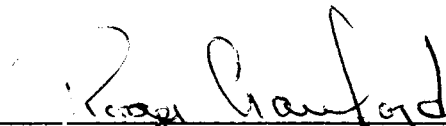
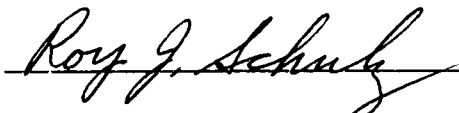
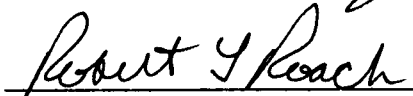


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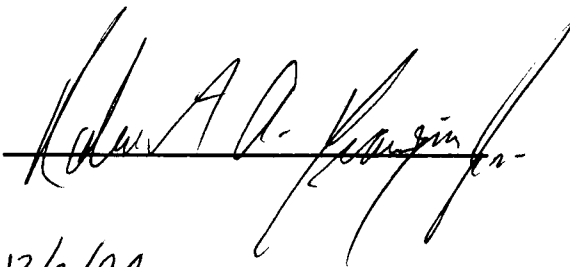

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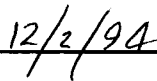
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Date

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CONTOURED ELECTRODE DESIGN
FOR A TRANSIENT
MHD ACCELERATOR

A Thesis Presented
for the Master of Science
Degree
University of Tennessee, Knoxville

Robert A. Yeargin, Jr
December 1994

DEDICATION

This thesis is dedicated to all those people who have encouraged me and been interested in this work. It is for those who stood by me and understood the hard hours of work and who helped me to see this thesis to its conclusion.

I especially want to dedicated this thesis to Gary R. Gober, Attorney at Law, for sponsoring my education at the University of Tennessee Space Institute and providing for me financially. Without his sponsorship, I might not have been able to get my master's degree.

Lastly, I want to thank my mom for the leadership and support that has helped prepare me for the future God has for me. She has always been there to help me through the rough times. Her Godly values in her life have been ingrained into me so that I desire to do my best in every area of life.

ACKNOWLEDGEMENTS

I wish to especially mention my appreciation to Dr. Roger Crawford, my major professor, for his guidance, his patience, and his support in the work associated with this thesis. I also want to mention the other members on my committee, Dr. Roy J. Schulz and Robert L. Roach, who ensured that my work has met the highest academic standards associated with universities such as the University of Tennessee.

It was Jaime Taylor who gave me much assistance, helping me learn the Mega™ software and taking time to show me ways to use the software to simulate the excellent results which are contained in this work. He also allowed me to use his office completing the computer part of the thesis. For this and other areas of help, I am very thankful.

ABSTRACT

The simulation of hypersonic air streams at Mach numbers above 10 in ground test facilities is complicated by the extremely high stagnation temperatures and pressures that the facilities must endure. Operationally, nozzle throat heat transfer limits, air dissociation in the stagnation chambers, and NO_x formation are three facility shortcomings limiting true flight simulation at hypersonic Mach numbers. Many studies and experiments dating from the early 1960's to the present have supported the application of MHD acceleration of a pre-heated conducting gas for hypersonic simulation. The very high development and operating costs of a MHD-augmented continuous flow facility have stopped development of this concept for the last 25 years. Now new high temperature composite materials, improved computational fluid dynamics capability, and a renewed interest in hypersonic flight are making the MHD-augmented hypersonic flow facility essential to the further understanding of hypersonic fluid mechanics and heat transfer.

Due to the large development costs of a continuous flow MHD-augmented hypersonic flow facility, a transient MHD accelerator has been proposed as a low cost research facility for investigating the key technology issues. Studies at the University of Tennessee Space Institute in a

railgun research program have demonstrated a significant electromagnetic difference between pulsed or transient electric fields and those formed in steady state devices. Steady state MHD devices have a more uniform magnetic field and current density distributions. Pulsed or transient MHD devices accelerate a gas slug in a time varying magnetic field. Pulsed or transient MHD devices, therefore, lack the flow uniformity associated with steady state devices. A research facility needs a uniform freestream flow to accurately simulate the hypersonic flight conditions. Therefore, the electrode geometry is critical for providing the uniformity in the magnetic field, current density, and accelerating force.

The electrode geometry is a major contributor to reduce the non-uniformities in pulsed or transient MHD devices. The electrode configuration will be the determinant in obtaining a uniform accelerating force in the channel. The desired electrode geometry will produce a more uniform magnetic flux density and a more uniform current density, resulting in a more uniform magnetic force to propel the conducting gas down the channel.

Several electrode shapes were simulated to find an electrode geometry that provides the uniformity needed to accelerate the conducting gas down the channel. The initial accelerator concepts were for a rectangular electrode geometry. UTSI proposed to investigate other geometries

which produce a magnetic flux density and current density that reach uniformity at a quicker rate and without the current concentrations in the corners associated with a rectangular electrode geometry. Other criteria such as electrode fabrication costs were not taken into consideration but should be considered before building a device with one of the shape indicated in this thesis.

The electromagnetic code Mega™ has been used to evaluate the moving fields and current density as a slug of potassium-seeded air is being accelerated down a channel. The results of the study are that: (1) of the types of electrode shapes studied, none were able to eliminate the non-uniformity of the magnetic force in the initial time steps, and (2) some shapes can, however, reduce the non-uniformity to tolerable limits as early as 10 microseconds. The magnetic field was simulated in both 2-D and 3-D computer models to find the electrode shape with tolerable flow uniformity and to map the field distribution in the conducting gas.

The simulations show that 1) flat, smooth electrodes help maintain a uniform magnetic force; 2) in the first microseconds, the uniformity of the magnetic force varies little between hollow shapes and solid shapes; 3) a better magnetic force uniformity is provided with an electrode wider than the channel width and with a curved electrode end; and 4) if the current is increased, the magnetic force

will increase, but the uniformity of the magnetic force will remain almost the same.

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NOMENCLATURE

<u>SYMBOL</u>	<u>QUANTITY</u>	<u>UNITS</u>
A	Magnetic Vector Potential	Volts/m
B	Magnetic Flux Density	Tesla
c	Speed of Light	m/sec
D	Displacement	Coul/m ²
E	Electric Field	Volts/m
F	Magnetic Force, $\mathbf{J} \times \mathbf{B}$	Newton
H	Magnetic Field	Amp-Turn/m
I	Current	Ampere
J	Current Density	Amp/m ²
L'	Inductance/Rail Length	Henry/m
M'	Mutual Inductance/Rail Length	Henry/m
q	Point Charge	Coulomb
R	Resistance	Ohm
t	Time	second
v	Velocity	m/sec
V	Electric Scalar Potential	Volt
x	X-direction	meter
y	Y-direction	meter
z	Z-direction	meter
ρ	Charge Density	Coul/m ³
σ	Conductivity	mho/m
μ	Magnetic Permeability	Henry/m
ϵ	Dielectric Constant	-----

INTRODUCTION

Just over 25 years ago, the elimination of the X-15 program resulted in the cancellation of the Hypersonic Research Engine (HRE) program.¹ The HRE program had been working towards a hydrogen-fueled, supersonic combustion ramjet (scramjet) engine which would fly at Mach numbers above six.^{2,3} The X-15 was the first plane to reach hypersonic speeds and would have been able to test the hypersonic research engine.

Using the data obtained from the X-15, the X-20 Dynasoar design was finalized in 1963 to take advantage of the hypersonic flows.⁴ The program was eliminated without a test plane being built. Two main reasons exist for the elimination of this program. First, hypersonic flows were not fully understood in 1963.⁴ Second, no means existed to verify the hypersonic test data on a non-blunt nosed object.^{5,6} Much testing was needed to find materials to handle the higher temperatures and pressures associated with the flows. A reduction of the size and weight of the aircraft equipment was also necessary.

The space shuttle Columbia was designed in the late 1970's based mainly on the X-15 and X-20 information and flew for the first time in April 1981.⁷ Other hypersonic vehicles have been built on the improving knowledge of the hypersonic flows, on better materials, and on a reduction of

size and weight of the many components used by the aircraft.⁸

With the current U.S. national interest in the Aerospace Plane¹ and its hypersonic flight speeds, engineers need to accurately predict the aerothermodynamic performance of a hypersonic vehicle and increase its endurance under hypersonic conditions.⁹ The only hypersonic vehicles flying above Mach 6 have been either blunt-nosed configurations or time-limited configurations. The blunt-nosed configurations (rockets) must have extensive thermal protection in their frames. Time-limited configurations (X-15) cannot remain in hypersonic speeds for long durations without causing serious problems due to the high temperatures and high pressures that the engine parts would experience. At present, Computational Fluid Dynamics (CFD) methods used to obtain theoretical estimates of hypersonic flow fields need experimental validation. They require testing aircraft models or components at speeds above Mach 5, with high temperatures, high pressures, high enthalpies and for long durations. Without the use of ground testing, reliable methods essential to the prediction and interpretation of the environment of a vehicle for varying Reynold's numbers and Mach numbers will be risky and costly.¹⁰

Hypersonic wind tunnels offer an extremely efficient way to study aerodynamics, stability, control, and heat transfer effects.⁹ At present, though, there is little ability to test hypersonic vehicles in a wind tunnel much

above Mach 8 and simulate all applicable similarity parameters;² hence, only limited testing of advanced, hypersonic and air-breathing propulsion systems has been done. Heat transfer, thermal properties, and some physical characteristics do not scale reliably to a larger model in present hypersonic wind tunnels.^{10,11} At high Mach numbers ($M > 12$), tests become very expensive and time consuming to produce the necessary large number of test conditions.⁹

Some of the problems associated with hypersonic wind-tunnel simulations are: 1) the data acquired will not be at the desired flight Reynold's number; 2) it may not be possible to reach the correct Mach number; 3) test facilities running for minutes would require a very large amount of power (gigawatt range) for the entire test duration;⁹ 4) simulating flight conditions at hypersonic Mach numbers (6 and up) results in extremely high stagnation pressures and temperatures;^{1,2} and 5) complex materials and complex cooling systems would also be required.³

Many of these problems would be solved with the use of a magnetohydrodynamic (MHD) accelerator to augment a high temperature hypersonic wind-tunnel. Figure 1¹² shows a schematic of a pulsed MHD accelerator apparatus. A MHD accelerator would be introduced into the ground testing system after the supersonic nozzle and before the test chamber. A slightly conductive gas is introduced into the

SCHEMATIC OF PULSE MHD ACCELERATOR APPARATUS

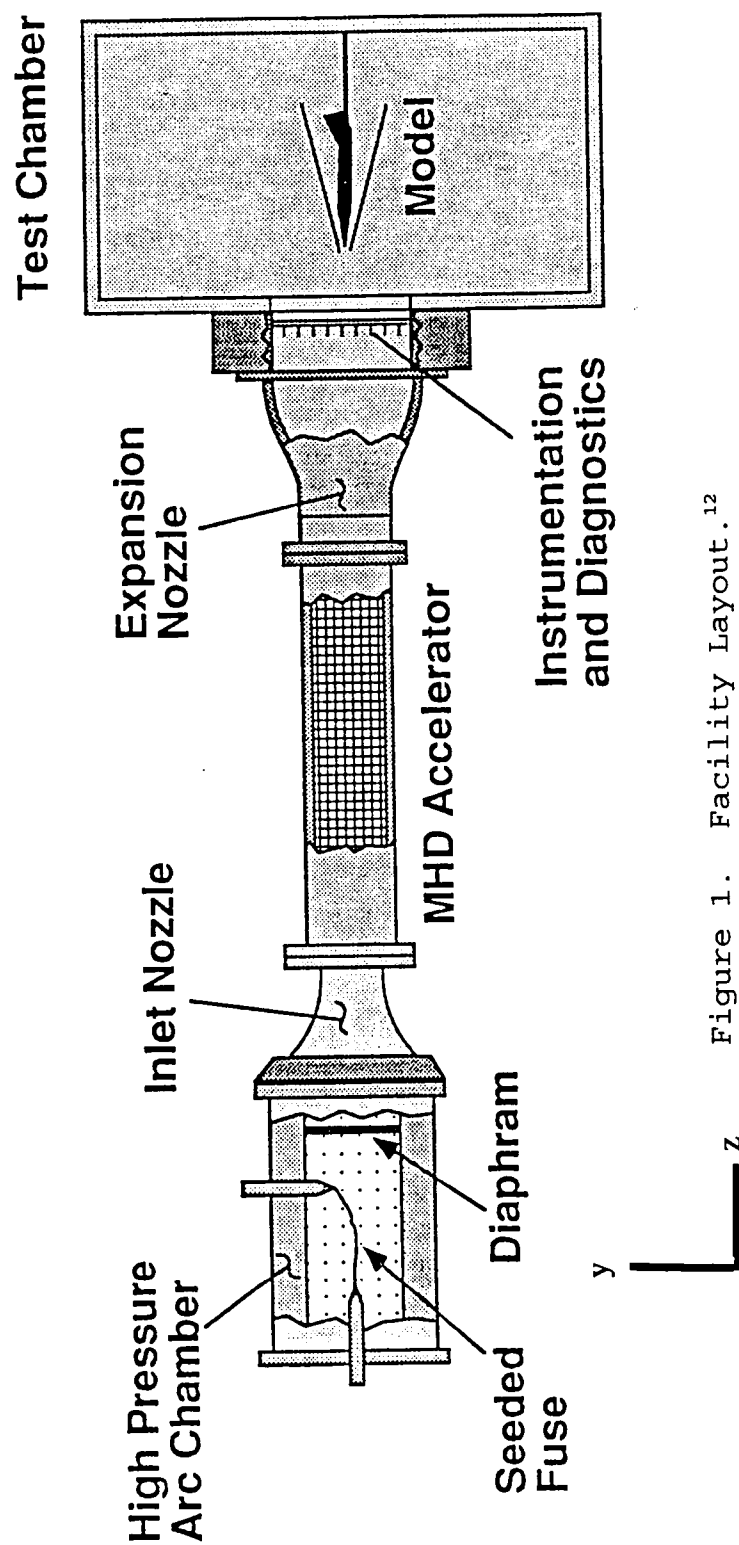


Figure 1. Facility Layout.¹²

system before the nozzle. Using electromagnetics, the conductive gas, or plasma, reaching the MHD accelerator will be accelerated when contact is made with the current in the cathode. The current in the cathode will pass through the conductive gas and into the anode. The current passing through the conductive gas in the presence of a normal magnetic field accelerates the gas down the channel. Additionally, a hypersonic expansion inserted after the MHD accelerator will further increase the speed of the gas.

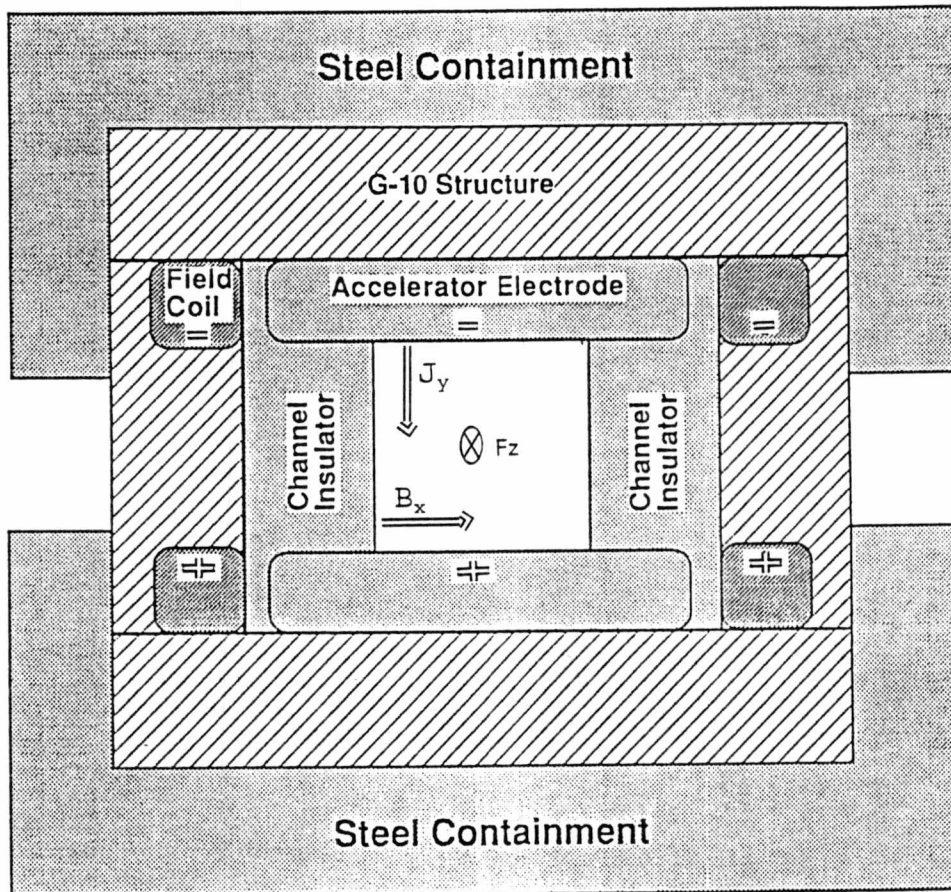
A transient MHD accelerator uses a burst of power for a couple of milliseconds or less to accelerate an electrically conductive gas from supersonic speeds to well into the hypersonic range. Simple capacitors or other energy storage devices provide the necessary current and eliminate the instantaneous and long lasting gigawatt power drain. The total power required in a transient MHD accelerator would be approximately 4 MJ for the example in this thesis.

Another advantage of the MHD accelerators is that they offer lower static pressures and static temperatures. Since the flow is accelerated by MHD body forces, the facility does not experience the very high stagnation temperatures and pressures in the nozzle area. This decrease in static temperatures and static pressures has the advantage of permitting acceleration of a gas to higher Mach numbers before reaching either the thermal limits of oxygen

dissociation or the facility's maximum allowable temperature. The surface temperature of the MHD accelerator is kept low because of the short period of contact between the plasma and the surface material.¹³ However, since the gas is moving at very high velocities, the required total enthalpy can be obtained to correctly simulate high Mach number flows.

A transient MHD accelerator has an accelerator channel with electrodes above and below the channel. The gas flows down the channel. Figure 2 shows the schematic of a proposed MHD accelerator.¹² Current passes into one electrode (the cathode), down through the conductive gas, and into the other electrode (the anode). Lorentz's $\mathbf{J} \times \mathbf{B}$ force describes the distribution of the accelerating magnetic force throughout the conducting gas. A uniform magnetic force is needed in the plasma to prevent non-uniform gas acceleration during the transient operation. The hypersonic-test-section flow must have uniform properties in order to provide a true simulation of flight at hypersonic speeds. Although many technical issues of a transient MHD accelerator must be resolved before routine testing can be based on the device, one important concern at present is the electrode shape. This shape is mainly responsible for the uniformity of the magnetic flux density and the current density.

Previous plasma armature railgun research has been done



The Lorentz Forces
are into the page

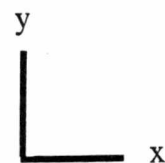


Figure 2. Accelerator Cross-Section.¹²

with rectangular-shaped electrodes where an object was pushed through a channel by MHD.^{3,12} The resulting flows contained non-uniformities in the magnetic force due to the current density concentrating in the corners of the channel containing the plasma. Therefore, an investigation into electrode shapes is needed to reduce the non-uniformities in the magnetic force.

1.0 TRANSIENT ELECTROMAGNETIC THEORY FOR MHD

Due to the complexity in the transient electromagnetic theory for magnetohydrodynamic (MHD) devices, a short but thorough explanation follows. The interaction of a conducting gas and a magnetic field is described by the equations of magnetohydrodynamics (MHD).¹⁴ The conducting gas or plasma is a high-temperature, electrically-conducting plasma passing through a nozzle and into a channel. In the channel the plasma passes through a toroidal coil or, in this case, between two electrodes where the plasma comes in contact with a magnetic field.^{14,15,16}

An electromagnetic field is associated with a current passing through a conductive substance. A field is generated around the path of the current as shown in Figure 3. Increasing current strength increases the strength in the field.

Transient electromagnetic phenomena are governed by Maxwell's equations, see Jackson.²⁰ These equations are:

$$\nabla \cdot \mathbf{D} = 4 \pi \rho \quad (1)$$

$$\nabla \times \mathbf{H} = \frac{4 \pi}{c} \mathbf{J} + \frac{1}{c} \frac{\partial \mathbf{D}}{\partial t} \quad (2)$$

$$\nabla \cdot \mathbf{B} = 0 \quad (3)$$

$$\nabla \times \mathbf{E} + \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = 0 \quad (4)$$

where $\mathbf{D}$ is the electric or dielectric displacement, $\mathbf{B}$ is the

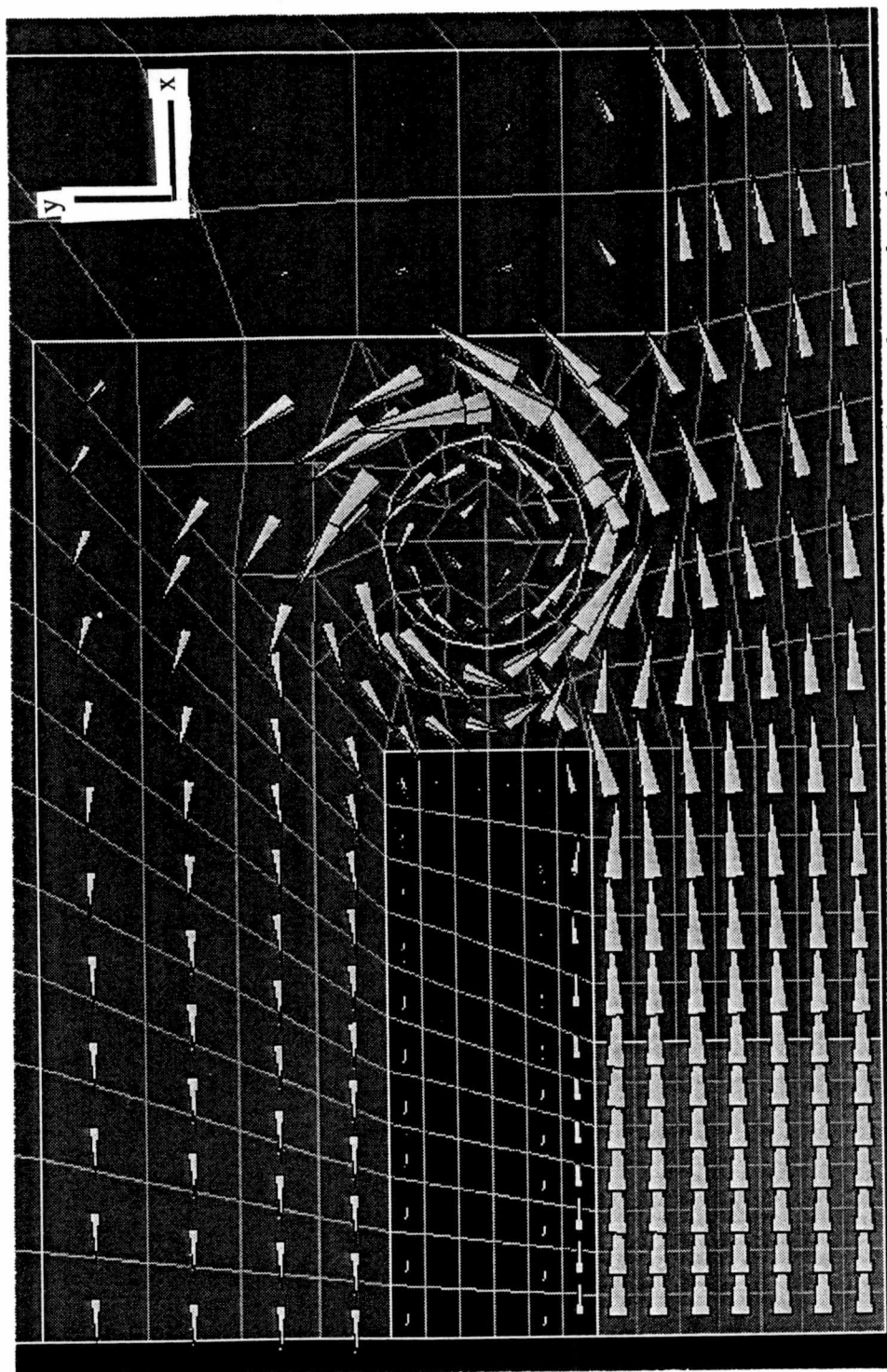


Figure 3. A Field Surrounds the Current Passing through the Electrode (in black) and the Circular Coil (to the Electrode's Right) of the Upper Right Quarter of the Accelerator Model.

magnetic induction vector or magnetic flux density, $\mathbf{H}$ is the magnetic field, $\mathbf{E}$ is the electric field, $\mathbf{J}$ is the current density, ρ is the charge density, c is the speed of light, and t is the time. Equation 1 is Coulomb's law. Equation 2 is Ampère's law, although $\nabla \cdot \mathbf{J} \neq 0$ since, with transient electromagnetics used in an accelerator, steady state will never be reached. Equation 3 is included because of the absence of free magnetic poles. Equation 4 is Faraday's law. The dielectric displacement is related²⁰ to the electric field by

$$\mathbf{D} = \epsilon \mathbf{E}$$

and the magnetic flux density is related²⁰ to the magnetic field by

$$\mathbf{B} = \mu \mathbf{H}$$

where ϵ is the dielectric constant or the relative electric permittivity, and μ is the permeability.

