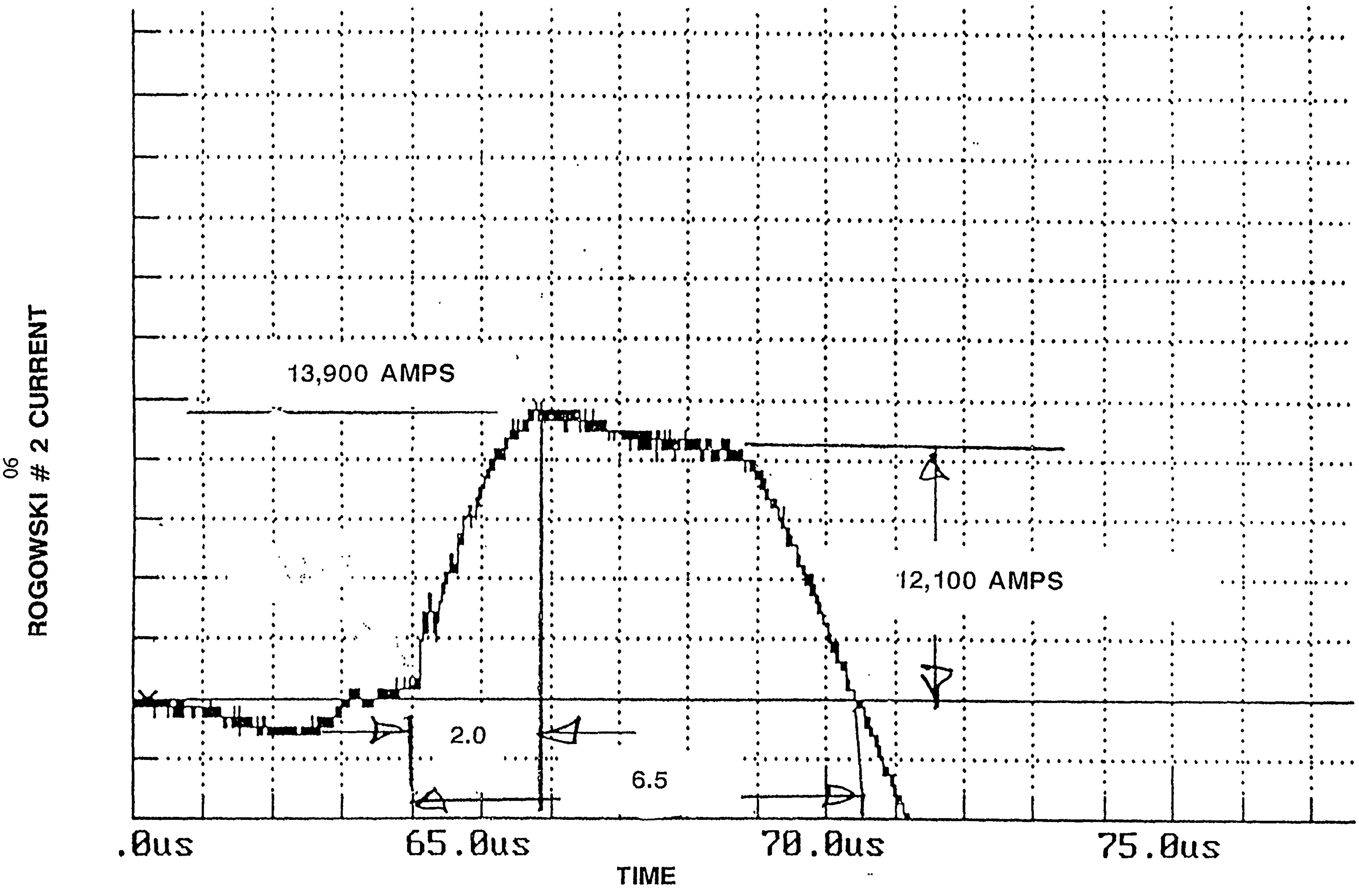

FIGURE G4. (L/C) LOAD CURRENT VERSUS TIME/TEST # 2/AREA II/ROGOWSKI # 2

Appendix H

Test 5/Design 7/Configurations And Experimental Data

Figures

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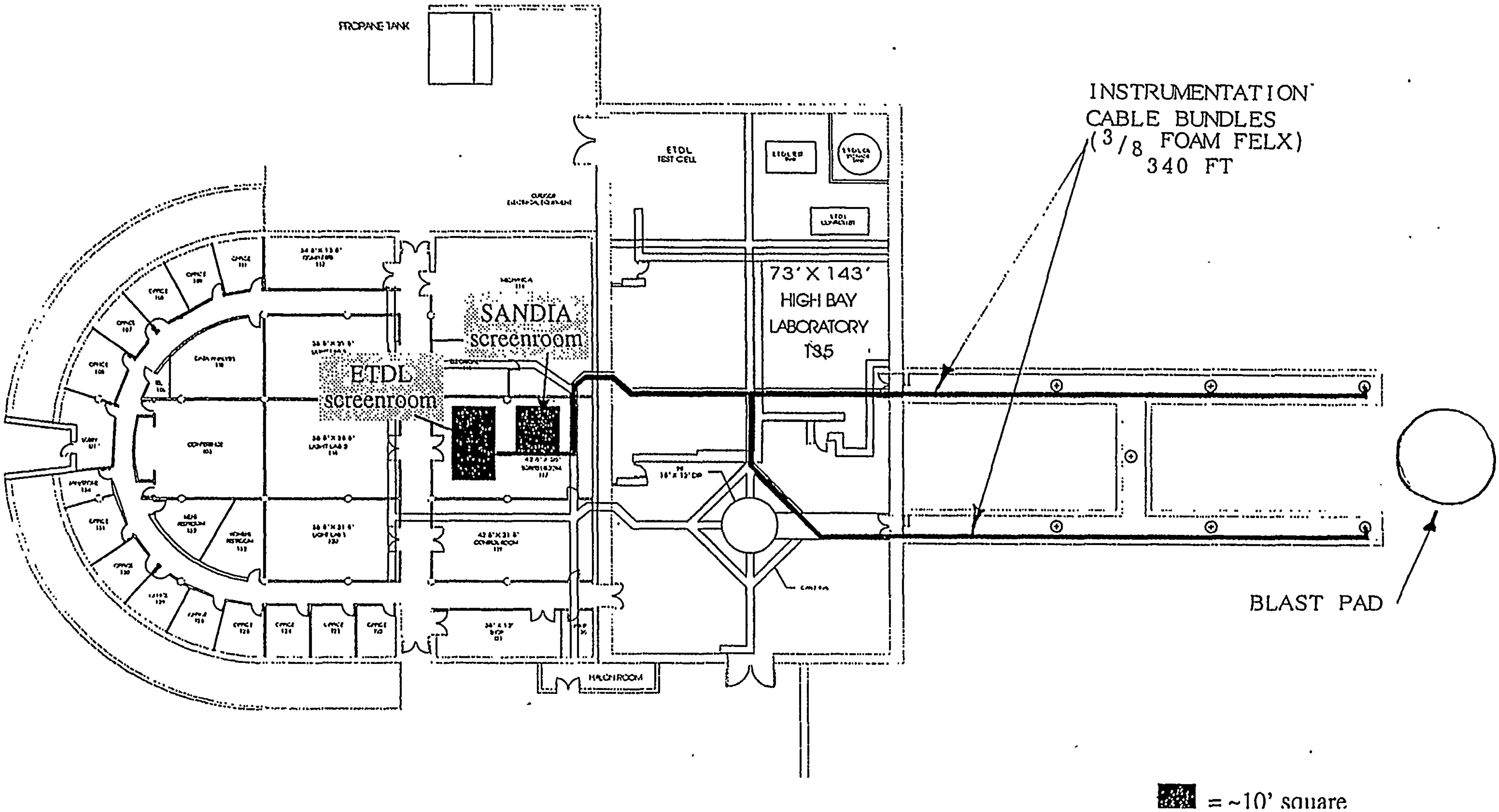