When a moving conductive slug of gas reaches a point at which it completes an electric circuit, a current passes through the conducting gas that, in the presence of a transverse magnetic field, produces electromagnetic forces. The electrically conductive gas transfers the current from the negative electrode (cathode) through the channel and to the positive electrode (anode) as seen in Figure 4.¹⁵ The plasma flowing through a magnetic field generates an electric field.¹⁷ A Lorentz force due to the vector cross product of the current density and magnetic flux density is

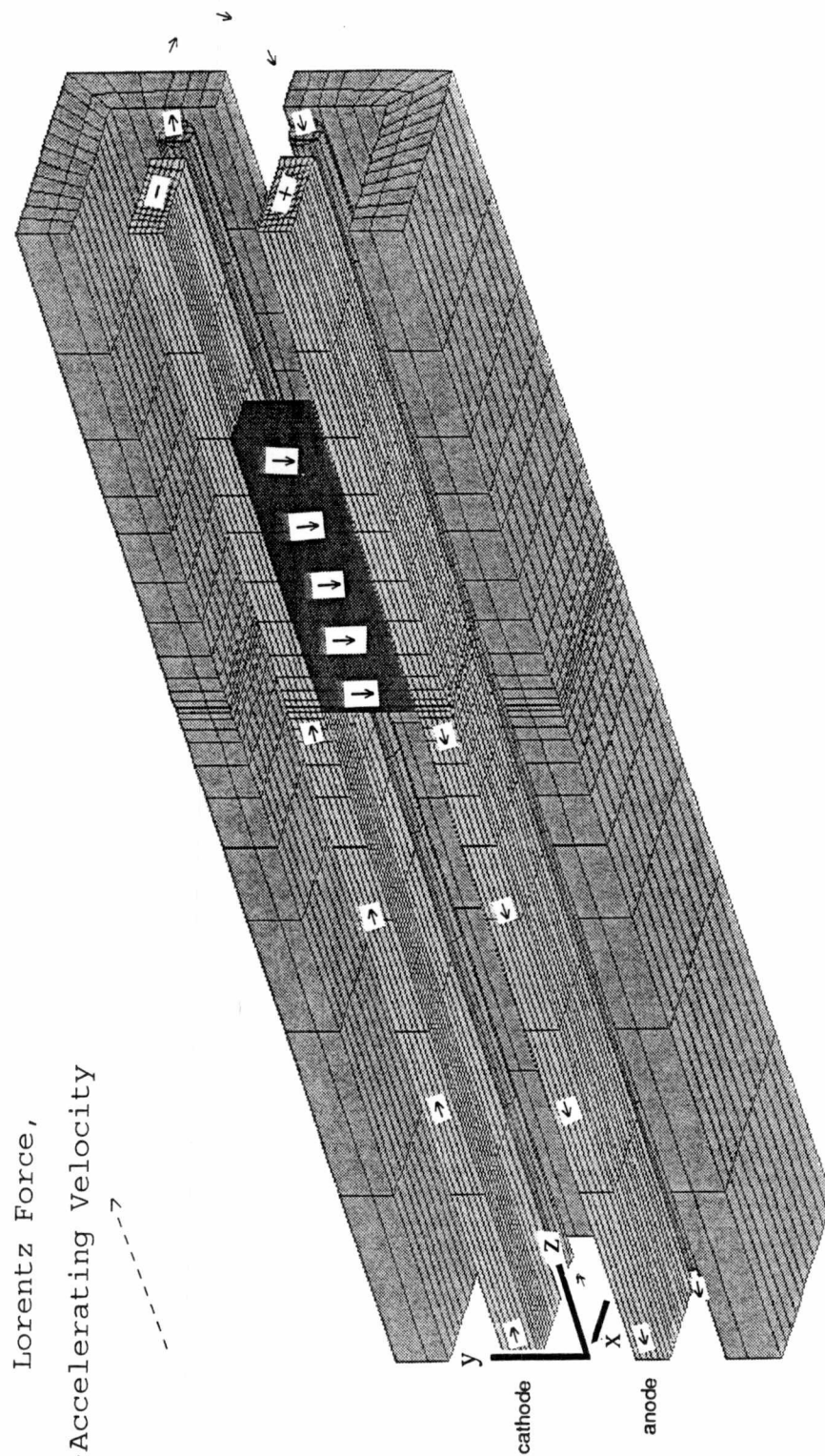


Figure 4. Current Traveling through a MHD Accelerator.

then experienced by the plasma. For an accelerator, the Lorentz force accelerates the gas down the channel undisturbed. For a generator, on the other hand, the gas flow is slowed since the current in the coil flows in the opposite direction from that of the electrode.

The conductivity of the plasma is important. By Ohm's law, $V = IR$ (where V is the voltage, I is the current, and R is the resistance). With a constant current, an increase in resistance results in an increase in the voltage. If the conductivity of the plasma decreases, there is an increase of voltage required to force current through the conducting gas. This results in an increase in the Ohmic heating losses, and an increase in the plasma temperature. The reduction of conductivity in the plasma will not continue due to the possibilities of the current finding a path of lesser resistance outside of the plasma. As the temperature of the gas rises with the increase in Ohmic heating, the conductivity increases.¹⁸ Figure 5 shows the rise in conductivity of a 2% potassium-seeded plasma with temperature.

The temperature and pressure of the gas are substantial factors that determine the conductivity.¹⁵ With an inlet temperature in the accelerator of approximately 3500 K, the conductivity of the plasma would initially be below 100 mho/m for a pressure of 20 atm or greater.

The Lorentz force equation^{20,21} for a single charged

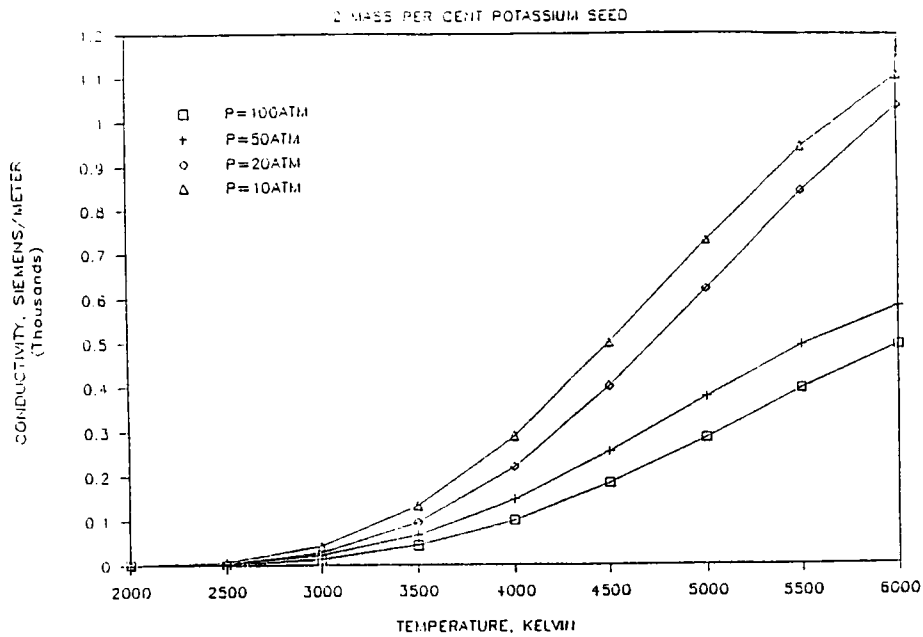


Figure 5. Conductivity of Air Seeded with 2% Potassium.

particle is

$$\mathbf{F} = q \left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right)$$

where $\mathbf{F}$ is the total electromagnetic force acting on a point charge q , and $\mathbf{v}$ is the velocity of the charged particle. The equivalent equation of force per unit volume acting on a current is

$$\mathbf{F} = \mathbf{J} \times \mathbf{B}, \quad (5)$$

assuming the fluid is a simple continuum with a scalar conductivity.^{16,20,21}

When a current passes through the plasma, a magnetic force in an accelerator accelerates the plasma down the channel with a magnitude of $F_z = J_x * B_y - J_y * B_x$ (where F_z

is the magnetic force in the z-direction; J_x and J_y are the current density in the x- and y-direction, respectively; and B_x and B_y are the magnetic flux density in the x- and y-direction, respectively). The J_y and B_x terms will be relatively large compared to the magnitudes of the densities in the other directions, and they will generate the dominant magnetic force down the channel in the desired direction. Problems of non-uniform flow arise when the magnetic flux density and the current density are non-uniform.

Equations 1-5 can be solved for steady cases without difficulty. However, for MHD acceleration in a transient device, the accelerator configuration must be examined by a time dependent finite element model. The Mega™ computer code uses a finite element procedure to solve the transient equation of electrodynamic motion with accuracy. It was chosen to perform the calculations in this thesis.

An MHD accelerator has also been noted as having serious erosion, corrosion, mechanical stresses, and thermal stresses on the electrode's surface and on the insulator walls.¹⁵ These problems must be solved before MHD can be used as an effective accelerator. Since these problems are not related to the shape of the electrode, they will not be examined at this time.

2.0 MEGA™

The Mega™ software package was developed at the University of Bath, England, as a means to model electromagnetic devices.²² These devices can be as simple as a 2-D bar in an uniform field or as complex as a 3-D 3-phase linear motor.²³ Some of the capabilities of Mega™ include the solution of the following: 2-D and 3-D magnetostatics, 2-D and 3-D electrostatics, transient eddy currents with multiple forcing functions, surface impedance elements for small skin depth conditions (linear or non-linear), 2-D and 3-D moving conductor problems.²²

Mega™ consists of two programs: One for solving stationary and moving electromagnetic models and another for creating, editing, and presenting electromagnetic models.²² First, the formation of the equations used by Mega™ will be discussed followed by a brief introduction of how the MHD model was created. In Appendix A, a closer examination of the creation of the MHD accelerator model and the editing techniques of Mega™ will be provided. The simulation capabilities of the model will also be discussed. The degrees of uniformity will be presented in the remaining chapters starting with the magnetic flux density.

2.1 MEGASOLVE

MEGASOLVE is the program inside Mega™ used to solve the various electromagnetic models. It solves an appropriate set of Maxwell's equations. Maxwell's equations²⁰ are the foundational equations used in Mega's™ field equations.²² The four basic equations²² used in Mega™ are:

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\mathbf{B} = \mathbf{B}(\mathbf{H})$$

$$\mathbf{J} = \sigma \mathbf{E},$$

where $\mathbf{H}$ is the magnetic field, $\mathbf{J}$ is the current density, $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic flux density, t is time, and σ is the conductivity.

In electromagnetics the electric fields, the magnetic flux densities, and the current densities are often better expressed in terms of potentials.²⁰ Depending on the type of problem and the material being modelled, Mega™ uses potentials in its calculations based on a variety of representations.²² For 3-D problems Mega™ uses the AV, magnetic vector ($\mathbf{A}$) and electric scalar (V) potentials, representation that normally is used for solving electromagnetic fields. Although this method is accurate in finite element models, it generally has more unknowns than are necessary, and the vector potentials must be gauged leading to possible over-constraints.²⁴ As stated in the

Mega™ manual,²² the following additional equations have been included below.

$$\mathbf{B} = \nabla \times \mathbf{A}$$

$$\mathbf{E} = \frac{-\partial \mathbf{A}}{\partial t} - \nabla V$$

The ∇V term is used in allowing jumps in conductivity to be modeled correctly.²² The Mega™ program may be applied gauged or ungauged with a correction term to define the divergence of $\mathbf{A}$

$$\mathbf{J} = \nabla \times \mathbf{H},$$

yielding

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} + \sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla V \right) = 0.$$

The solution of these equations by finite element techniques requires an augmented set of equations²² as follows:

$$\nabla \times \frac{1}{\mu} (\nabla \times \mathbf{A}) - \left\{ \frac{1}{\mu} \nabla^2 \mathbf{A} \right\} + \sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla V \right) = 0 \quad (6)$$

$$\nabla \cdot \sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla V \right) = 0$$

$$\mathbf{A} \cdot \hat{\mathbf{n}} = 0.$$

The $\{\}$ term is a correction term forcing the divergence of $\mathbf{A}$ to be zero.²² The last equation is a boundary condition that forces a zero magnetic flux at the outer boundary.

Velocity of the plasma can be introduced through the Mega™ solver. This provides the option of solving the transient electromagnetic equations for moving magnetohydrodynamic models. The velocity creates eddy

currents in the electrodes. These eddy currents, in turn, create secondary magnetic fields opposing the inducing magnetic field.¹⁵

2.2 MEGAVIEW

MEGAVIEW is used for defining, post processing, and editing electromagnetic models.²² Screen prompts lead the user to perform the desired tasks, and very few memorized commands are necessary. An electromagnetic device can be created, edited, or examined simply by performing simple steps.

Once created, the solving program computes the magnetic flux densities, current densities, magnetic forces, and other magnetic and electric properties for the device created. Mega™ also allows a user to examine these characteristics as they are influenced by time.

Mega™ allows a user to assign the material characteristics, such as conductivity and current/voltage conditions on each part. Boundary conditions can also be established and used to imply symmetry or an ambient state. The time step can be adjusted to examine events that change over a period down to 1 microsecond or smaller. (This is important since a steady state will never be reached in the transient accelerator.) The plasma should leave the accelerator within a millisecond due to the length of the

accelerator channel in relation to the speed of the plasma.

Using Mega™, the electrode's design may be easily changed in the program and the data re-calculated to find the results for other electrode shapes. The magnetic flux density and current density distributions can then be re-examined.

3.0 APPROACH FOR FINDING MAGNETIC FORCE UNIFORMITY

The previous section shows how to create an MHD accelerator model using Mega™. The model simulates a small scale facility for investigation of the performance and for obtaining the necessary data for design of a larger facility. The channel in this small scale model is only 5 cm by 5 cm. The outer dimensions including the iron containment shell is only 21.8 cm by 20.3 cm. In the creation of an accelerator model, several variables were set as constants (i.e., velocity, conductivity, all lengths, and current). Different electrode-shaped models were considered, and each originated from the same 2-D model with the exception of the electrode shape.

First, the arrangement and the dimensions of the structure were considered. This was determined from the proposed configuration shown in Figure 2.¹² A electrode and coil were made of copper. Initially, the electrode and coil were given a current of 200 amps. Later the current was increased to 2,000 amps, to 20,000 amps, and for a single simulation to 200,000 amps. With 200 amps, the current density penetrates the back of the plasma with some current density returning to the cathode in the front of the plasma. This produces a braking force in the front of the plasma, slowing the flow even as late as 50 microseconds. It is expected that a braking force will exist with 20,000 amps or

greater at some early time (before 1 microsecond), but the accelerating forces in the back of the plasma will always produce a positive net force. In practice, 200,000 amps would be closer to the current used, but this would only change the magnitude of the magnetic force and cause the trends to occur at faster rates.

In reference 26, this double electrode or augmented-electrode configuration is used to increase the magnetic force from

$$F = \frac{1}{2} L' * I^2$$

of the single electrode to

$$F = \frac{1}{2} L' * (I_2)^2 + M'_{12} * I_1 * I_2$$

of the augmented electrode configuration where L' , M' , I_1 , and I_2 are the inductance per rail length, the mutual inductance per rail length, the current of the coil, and the current of the electrode, respectively. For the accelerator model, the coil (or second electrode) that was added to the device doubled the net accelerating force. However, the augmented electrode configuration has the disadvantage of a force pushing the two electrodes in opposite directions requiring extra containment to keep the model together.²⁶

The iron containment shell's shape and size were determined by structural requirements. Experiments show that the shell has little or no bearing on the magnetic fields but is critical to hold the accelerator together during a test.

For purposes of the simulation, a step input was used for the current. This produces benefits of instantaneously getting the current everywhere in the accelerator model and simplifies the input for the current versus time profile.

The channel insulator structure is used as a side wall for the accelerator channel. It is represented by the characteristics of air in Mega™ and would only change shape to fit flush against the electrode. The insulator provides the necessary containment and holds the model parts in their perspective position.

The plasma is air with 2% potassium seed. In Mega™ this is determined only by the conductivity given to the element. Initially the conductivity was set to 1×10^5 mho/m. Since Mega™ was designed for calculating magnetic characteristics for metallic objects, it was unclear how accurate the results would be with low conductivity materials. Tests were simulated and trends were compared to simulations with a conductivity of 100 mho/m. The trends of both conductivities and the expected results were the same.

The conductivity of the plasma will vary with the temperature and the pressure as shown in Figure 5. Mega™ has no ability to vary the conductivity as temperature and pressure increase. Therefore, the simulations are run at a constant conductivity. For comparing the shapes of the electrode, the comparison will be accurate. With an increasing conductivity, as seen with the initial

conductivity settings, the accelerating force will increase in the back of the plasma and decrease toward the front.

The plasma's length is set to 15 cm. The width and height are set to 5 cm each. In an experimental model the plasma will not have straight, solid faces in the front and back, but for a comparison they have been assumed. The velocity of the plasma was set at 1000 m/s.²⁷ The speed of the incoming air can vary in the supersonic range and is not limited to a certain Mach number. The 1000 m/s was used as a simulation velocity for comparison purposes only. An increase to 2000 m/s was evaluated with only a small increase in the accelerating force (about 0.3%).

Over fifty different electrode shapes have been simulated and compared to the rectangular electrode shape used in the UTSI railgun research. These were simulated both in two-dimensions and in three-dimensions. Early time periods in microseconds were used to compare the magnetic flux density and the current density to find the most uniform magnetic force. Two shapes that were compared are shown in Figures 6 and 7. These shapes were selected because of their ability to produce a better uniformity. These shapes are hollow to improve transient current distribution and to allow coolant to flow, reducing the temperature of the device and the erosion of the electrode. Other shapes are contained in Appendix B with corresponding results in the magnetic force section. All the electrode

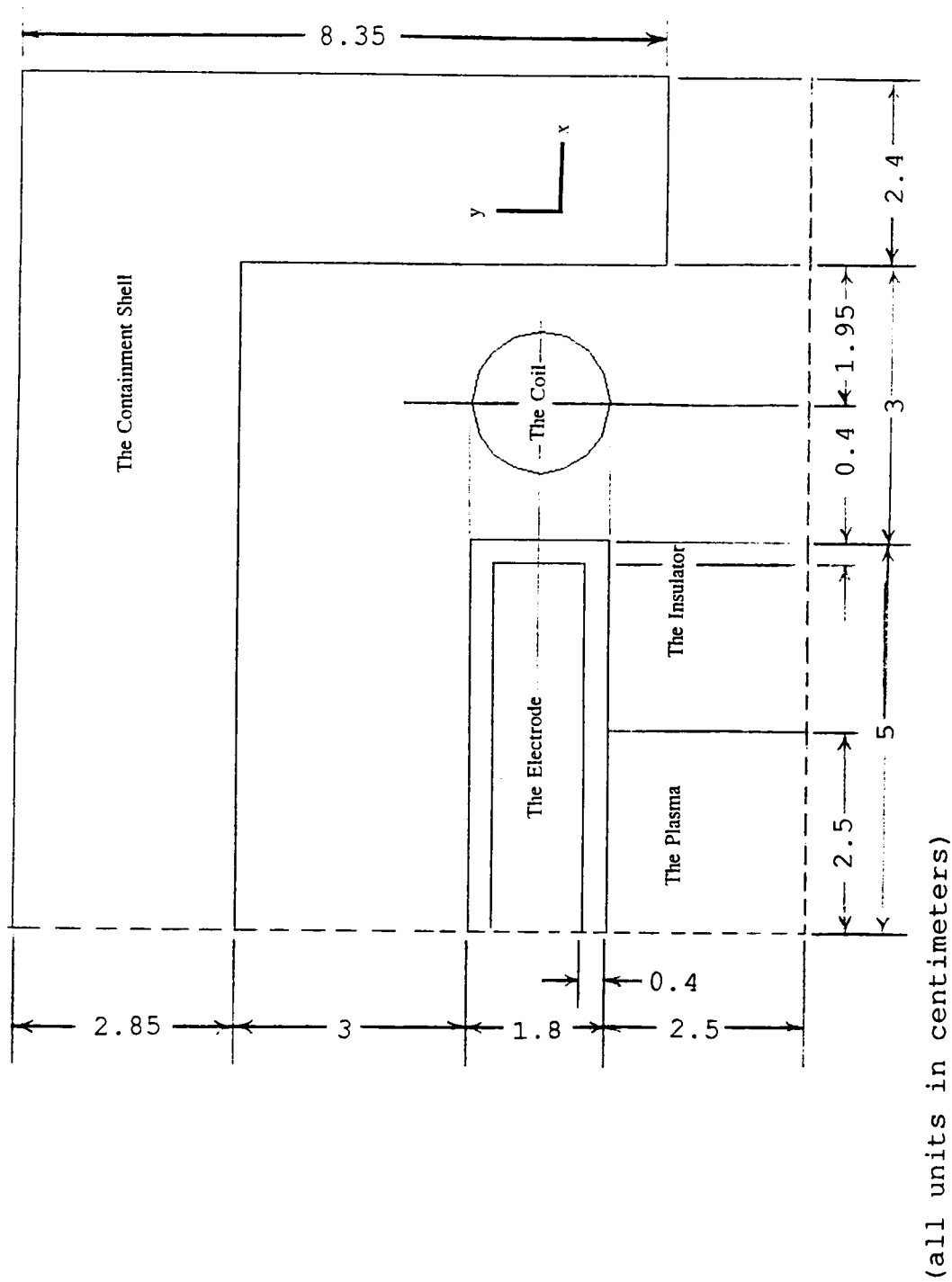
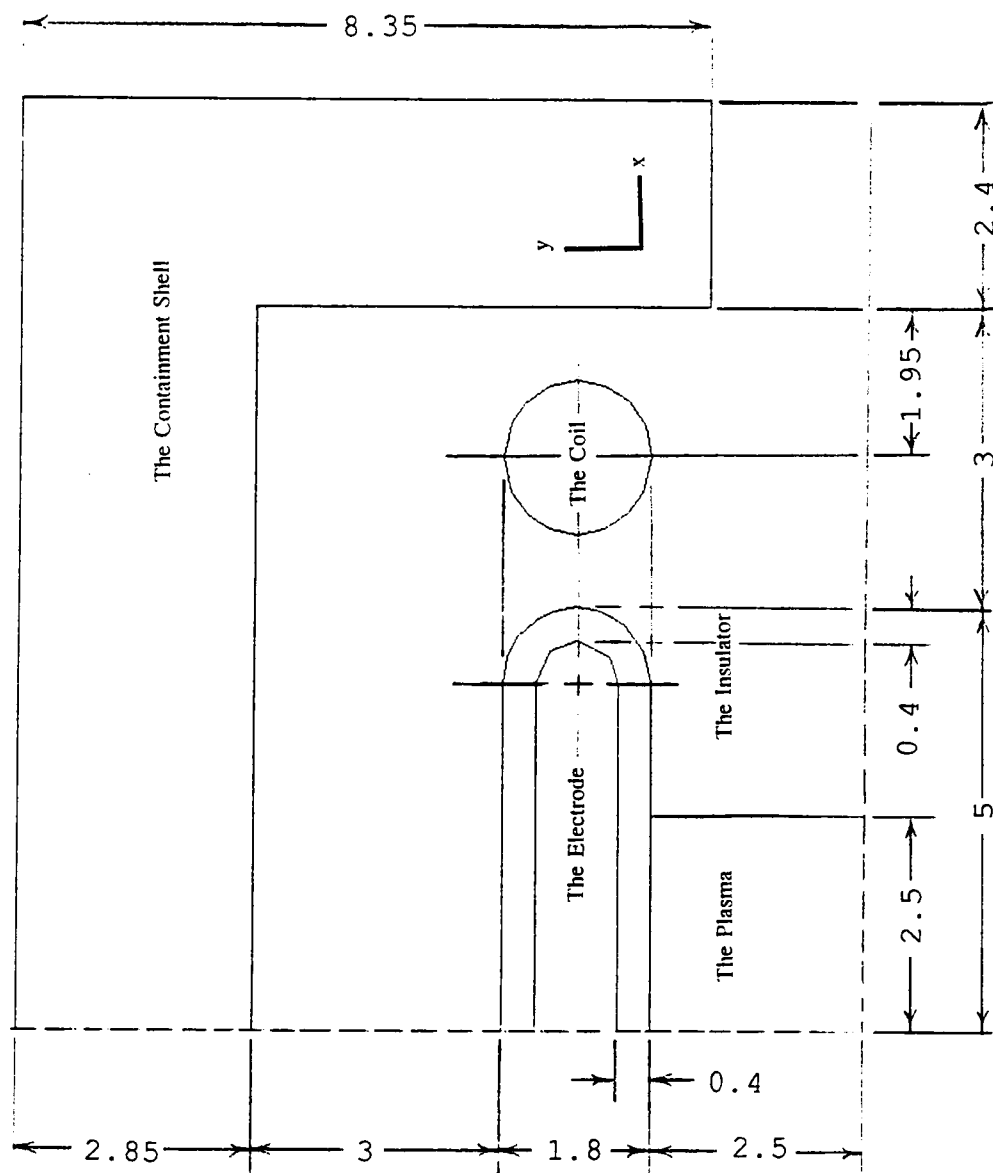


Figure 6. The Quarter of the Hollow-Rectangular-Electrode MHD Accelerator.



(all units in centimeters)

Figure 7. The Quarter of the Hollow-Curve-Ended-Electrode MHD Accelerator.

shapes have the same width (10 cm). Other possible shapes could also be formed, but the hollow curve-ended electrode was selected for the purpose of comparison with the hollow rectangular electrode.

These hollow shapes were re-examined with both 2-D and 3-D simulations. The magnetic flux densities are compared in section 4, and the current densities are compared in section 5.

The magnetic force per unit volume, produced by the $\mathbf{J} \times \mathbf{B}$ product in the seeded air, was examined for uniformity throughout the plasma. This comparison is in section 6.

4.0 EVALUATING THE MAGNETIC FLUX DENSITY

The magnetic flux density, $\mathbf{B}$, is a field created by a magnetic circuit. As current passes through a conductive material, a magnetic dipole is formed, and the direction the dipole aligns itself is the magnetic flux direction.²⁰ The magnetic flux density plays a major role in the determination of the magnetic force ($\mathbf{F} = \mathbf{J} \times \mathbf{B}$). The magnetic flux density, $\mathbf{B}$, is measured in Tesla and is a vector quantity.

A magnetic flux density is produced by the currents in the two field coils and the current in the top and bottom channel electrodes. Figure 8a-c shows a simulated magnetic flux density in a quarter of a MHD accelerator at 20 microseconds at three different stations. The length of the arrow represents the magnitude. The arrow's point represents the direction of the magnetic flux. Figure 8a shows the magnetic flux density in the front of the plasma; Figure 8b, shows it 9 cm from the back; and figure 8c shows it at the back. The front of the plasma sees less magnetic flux density than the back of the plasma. A contour plot has also been included in Figure 8a-c showing the uniformity of the magnetic flux density in the x-direction.