FIGURE H1. HERTF SITE INSTRUMENTATION/RECORDING CABLE BUNDLE CONFIGURATION

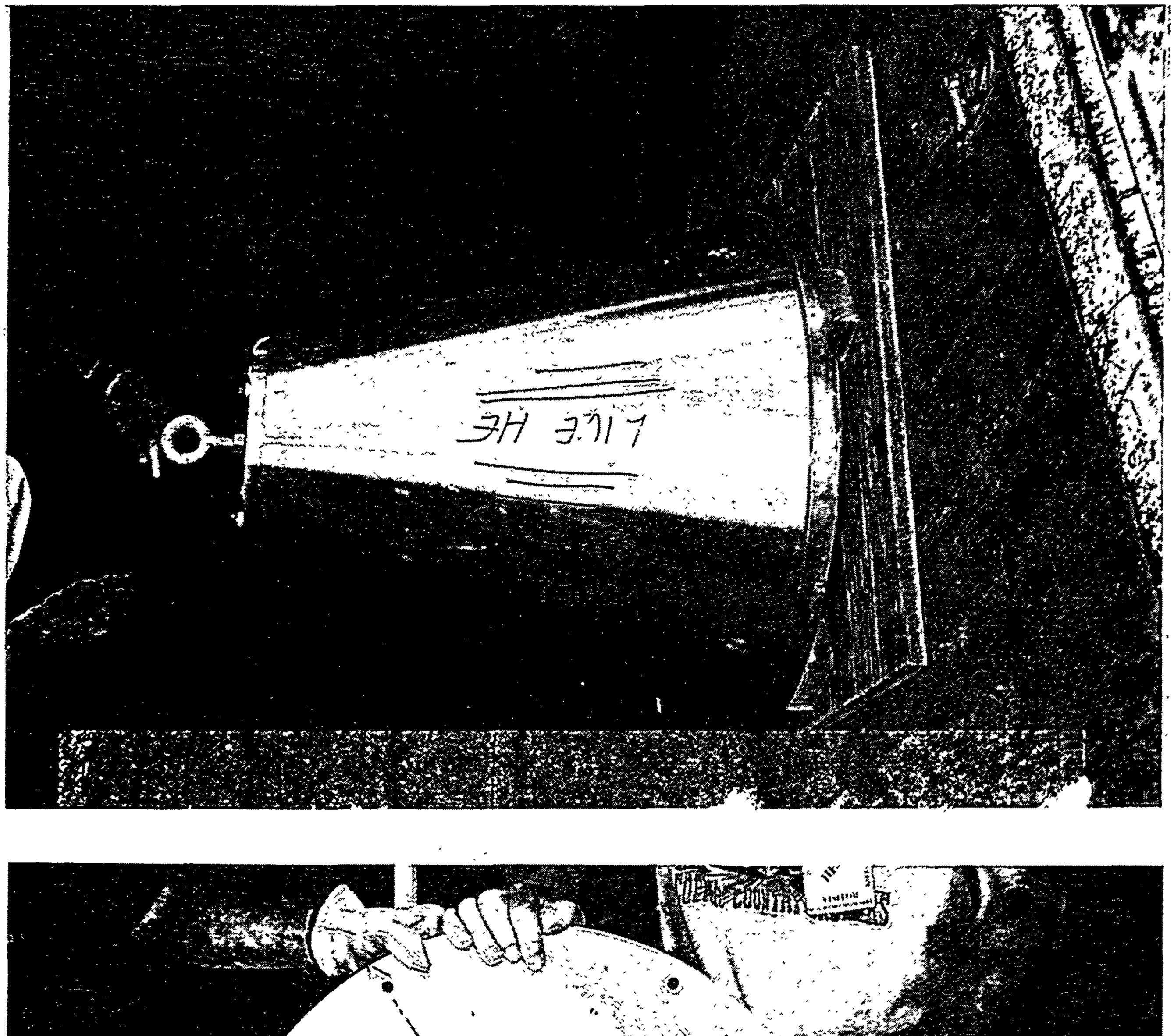


FIGURE H2. EXPLOSIVE DRIVER DESIGN # 7/SHOCKTUBE END VIEW

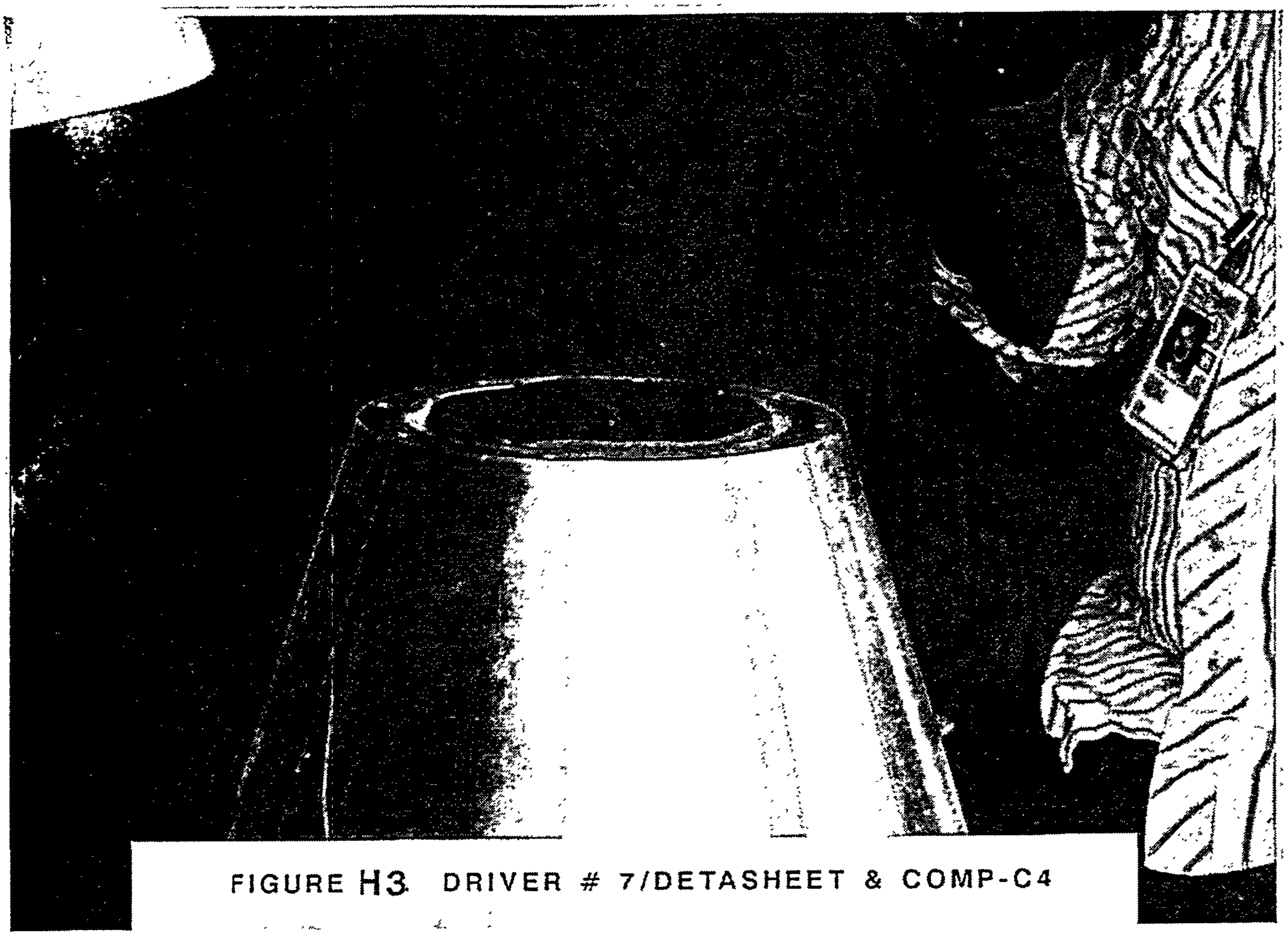


FIGURE H3 DRIVER # 7/DETASHEET & COMP-C4