The magnetic flux density is primarily in the x-direction. Figure 9 shows the magnetic flux density in the hollow rectangular electrode and the hollow curve-ended

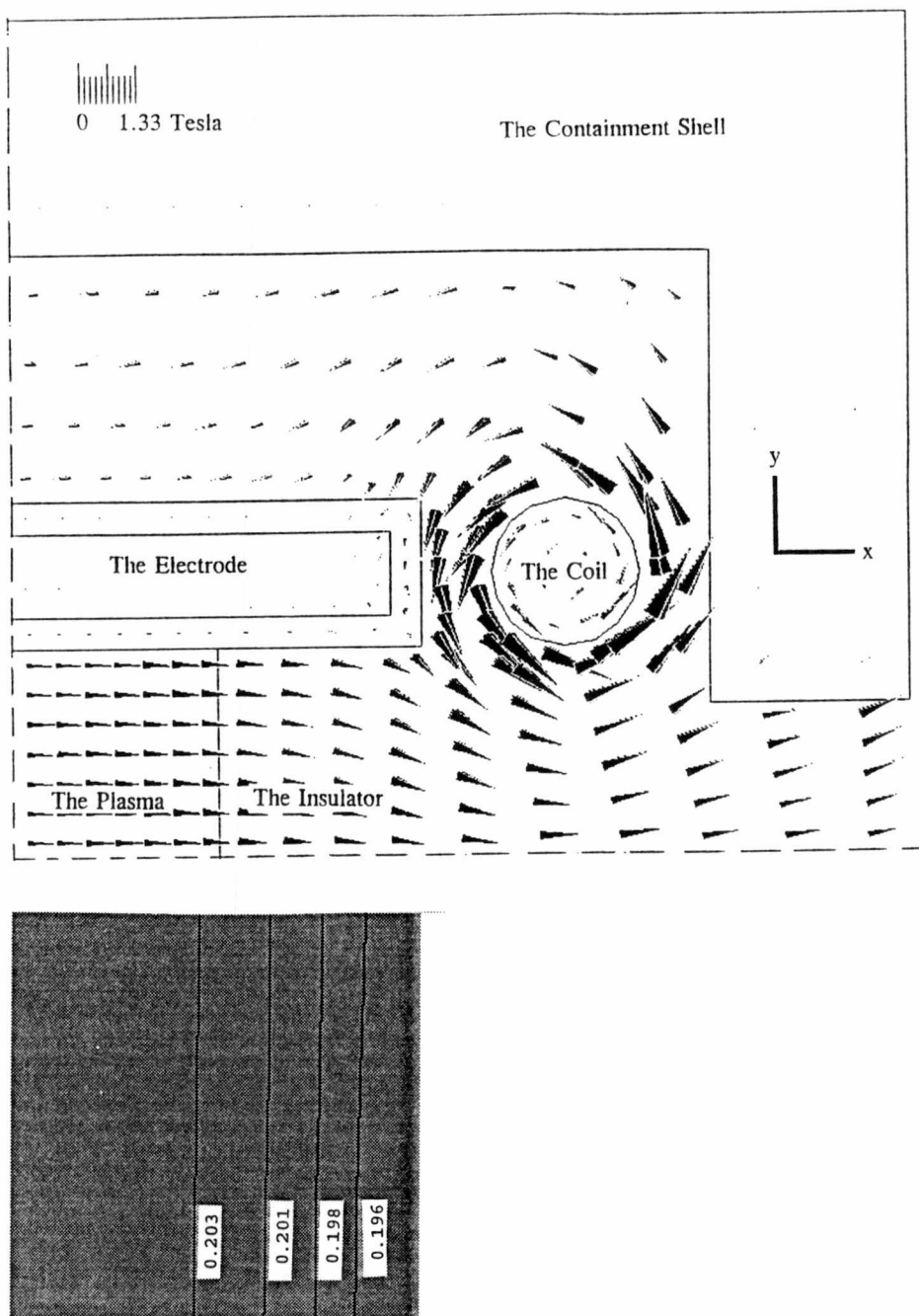


Figure 8. The Simulated Magnetic Flux Density in the Quarter of the MHD Accelerator in the XY Plane at 20 Microseconds and a Contour Plot of the Magnetic Flux Density in the X-Direction from the Channel Containing the Plasma.
a) In the Front of the Plasma.

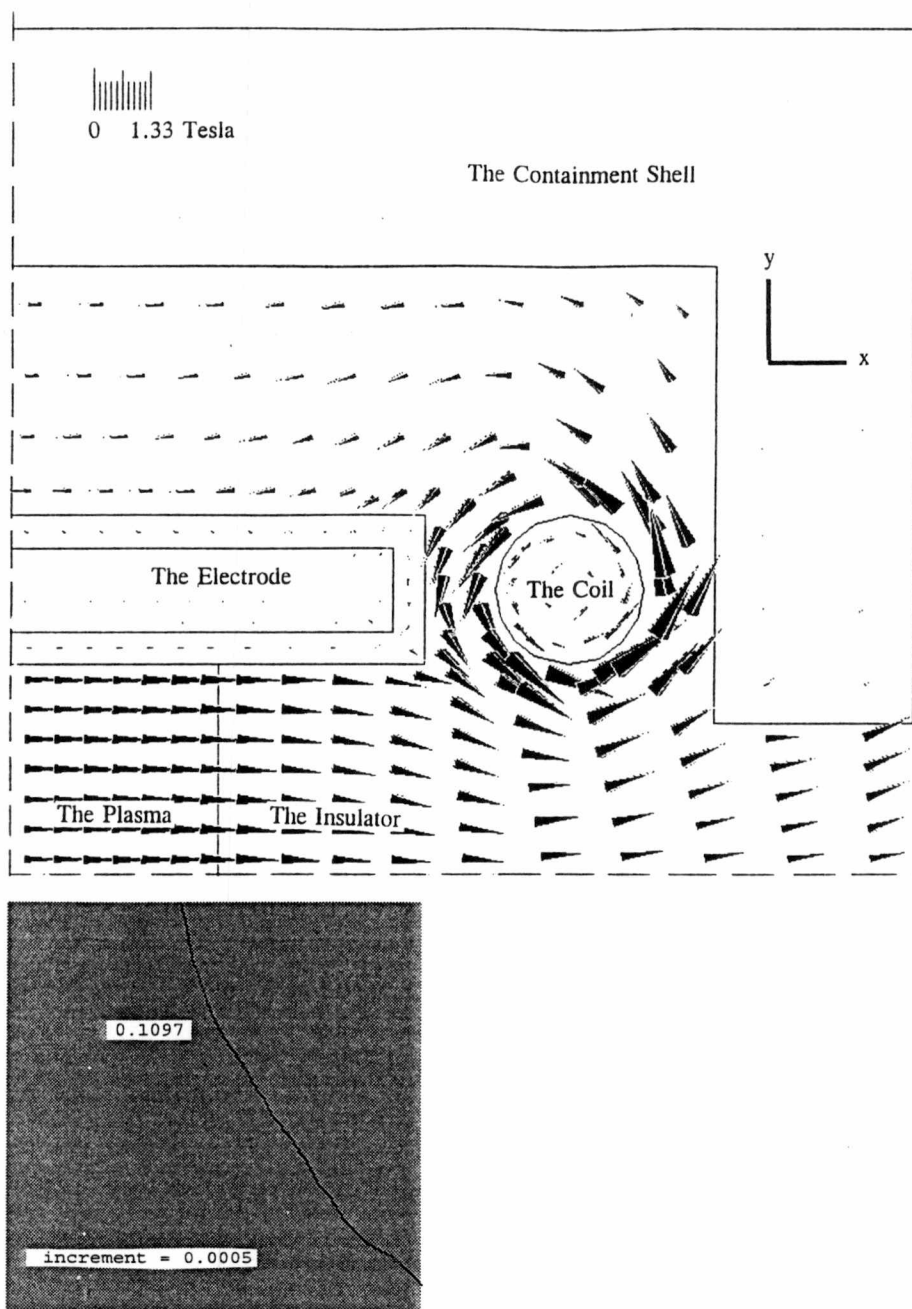


Figure 8 Continued.
b) 9 cm From the Back of the Plasma.

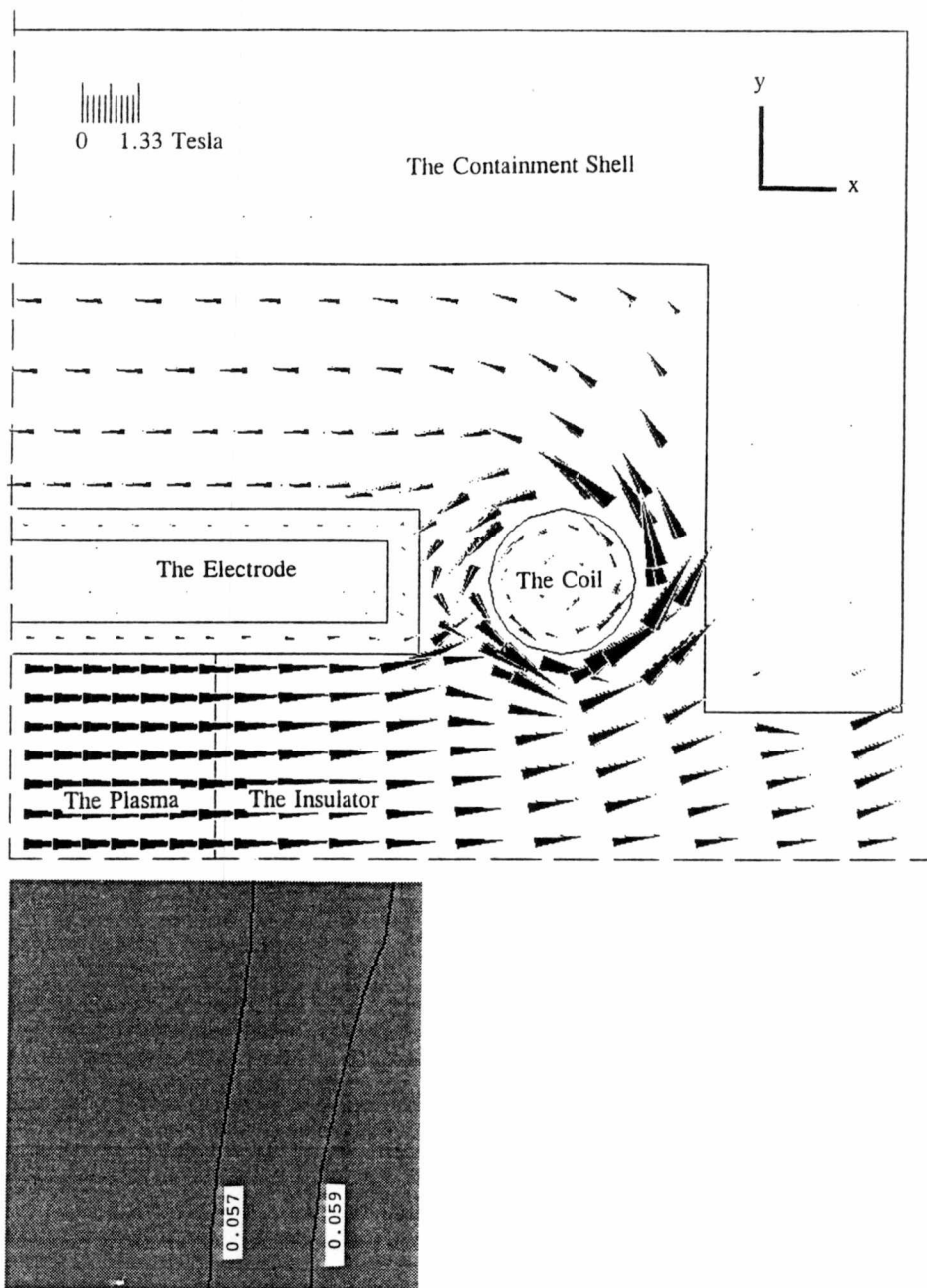


Figure 8 Continued.
c) In the Back of the Plasma.

electrode at 20,000 amps and a velocity of 2000 m/s. The hollow rectangular electrode is located on the left side of the page and the hollow curve-ended electrode on the right side of the page. The B_x term at the top of the page is the primary magnetic flux density and stabilizes at values above 0.1 Tesla. The B_y is three magnitudes smaller with values around 10^{-4} . The B_z term is only half of a magnitude smaller (about 0.045 Tesla) along the insulator wall and as low as one and a half magnitudes smaller (about 0.005 Tesla) in the vertical middle of the channel.

It should be mentioned that four locations were selected to show the trends in the magnetic flux density as a function of time. These four points are: 1) at the channel directly below the middle of the electrode, 2) at the corner of the channel, 3) at the middle of the channel, and 4) at the channel directly next to the center of the insulator wall. These points are used to show uniformity by presenting the extreme values that occur on the corners of the quadrant in the channel.

A comparison in Figure 9a shows a 53% better uniformity in the hollow curve-ended electrode as opposed to the hollow rectangular electrode. This is determined by the closeness of the values from the four points being examined. Figure 9b values are so small that they have no effect on the uniformity. Figure 9c shows values along the insulator wall that are high enough to affect the magnetic force in the

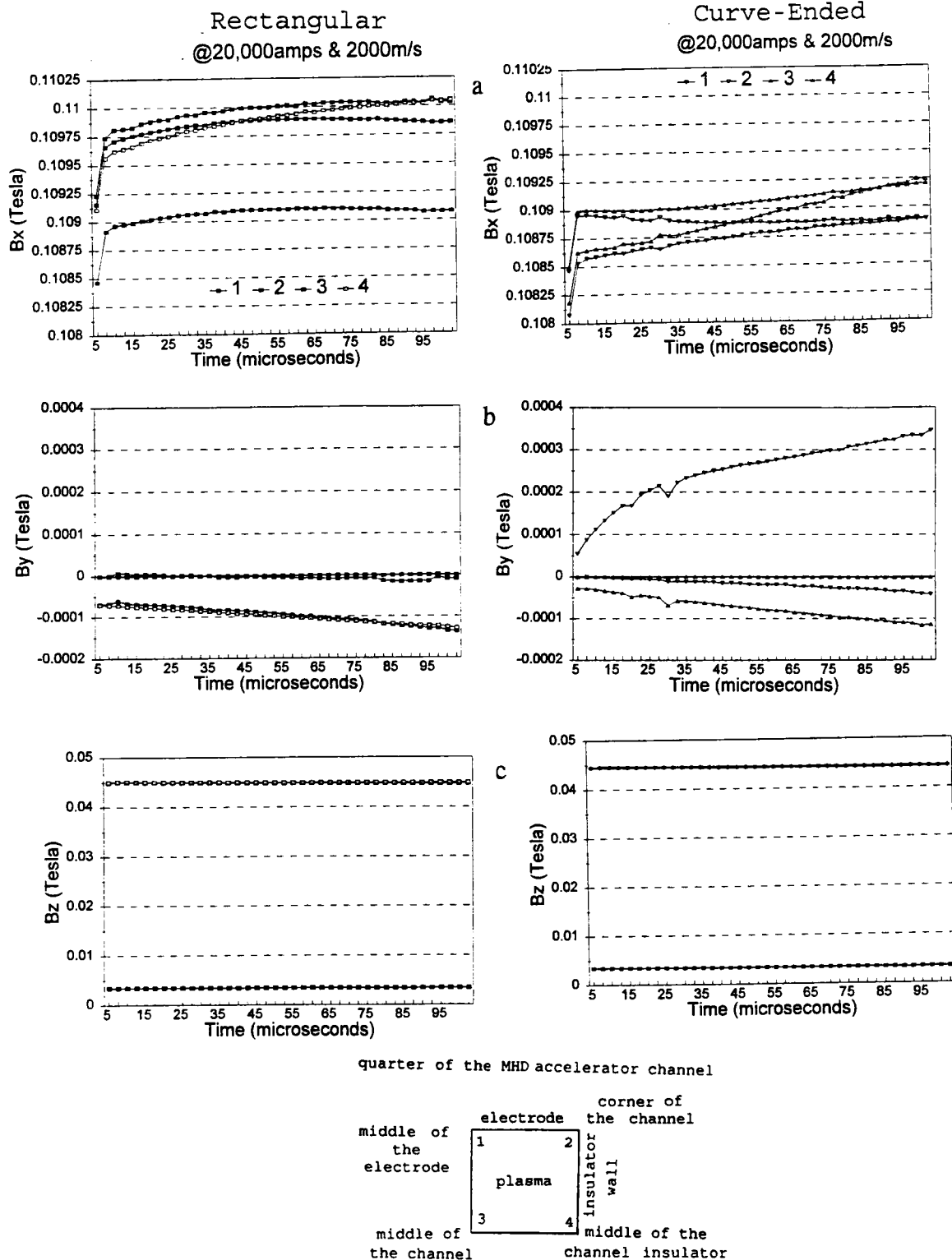


Figure 9. The Trends in the Magnetic Flux Density at 9 cm from the Back of the Plasma as a Function of Time.

x-direction. The values of these B_z densities decrease the farther from the insulator wall that is being examined. Appendix C shows more detail of the magnetic flux density at two additional depths in the plasma, the front and the back. The values for B_x and B_y increase in the back of the plasma. The values for B_z are greater in the middle of the plasma and shrink approximately 25% in the front and approximately 60% in the back.

5.0 EVALUATING THE CURRENT DENSITY

The current density, $\mathbf{J}$, is associated with moving charges. From the continuity equation,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{J} = 0,$$

where ρ is the charge density, t is the time, and $\mathbf{J}$ is the current density. The current density always follows the path of the current. The units for current density are ampere per cross-sectional area (amp/m^2).

Figure 10a-c shows the simulated current density in a quarter section of a MHD accelerator at 20 microseconds. The length of the arrow shows the magnitude of the current density, and the arrow's point shows the direction. Figures 10a (the front), 10b (9 cm from the back), and somewhat in 10c (the back) show directional current density variations at the end of the electrode due to the corners. If the channel had been closer to the corner of the electrode, the current density would have been more erratic. A contour plot has also been included showing the uniformity of the current density in the y -direction.

The path of the current density can be seen as it works its way around the electrode's thin walls.

Figure 11a-c shows the current densities in the YZ plane at 1, 12.5 and 24 cm, respectively, from the center of the plasma. The primary current density is in the y -

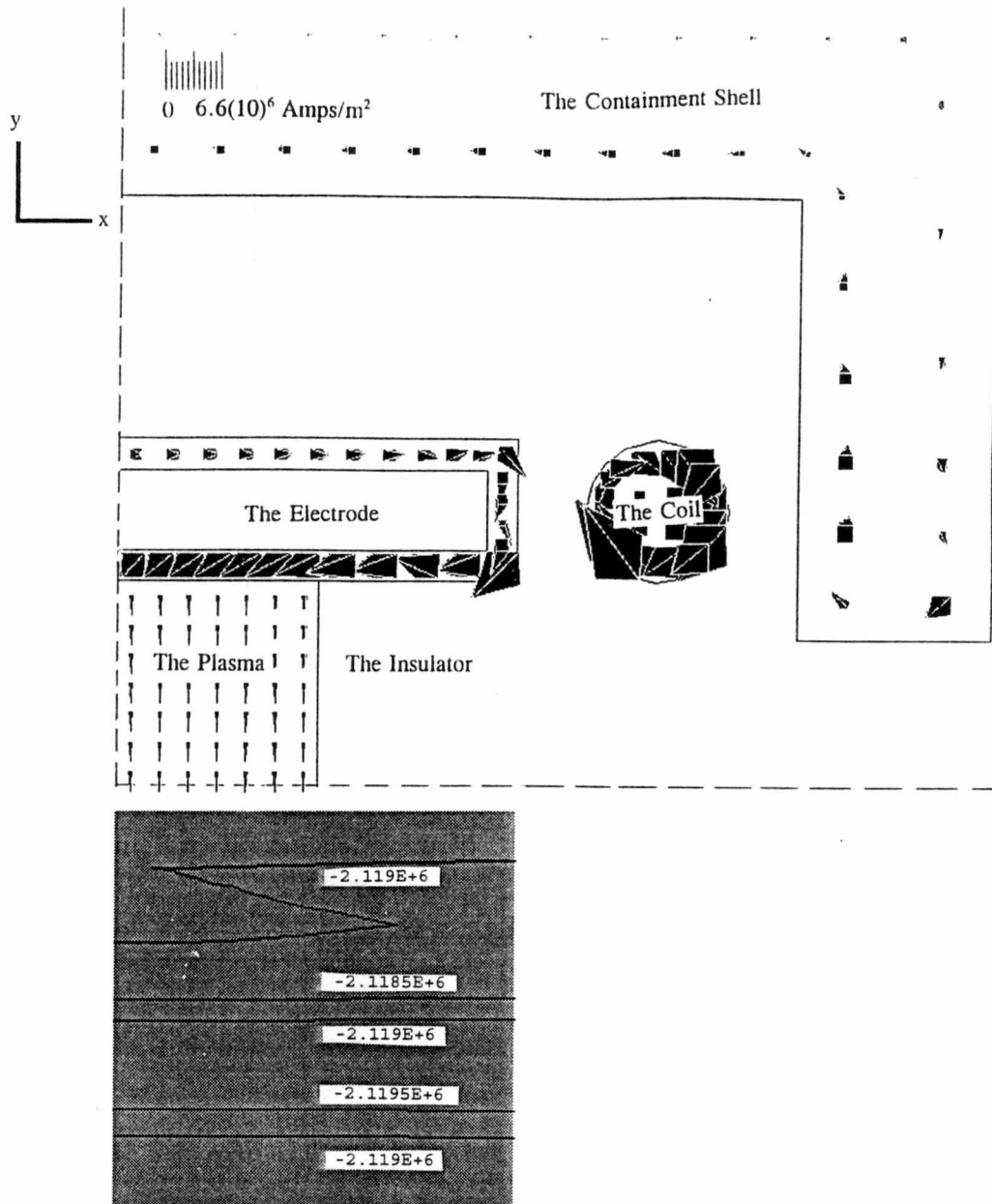


Figure 10. The Simulated Current Density in the Quarter of the MHD Accelerator in the XY Plane at 20 Microseconds and a Contour Plot of the Current Densities in the Y-Direction Containing the Plasma.

a) A XY Slice of the Accelerator at the Front of the Plasma.

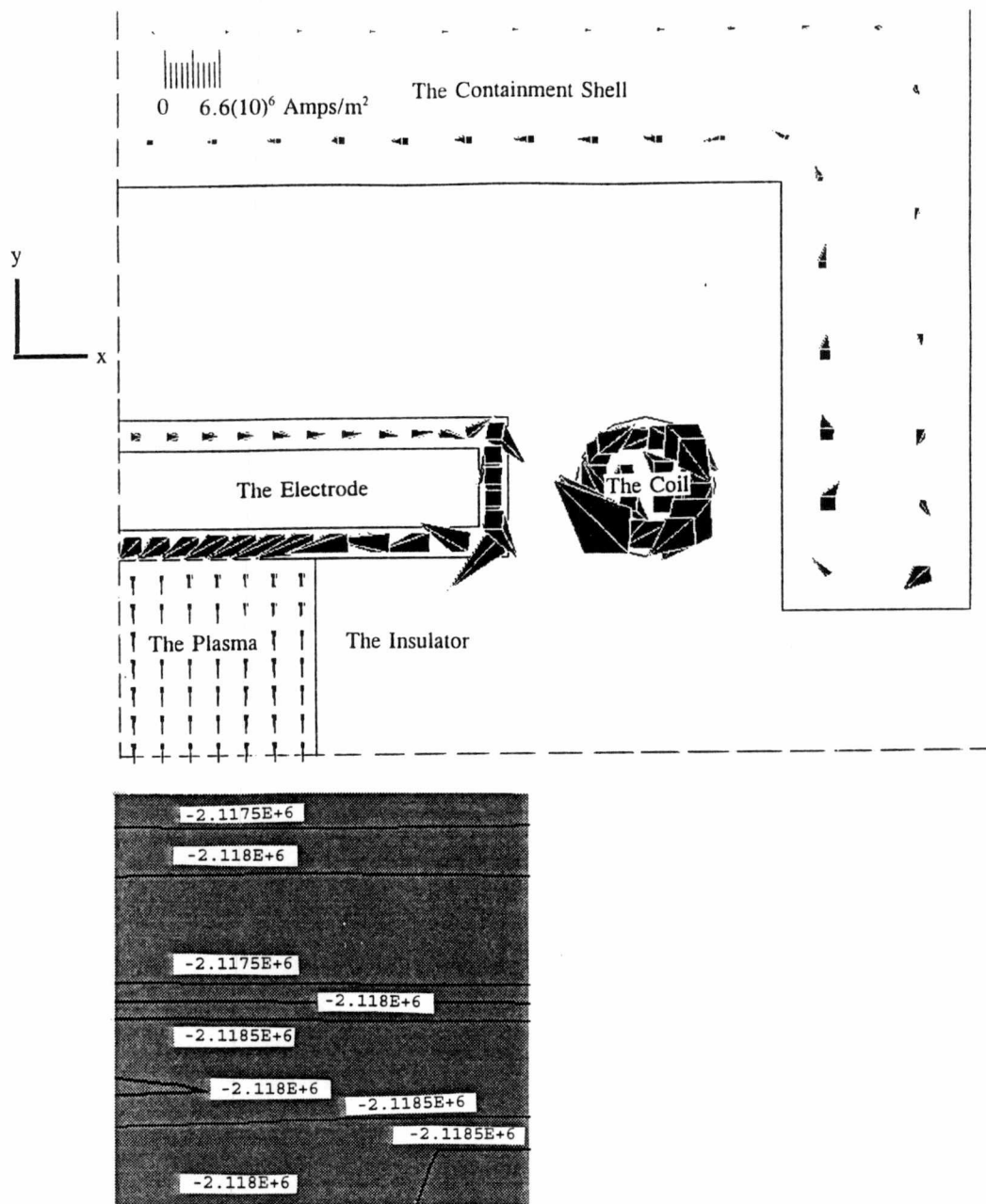
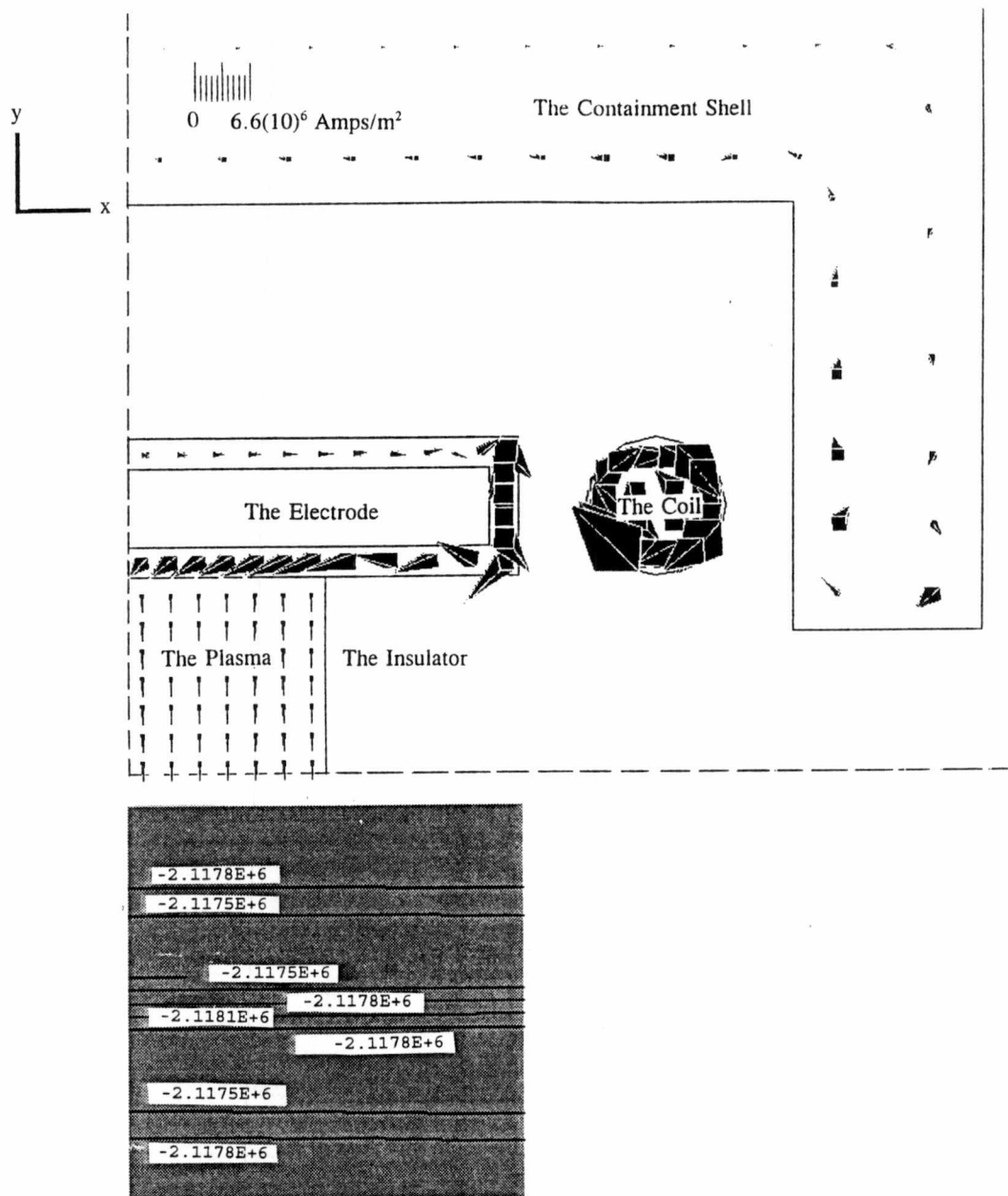


Figure 10. Continued.

b) A XY Slice of the Accelerator at 9 cm from the Back of the Plasma.



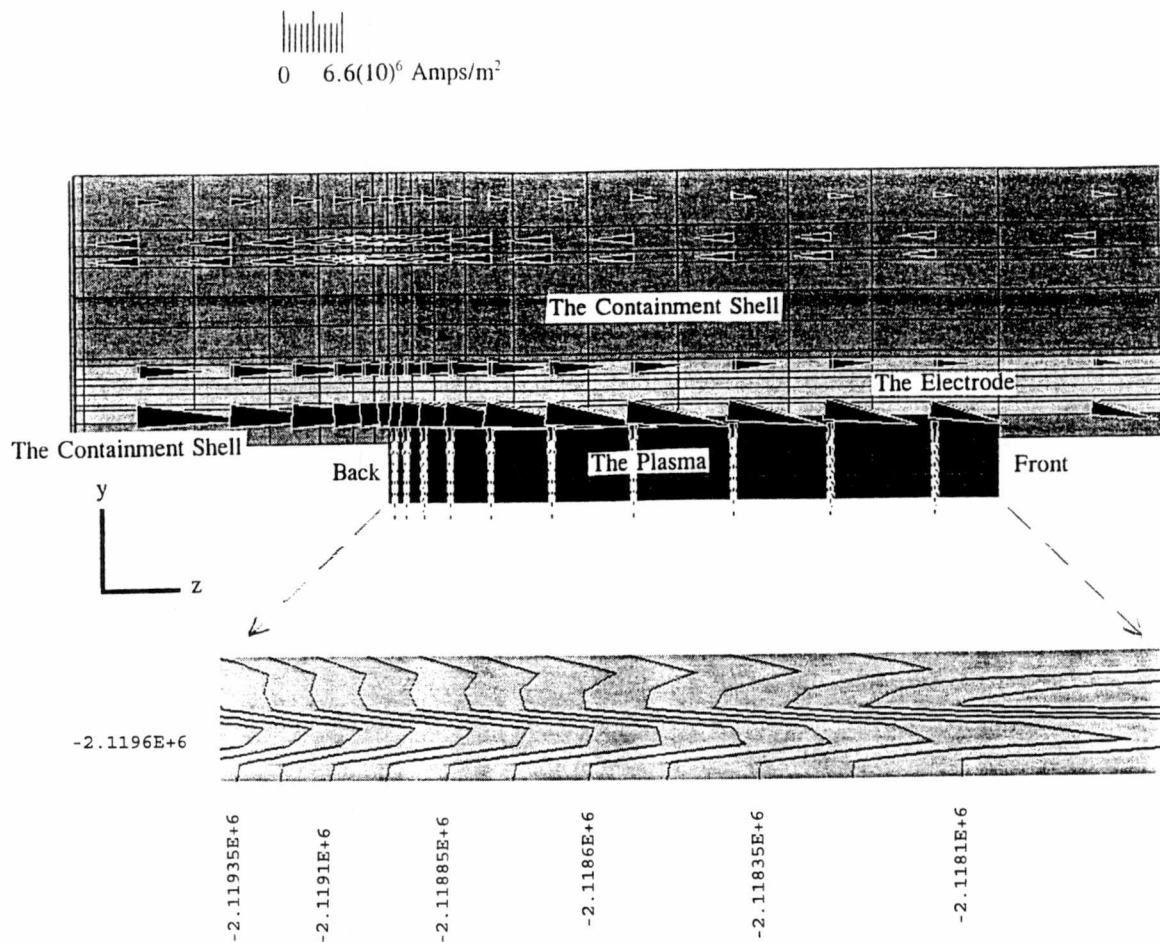


Figure 11. The Simulated Current Density in the Quarter of the MHD Accelerator in the YZ Plane at 20 Microseconds and a Contour Plot of the Current Densities in the Y-Direction Containing the Plasma.

a) A YZ Slice of the Accelerator at 1 mm from the Middle of the Channel.

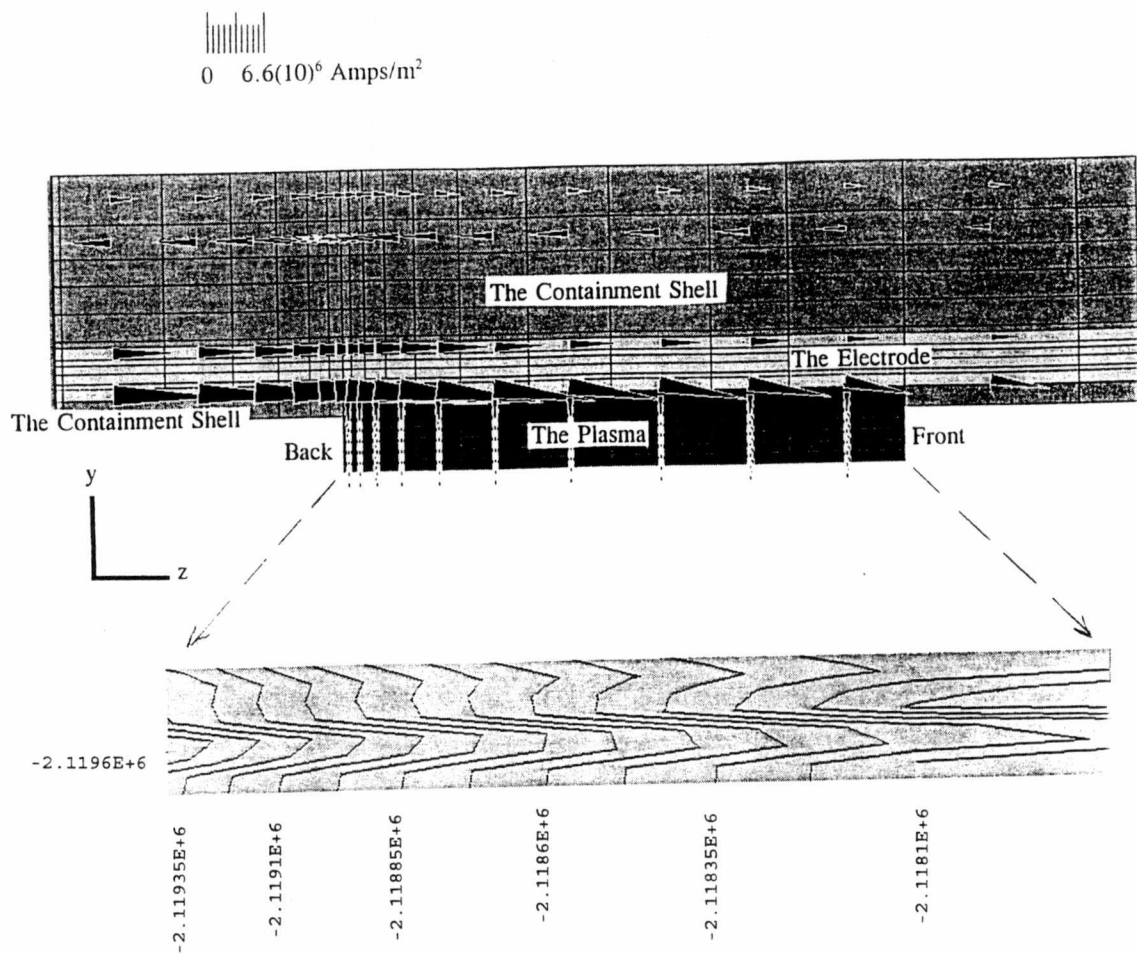


Figure 11. Continued.
 b) A YZ Slice of the Accelerator at 12.5 mm from the Middle of the Channel.

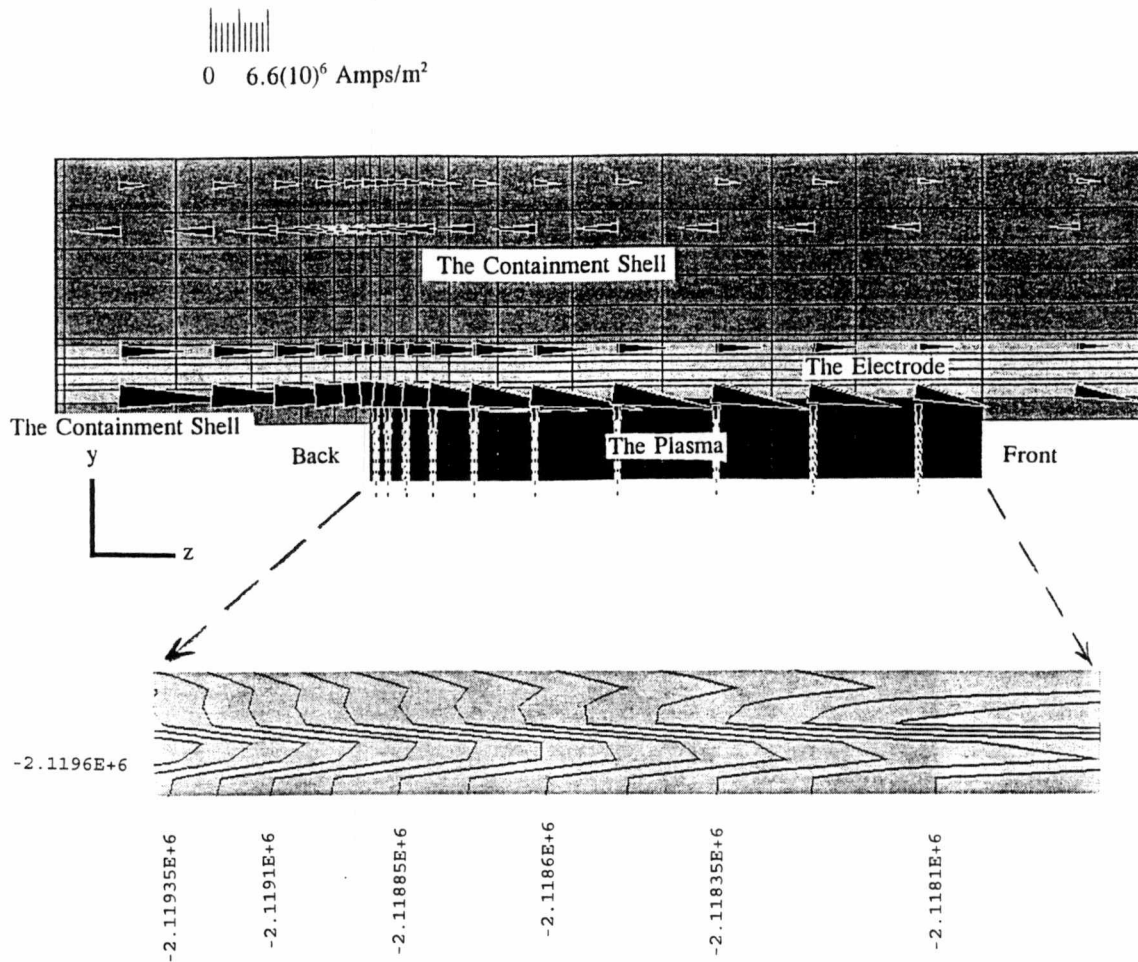


Figure 11. Continued.

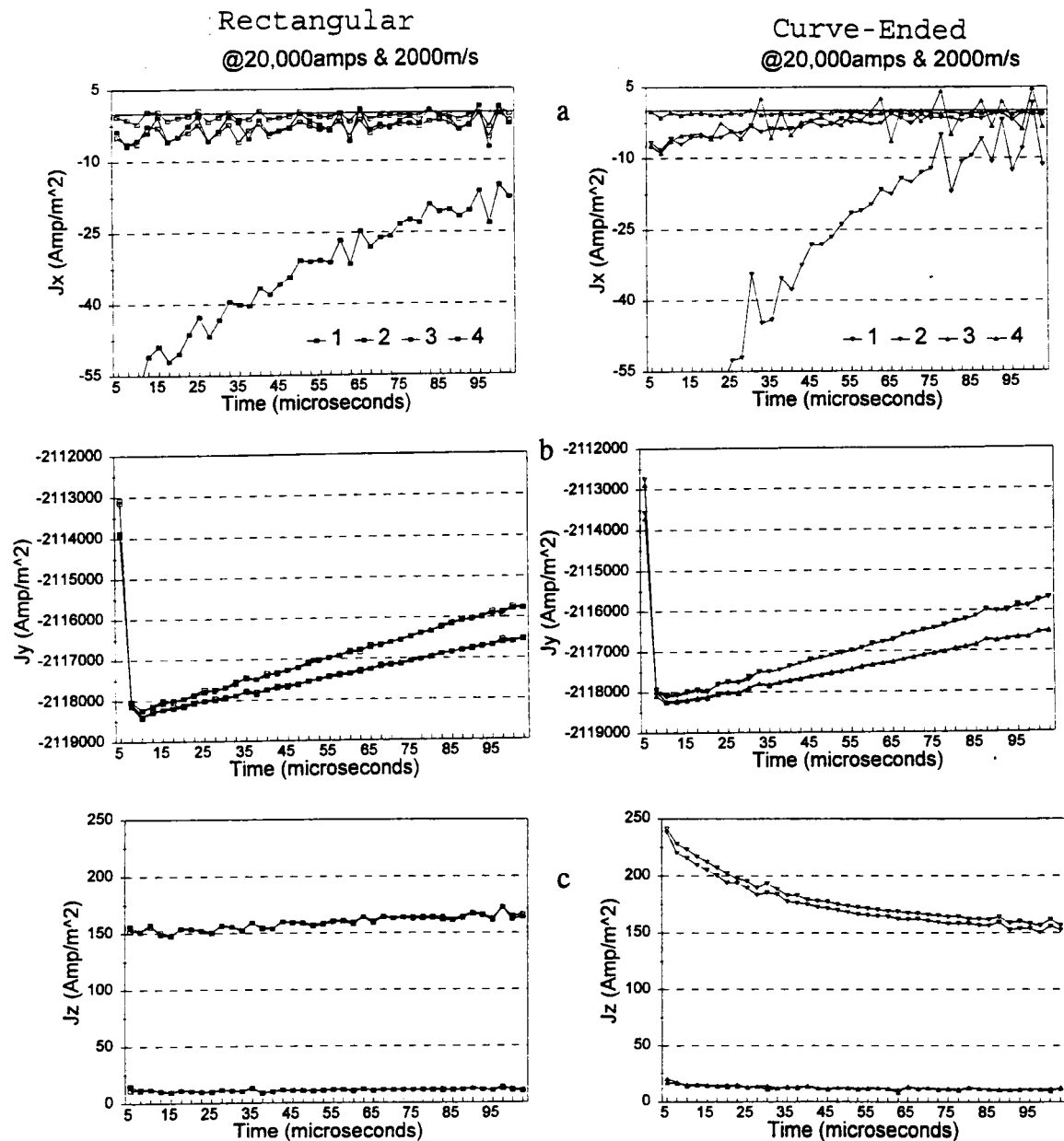
c) A YZ Slice of the Accelerator at 1 mm from the Insulator Wall.

direction. A contour plot has been included to show the uniformity of the current density in the y-direction from the front and to the back of the plasma. The 4 mm thickness of the electrode's skin limits the eddy currents. The gaps without arrows are air, but the shade of the color is kept from the object of the device located behind the insulator gaps.

Four locations were selected to show the trends in the magnetic flux density as a function of time. These four points are: 1) at the channel directly below the middle of the electrode, 2) at the corner of the channel, 3) at the middle of the channel, and 4) at the channel directly next to the center of the insulator wall. These points are used to show uniformity by presenting the extreme values that occur on the corners of the quadrant in the channel.

In Figure 12, the hollow rectangular electrode and the hollow, curve-ended electrode's current densities are compared. The hollow rectangular electrode is on the left while the hollow curve-ended electrode is on the right. The primary current density is in the y-direction with magnitudes of 10^6 amps/m². J_x is five magnitudes smaller (less than 55 amps/m²), and J_z is four magnitudes smaller (less than 200 amps/m²).

Figure 12a shows the effects of the current density in the x-direction as being negligible. Figure 12b shows almost the same uniformity in both electrode shapes. The



quarter of the MHD accelerator channel

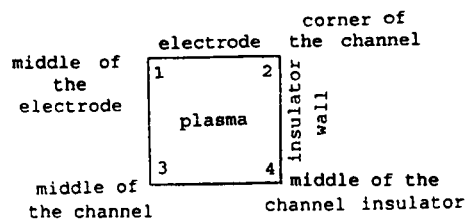


Figure 12. The Trends in the Current Density at 9 cm from the Back of the Plasma as a Function of Time.

channel along the electrode has the smaller current densities in the y-direction due to the turning of the current from the cathode and into the plasma (or out of the plasma and into the anode). Figure 12c shows the current density in the z-direction as being negligible. Its values are higher along the electrodes due also to the turning of the current into the plasma or out of the plasma.

Appendix D shows more details in the trends of the current densities. Also trends in the front and back of the plasma are examined.

6.0 EVALUATING THE MAGNETIC FORCE

The magnetic force, $\mathbf{F}$, is produced by the electrode's current and the magnetic field in the channel. As the current passes through the conducting gas, a $\mathbf{J} \times \mathbf{B}$ force per unit volume is produced perpendicular to the magnetic flux density and the current density. It is this accelerating force that must be uniform across the channel. The accelerating force is measured in newtons per cubic meter.

By observation in Figure 13a-c there exists a magnetic pull of the plasma toward the center of the channel and away from the channel insulator. Each electrode creates a strong force in the back of the plasma, and the force becomes smaller toward the front of the plasma. Figure 13a shows data for the front of the plasma, 13b shows data 9 cm behind the front, and 13c shows data for the back of the plasma. The magnetic force in the electrode's rectangular end is greater in the front of the plasma, but the magnetic force in the electrode along the channel is greater in the back of the plasma. A contour plot has been included to show the uniformity of the magnetic force in the z-direction.

Forces in the YZ plane are shown in Figure 14a-c (where 14a is 1 mm away from the center of the channel, 14c is 1 mm away from the insulator wall, and 14b is directly between these two points). There is a smaller accelerating force in the front of the plasma. The difference in this body force

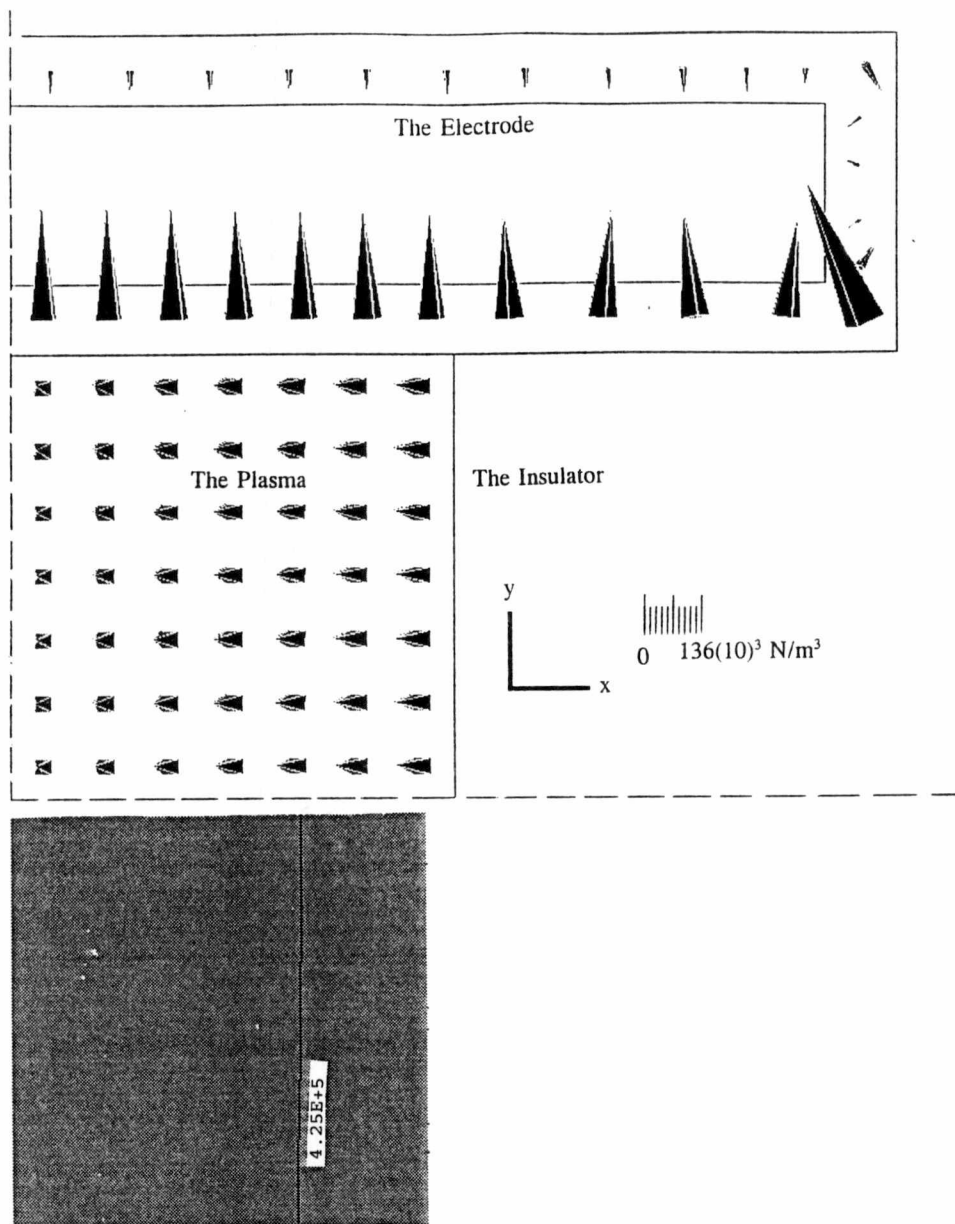


Figure 13. The Simulated Magnetic Force in the Quarter of the MHD Accelerator in the XY Plane at 20 Microseconds and a Contour Plot of the Magnetic Force Accelerating the Gas down the Channel.

a) A XY Slice of the Accelerator at the Front of the Plasma.