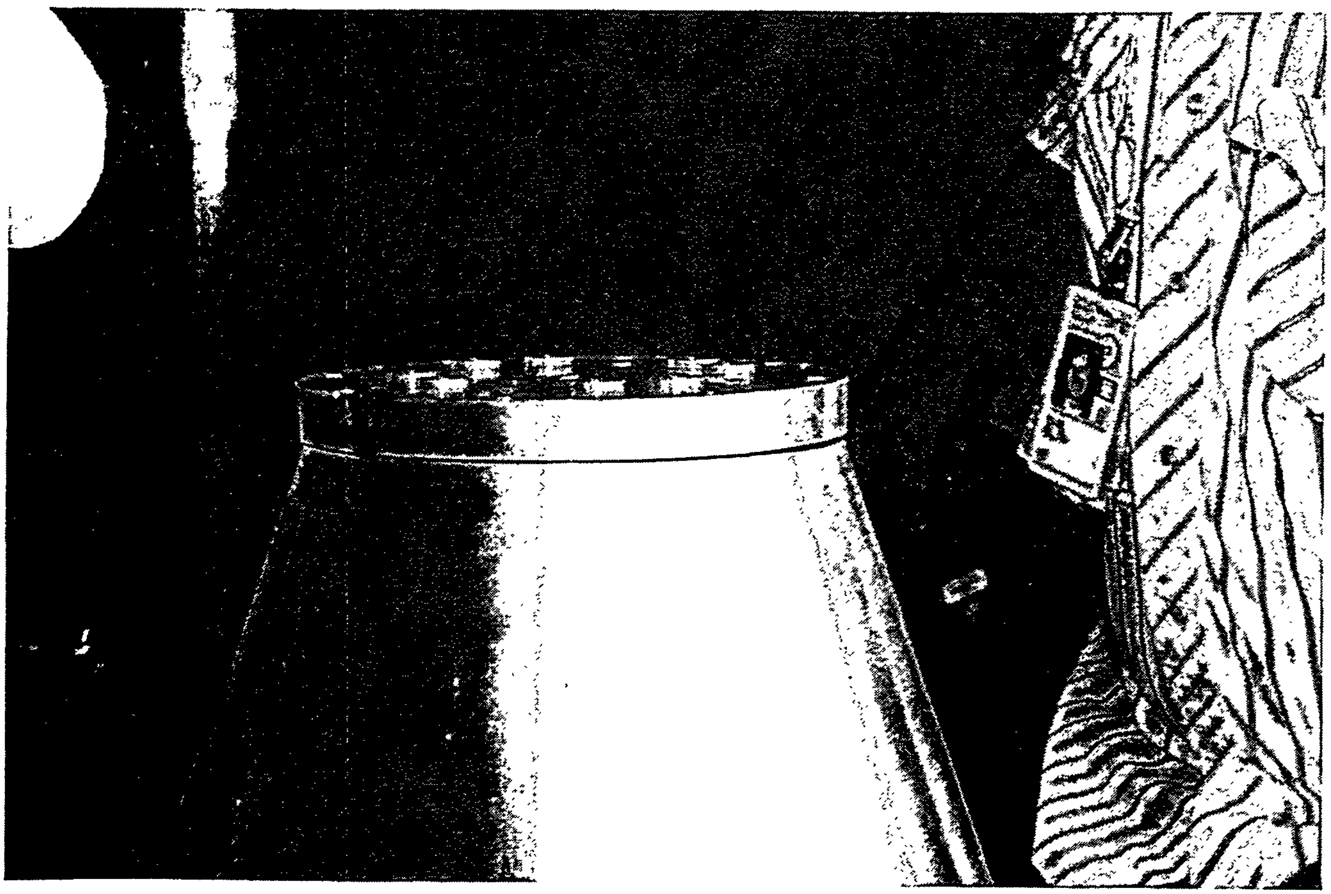


FIGURE H4 DRIVER # 7/ALUMINUM DETONATOR HOLDER COVER INSTALLED

FIGURE H5. SHOCKTUBE IONIZATION PINS & FIBRE OPTIC DIAGNOSTICS

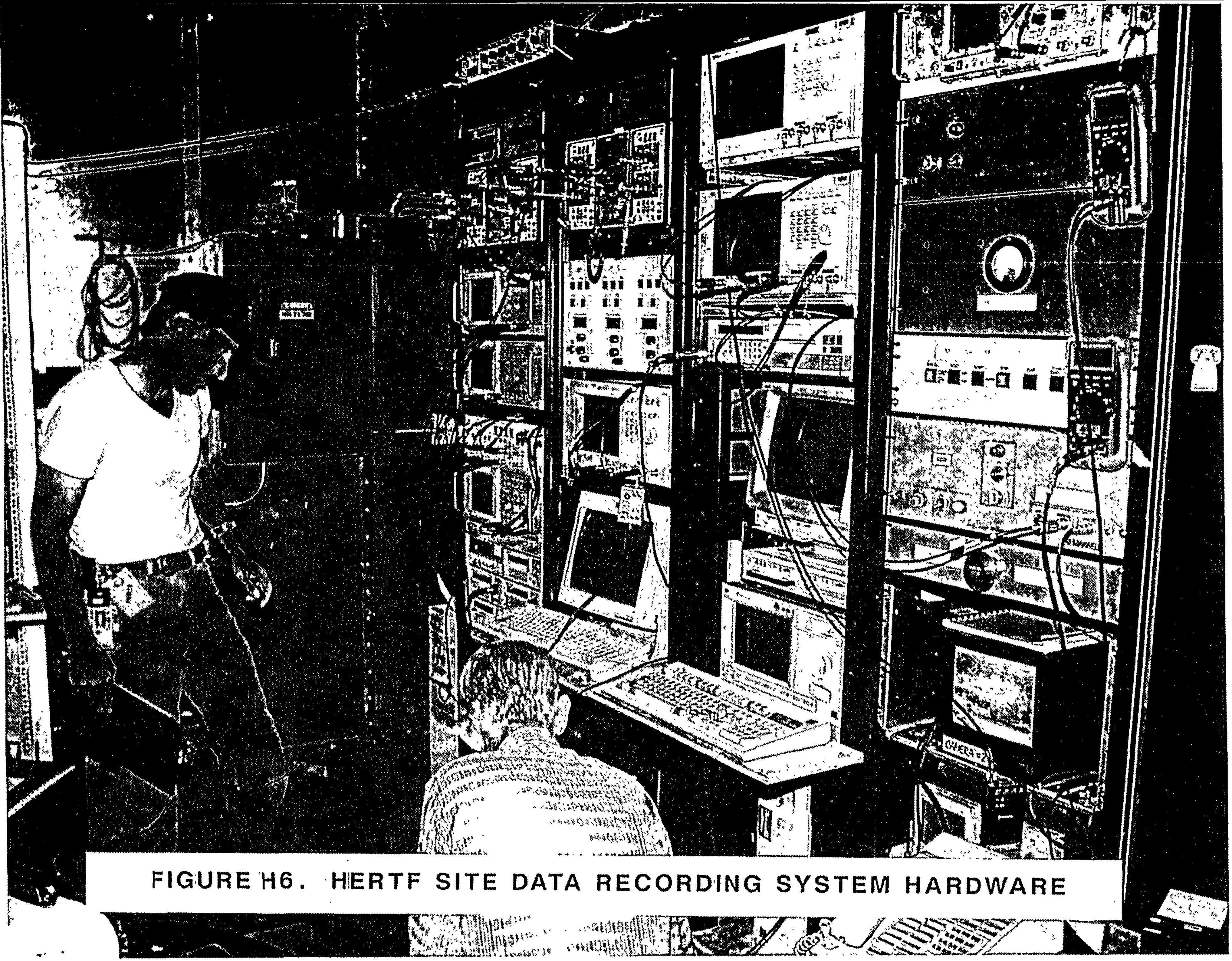


FIGURE H6. HERTF SITE DATA RECORDING SYSTEM HARDWARE