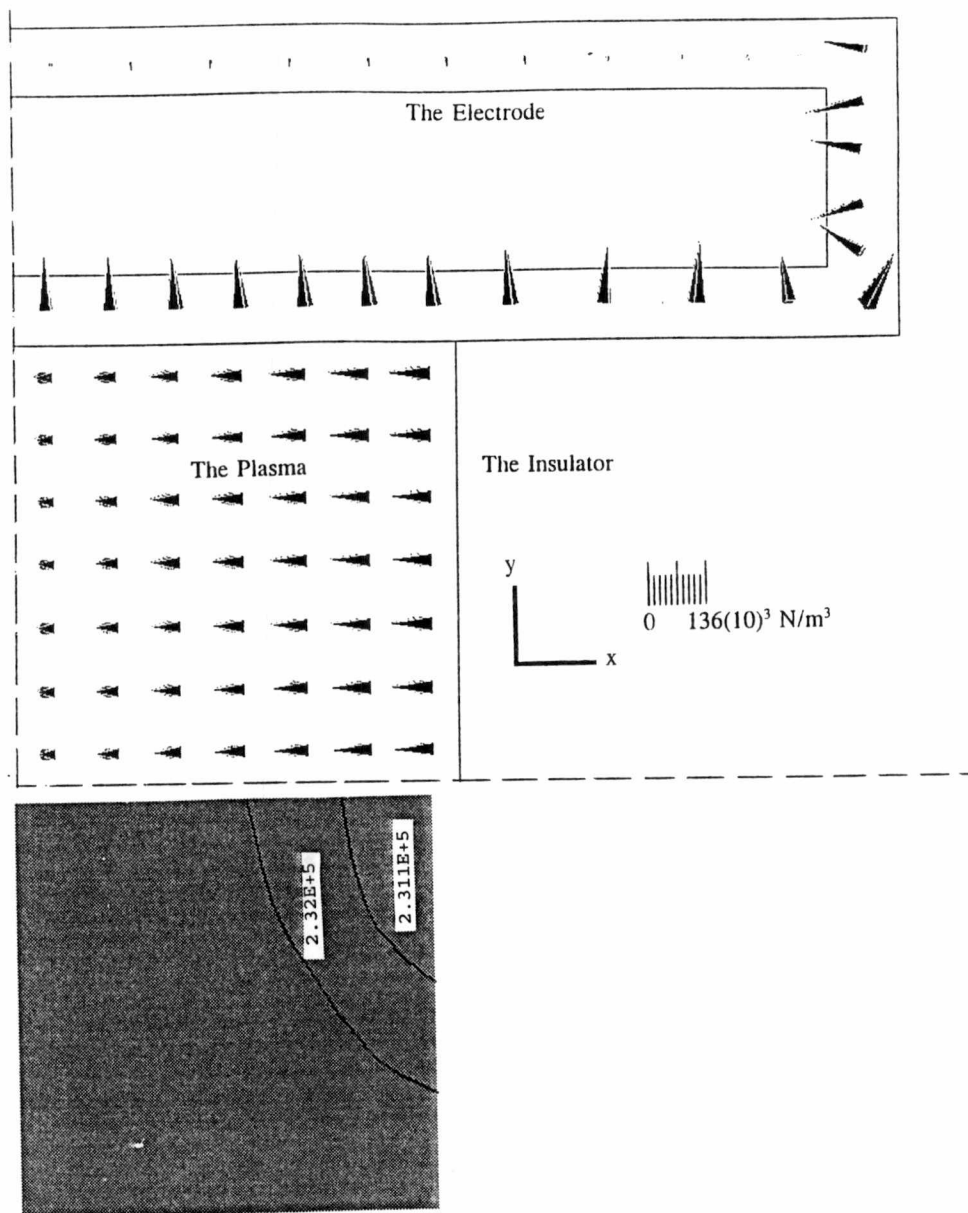


Figure 13. Continued.

b) A XY Slice of the Accelerator at 9 cm from the Back of the Plasma.

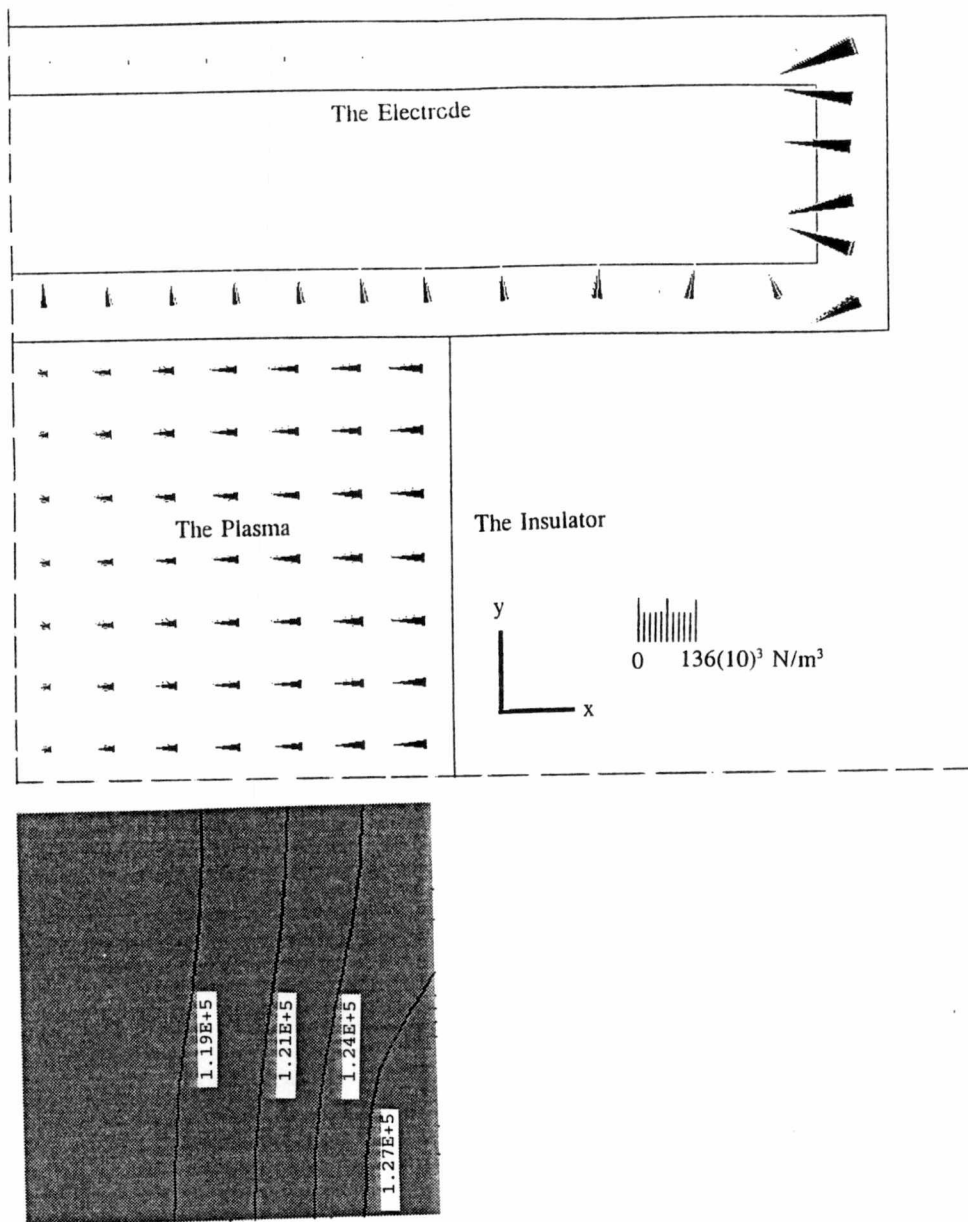


Figure 13. Continued.

c) A XY Slice of the Accelerator at the Back of the Plasma.

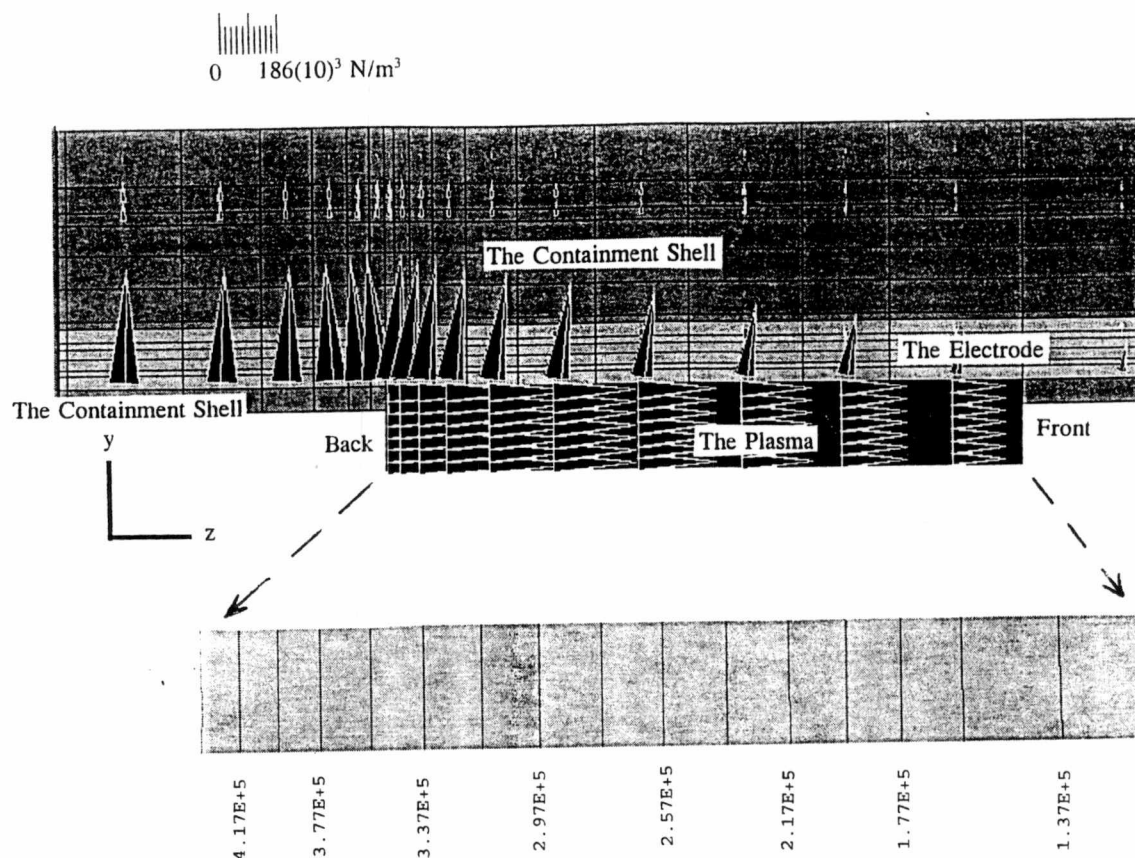


Figure 14. The Simulated Magnetic Force in the Quarter of the MHD Accelerator in the YZ Plane at 20 Microseconds and a Contour Plot of the Magnetic Force Accelerating the Gas down the channel.

a) A YZ Slice of the Accelerator at 1 mm from the Middle of the Channel.

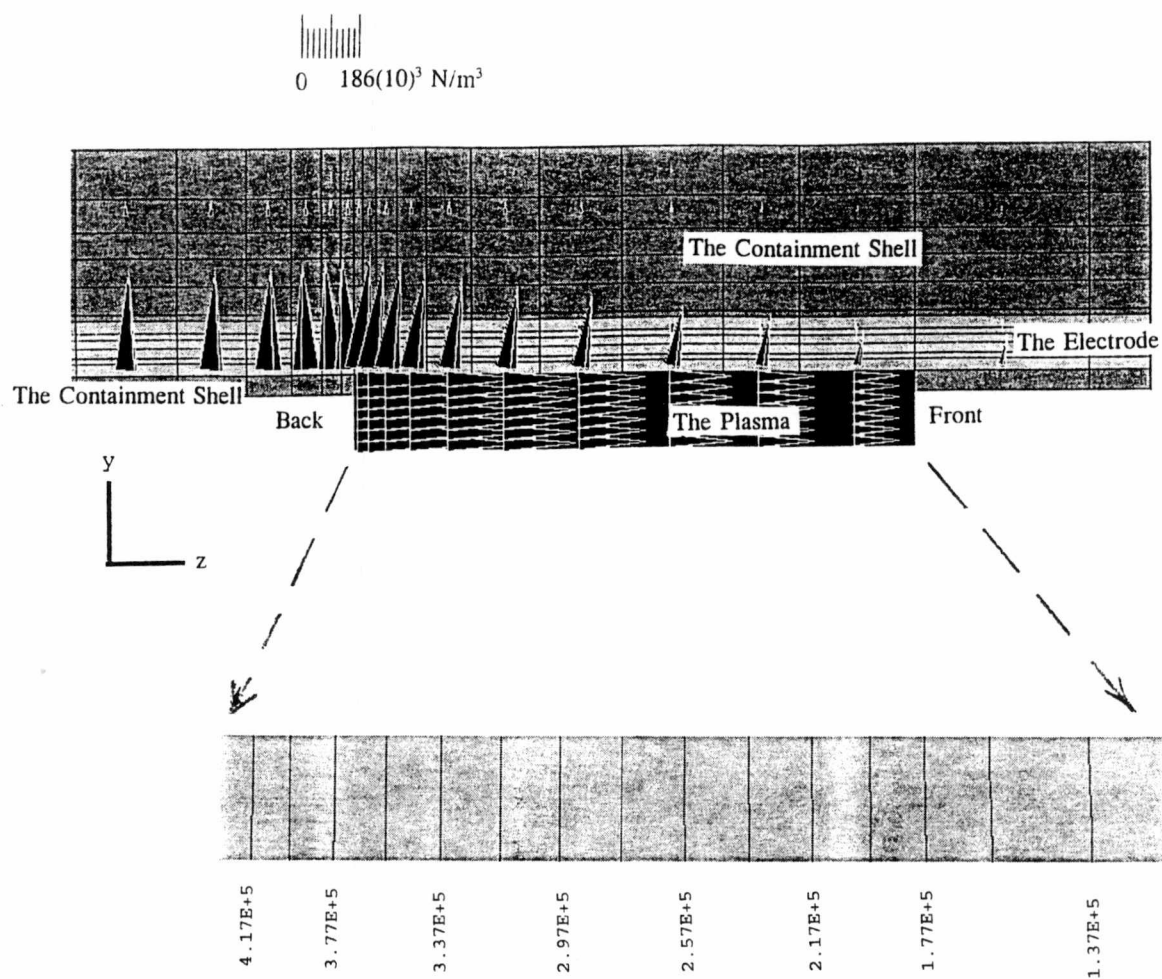


Figure 14. Continued.
 b) A YZ Slice of the Accelerator at 12.5 mm from the Middle of the Channel.

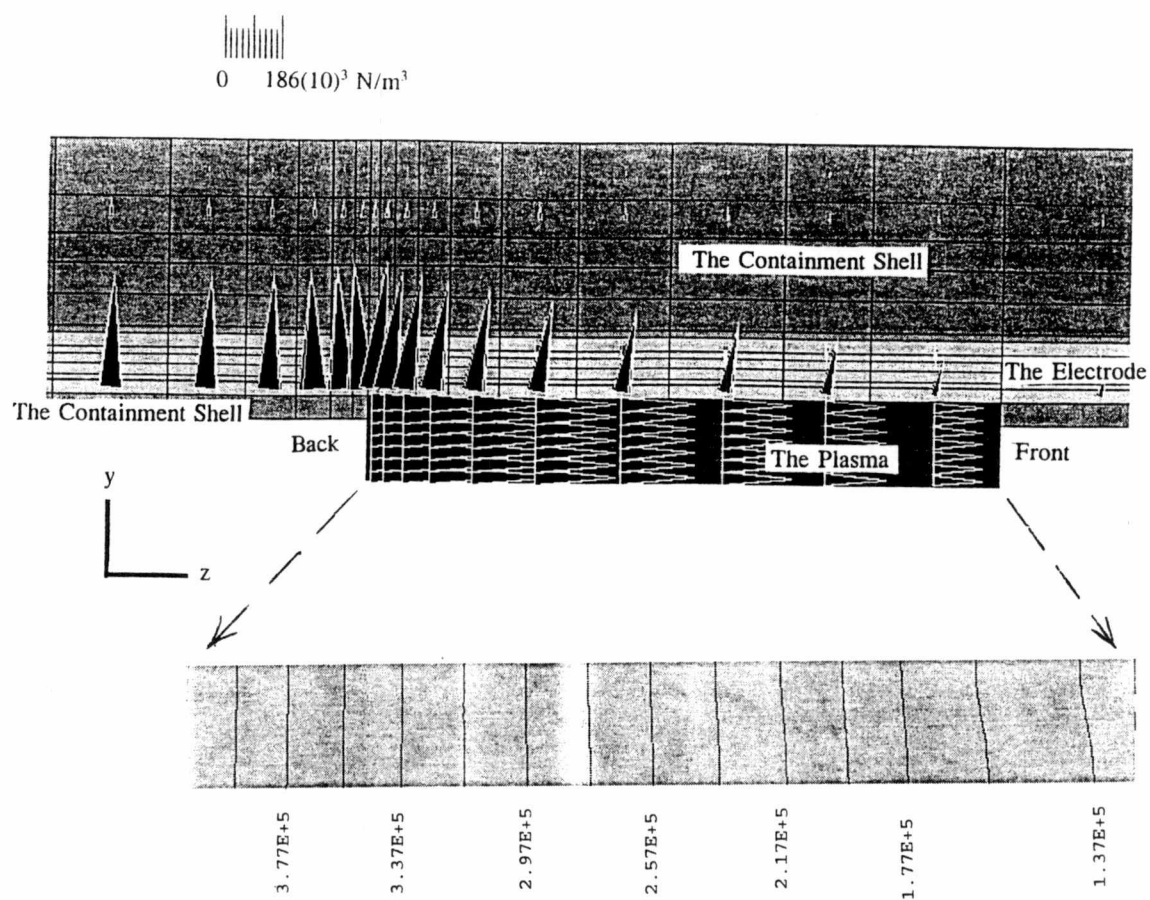
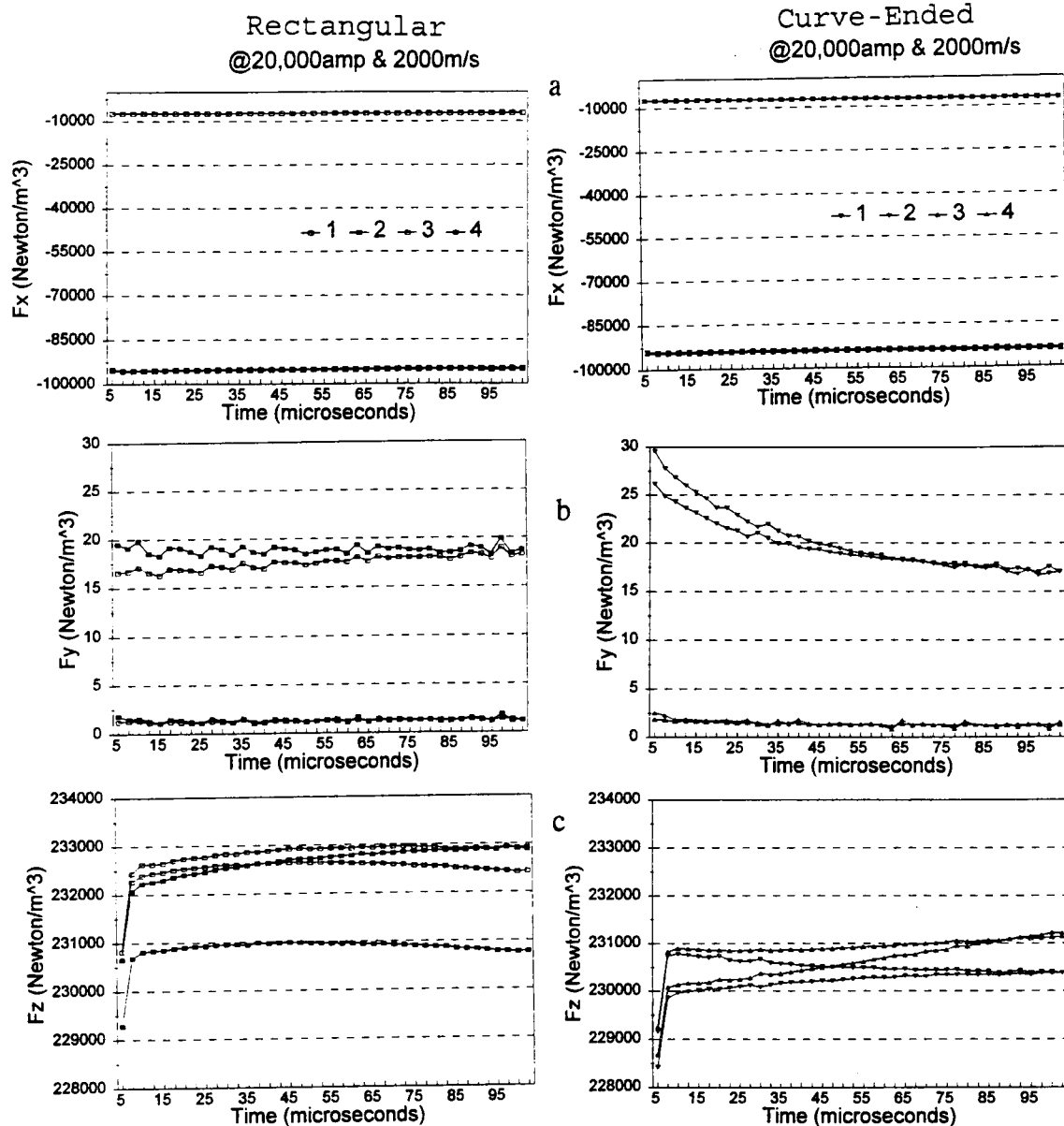


Figure 14. Continued.

c) A YZ Slice of the Accelerator at 1 mm from the Insulator Wall.

is about $315,000 \text{ N/m}^3$. This smaller accelerating force in the front increases slightly as time increases. The larger accelerating forces seen at the back of the plasma decreases slightly as the time increases. Since the higher accelerating forces in the plasma are always in the back, the plasma remains compact. Figures 15a and c show the magnitude of the force in the z-direction is greater in the vertical middle than along the insulator wall. A contour plot shows the uniformity in the magnetic force in the z-direction. In E the higher accelerating forces in the back of the plasma are shown by observing the y-axis and its greater magnitudes in E3c than in E3a and E3b. E3c also shows the magnitude of the force in the z-direction being greater in the vertical middle than along the insulator wall.

Figure 15 shows the trends in the magnetic force of the hollow rectangular electrode and of the hollow curve-ended electrode. The hollow rectangular electrode is on the left of the figure and the hollow curve-ended electrode on the right. The magnetic force in the z-direction is the primary force. The F_x is also large (but about 50% smaller than the F_z component) along the insulator wall pushing toward the center of the channel. This force decreases the closer to the center of the channel that is being observed. The F_y force is four magnitudes smaller than the F_z component and, hence, negligible.



quarter of the MHD accelerator channel

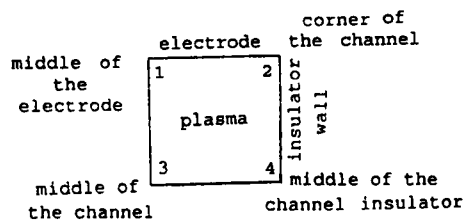


Figure 15. The Trends in the Magnetic Force at 9 cm from the Back of the Plasma as a Function of Time.

Figure 15a shows a steady decrease in the magnetic force away from the insulator wall. This figure shows only the extremes, but studies show that the reduction in this force is continual and reaches zero in the direct center of the channel. Figure 15b shows the magnetic force in the y-direction which is negligible. In Figure 15c the magnetic force in the z-direction of hollow curve-ended electrode is three times more uniform than the hollow rectangular electrode. The hollow rectangular electrode has a larger accelerating force, but it suffers from a lack of uniformity.

Figure 16 and 17 show uniformity of the quartered MHD accelerator with the hollow-rectangular and with the hollow-curve-ended electrode shapes, respectively. The shapes are shown in Figures 6 and 7. The standard deviation percentage difference (SDPD) of the accelerating force, F_z , shows the uniformity in the channel at various depths or levels from the back of the plasma to the front. The two columns on the left of each of these figures show the distribution of the SDPD at the points examined in each of the levels or depths as it relates to the other points of that level or depth. For example, in figure 16 of the hollow-rectangular-electrode shape at a time of 5 microseconds and at level 11 (or the back of the plasma), a SDPD of 1.89 is observed in the center of the channel next to the electrode. All of the points are compared by an average accelerating force, $(F_z)_{avg}$,

using the SDPD equation:

$$\text{SDPD} = \frac{(F_z)_{\text{at the point}} - (F_z)_{\text{avg}}}{(F_z)_{\text{avg}}} * 100.$$

The average accelerating force is the average of all the forces examined at the level or depth in the plasma. A positive SDPD results from a force greater than the average, and, hence, a negative SDPD results from a force less than the average. A zero SDPD or a negative zero SDPD results in a number equal to or very close to the average accelerating force at that level.

These numbers rate the uniformity simulated by their closeness to zero. For example, in figure 16, levels 17 and 18 (located in the middle of the plasma) are much closer to uniformity than the back (level 11) or the front (level 20) of the plasma.

The right-hand column on the even-numbered appendices gives the average or mean accelerating force represented by each level or depth. The SDPD is also shown for each level.