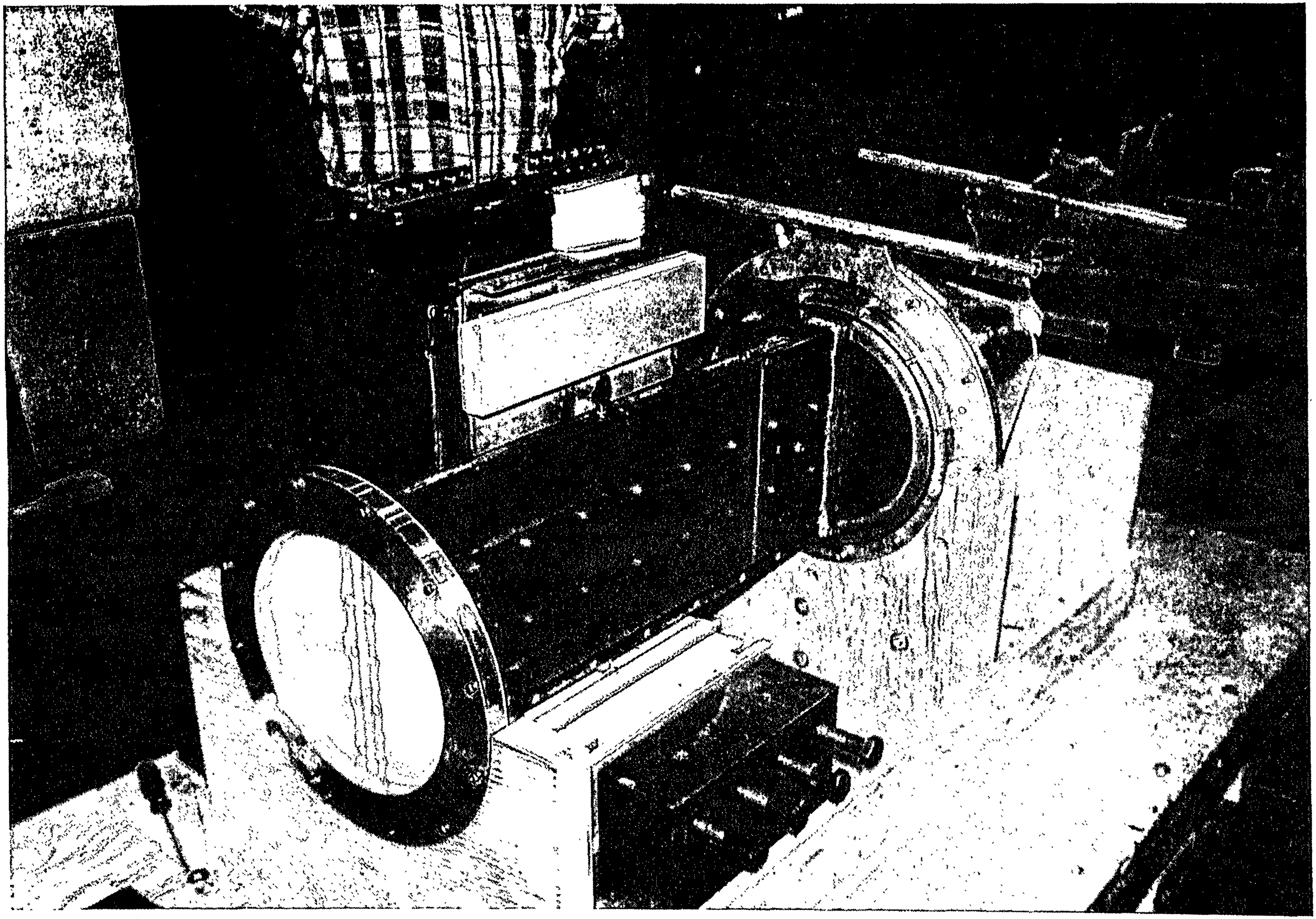
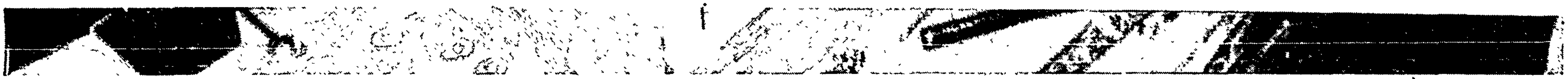


FIGURE H7. DESIGN # 7 EXPLOSIVE-DRIVEN MHD GENERATOR/ELECTROMAGNET COIL CONFIGURATION



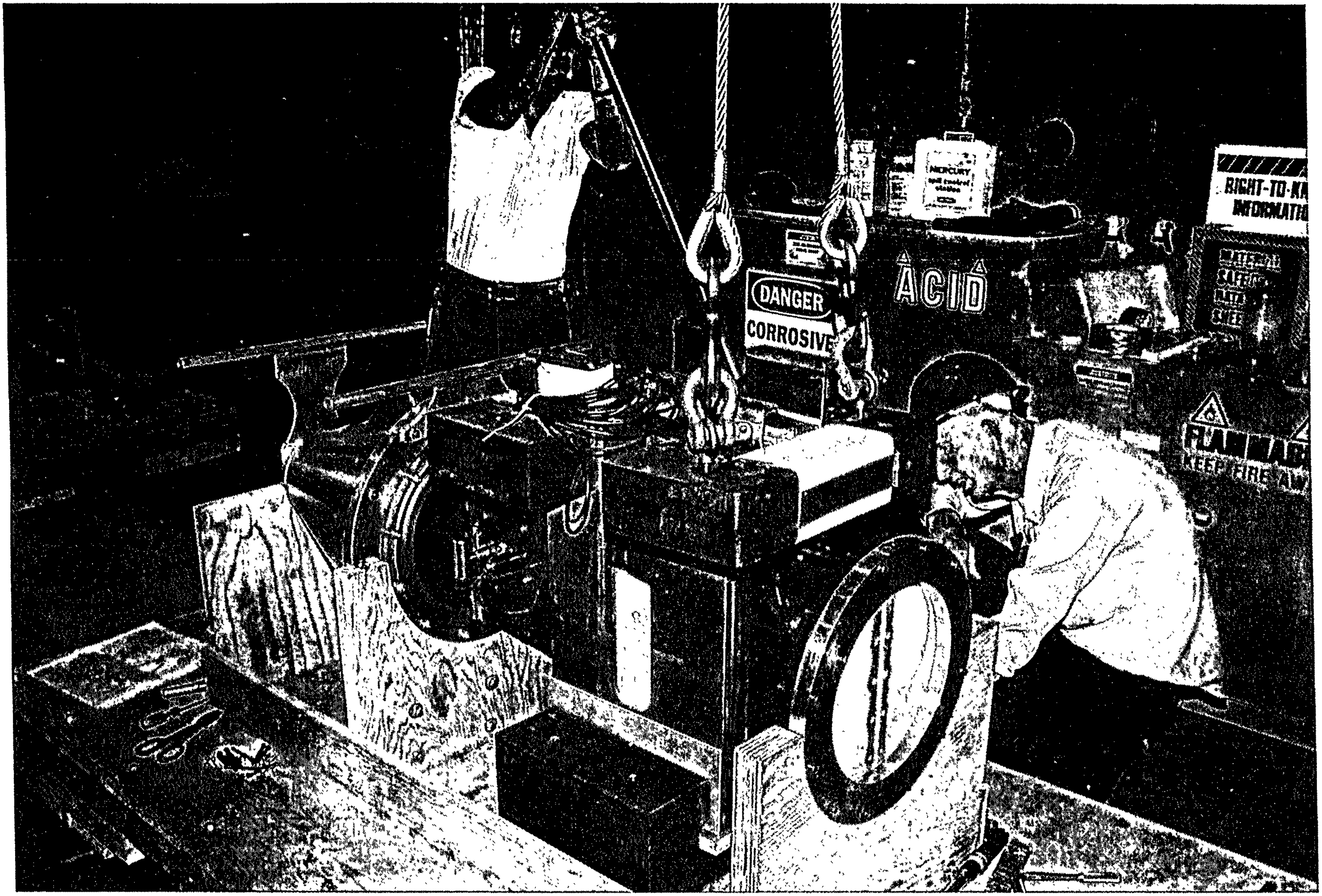
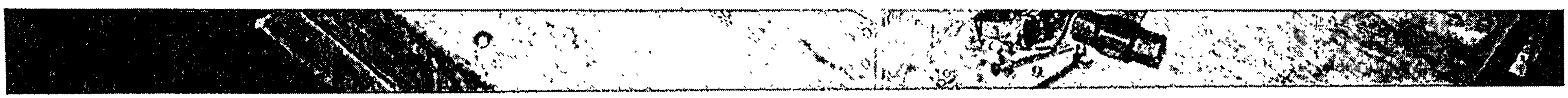


FIGURE H8 DESIGN # 7 EXPLOSIVE-DRIVEN MHD GENERATOR/ELECTROMAGNET COIL CONFIGURATION



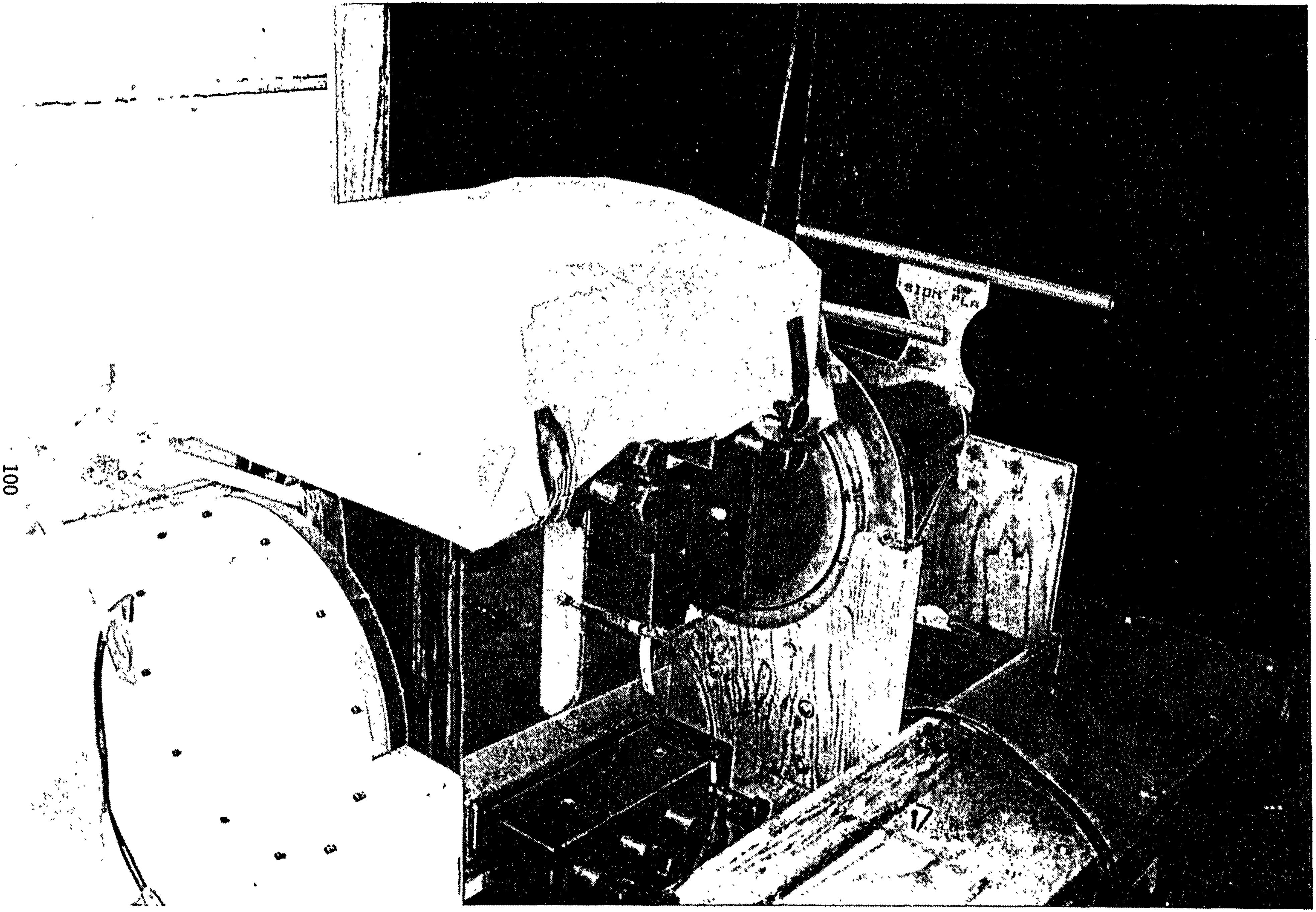
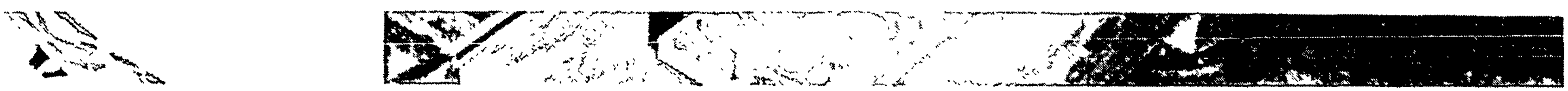
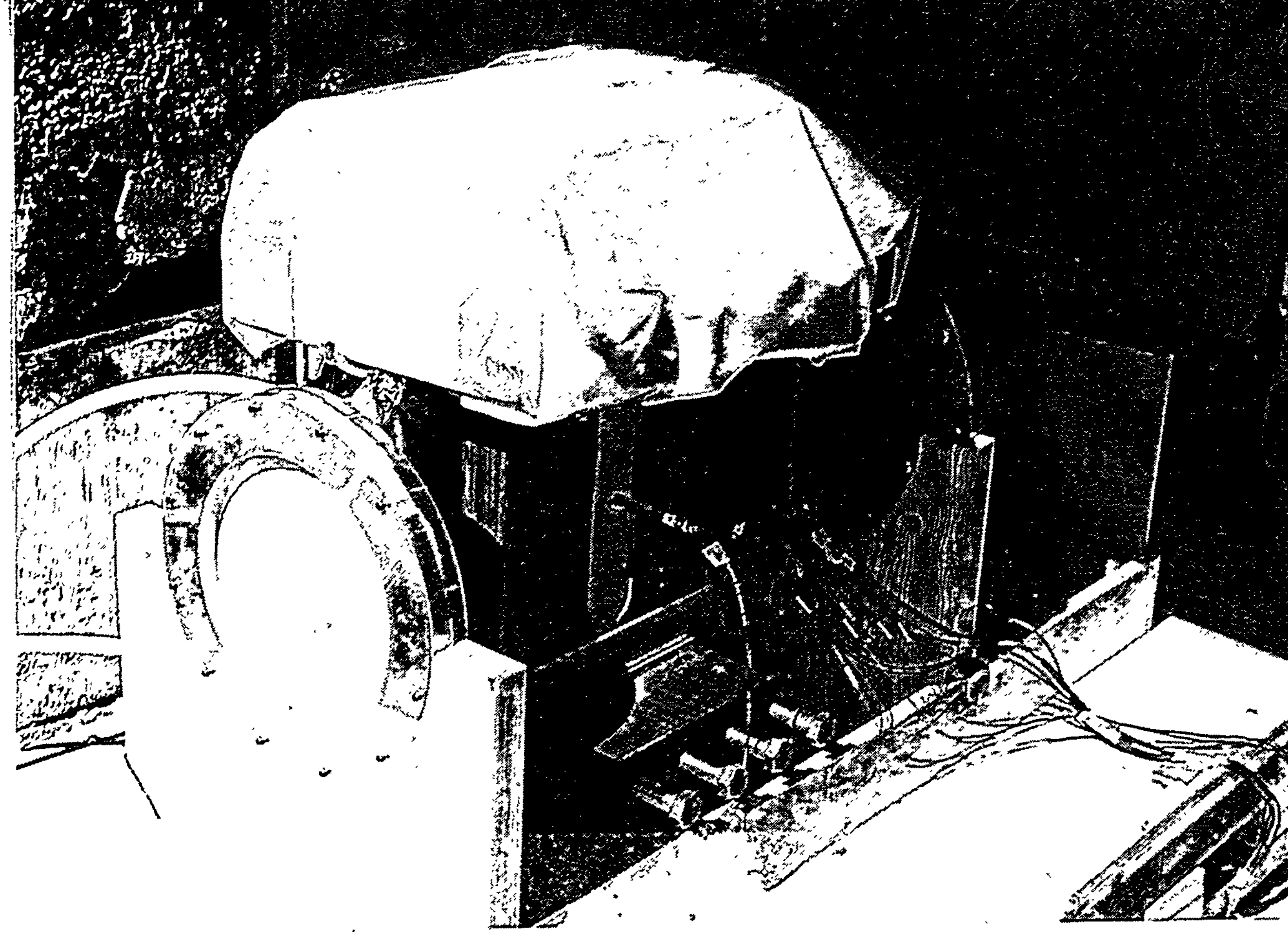