The uniformity of the magnetic force in the z-direction was estimated for various electrode shapes by taking the standard deviation of the percentage difference between the simulated value and the average value for a constant z value (or depth) in the plasma. The current was 2,000 amps, and the time was 50 microseconds. The results are found in Table 1. The standard deviation percentage differences represent uniformity in the z-direction magnetic force. A

Level 11 (15 cm - the Back)								Level 16 (11.06 cm)								Level = 11 (15 cm - the Back)							
1.89	1.68	1.25	0.57	-0.39	-1.78	-3.55		0.34	0.30	0.22	0.09	-0.08	-0.30	-0.59		Mean 0.808 N							
1.90	1.68	1.25	0.57	-0.38	-1.77	-3.53		0.34	0.30	0.21	0.09	-0.08	-0.30	-0.59		S.D. % Diff 1.841 %							
1.90	1.69	1.26	0.58	-0.37	-1.74	-3.49		0.34	0.30	0.22	0.10	-0.07	-0.29	-0.58									
1.91	1.70	1.27	0.60	-0.34	-1.70	-3.43		0.34	0.30	0.22	0.09	-0.08	-0.29	-0.58		Level = 12 (14.7 cm)							
1.91	1.70	1.28	0.61	-0.32	-1.67	-3.37		0.34	0.30	0.21	0.09	-0.08	-0.30	-0.57		Mean 0.787 N							
1.92	1.71	1.29	0.63	-0.30	-1.63	-3.32		0.34	0.30	0.22	0.09	-0.07	-0.29	-0.57		S.D. % Diff 1.686 %							
1.92	1.71	1.29	0.63	-0.29	-1.63	-3.29		0.34	0.30	0.22	0.09	-0.07	-0.29	-0.56									
																Level = 13 (14.25 cm)							
																Mean 0.758 N							
																S.D. % Diff 1.354 %							
Level 12 (14.7 cm)								Level 17 (9.78 cm)								Level = 14 (13.58 cm)							
1.77	1.57	1.14	0.49	-0.44	-1.65	-3.21		-0.01	-0.01	-0.00	0.00	0.03	0.09	0.20		Mean 0.72 N							
1.78	1.57	1.14	0.49	-0.43	-1.64	-3.19		-0.01	-0.01	-0.01	-0.01	0.02	0.07	0.18		S.D. % Diff 0.979 %							
1.78	1.58	1.15	0.50	-0.41	-1.61	-3.14		-0.01	-0.02	-0.02	-0.01	0.00	0.05	0.14									
1.79	1.58	1.17	0.52	-0.38	-1.57	-3.09		-0.02	-0.02	-0.02	-0.02	-0.02	0.02	0.09		Level = 15 (12.57 cm)							
1.79	1.59	1.17	0.53	-0.36	-1.54	-3.03		-0.03	-0.03	-0.03	-0.04	-0.04	-0.02	0.04		Mean 0.671 N							
1.80	1.60	1.18	0.55	-0.34	-1.51	-2.98		-0.03	-0.04	-0.04	-0.05	-0.05	-0.03	0.02		S.D. % Diff 0.527 %							
1.80	1.59	1.18	0.54	-0.34	-1.50	-2.96		-0.04	-0.04	-0.05	-0.05	-0.06	-0.04	-0.00									
																Level = 16 (11.06 cm)							
																Mean 0.605 N							
																S.D. % Diff 0.316 %							
Level 13 (14.25 cm)								Level 18 (6 cm)								Level = 17 (9.78 cm)							
1.48	1.29	0.91	0.34	-0.43	-1.40	-2.50		0.13	0.13	0.13	0.13	0.13	0.10	0.05		Mean 0.526 N							
1.48	1.29	0.91	0.34	-0.43	-1.39	-2.49		0.12	0.12	0.12	0.12	0.10	0.06	-0.01		S.D. % Diff 0.056 %							
1.49	1.30	0.93	0.36	-0.41	-1.36	-2.44		0.12	0.12	0.11	0.10	0.07	0.01	-0.10									
1.49	1.31	0.94	0.37	-0.39	-1.33	-2.39		0.10	0.10	0.08	0.06	0.01	-0.08	-0.24		Level = 18 (6 cm)							
1.50	1.31	0.95	0.39	-0.37	-1.29	-2.34		0.08	0.07	0.05	0.02	-0.05	-0.17	-0.37		Mean 0.432 N							
1.50	1.32	0.95	0.40	-0.35	-1.27	-2.29		0.07	0.06	0.04	-0.01	-0.09	-0.24	-0.48		S.D. % Diff 0.159 %							
1.50	1.32	0.95	0.40	-0.35	-1.26	-2.27		0.06	0.04	0.02	-0.04	-0.13	-0.28	-0.54									
																Level = 19 (3.59 cm)							
																Mean 0.346 N							
																S.D. % Diff 0.835 %							
Level 14 (13.58 cm)								Level 19 (3.59 cm)								Level = 20 (Front of Plasma)							
1.08	0.94	0.65	0.23	-0.33	-1.01	-1.83		-0.78	-0.67	-0.45	-0.11	0.39	1.09	2.07		Mean 0.225 N							
1.08	0.94	0.65	0.23	-0.32	-1.00	-1.81		-0.79	-0.69	-0.48	-0.14	0.35	1.03	1.97		S.D. % Diff 2.37 %							
1.09	0.95	0.66	0.24	-0.31	-0.98	-1.77		-0.81	-0.71	-0.51	-0.19	0.27	0.90	1.77									
1.09	0.95	0.67	0.26	-0.29	-0.95	-1.73		-0.85	-0.75	-0.56	-0.26	0.16	0.73	1.51									
1.10	0.95	0.68	0.27	-0.27	-0.92	-1.69		-0.87	-0.79	-0.60	-0.33	0.06	0.57	1.25									
1.10	0.96	0.68	0.28	-0.25	-0.89	-1.64		-0.89	-0.81	-0.64	-0.38	-0.03	0.44	1.05									
1.10	0.96	0.68	0.28	-0.25	-0.88	-1.62		-0.90	-0.82	-0.66	-0.41	-0.07	0.37	0.94									
Level 15 (12.57 cm)								Level 20 (the Front)															
0.60	0.52	0.35	0.10	-0.21	-0.58	-0.96		-2.56	-2.16	-1.38	-0.23	1.27	3.07	5.11									
0.60	0.52	0.35	0.10	-0.21	-0.57	-0.95		-2.58	-2.19	-1.43	-0.29	1.18	2.93	4.89									
0.61	0.52	0.36	0.11	-0.20	-0.55	-0.92		-2.62	-2.24	-1.50	-0.40	1.01	2.67	4.49									
0.61	0.52	0.36	0.12	-0.19	-0.53	-0.90		-2.69	-2.32	-1.59	-0.54	0.80	2.34	3.98									
0.61	0.53	0.37	0.13	-0.17	-0.51	-0.86		-2.75	-2.39	-1.69	-0.68	0.58	2.02	3.46									
0.62	0.53	0.37	0.14	-0.16	-0.49	-0.82		-2.78	-2.44	-1.75	-0.78	0.43	1.76	3.06									
0.61	0.53	0.37	0.13	-0.16	-0.49	-0.81		-2.80	-2.46	-1.79	-0.83	0.34	1.64	2.85									

Figure 16. The Uniformity of the Magnetic Force or Accelerating Force for the Hollow-Rectangular Electrode at 20,000 amps and 2,000 m/s at each Depth Simulated Using the Standard Deviation Percentage Difference Method. (The Numbers in Each block represents a percentage.)
a) At 5 Microseconds.

Level 11 (15 cm - the Back) 1.85 1.85 1.22 0.56 -0.37 -1.73 -3.47 1.85 1.85 1.22 0.56 -0.37 -1.72 -3.45 1.85 1.85 1.23 0.56 -0.36 -1.70 -3.42 1.86 1.86 1.25 0.59 -0.33 -1.86 -3.35 1.86 1.86 1.25 0.61 -0.30 -1.62 -3.30 1.86 1.86 1.26 0.63 -0.28 -1.60 -3.24 1.86 1.85 1.25 0.61 -0.29 -1.59 -3.21	Level 16 (11.06 cm) 0.34 0.30 0.22 0.10 -0.07 -0.28 -0.56 0.34 0.30 0.21 0.09 -0.07 -0.28 -0.56 0.33 0.29 0.21 0.09 -0.07 -0.28 -0.56 0.31 0.27 0.19 0.08 -0.08 -0.29 -0.56 0.33 0.29 0.22 0.10 -0.07 -0.29 -0.56 0.33 0.29 0.21 0.09 -0.08 -0.29 -0.55 0.32 0.28 0.19 0.07 -0.08 -0.28 -0.55	Level = 11 (15 cm - the Back) Mean 0.801 N S.D. % Diff 1.798 % Level = 12 (14.7 cm) Mean 0.78 N S.D. % Diff 1.639 % Level = 13 (14.25 cm) Mean 0.751 N S.D. % Diff 1.308 % Level = 14 (13.58 cm) Mean 0.714 N S.D. % Diff 0.937 % Level = 15 (12.57 cm) Mean 0.667 N S.D. % Diff 0.496 % Level = 16 (11.06 cm) Mean 0.603 N S.D. % Diff 0.305 % Level = 17 (9.78 cm) Mean 0.527 N S.D. % Diff 0.057 % Level = 18 (6 cm) Mean 0.435 N S.D. % Diff 0.184 % Level = 19 (3.59 cm) Mean 0.35 N S.D. % Diff 0.793 % Level = 20 (Front of Plasma) Mean 0.227 N S.D. % Diff 2.359 %
Level 12 (14.7 cm) 1.73 1.53 1.12 0.47 -0.42 -1.61 -3.12 1.73 1.52 1.11 0.47 -0.42 -1.60 -3.11 1.73 1.53 1.12 0.49 -0.40 -1.57 -3.06 1.76 1.55 1.14 0.51 -0.37 -1.53 -3.01 1.75 1.55 1.14 0.52 -0.35 -1.49 -2.94 1.75 1.55 1.14 0.53 -0.33 -1.46 -2.89 1.73 1.54 1.14 0.52 -0.34 -1.48 -2.88	Level 17 (9.78 cm) 0.02 0.02 0.02 0.02 0.04 0.09 0.20 0.00 0.00 -0.00 -0.00 0.01 0.05 0.15 0.02 0.01 0.01 0.01 0.01 0.04 0.13 0.02 0.01 0.00 -0.00 -0.00 0.01 0.06 -0.02 -0.02 -0.03 -0.04 -0.05 -0.04 -0.01 -0.05 -0.06 -0.07 -0.07 -0.07 -0.05 -0.01 -0.06 -0.06 -0.06 -0.06 -0.06 -0.05 -0.01	
Level 13 (14.25 cm) 1.44 1.26 0.89 0.34 -0.41 -1.35 -2.41 1.44 1.25 0.88 0.32 -0.42 -1.36 -2.41 1.43 1.26 0.89 0.34 -0.40 -1.31 -2.35 1.46 1.27 0.91 0.37 -0.37 -1.28 -2.31 1.45 1.27 0.92 0.38 -0.34 -1.25 -2.25 1.46 1.27 0.92 0.38 -0.34 -1.23 -2.21 1.44 1.26 0.91 0.36 -0.35 -1.22 -2.19	Level 18 (6 cm) 0.18 0.17 0.16 0.15 0.12 0.08 0.01 0.16 0.15 0.14 0.14 0.11 0.04 -0.06 0.15 0.14 0.13 0.10 0.06 -0.03 -0.16 0.14 0.13 0.11 0.07 -0.01 -0.12 -0.31 0.11 0.10 0.07 0.03 -0.06 -0.20 -0.43 0.11 0.10 0.06 0.00 -0.10 -0.26 -0.52 0.08 0.06 0.03 -0.05 -0.16 -0.33 -0.60	
Level 14 (13.58 cm) 1.04 0.90 0.63 0.23 -0.31 -0.96 -1.75 1.04 0.90 0.63 0.22 -0.31 -0.96 -1.74 1.04 0.91 0.64 0.24 -0.29 -0.93 -1.70 1.04 0.90 0.62 0.23 -0.29 -0.92 -1.67 1.05 0.92 0.65 0.26 -0.26 -0.88 -1.62 1.06 0.92 0.66 0.27 -0.24 -0.85 -1.55 1.04 0.91 0.65 0.27 -0.24 -0.84 -1.53	Level 17 (9.78 cm) -0.71 -0.61 -0.40 -0.08 0.39 1.05 2.00 -0.75 -0.65 -0.44 -0.12 0.35 0.98 1.89 -0.72 -0.64 -0.46 -0.16 0.28 0.88 1.71 -0.79 -0.70 -0.52 -0.25 0.15 0.70 1.44 -0.84 -0.76 -0.59 -0.33 0.03 0.52 1.18 -0.86 -0.78 -0.63 -0.40 -0.07 0.36 0.94 -0.87 -0.79 -0.63 -0.39 -0.08 0.33 0.83	
Level 15 (12.57 cm) 0.57 0.49 0.33 0.09 -0.21 -0.55 -0.91 0.57 0.49 0.32 0.09 -0.21 -0.55 -0.90 0.59 0.50 0.33 0.10 -0.19 -0.52 -0.87 0.57 0.49 0.33 0.10 -0.18 -0.50 -0.84 0.57 0.50 0.34 0.12 -0.16 -0.48 -0.81 0.58 0.50 0.35 0.14 -0.14 -0.46 -0.76 0.57 0.49 0.34 0.12 -0.14 -0.45 -0.75	Level 20 (the Front) -2.55 -2.15 -1.35 -0.21 1.28 3.09 5.13 -2.56 -2.17 -1.41 -0.28 1.19 2.94 4.89 -2.61 -2.23 -1.49 -0.39 1.02 2.66 4.46 -2.69 -2.32 -1.60 -0.55 0.78 2.31 3.92 -2.74 -2.38 -1.68 -0.68 0.56 1.98 3.41 -2.77 -2.42 -1.75 -0.77 0.43 1.75 3.03 -2.79 -2.45 -1.79 -0.84 0.32 1.61 2.83	

Figure 16. Continued.
b) At 10 Microseconds.

Level 11 (15 cm - the Back) 1.83 1.62 1.20 0.55 -0.37 -1.74 -3.46 1.85 1.64 1.22 0.57 -0.36 -1.71 -3.43 1.88 1.68 1.25 0.59 -0.31 -1.66 -3.36 1.86 1.65 1.24 0.58 -0.33 -1.66 -3.34 1.85 1.63 1.22 0.58 -0.33 -1.63 -3.30 1.86 1.66 1.23 0.60 -0.30 -1.58 -3.21 1.83 1.64 1.22 0.58 -0.32 -1.62 -3.13	Level 16 (11.06 cm) 0.33 0.29 0.21 0.08 -0.09 -0.30 -0.57 0.34 0.30 0.21 0.09 -0.08 -0.29 -0.56 0.36 0.32 0.24 0.12 -0.04 -0.26 -0.53 0.32 0.28 0.21 0.09 -0.07 -0.28 -0.57 0.30 0.26 0.17 0.05 -0.10 -0.31 -0.58 0.32 0.28 0.20 0.08 -0.07 -0.28 -0.54 0.31 0.27 0.20 0.09 -0.06 -0.26 -0.52	Level = 11 (15 cm - the Back) Mean 0.803 N S.D. % Diff 1.786 % Level = 12 (14.7 cm) Mean 0.781 N S.D. % Diff 1.628 % Level = 13 (14.25 cm) Mean 0.753 N S.D. % Diff 1.297 % Level = 14 (13.58 cm) Mean 0.716 N S.D. % Diff 0.925 % Level = 15 (12.57 cm) Mean 0.668 N S.D. % Diff 0.49 % Level = 16 (11.06 cm) Mean 0.604 N S.D. % Diff 0.303 % Level = 17 (9.78 cm) Mean 0.528 N S.D. % Diff 0.052 % Level = 18 (6 cm) Mean 0.436 N S.D. % Diff 0.193 % Level = 19 (3.59 cm) Mean 0.35 N S.D. % Diff 0.814 % Level = 20 (Front of Plasma) Mean 0.227 N S.D. % Diff 2.383 %
Level 12 (14.7 cm) 1.72 1.52 1.11 0.47 -0.43 -1.80 -3.11 1.72 1.52 1.12 0.48 -0.41 -1.56 -3.08 1.75 1.56 1.15 0.53 -0.36 -1.53 -3.02 1.73 1.53 1.13 0.50 -0.37 -1.53 -3.01 1.72 1.52 1.11 0.50 -0.37 -1.51 -2.95 1.74 1.53 1.14 0.52 -0.34 -1.45 -2.86 1.71 1.52 1.12 0.49 -0.37 -1.49 -2.79	Level 17 (9.78 cm) -0.02 -0.02 -0.02 -0.01 0.02 0.07 0.19 -0.02 -0.02 -0.01 -0.00 0.02 0.07 0.17 0.01 0.00 -0.01 -0.01 0.01 0.05 0.14 -0.01 -0.02 -0.03 -0.03 -0.03 -0.01 0.05 -0.03 -0.03 -0.04 -0.04 -0.04 -0.03 0.00 -0.01 -0.02 -0.02 -0.03 -0.03 -0.02 0.03 -0.03 -0.03 -0.04 -0.05 -0.05 -0.04 -0.00	
Level 13 (14.25 cm) 1.42 1.24 0.88 0.33 -0.42 -1.35 -2.42 1.44 1.25 0.89 0.34 -0.41 -1.34 -2.39 1.46 1.28 0.92 0.37 -0.37 -1.29 -2.33 1.43 1.26 0.90 0.36 -0.38 -1.28 -2.31 1.42 1.24 0.89 0.35 -0.37 -1.25 -2.26 1.43 1.26 0.90 0.37 -0.34 -1.20 -2.16 1.41 1.24 0.88 0.35 -0.36 -1.21 -2.11	Level 18 (6 cm) 0.16 0.16 0.15 0.14 0.12 0.09 0.03 0.16 0.16 0.15 0.13 0.09 0.04 -0.04 0.19 0.19 0.18 0.14 0.09 0.01 -0.12 0.14 0.13 0.11 0.07 0.00 -0.11 -0.30 0.10 0.09 0.06 0.00 -0.08 -0.22 -0.46 0.11 0.09 0.06 -0.01 -0.11 -0.29 -0.56 0.07 0.05 0.02 -0.05 -0.17 -0.34 -0.63	
Level 14 (13.58 cm) 1.03 0.89 0.62 0.22 -0.31 -0.97 -1.74 1.04 0.90 0.63 0.23 -0.30 -0.95 -1.72 1.07 0.93 0.66 0.26 -0.27 -0.91 -1.67 1.04 0.90 0.64 0.25 -0.27 -0.90 -1.65 1.02 0.89 0.62 0.23 -0.27 -0.89 -1.62 1.03 0.89 0.64 0.25 -0.24 -0.84 -1.53 1.00 0.87 0.62 0.24 -0.24 -0.82 -1.48	Level 19 (3.59 cm) -0.74 -0.63 -0.42 -0.09 0.40 1.09 2.05 -0.74 -0.64 -0.43 -0.10 0.38 1.04 1.97 -0.75 -0.65 -0.45 -0.14 0.31 0.93 1.77 -0.82 -0.73 -0.54 -0.24 0.16 0.70 1.44 -0.86 -0.77 -0.59 -0.33 0.03 0.52 1.15 -0.87 -0.79 -0.63 -0.39 -0.05 0.40 0.98 -0.92 -0.85 -0.69 -0.46 -0.13 0.28 0.82	
Level 15 (12.57 cm) 0.56 0.48 0.32 0.09 -0.21 -0.55 -0.91 0.57 0.49 0.33 0.10 -0.19 -0.54 -0.89 0.60 0.52 0.36 0.13 -0.16 -0.50 -0.84 0.57 0.48 0.33 0.10 -0.18 -0.51 -0.85 0.55 0.48 0.33 0.11 -0.17 -0.49 -0.82 0.57 0.49 0.34 0.13 -0.14 -0.44 -0.73 0.55 0.47 0.32 0.10 -0.16 -0.45 -0.73	Level 20 (the Front) -2.50 -2.10 -1.32 -0.16 1.34 3.16 5.23 -2.53 -2.14 -1.37 -0.24 1.23 3.00 4.98 -2.57 -2.19 -1.44 -0.35 1.06 2.73 4.56 -2.68 -2.32 -1.60 -0.54 0.79 2.34 3.96 -2.79 -2.43 -1.74 -0.73 0.54 1.96 3.38 -2.84 -2.49 -1.81 -0.83 0.37 1.71 3.00 -2.89 -2.54 -1.87 -0.91 0.25 1.55 2.81	

Figure 16. Continued.
c) At 25 Microseconds.

Level 11 (15 cm - the Back) 1.84 1.63 1.23 0.57 -0.35 -1.72 -3.42 1.86 1.65 1.23 0.58 -0.33 -1.67 -3.40 1.92 1.71 1.29 0.62 -0.26 -1.61 -3.30 1.83 1.64 1.22 0.58 -0.32 -1.62 -3.31 1.77 1.60 1.18 0.57 -0.35 -1.65 -3.30 1.82 1.62 1.21 0.57 -0.32 -1.55 -3.18 1.77 1.57 1.16 0.53 -0.42 -1.72 -2.97	Level 16 (11.06 cm) 0.34 0.29 0.21 0.08 -0.06 -0.29 -0.55 0.35 0.31 0.22 0.09 -0.07 -0.28 -0.53 0.39 0.36 0.28 0.16 0.00 -0.21 -0.48 0.31 0.27 0.20 0.09 -0.07 -0.28 -0.57 0.25 0.21 0.13 0.01 -0.13 -0.33 -0.61 0.30 0.26 0.18 0.07 -0.06 -0.28 -0.53 0.28 0.25 0.18 0.07 -0.07 -0.24 -0.48	Level=11 (15 cm - the Back) Mean 0.805 N S.D. % Diff 1.765 % Level = 12 (14.7 cm) Mean 0.783 N S.D. % Diff 1.596 % Level = 13 (14.25 cm) Mean 0.755 N S.D. % Diff 1.267 % Level = 14 (13.58 cm) Mean 0.718 N S.D. % Diff 0.896 % Level = 15 (12.57 cm) Mean 0.67 N S.D. % Diff 0.471 % Level = 16 (11.06 cm) Mean 0.606 N S.D. % Diff 0.297 % Level = 17 (9.78 cm) Mean 0.529 N S.D. % Diff 0.065 % Level = 18 (6 cm) Mean 0.436 N S.D. % Diff 0.211 % Level = 19 (3.59 cm) Mean 0.35 N S.D. % Diff 0.855 % Level = 20 (Front of Plasma) Mean 0.227 N S.D. % Diff 2.449 %
Level 12 (14.7 cm) 1.71 1.52 1.12 0.47 -0.41 -1.57 -3.06 1.73 1.52 1.13 0.49 -0.40 -1.55 -3.02 1.78 1.58 1.19 0.56 -0.31 -1.47 -2.95 1.70 1.51 1.11 0.49 -0.36 -1.50 -2.97 1.67 1.47 1.07 0.45 -0.39 -1.49 -2.92 1.69 1.49 1.09 0.47 -0.36 -1.42 -2.78 1.64 1.44 1.04 0.41 -0.48 -1.52 -2.60	Level 17 (9.78 cm) -0.04 -0.03 -0.02 -0.01 0.03 0.10 0.22 -0.03 -0.03 -0.01 0.01 0.04 0.10 0.21 0.01 0.00 -0.00 0.00 0.03 0.08 0.18 -0.02 -0.03 -0.04 -0.04 -0.04 -0.02 0.02 -0.05 -0.05 -0.05 -0.05 -0.05 -0.05 -0.03 -0.02 -0.02 -0.02 -0.02 -0.01 0.00 0.05 -0.05 -0.05 -0.05 -0.06 -0.05 -0.03 0.02	
Level 13 (14.25 cm) 1.42 1.23 0.88 0.33 -0.41 -1.33 -2.38 1.43 1.26 0.89 0.35 -0.38 -1.30 -2.35 1.48 1.31 0.95 0.41 -0.32 -1.24 -2.27 1.42 1.24 0.89 0.35 -0.37 -1.26 -2.27 1.36 1.19 0.85 0.32 -0.38 -1.25 -2.24 1.38 1.21 0.86 0.34 -0.34 -1.16 -2.09 1.33 1.15 0.79 0.27 -0.41 -1.18 -1.96	Level 18 (6 cm) 0.16 0.15 0.15 0.15 0.13 0.11 0.07 0.17 0.17 0.16 0.14 0.10 0.06 -0.01 0.24 0.24 0.23 0.20 0.14 0.06 -0.06 0.15 0.14 0.12 0.08 0.02 -0.10 -0.30 0.08 0.07 0.04 -0.01 -0.10 -0.25 -0.51 0.10 0.08 0.05 -0.02 -0.13 -0.31 -0.60 0.04 0.01 -0.02 -0.10 -0.22 -0.39 -0.68	
Level 14 (13.58 cm) 1.02 0.89 0.62 0.22 -0.30 -0.94 -1.70 1.03 0.90 0.63 0.24 -0.28 -0.92 -1.67 1.08 0.95 0.68 0.29 -0.21 -0.85 -1.60 1.02 0.89 0.62 0.24 -0.26 -0.88 -1.63 0.97 0.83 0.57 0.20 -0.30 -0.89 -1.60 0.98 0.84 0.59 0.23 -0.24 -0.80 -1.46 0.91 0.78 0.54 0.19 -0.26 -0.79 -1.35	Level 19 (3.59 cm) -0.74 -0.63 -0.41 -0.06 0.45 1.16 2.15 -0.73 -0.63 -0.41 -0.07 0.44 1.13 2.09 -0.73 -0.64 -0.42 -0.09 0.37 1.02 1.89 -0.87 -0.76 -0.55 -0.25 0.16 0.72 1.47 -0.90 -0.81 -0.63 -0.36 0.01 0.51 1.14 -0.92 -0.84 -0.68 -0.43 -0.07 0.40 0.99 -1.04 -0.96 -0.79 -0.54 -0.19 0.22 0.82	
Level 15 (12.57 cm) 0.56 0.48 0.32 0.10 -0.19 -0.53 -0.88 0.57 0.49 0.34 0.11 -0.18 -0.52 -0.86 0.61 0.53 0.38 0.16 -0.13 -0.45 -0.79 0.54 0.46 0.32 0.10 -0.19 -0.50 -0.85 0.50 0.43 0.30 0.09 -0.18 -0.49 -0.82 0.53 0.46 0.32 0.12 -0.13 -0.41 -0.68 0.48 0.41 0.26 0.06 -0.18 -0.43 -0.66	Level 20 (the Front) -2.47 -2.07 -1.27 -0.09 1.44 3.30 5.44 -2.51 -2.11 -1.32 -0.17 1.32 3.13 5.16 -2.55 -2.16 -1.41 -0.29 1.15 2.85 4.71 -2.73 -2.36 -1.64 -0.57 0.79 2.37 4.02 -2.91 -2.54 -1.84 -0.81 0.48 1.93 3.37 -2.98 -2.62 -1.92 -0.92 0.31 1.69 3.01 -3.06 -2.72 -2.01 -1.05 0.15 1.51 2.94	

Figure 16. Continued.
d) At 50 Microseconds.