FIGURE H9 DESIGN # 7 EXPLOSIVE-DRIVEN MHD GENERATOR/ELECTROMAGNET COIL CONFIGURATION





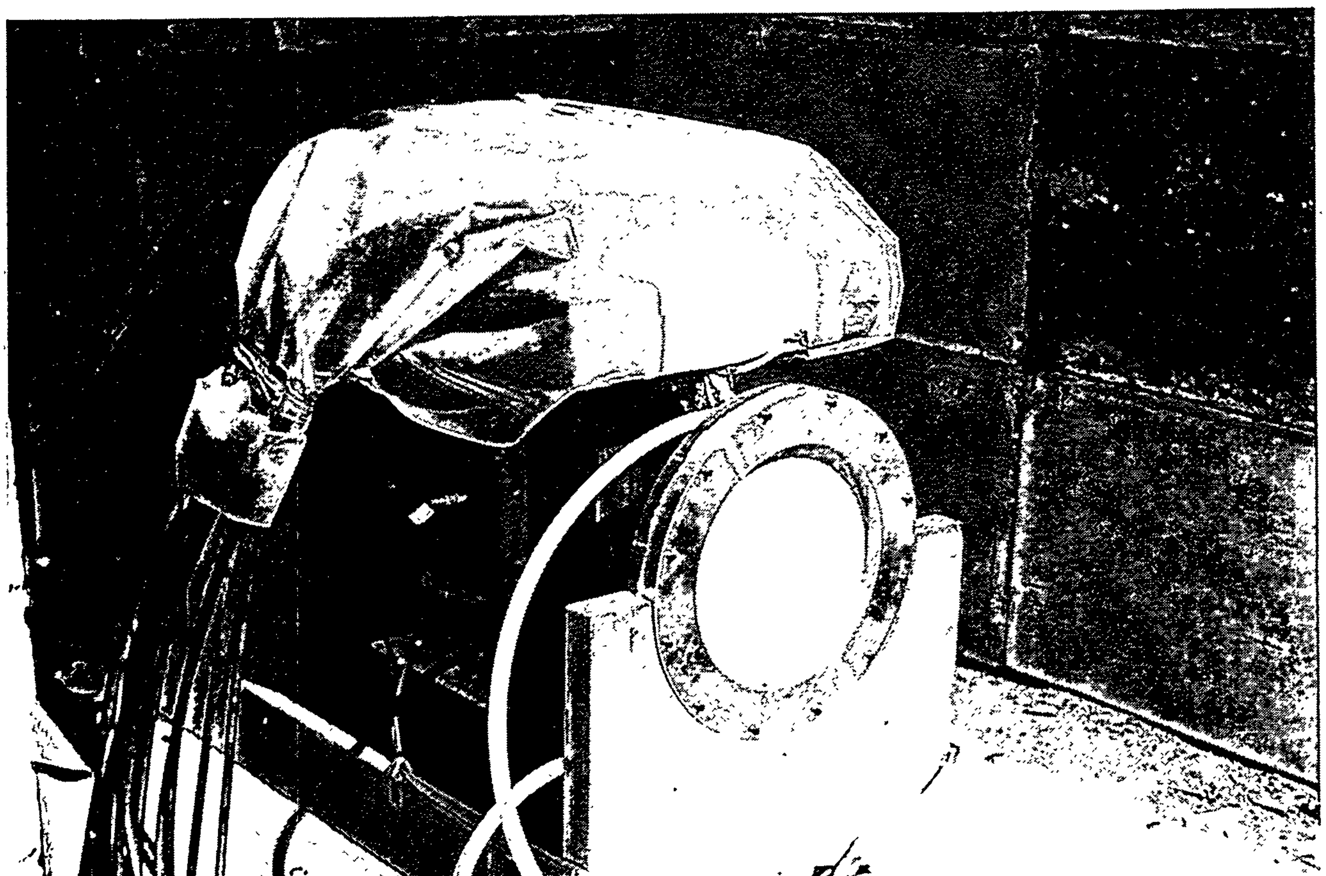


FIGURE H10. EDMG DESIGN#7 TEST CONFIGURATION

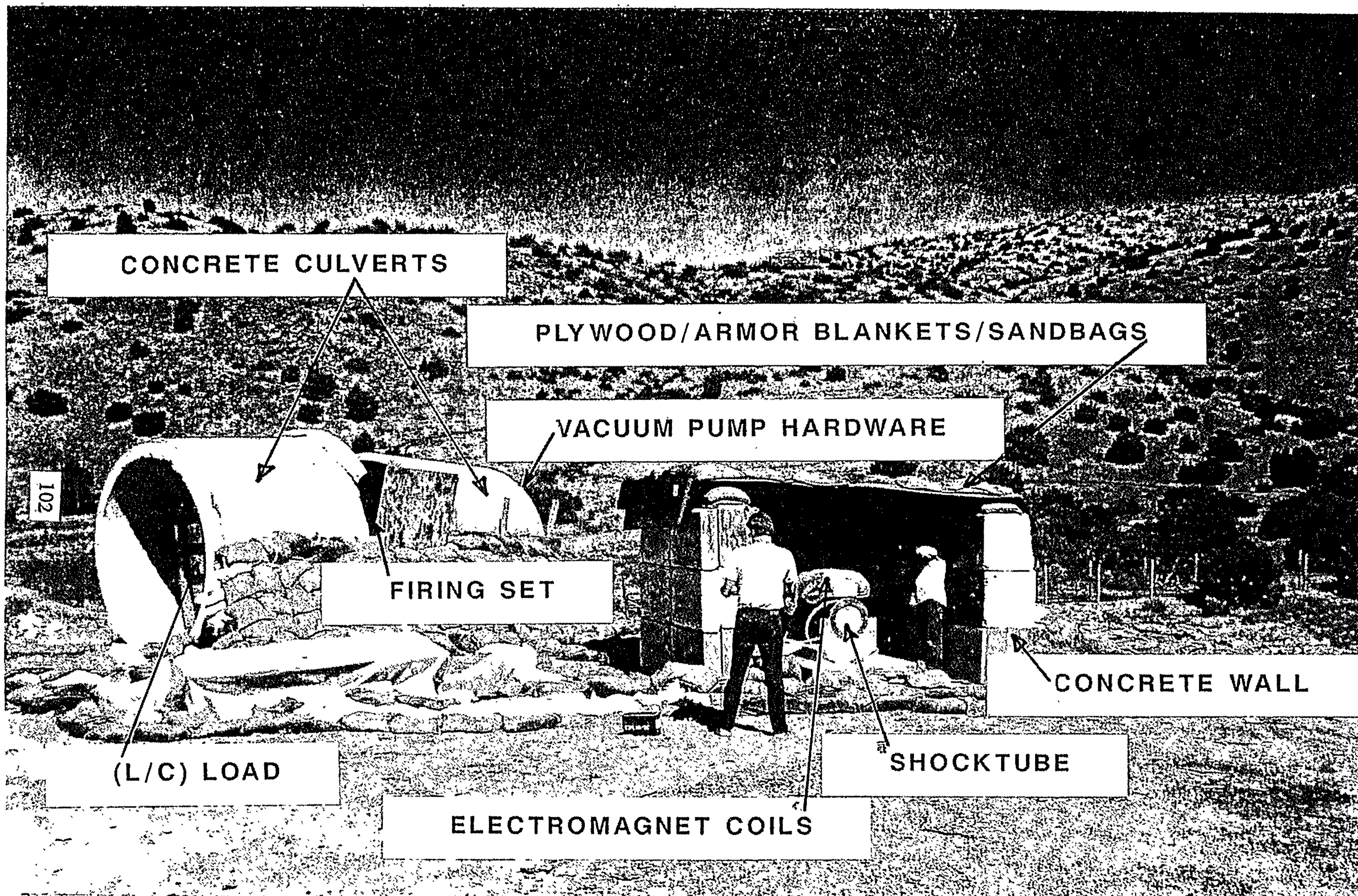


FIGURE H11. EXPLOSIVELY-DRIVEN MHD GENERATOR/HERTF SITE CONFIGURATION

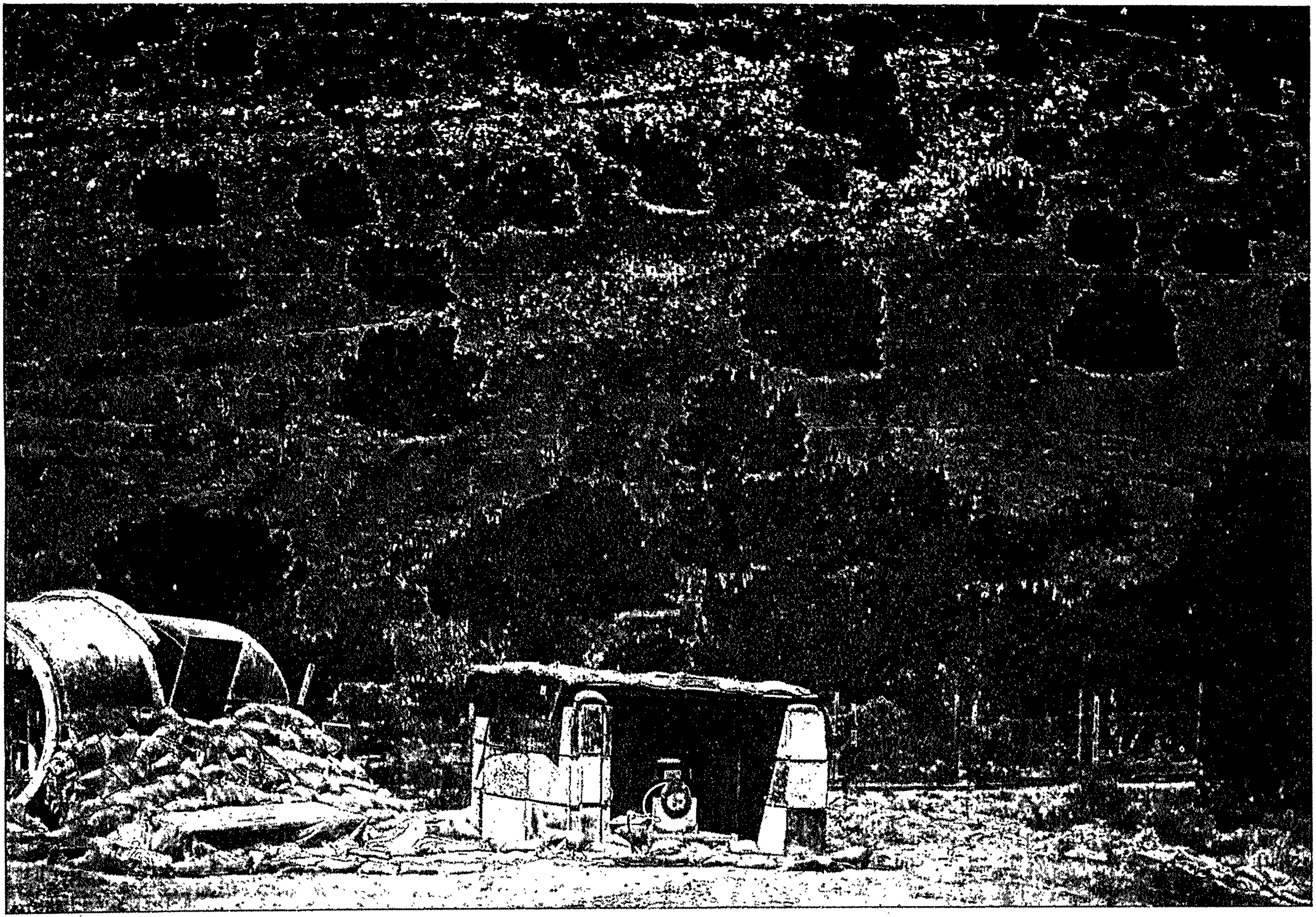