Level 11 (15 cm - the Back)		Level 16 (11.06 cm)		Level = 11 (15 cm - the Back)
1.82 1.60 1.16 0.45 -0.54 -2.00 -3.86		0.25 0.24 0.14 -0.01 -0.23 -0.52 -0.91		Mean 0.814 N
1.83 1.62 1.17 0.48 -0.50 -1.94 -3.78		0.29 0.25 0.16 0.01 -0.20 -0.48 -0.86		S.D. % Diff 1.819 %
1.86 1.65 1.21 0.53 -0.42 -1.82 -3.61		0.32 0.28 0.19 0.05 -0.13 -0.39 -0.73		
1.88 1.67 1.25 0.59 -0.33 -1.68 -3.40		0.33 0.30 0.22 0.10 -0.07 -0.29 -0.57		Level = 12 (14.7 cm)
1.90 1.70 1.29 0.65 -0.24 -1.53 -3.17		0.35 0.31 0.24 0.13 -0.00 -0.18 -0.41		Mean 0.792 N
1.93 1.72 1.32 0.69 -0.17 -1.41 -2.96		0.35 0.32 0.25 0.16 0.05 -0.08 -0.24		S.D. % Diff 1.665 %
1.92 1.72 1.33 0.70 -0.17 -1.32 -2.79		0.35 0.31 0.25 0.16 0.03 -0.01 -0.11		
				Level = 13 (14.25 cm)
				Mean 0.763 N
				S.D. % Diff 1.338 %
Level 12 (14.7 cm)		Level 17 (9.78 cm)		Level = 14 (13.58 cm)
1.70 1.48 1.05 0.37 -0.59 -1.87 -3.53		-0.06 -0.06 -0.08 -0.09 -0.10 -0.11 -0.08		Mean 0.725 N
1.71 1.50 1.07 0.40 -0.55 -1.81 -3.45		-0.05 -0.05 -0.06 -0.08 -0.08 -0.08 -0.06		S.D. % Diff 0.97 %
1.74 1.53 1.11 0.46 -0.46 -1.69 -3.28		-0.03 -0.04 -0.04 -0.05 -0.05 -0.04 0.01		
1.76 1.56 1.15 0.51 -0.38 -1.56 -3.07		-0.03 -0.03 -0.03 -0.03 -0.03 0.02 0.09		Level = 15 (12.57 cm)
1.79 1.59 1.19 0.57 -0.29 -1.41 -2.83		-0.02 -0.02 -0.01 -0.00 0.03 0.08 0.18		Mean 0.675 N
1.80 1.61 1.21 0.61 -0.21 -1.28 -2.61		-0.02 -0.01 -0.01 0.01 0.06 0.15 0.30		S.D. % Diff 0.533 %
1.80 1.61 1.22 0.62 -0.22 -1.19 -2.45		-0.02 -0.02 -0.01 0.00 0.03 0.20 0.39		
				Level = 16 (11.06 cm)
				Mean 0.607 N
				S.D. % Diff 0.331 %
Level 13 (14.25 cm)		Level 18 (6 cm)		Level = 17 (9.78 cm)
1.40 1.21 0.82 0.22 -0.59 -1.62 -2.83		0.10 0.10 0.09 0.07 0.04 -0.03 -0.15		Mean 0.526 N
1.42 1.23 0.84 0.25 -0.55 -1.57 -2.75		0.10 0.10 0.09 0.07 0.03 -0.05 -0.18		S.D. % Diff 0.098 %
1.44 1.26 0.88 0.31 -0.47 -1.45 -2.58		0.11 0.11 0.10 0.07 0.03 -0.06 -0.21		
1.47 1.29 0.92 0.36 -0.38 -1.31 -2.37		0.10 0.10 0.09 0.06 0.01 -0.09 -0.25		Level = 18 (6 cm)
1.50 1.32 0.96 0.42 -0.29 -1.16 -2.13		0.09 0.09 0.07 0.04 -0.01 -0.11 -0.29		Mean 0.429 N
1.51 1.34 0.99 0.46 -0.22 -1.04 -1.92		0.09 0.08 0.06 0.03 -0.03 -0.12 -0.29		S.D. % Diff 0.115 %
1.51 1.34 1.00 0.47 -0.22 -0.95 -1.75		0.07 0.06 0.04 -0.00 -0.08 -0.11 -0.26		
				Level = 19 (3.59 cm)
				Mean 0.341 N
				S.D. % Diff 0.835 %
Level 14 (13.58 cm)		Level 19 (3.59 cm)		Level = 20 (Front of Plasma)
1.01 0.86 0.56 0.11 -0.48 -1.24 -2.17		-0.79 -0.68 -0.47 -0.13 0.37 1.05 2.01		Mean 0.217 N
1.02 0.87 0.58 0.14 -0.45 -1.18 -2.08		-0.80 -0.70 -0.48 -0.15 0.33 1.00 1.92		S.D. % Diff 2.457 %
1.05 0.91 0.62 0.20 -0.36 -1.07 -1.92		-0.81 -0.71 -0.51 -0.19 0.27 0.89 1.75		
1.07 0.94 0.66 0.25 -0.28 -0.93 -1.72		-0.84 -0.75 -0.55 -0.25 0.17 0.74 1.51		
1.10 0.96 0.69 0.31 -0.19 -0.79 -1.48		-0.87 -0.78 -0.60 -0.32 0.07 0.59 1.28		
1.10 0.97 0.72 0.34 -0.12 -0.66 -1.27		-0.89 -0.81 -0.64 -0.38 -0.01 0.49 1.13		
1.10 0.97 0.72 0.35 -0.13 -0.57 -1.11		-0.92 -0.83 -0.67 -0.42 -0.10 0.44 1.06		
Level 15 (12.57 cm)		Level 20 (the Front)		
0.54 0.44 0.26 -0.02 -0.37 -0.81 -1.30		-2.61 -2.20 -1.39 -0.19 1.37 3.27 5.44		
0.55 0.46 0.28 0.01 -0.33 -0.75 -1.23		-2.64 -2.24 -1.44 -0.27 1.27 3.10 5.17		
0.58 0.49 0.32 0.07 -0.26 -0.64 -1.07		-2.69 -2.30 -1.52 -0.39 1.07 2.81 4.71		
0.59 0.51 0.35 0.12 -0.18 -0.52 -0.89		-2.77 -2.39 -1.65 -0.56 0.82 2.42 4.11		
0.62 0.54 0.39 0.18 -0.09 -0.39 -0.67		-2.84 -2.47 -1.76 -0.72 0.57 2.03 3.49		
0.62 0.55 0.41 0.20 -0.03 -0.27 -0.47		-2.88 -2.53 -1.84 -0.85 0.38 1.74 3.04		
0.62 0.54 0.40 0.20 -0.05 -0.19 -0.32		-2.92 -2.57 -1.89 -0.93 0.23 1.60 2.82		

Figure 17, The Uniformity of the Magnetic Force or Accelerating Force for the Hollow Curve-Ended Electrode at 20,000 amps and 2,000 m/s at each Depth Simulated Using the Standard Deviation Percentage Difference Method. (The Numbers in Each block represents a percentage.)
a) At 5 Microseconds.

Level 11 (15 cm - the Back) 1.78 1.56 1.13 0.44 -0.52 -1.94 -3.77 1.79 1.58 1.14 0.47 -0.48 -1.89 -3.69 1.82 1.61 1.19 0.52 -0.41 -1.77 -3.52 1.84 1.63 1.21 0.57 -0.33 -1.65 -3.32 1.84 1.64 1.25 0.62 -0.24 -1.50 -3.10 1.87 1.67 1.28 0.66 -0.16 -1.36 -2.87 1.87 1.67 1.28 0.67 -0.19 -1.25 -2.63	Level 16 (11.06 cm) 0.28 0.24 0.14 -0.01 -0.22 -0.50 -0.88 0.29 0.24 0.15 0.01 -0.19 -0.46 -0.82 0.31 0.27 0.19 0.06 -0.12 -0.37 -0.70 0.31 0.27 0.20 0.08 -0.07 -0.28 -0.56 0.31 0.28 0.21 0.11 -0.02 -0.18 -0.40 0.34 0.30 0.24 0.14 0.04 -0.07 -0.22 0.34 0.31 0.24 0.15 0.01 0.04 -0.02	Level = 11 (15 cm - the Back) Mean 0.806 N S.D. % Diff 1.769 % Level = 12 (14.7 cm) Mean 0.785 N S.D. % Diff 1.614 % Level = 13 (14.25 cm) Mean 0.756 N S.D. % Diff 1.288 % Level = 14 (13.58 cm) Mean 0.719 N S.D. % Diff 0.925 % Level = 15 (12.57 cm) Mean 0.67 N S.D. % Diff 0.502 % Level = 16 (11.06 cm) Mean 0.605 N S.D. % Diff 0.318 % Level = 17 (9.78 cm) Mean 0.527 N S.D. % Diff 0.098 % Level = 18 (6 cm) Mean 0.432 N S.D. % Diff 0.141 % Level = 19 (3.59 cm) Mean 0.344 N S.D. % Diff 0.807 % Level = 20 (Front of Plasma) Mean 0.219 N S.D. % Diff 2.456 %
Level 12 (14.7 cm) 1.66 1.45 1.03 0.37 -0.57 -1.82 -3.44 1.66 1.46 1.04 0.39 -0.53 -1.76 -3.36 1.70 1.50 1.08 0.45 -0.45 -1.64 -3.20 1.71 1.51 1.11 0.49 -0.37 -1.51 -2.98 1.72 1.53 1.14 0.54 -0.29 -1.37 -2.76 1.74 1.55 1.17 0.58 -0.21 -1.23 -2.51 1.75 1.56 1.18 0.59 -0.24 -1.11 -2.28	Level 17 (9.78 cm) -0.04 -0.05 -0.06 -0.08 -0.09 -0.10 -0.09 -0.04 -0.05 -0.05 -0.07 -0.08 -0.08 -0.06 -0.03 -0.03 -0.04 -0.05 -0.05 -0.04 -0.00 -0.02 -0.03 -0.03 -0.03 -0.02 0.00 0.06 -0.02 -0.02 -0.02 -0.01 0.01 0.07 0.16 -0.01 -0.01 -0.01 0.00 0.05 0.15 0.29 -0.01 -0.01 -0.01 -0.01 -0.01 0.22 0.43	
Level 13 (14.25 cm) 1.37 1.18 0.80 0.22 -0.57 -1.57 -2.74 1.37 1.19 0.82 0.24 -0.54 -1.52 -2.66 1.40 1.22 0.85 0.30 -0.45 -1.40 -2.50 1.42 1.24 0.89 0.35 -0.37 -1.27 -2.29 1.42 1.25 0.91 0.39 -0.29 -1.13 -2.06 1.45 1.28 0.94 0.43 -0.21 -0.98 -1.82 1.45 1.28 0.95 0.44 -0.24 -0.86 -1.59	Level 18 (6 cm) 0.14 0.13 0.12 0.09 0.04 -0.05 -0.19 0.14 0.13 0.12 0.08 0.03 -0.07 -0.22 0.15 0.14 0.13 0.09 0.03 -0.08 -0.25 0.13 0.12 0.10 0.06 -0.00 -0.11 -0.31 0.11 0.10 0.08 0.04 -0.03 -0.15 -0.35 0.11 0.10 0.07 0.02 -0.04 -0.14 -0.34 0.09 0.08 0.05 -0.01 -0.13 -0.10 -0.26	
Level 14 (13.58 cm) 0.97 0.83 0.54 0.11 -0.47 -1.19 -2.09 0.98 0.84 0.56 0.13 -0.43 -1.14 -2.01 1.01 0.87 0.60 0.19 -0.35 -1.02 -1.85 1.02 0.89 0.63 0.23 -0.27 -0.90 -1.64 1.03 0.90 0.65 0.28 -0.19 -0.76 -1.42 1.05 0.92 0.68 0.32 -0.12 -0.61 -1.19 1.05 0.93 0.69 0.33 -0.14 -0.49 -0.96	Level 17 (9.78 cm) -0.74 -0.63 -0.43 -0.10 0.38 1.04 1.97 -0.75 -0.65 -0.44 -0.12 0.34 0.98 1.88 -0.76 -0.67 -0.48 -0.17 0.27 0.87 1.70 -0.81 -0.72 -0.53 -0.25 0.16 0.70 1.44 -0.85 -0.76 -0.59 -0.33 0.05 0.54 1.19 -0.87 -0.79 -0.63 -0.39 -0.03 0.45 1.05 -0.89 -0.82 -0.66 -0.44 -0.15 0.43 1.03	
Level 15 (12.57 cm) 0.51 0.42 0.25 -0.01 -0.35 -0.77 -1.24 0.52 0.43 0.26 0.01 -0.32 -0.72 -1.17 0.55 0.46 0.30 0.06 -0.25 -0.61 -1.02 0.55 0.48 0.32 0.10 -0.18 -0.50 -0.84 0.56 0.49 0.35 0.15 -0.09 -0.37 -0.63 0.58 0.51 0.38 0.18 -0.02 -0.23 -0.40 0.59 0.52 0.38 0.18 -0.06 -0.12 -0.20	Level 20 (the Front) -2.58 -2.17 -1.38 -0.16 1.40 3.29 5.46 -2.61 -2.21 -1.41 -0.24 1.29 3.12 5.19 -2.66 -2.27 -1.50 -0.37 1.09 2.82 4.71 -2.75 -2.38 -1.64 -0.56 0.82 2.40 4.09 -2.85 -2.49 -1.77 -0.74 0.55 2.01 3.46 -2.90 -2.55 -1.86 -0.88 0.36 1.72 3.01 -2.94 -2.60 -1.93 -0.98 0.16 1.60 2.83	

Figure 17. Continued.
b) At 10 Microseconds.

Level 11 (15 cm - the Back) 1.77 1.56 1.13 0.44 -0.51 -1.92 -3.73 1.79 1.58 1.15 0.48 -0.47 -1.86 -3.66 1.83 1.62 1.20 0.54 -0.38 -1.74 -3.48 1.81 1.61 1.20 0.56 -0.32 -1.64 -3.30 1.80 1.60 1.21 0.60 -0.25 -1.49 -3.10 1.84 1.64 1.25 0.63 -0.16 -1.33 -2.81 1.82 1.63 1.22 0.61 -0.29 -1.21 -2.44	Level 16 (11.06 cm) 0.28 0.23 0.14 -0.00 -0.21 -0.48 -0.85 0.29 0.25 0.16 0.02 -0.18 -0.44 -0.79 0.32 0.28 0.20 0.08 -0.10 -0.33 -0.66 0.29 0.26 0.19 0.08 -0.07 -0.27 -0.55 0.28 0.24 0.17 0.08 -0.04 -0.19 -0.41 0.31 0.27 0.21 0.11 0.03 -0.05 -0.19 0.30 0.27 0.21 0.09 -0.07 0.13 0.10	Level = 11 (15 cm - the Back) Mean 0.807 N S.D. % Diff 1.745 % Level = 12 (14.7 cm) Mean 0.786 N S.D. % Diff 1.589 % Level = 13 (14.25 cm) Mean 0.757 N S.D. % Diff 1.283 % Level = 14 (13.58 cm) Mean 0.72 N S.D. % Diff 0.9 % Level = 15 (12.57 cm) Mean 0.671 N S.D. % Diff 0.482 % Level = 16 (11.06 cm) Mean 0.606 N S.D. % Diff 0.304 % Level = 17 (9.78 cm) Mean 0.527 N S.D. % Diff 0.116 % Level = 18 (6 cm) Mean 0.432 N S.D. % Diff 0.135 % Level = 19 (3.59 cm) Mean 0.344 N S.D. % Diff 0.852 % Level = 20 (Front of Plasma) Mean 0.219 N S.D. % Diff 2.513 %
Level 12 (14.7 cm) 1.65 1.45 1.03 0.37 -0.56 -1.80 -3.41 1.66 1.46 1.05 0.39 -0.52 -1.74 -3.32 1.70 1.50 1.10 0.47 -0.42 -1.61 -3.15 1.69 1.49 1.10 0.49 -0.37 -1.49 -2.97 1.69 1.49 1.10 0.51 -0.30 -1.36 -2.74 1.71 1.52 1.13 0.54 -0.22 -1.19 -2.45 1.69 1.50 1.12 0.50 -0.35 -1.06 -2.09	Level 17 (9.78 cm) -0.06 -0.06 -0.07 -0.08 -0.08 -0.07 -0.04 -0.05 -0.06 -0.06 -0.06 -0.06 -0.05 -0.01 -0.03 -0.03 -0.04 -0.04 -0.03 -0.01 0.04 -0.04 -0.04 -0.04 -0.04 -0.03 0.01 0.06 -0.05 -0.05 -0.04 -0.03 0.01 0.07 0.15 -0.03 -0.03 -0.03 -0.02 0.05 0.18 0.33 -0.05 -0.05 -0.05 -0.06 -0.08 0.30 0.54	
Level 13 (14.25 cm) 1.36 1.17 0.80 0.22 -0.56 -1.55 -2.72 1.37 1.19 0.82 0.25 -0.52 -1.50 -2.63 1.41 1.23 0.87 0.32 -0.43 -1.37 -2.45 1.40 1.22 0.88 0.35 -0.37 -1.26 -2.28 1.39 1.22 0.88 0.37 -0.29 -1.11 -2.04 1.41 1.24 0.90 0.40 -0.21 -0.94 -1.76 1.40 1.22 0.88 0.36 -0.33 -0.79 -1.42	Level 18 (6 cm) 0.14 0.13 0.12 0.10 0.06 -0.01 -0.12 0.14 0.14 0.12 0.09 0.05 -0.03 -0.16 0.17 0.17 0.15 0.12 0.07 -0.03 -0.18 0.12 0.12 0.10 0.07 0.01 -0.09 -0.28 0.08 0.07 0.05 0.01 -0.05 -0.15 -0.37 0.08 0.07 0.03 -0.02 -0.07 -0.14 -0.34 0.05 0.03 -0.01 -0.10 -0.25 -0.06 -0.19	
Level 14 (13.58 cm) 0.96 0.82 0.54 0.12 -0.45 -1.17 -2.05 0.98 0.84 0.56 0.14 -0.41 -1.11 -1.97 1.02 0.88 0.61 0.21 -0.32 -0.98 -1.80 1.00 0.87 0.61 0.23 -0.27 -0.88 -1.63 1.00 0.87 0.61 0.25 -0.20 -0.75 -1.41 1.01 0.89 0.64 0.29 -0.12 -0.58 -1.13 0.99 0.86 0.62 0.26 -0.23 -0.40 -0.80	Level 19 (3.59 cm) -0.75 -0.64 -0.42 -0.08 0.42 1.11 2.08 -0.75 -0.65 -0.43 -0.09 0.39 1.06 1.99 -0.77 -0.67 -0.46 -0.14 0.32 0.94 1.80 -0.85 -0.75 -0.56 -0.25 0.16 0.73 1.48 -0.90 -0.81 -0.63 -0.36 0.03 0.55 1.20 -0.92 -0.84 -0.69 -0.45 -0.06 0.46 1.09 -0.99 -0.91 -0.76 -0.56 -0.30 0.48 1.12	
Level 15 (12.57 cm) 0.50 0.42 0.25 -0.01 -0.34 -0.75 -1.21 0.51 0.43 0.26 0.01 -0.31 -0.70 -1.14 0.55 0.47 0.31 0.08 -0.22 -0.58 -0.98 0.53 0.45 0.31 0.09 -0.18 -0.49 -0.83 0.53 0.46 0.32 0.13 -0.10 -0.35 -0.63 0.55 0.48 0.35 0.16 -0.02 -0.19 -0.35 0.53 0.46 0.33 0.12 -0.14 -0.03 -0.07	Level 20 (the Front) -2.56 -2.14 -1.32 -0.10 1.49 3.43 5.66 -2.60 -2.19 -1.38 -0.19 1.37 3.24 5.36 -2.66 -2.26 -1.48 -0.33 1.15 2.91 4.86 -2.79 -2.41 -1.67 -0.58 0.82 2.43 4.14 -2.93 -2.56 -1.85 -0.81 0.51 1.99 3.44 -2.99 -2.64 -1.95 -0.97 0.29 1.69 2.99 -3.05 -2.71 -2.05 -1.13 -0.03 1.64 2.92	

Figure 17. Continued.
c) At 25 Microseconds.

Level 11 (15 cm - the Back) 1.75 1.56 1.12 0.47 -0.48 -1.90 -3.68 1.80 1.57 1.16 0.52 -0.42 -1.82 -3.61 1.87 1.65 1.23 0.58 -0.35 -1.69 -3.41 1.79 1.58 1.18 0.57 -0.32 -1.61 -3.26 1.75 1.56 1.16 0.57 -0.27 -1.47 -3.07 1.78 1.57 1.20 0.57 -0.17 -1.28 -2.77 1.73 1.54 1.13 0.49 -0.48 -1.19 -2.22	Level 16 (11.06 cm) 0.28 0.24 0.14 0.00 -0.19 -0.45 -0.80 0.30 0.25 0.16 0.03 -0.16 -0.40 -0.73 0.35 0.31 0.24 0.12 -0.04 -0.27 -0.58 0.26 0.24 0.17 0.07 -0.06 -0.25 -0.52 0.21 0.18 0.11 0.02 -0.08 -0.20 -0.42 0.27 0.23 0.16 0.06 0.02 -0.04 -0.14 0.24 0.21 0.14 0.01 -0.14 0.22 0.21	Level=11 (15 cm - the Back) Mean 0.809 N S.D. % Diff 1.712 % Level = 12 (14.7 cm) Mean 0.787 N S.D. % Diff 1.548 % Level = 13 (14.25 cm) Mean 0.759 N S.D. % Diff 1.223 % Level = 14 (13.58 cm) Mean 0.721 N S.D. % Diff 0.858 % Level = 15 (12.57 cm) Mean 0.672 N S.D. % Diff 0.451 % Level = 16 (11.06 cm) Mean 0.607 N S.D. % Diff 0.283 % Level = 17 (9.78 cm) Mean 0.528 N S.D. % Diff 0.144 % Level = 18 (6 cm) Mean 0.432 N S.D. % Diff 0.147 % Level = 19 (3.59 cm) Mean 0.343 N S.D. % Diff 0.928 % Level = 20 (Front of Plasma) Mean 0.218 N S.D. % Diff 2.597 %
Level 12 (14.7 cm) 1.65 1.45 1.04 0.38 -0.55 -1.76 -3.34 1.67 1.47 1.06 0.41 -0.50 -1.68 -3.25 1.72 1.53 1.13 0.51 -0.38 -1.54 -3.06 1.65 1.46 1.07 0.49 -0.35 -1.46 -2.93 1.63 1.43 1.04 0.46 -0.31 -1.35 -2.70 1.65 1.46 1.07 0.48 -0.24 -1.15 -2.36 1.58 1.41 1.01 0.35 -0.50 -1.00 -1.87	Level 17 (9.78 cm) -0.08 -0.08 -0.08 -0.07 -0.05 -0.02 0.04 -0.07 -0.07 -0.06 -0.05 -0.02 0.01 0.07 -0.03 -0.03 -0.04 -0.03 -0.01 0.04 0.11 -0.06 -0.07 -0.07 -0.05 -0.03 0.01 0.07 -0.09 -0.09 -0.08 -0.05 -0.00 0.07 0.14 -0.07 -0.06 -0.06 -0.04 0.06 0.21 0.39 -0.10 -0.10 -0.11 -0.13 -0.17 0.40 0.64	
Level 13 (14.25 cm) 1.35 1.16 0.80 0.25 -0.53 -1.52 -2.66 1.36 1.19 0.83 0.27 -0.48 -1.45 -2.58 1.43 1.25 0.90 0.35 -0.37 -1.31 -2.37 1.37 1.20 0.86 0.33 -0.36 -1.23 -2.23 1.31 1.16 0.83 0.34 -0.32 -1.10 -2.02 1.34 1.17 0.84 0.35 -0.22 -0.88 -1.66 1.28 1.11 0.76 0.22 -0.44 -0.69 -1.21	Level 18 (6 cm) 0.14 0.13 0.13 0.12 0.10 0.06 -0.01 0.14 0.14 0.14 0.12 0.08 0.03 -0.07 0.20 0.21 0.20 0.18 0.13 0.05 -0.08 0.11 0.11 0.09 0.07 0.03 -0.06 -0.24 0.03 0.02 -0.00 -0.03 -0.07 -0.16 -0.37 0.04 0.02 -0.02 -0.08 -0.10 -0.16 -0.34 -0.04 -0.06 -0.12 -0.24 -0.40 -0.03 -0.15	
Level 14 (13.58 cm) 0.94 0.81 0.54 0.13 -0.43 -1.12 -1.98 0.96 0.84 0.57 0.16 -0.37 -1.06 -1.89 1.02 0.89 0.64 0.25 -0.27 -0.91 -1.71 0.96 0.84 0.59 0.23 -0.26 -0.85 -1.57 0.93 0.80 0.55 0.21 -0.22 -0.74 -1.39 0.94 0.81 0.57 0.24 -0.13 -0.53 -1.04 0.87 0.75 0.51 0.14 -0.32 -0.29 -0.61	Level 19 (3.59 cm) -0.76 -0.64 -0.42 -0.05 0.48 1.22 2.23 -0.75 -0.65 -0.42 -0.06 0.47 1.19 2.17 -0.77 -0.67 -0.44 -0.09 0.40 1.06 1.97 -0.92 -0.81 -0.58 -0.26 0.18 0.77 1.55 -0.98 -0.88 -0.69 -0.39 0.03 0.57 1.23 -1.01 -0.94 -0.78 -0.53 -0.08 0.50 1.16 -1.16 -1.08 -0.94 -0.75 -0.48 0.54 1.24	
Level 15 (12.57 cm) 0.49 0.41 0.25 0.01 -0.31 -0.70 -1.16 0.51 0.43 0.27 0.03 -0.27 -0.65 -1.07 0.56 0.49 0.33 0.11 -0.17 -0.52 -0.90 0.50 0.42 0.28 0.08 -0.18 -0.47 -0.80 0.46 0.40 0.28 0.10 -0.11 -0.34 -0.61 0.49 0.43 0.30 0.12 -0.02 -0.14 -0.27 0.44 0.37 0.23 0.01 -0.23 0.06 0.05	Level 20 (the Front) -2.53 -2.10 -1.26 -0.01 1.63 3.62 5.94 -2.57 -2.15 -1.32 -0.10 1.49 3.42 5.61 -2.64 -2.23 -1.44 -0.26 1.25 3.06 5.06 -2.84 -2.46 -1.71 -0.60 0.83 2.48 4.22 -3.06 -2.69 -1.97 -0.91 0.44 1.95 3.41 -3.14 -2.79 -2.10 -1.11 0.20 1.66 2.97 -3.22 -2.88 -2.23 -1.35 -0.27 1.71 3.02	

Figure 17. Continued.
d) At 50 Microseconds.

0.00% represents a flow that is completely uniform. The middle of the plasma will always be more uniform than the front or the back of the plasma. Comparing a shape with its hollow counterpart, the uniformity does not change substantially. It should be noted that the shapes included in Table 1 represent only the uniformity of some of the electrode shapes that were examined.

Table 2 shows the standard deviation of the percentage difference in the accelerating magnetic force with a higher current and at an earlier time of 5 microseconds. Interestingly, the uniformity did not change significantly with increased current. This magnetic force uniformity simulated in the first four shapes of Table 2 produced an acceptable uniform flow. The uniformity of each of the level is recorded in tabular form in Figure 16 and in

Table 1. The Std % Difference in the Accelerating Magnetic Force (F_z) for Various Electrode Shapes at 2,000 amps.