FIGURE H12 HERTF SITE/EDMG DESIGN#7/ELECTROMAGNET TEST CONFIGURATION

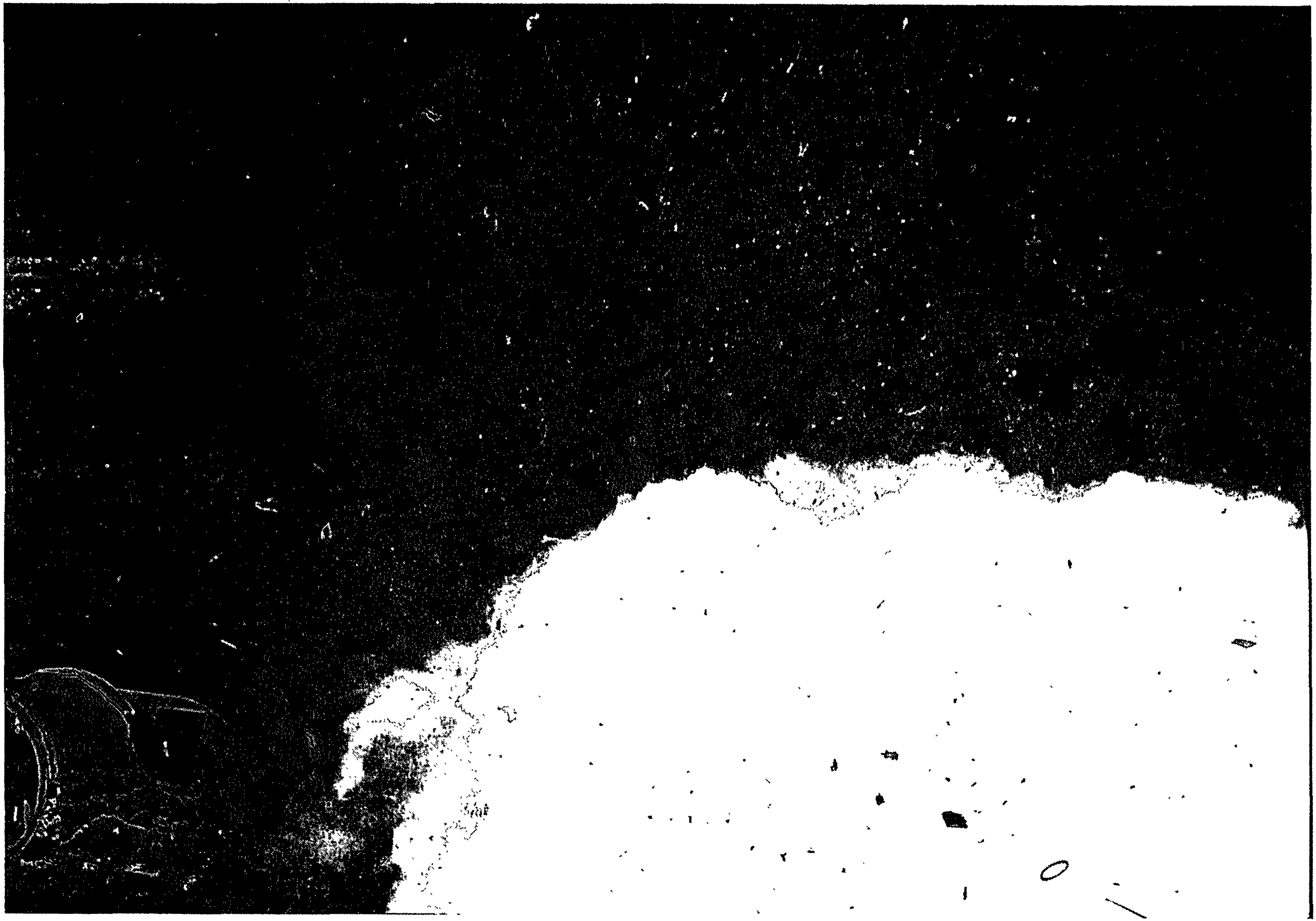


FIGURE H13 HERTF SITE/EDMG DESIGN#7/ELECTROMAGNET POST DETONATION

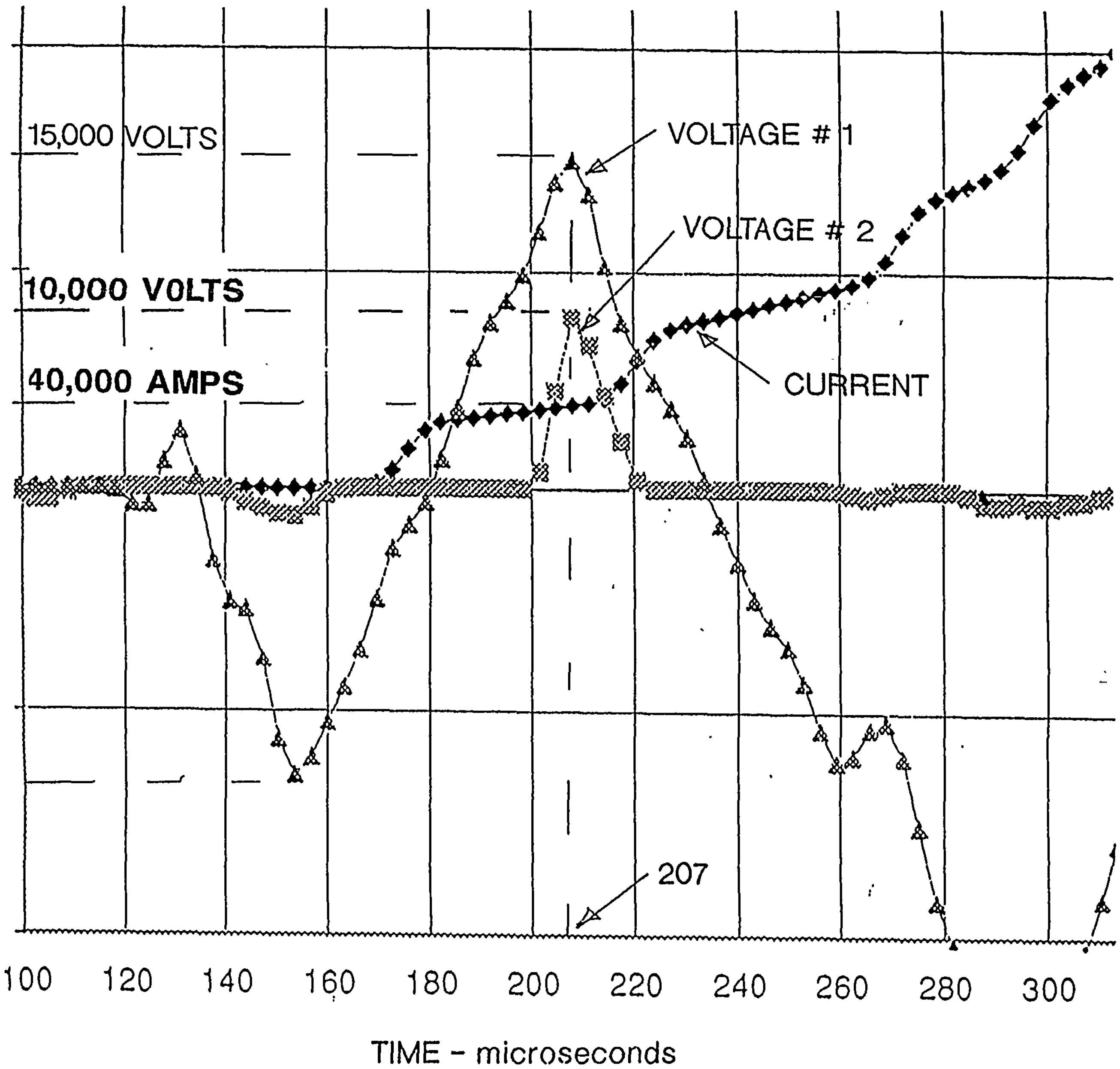


FIGURE H14 INDUCTIVE-CAPACITIVE LOAD VOLTAGES AND CURRENT/HERTF TEST

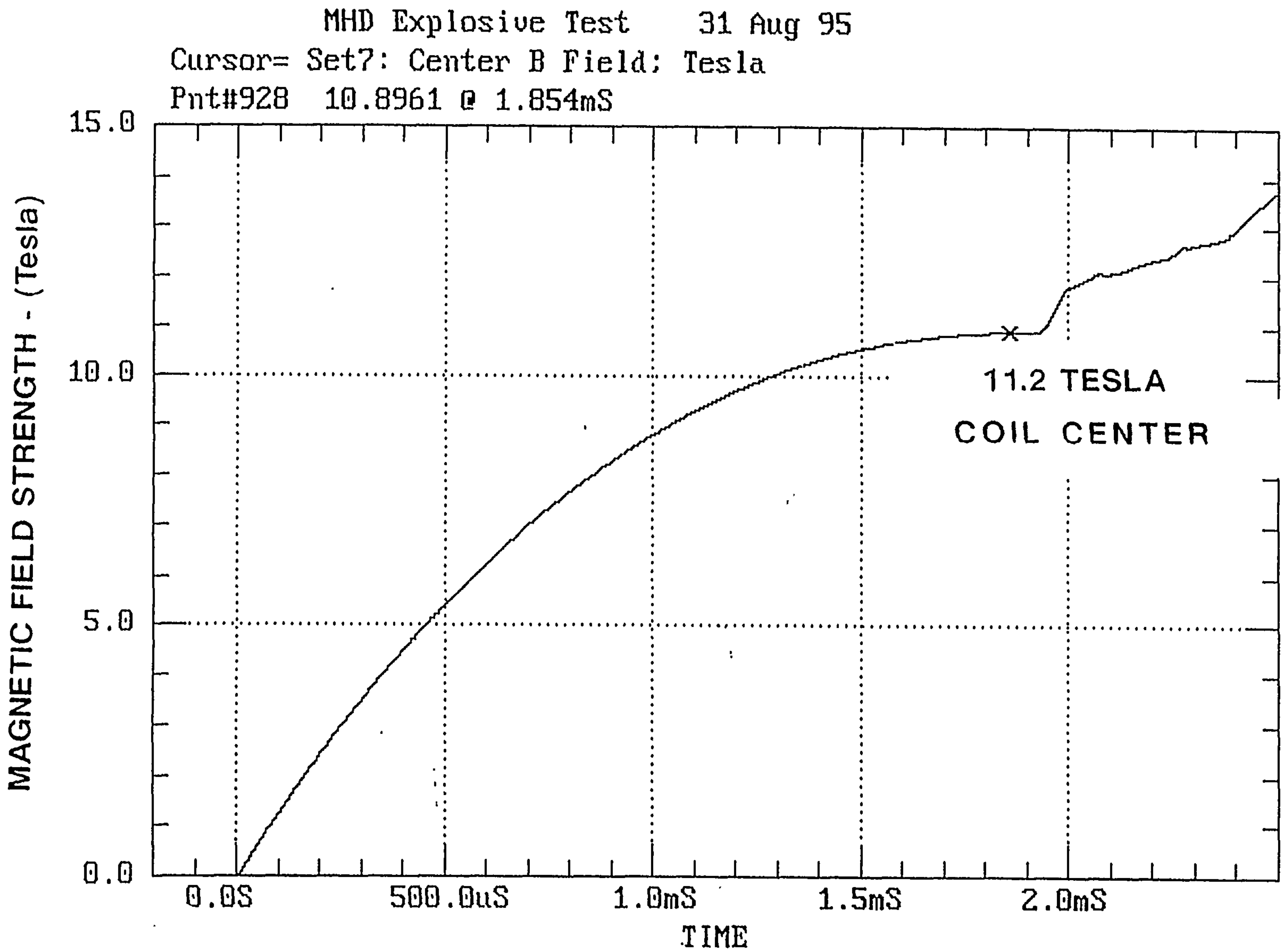


FIGURE H15. MAGNETIC FIELD STRENGTH VERSUS TIME/HERTF TEST

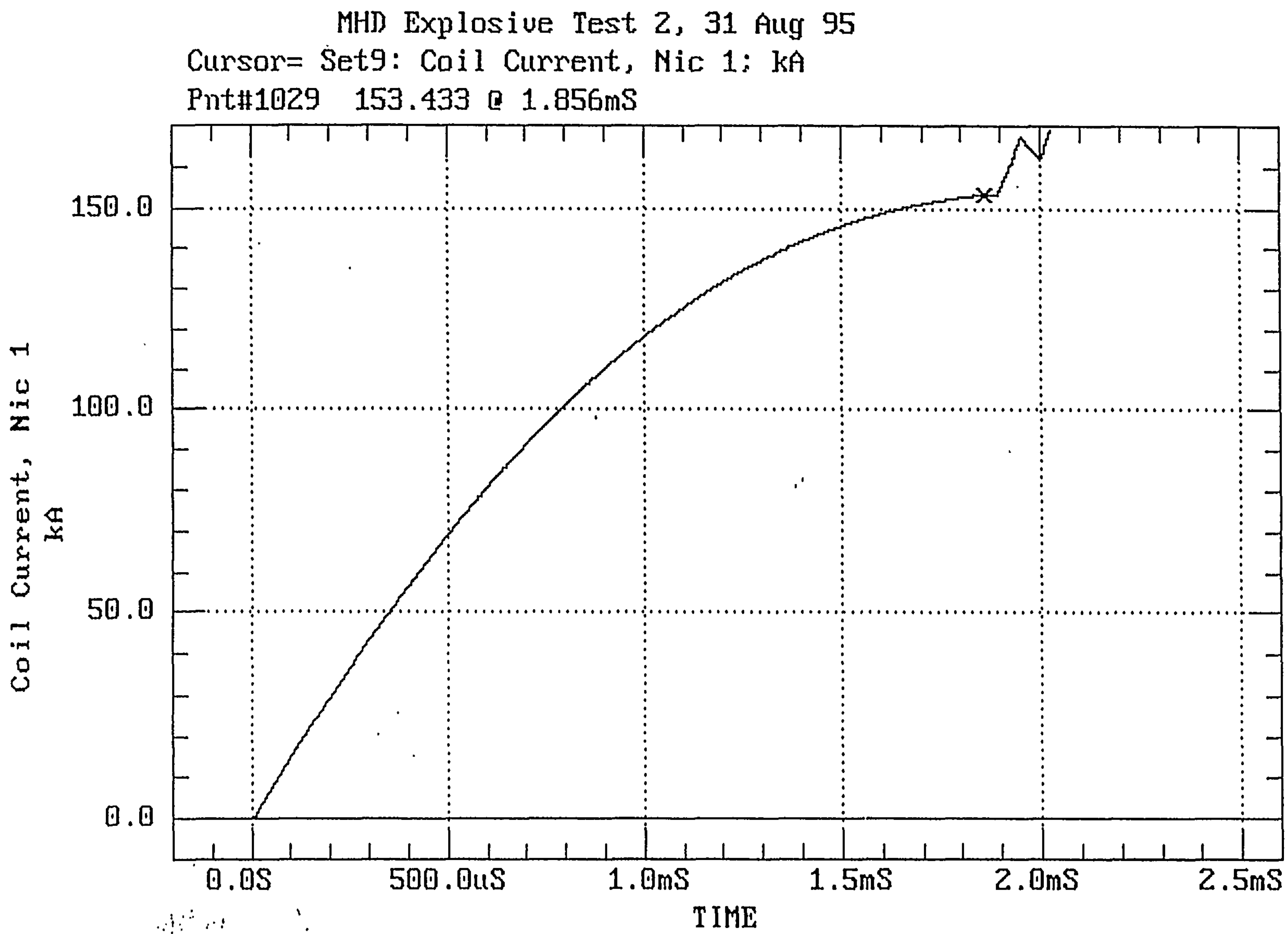


FIGURE H16. ELECTROMAGNET COIL CURRENT VERSUS TIME/HERTF TEST

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Amarillo, TX 79177

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K. Hackett
J. Gaudet
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