Shape	Back	11.06 cm	6.0 cm	Front
Solid Rectangle (18 mm)	1.77%	0.30%	0.21%	2.44%
Hollow Rectangle (4 mm)	1.80	0.30	0.21	2.32
Solid Curve-Ended	1.76	0.32	0.18	2.49
Hollow Curve-Ended (4 mm)	1.74	0.33	0.15	2.51
Solid Elliptical	2.38	1.06	0.97	1.83
Hollow Elliptical (4 mm)	2.40	1.09	0.94	1.81
One-Side Curved(Big Radius)	2.38	1.06	0.89	1.83
One-Side Curved(Sm. Radius)	2.65	1.36	1.20	1.62

Table 2. The Std % Difference in the Accelerating Magnetic Force (F_z) for Various Electrode Shapes at 20,000 amps.

Shape	Back	11.06 cm	6.0 cm	Front
Hollow Rectangle (4 mm)	1.84%	0.32%	0.16%	2.37%
Hollow Curve-Ended (4 mm)	1.82	0.33	0.12	2.46
Thin Rectangle (4 mm)	1.77	0.30	0.18	2.52
Solid Rectangle (18 mm)	1.84	0.32	0.16	2.37
Solid Elliptical	2.38	1.07	0.91	1.83

Appendix F as a percentage difference. The percentage difference is calculated for each finite element in the placement at four times (5, 10, 25, and 50 microseconds). Also, the average newton force in the z-direction down the channel and the overall percentage difference standard deviation are given at the righthand side of Appendix F. The five shapes in Table 2 can be found in Figure 16 and in Appendix F for a more detailed examination of the simulated data.

Table 3 shows the total integrated force from the integration of the $\mathbf{J} \times \mathbf{B}$ body force integrated over the entire plasma element for various electrode shapes. The value changes very little with respect to time, so 20 microseconds was used in the table. The current is 20,000 amps, and the velocity is 2,000 m/s. The entire plasma force is recorded in Table 3 and not just the quarter of the MHD accelerator that was used to simulate the condition. The elliptical shape, even though its uniformity is worse

Table 3. $\mathbf{J} \times \mathbf{B}$ Force over the Entire Plasma.

<u>Shape</u>	<u>Force</u>
Hollow Rectangle	119.24 N
Hollow Curve-Ended	118.68
Thin Rectangle	120.08
Solid Rectangle	119.16
Elliptical	119.84

than the other four, still produces about the same force as the other shapes. The thin rectangle shape, reducing a solid rectangle to a thickness of 4 mm and holding the coil size constant, produces a slightly larger force. The thin rectangular electrode also produces the best uniformity in the back of the plasma where the stronger accelerating forces in the z-direction occur.

Another test was simulated using the hollow curve-ended-electrode, MHD accelerator at 200,000 amps with a velocity of 2000 m/s. The hollow curve-ended electrode was used because of the uniformity shown in Table 2. The 200,000 amps represents a more realistic representation of the current used in a MHD accelerator for accelerating air. The purpose of this simulation was to demonstrate the magnitude of the integrated force and the magnitude of the expected magnetic flux density. The integrated $\mathbf{J} \times \mathbf{B}$ accelerating force (F_z) in the entire slug of plasma was 11,868 newtons. The average magnetic flux density (B_x) in the back of the plasma was 28.5 Tesla.

7.0 DISCUSSION OF RESULTS

A critical need in the progress of aeronautics is for hypersonic speeds to be simulated accurately in ground test facilities. Present facilities are not available to meet these needs. An MHD research accelerator is being proposed to meet some of these needs. In order to handle the challenges of hypersonic flows, a MHD accelerator must be able to produce a uniform accelerating force to propel a gas from supersonic speeds to hypersonic speeds. The main component in producing the uniform accelerating force is in the electrode shape.

For the fifty electrode shapes tested in preparation for this thesis, two of the shapes giving favorable levels of uniformity have been compared in detail. Trends have been examined in the magnetic flux density, in the current density, and in the resulting magnetic force.

The magnetic flux density in the plasma is strongest in the x-direction. These values also remain positive. In the y-direction the magnetic flux density acts irregularly, especially in the corners of the channel, but the mostly-negative values are low in comparison to B_x . In the z-direction, the positive values are almost constant with no irregularities. The z-direction's highest values are along the insulator wall.

The current density in the plasma is strongest in the

y-direction because of the applied electric field. These values travel through the plasma and slowly decrease as time increases. In the x-direction, the negative values of the current density are larger in the corners of the channel and close to zero at the other points examined. Irregularities occur in the corners of the channel of the hollow rectangular electrode shape from the 90° corners of the electrode ends. The z-direction current density is primarily along the electrode wall and remains positive. In the front of the plasma for the curve-ended electrode, the corner-of-the-channel current density is low. Both J_x and J_z are small in relation to J_y and can be considered negligible.

The accelerating magnetic force in the z-direction is always stronger toward the back of the plasma than in the front. Hence, the plasma stays together and will not separate into separate slugs as it travels down the channel. The x-direction magnetic force pushes the slug toward the center of the channel. It is stronger along the insulator walls. The force toward the center approaches zero in the middle of the channel. This result may be desirable since the wall's viscous forces will slow the fluid as it comes in contact with the wall. In the y-direction, the forces are very small.

In examining electrode shapes with a radius of curvature in the channel, like the elliptical electrode,

greater non-uniformities exist in the accelerating forces than in the electrode shapes with no curvature in the channel. This was shown in Tables 1 and 2 by comparing the results of the elliptical electrode shape with the results of one of the other shapes.

Comparing the standard deviation percentage differences between solid shapes and their hollow counterparts shows very little variations in the early period of Table 2. In later times (i.e., milliseconds), the hollow shapes produce better uniformity due to the forcing of the current to remain closer to the surface and not penetrate to the center of the electrode like it would for a solid electrode shape.

The magnetic body forces resulting from the electrodes that do not extend beyond the channel sidewalls leave greater non-uniformities due to the current densities moving around the ends of the electrode. Depending on the ends' shape, the electrode can produce large non-uniformities. To reduce the non-uniformities, the electrode can be extended beyond the channel; however, this reduces the inductance per rail length and the overall accelerating Force (F_z).

Comparing the results from Tables 1 and 2, increasing the current did not change the levels of body force uniformity. With a current of, say, 200,000 amps, the expected uniformity would be very close to the values of Tables 1 and 2 for the particular electrode shape. Of course, an increase in the current increases the magnetic

flux densities, the current densities, and the magnetic forces.

Four of the shapes in Table 2, namely, the hollow rectangular, the hollow curve-ended, the thin rectangular, and the solid rectangular electrodes, show very favorable levels of body force uniformity with the standard deviation percentage differences staying mostly below 1% in the entire plasma as shown in Figure 16 and in Appendix F. These would produce accelerating forces necessary to uniformly accelerate the gas into the hypersonic range.

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BIBLIOGRAPHY

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APPENDICES

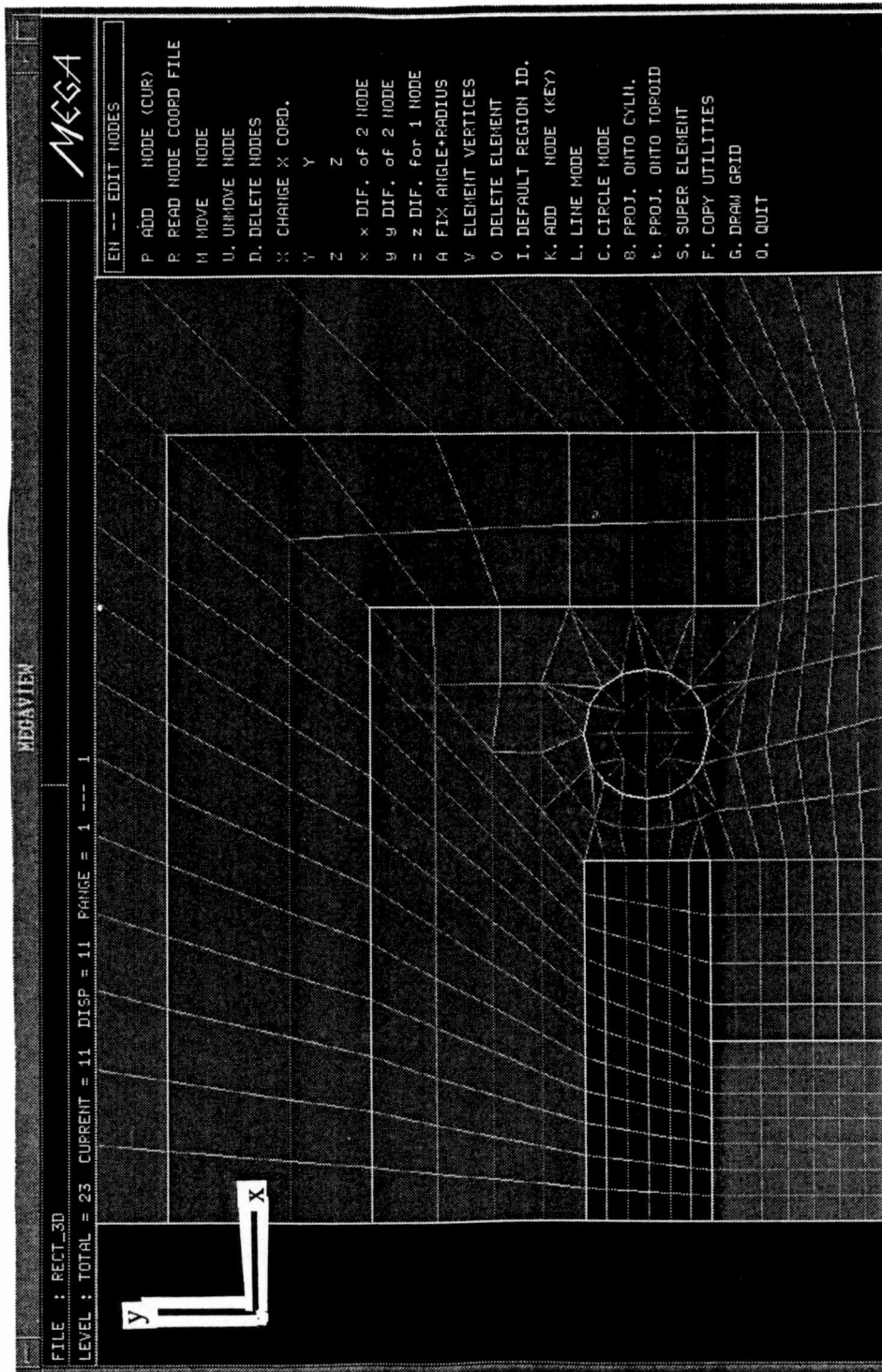
A MORE ABOUT MEGA

Mega™ strictly uses SI units (i.e., length is always measured in meters). For each electrode model, a finite element structure is created. Using the dimensions of the desired model,¹² corner points of the model are inputted using the keyboard in the Edit Node (EN) section of Mega™.²⁵ A1 shows the initial screen of the edit node section of Mega™. Points or nodes may be entered with the keyboard (after hitting "K") or where the crosshairs are located (by hitting "P").

The points can be connected by many methods, but the most common method is to use Super Element inside Edit Nodes. Super Element asks for the points on each side of a section of the device or will create points between two corners. The distribution of these points can also concentrate towards one of the corner points.

Mega™ permits the use of either triangular or quadrilateral elements. Elements with 90° corners give the most accurate results. Triangular elements reduce the accuracy in a finite element model, but to form certain shapes (i.e., curved shapes), they become a better choice than using large obtuse-angled elements.

After the electrode finite element geometry has been created, different physical properties must be given to the parts of the model using the Edit Region (ER) portion of Mega™.²⁵ A2 shows the initial screen of the edit region



A1 The Main Edit Node Menu Screen.

region section of Mega™. Here all of the elements of the structure are given their characteristics (i.e., conductivity and velocity). Conductivity, for example, is 0.0 for air, 5.5×10^7 mho/m for copper, and 1.0×10^7 mho/m for iron. A plasma has a much lower conductivity than metals. Its conductivity will vary significantly with its change in temperature and pressure; see Figure 5 for a 2% potassium-seeded plasma. Mega™ cannot vary conductivity while solving the electrodynamic problem. The conductivity can, however, be changed and then the problem resolved.

Velocity is also set for each element. A2 shows a velocity input value of -1000.0 m/s in the z-direction for the electrode. A -1000.0 m/s input value is also assigned to the coil and the containment shell, and the plasma is given a velocity of 0.0 m/s. The value for the electrode, coil, and containment shell are negative because the plasma is being stopped at some instant and these parts of the model have the effect of traveling -1000 m/s relative to the plasma.

Mega™ allows the time frame of interest to be changed in the Time Step (TS) section.²⁵ The starting time should always be 0.0 s, but the end time and interval time may change to provide a multiple time setting. Mega's™ results increase in accuracy starting with the second time interval. (The first time interval is always the starting time.) A3 shows the procedure in the time step section.

aixterm

REGION NAME :ELECTRODE

NON LINEAR B-H REGION :N

Y / N :

ENTER REL. PER. : 1.00000

ENTER CONDUCTIVITY : 5.500000E+07

VELOCITY REGION :Y

Y / N :

LINEAR VELOCITY OR SPIN :L

ENTER L/S :

VELOCITY IN X,Y AND Z : 0.000000E+00 0.000000E+00 -1000.00

DIRECTIONS :

THERMAL HEAT FLOW :N

Y / N :

OVER RIDE FORMULATION :N

Y / N :

[ER] USING FORMULATION I.D. 2052

[REGION_LIST] --- LIST REGION PROPERTIES

	ID	Ur	Cond.	Js.	Mag	Vel	Equation
AIR	2	1.000	0.0000E+00				MAGNETIC SCALAR
IRON	3	1.000	1.0000E+07	L			CURLCURL(A)
ELECTRODE	4	1.000	5.5000E+07	L			CURLCURL(A)
COIL	5	1.000	5.5000E+07	L			CURLCURL(A)
SEEDED AIR	6	1.000	100.0				CURLCURL(A)

EDIT REGION NO. :0

-ve for NULL / 0-QUITS :[]

A2 The Procedure in the Edit Region Section.

```

DO YOU WANT TO RESTART :N
      Y / N :
      START TIME IS : 0.000000E+00
      NEW VALUE or <CR> :
      END TIME IS : 5.000000E-05
      NEW VALUE or <CR> :
      TIME STEP IS : 2.500000E-05
      NEW VALUE or <CR> :2.5E-6
      THETA IS : 1.00000
      0.5 - 1.0 or <CR> :
      TIME STEP METHOD :
      GE / <CR> :
      OLD FASHIONED WAVE FILE :N
      Y / N :
      ICCG MAX ITERATIONS :300
      1 ... :
      ICCG TOLERANCE : 1.000000E-12
      :
      TS FILE NAME :RECT
      (FOR TIME STEP OUTPUT) :RECT_3D
      OUTPUT FILE --RECT_3D.TDAT
      START TIME -- 0.0000E+00
      STOP TIME -- 5.0000E-05
      TIME STEP -- 2.5000E-06
      THETA -- 1.000
      NONLINEAR -- F
      METHOD --
      WAVE NO. -- 0
      ICCG MAX ITS -- 300
      TOLERANCE -- 1.0000E-12
      DO YOU WISH TO EDIT :N
      Y / N :☐

```

A3 The Procedure in the Time Step Section.

To set the boundaries around a device, enter the Edit Boundaries (EB) section.²⁵ A4 and A5 show the menu for setting the boundaries as tangential flux and normal flux, respectively. In a 3-D model, the beginning (top) and end (bottom) must also have boundaries. A tangential flux boundary is created by an exact magnetic flux density mirror-image on the opposite side of the boundary. A normal flux boundary is represented by an exact current density mirror-image.

In 2-D model simulations, Mega™ assumes an infinitely long device, and hence, only the magnetic flux density from the electrodes can be accurately examined. The current in a 2-D simulation travels down the higher conductivity of the infinitely-long copper electrode and will not pass through the plasma. Therefore, the magnetic force is only established between the electrodes from cathode to anode. Since the lower conductivity of the plasma has finite length, it cannot be modeled in 2-D. In order to examine the current density and magnetic force as seen by a MHD accelerator model, a 3-D model must be created.

To make a 3-D model, first a 2-D model is created. Then the Edit Level (EL) part of the Mega™ program is used to create additional levels or depths into the z-direction.²⁵ In the models of the MHD accelerator electrode shapes used in the present thesis, 23 levels were created to project depth. They are in Table 4. These levels or depths are in

Table 4. The Z-Direction Lengths Between Elements.

level	depth	level	depth	level	depth
1	0.0000	9	0.4387	17	0.5122
2	0.1155	10	0.4455	18	0.5400
3	0.2281	11	0.4500	19	0.5741
4	0.3050	12	0.4530	20	0.6000
5	0.3563	13	0.4575	21	0.6388
6	0.3905	14	0.4642	22	0.6973
7	0.4133	15	0.4743	23	0.7800
8	0.4285	16	0.4894		

units of meters. Level 1 simulates the beginning of the channel and level 23, the end. The channel length is arbitrary. The lengths before and after the plasma are included as a reference and only serves to simulate the current density in the electrode and the eddy currents in a moving electrode.

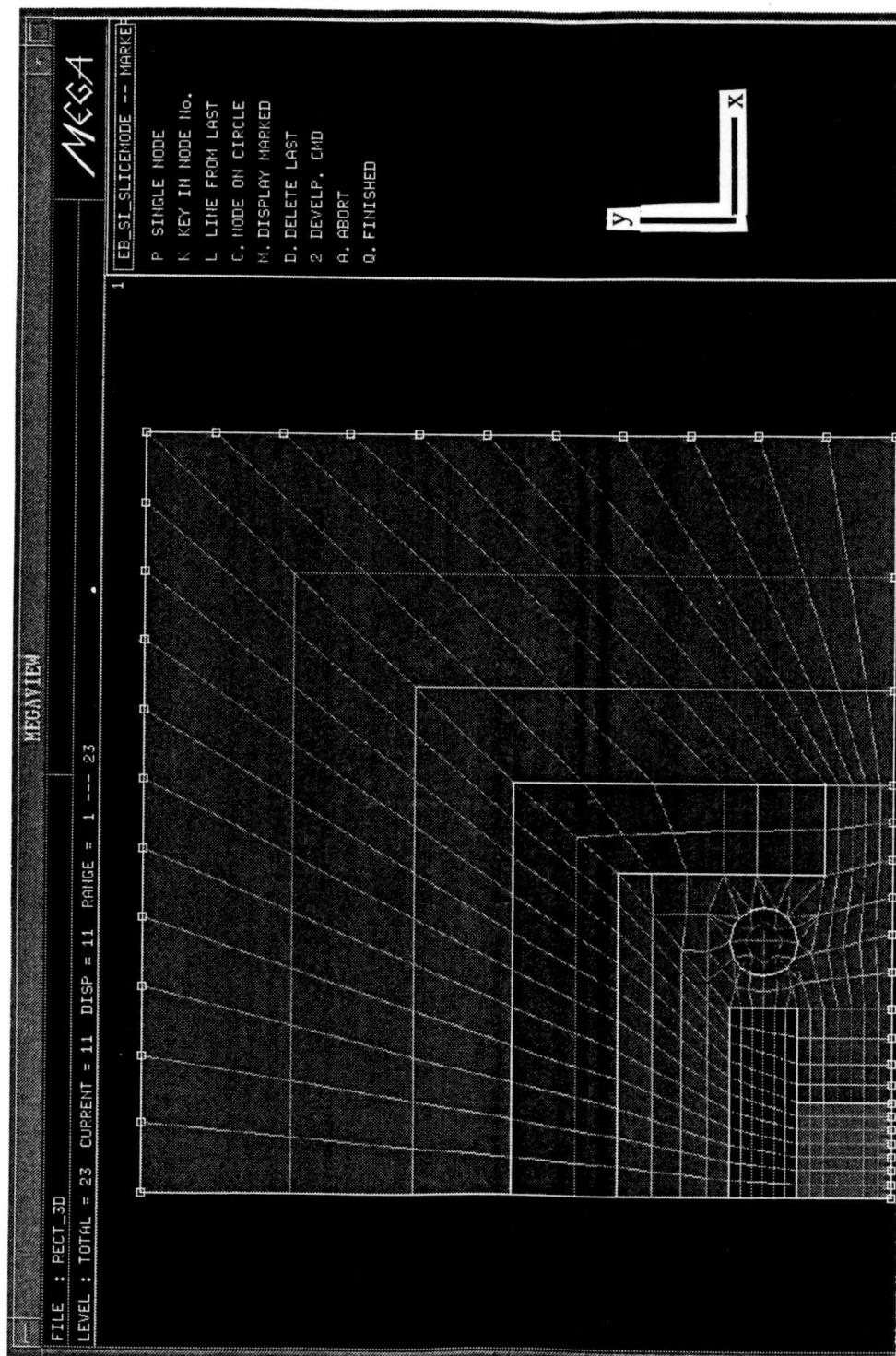
Mega™ only projects the 2-D model into the first level or station. Using Edit Elements (EE), each element is projected as needed into the additional levels or stations.²⁵ Levels 11 through 20 are the only levels that contain the plasma. (See Table 4.) The conducting gas for this analysis is given a depth of 15 cm (60 - 45 cm). The length of the plasma can be longer or shorter than 15 cm. For a shorter plasma, the current passing through a smaller volume of plasma would increase the magnetic force and produce a faster rate of uniformity. A longer plasma would produce a smaller force and would take longer to reach uniformity. Holding this length constant provides an effective way to compare the different electrode shapes.

Entering Edit Boundaries (EB), set the entrance (top) and exit (bottom) boundaries to be tangential.²⁵ This will prevent the magnetic flux density from penetrating them, and they will be the beginning and the end, respectively, of the channel and the device.

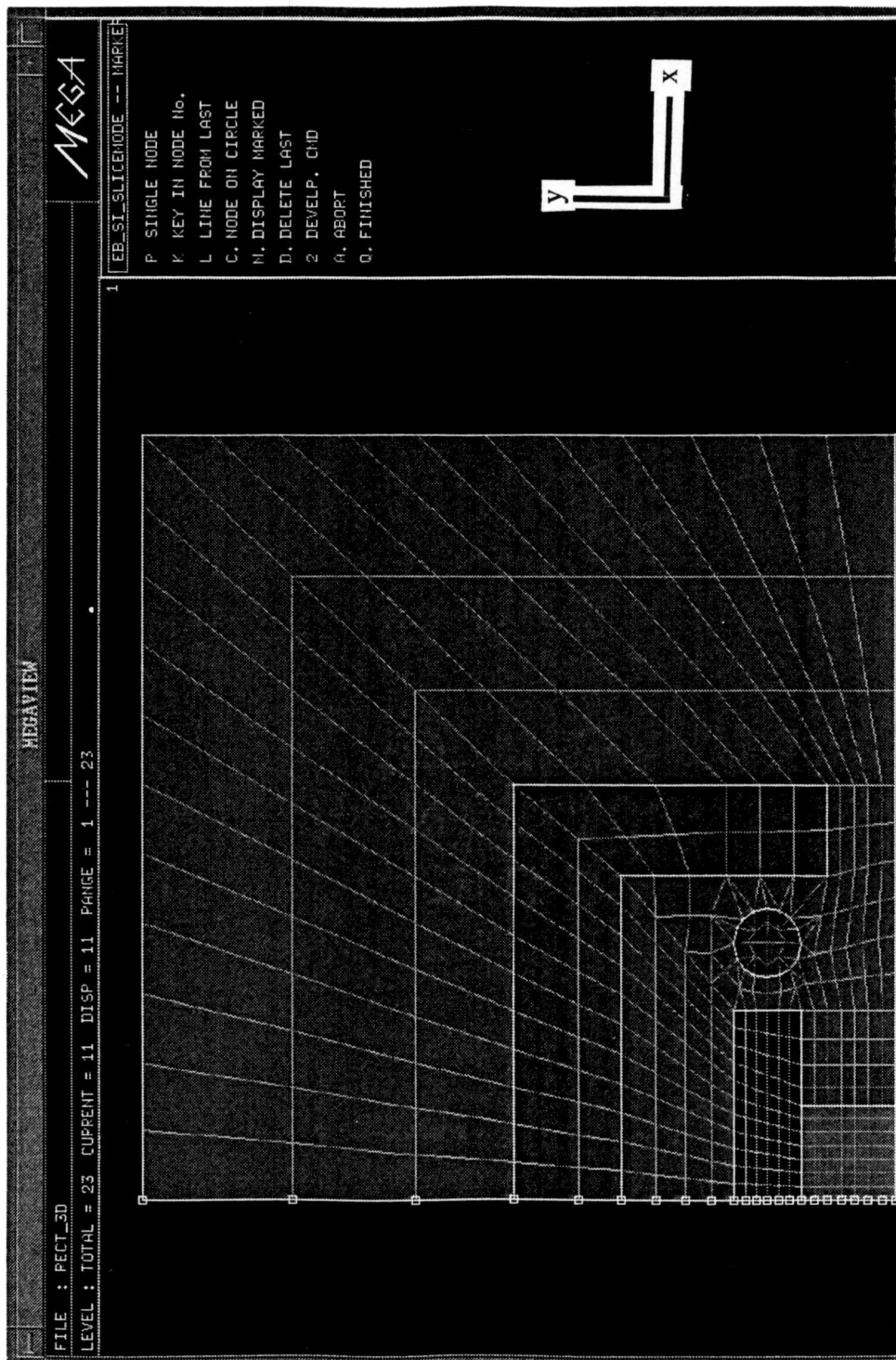
The side boundaries contain both tangential and normal fluxes. The vertical centerline down the middle of the accelerator should have a normal flux boundary allowing a normal component of magnetic flux density to penetrate but not allowing the current density. They are marked on the boundaries in A5 with squares. The horizontal centerline across the middle of the accelerator should have a tangential flux boundary. The outside boundaries of the accelerator should be set as tangential fluxes beyond a short distance (about an accelerator width or height). These are marked with squares in A4.

The importance in Mega™ of setting these centerline boundaries is to allow a quarter of the MHD accelerator to represent the entire accelerator. Mega™ has restrictions on the number of finite elements it can solve. Reducing the accelerator to only a symmetric quarter allows smaller elements to be used before the equation limitations on Mega™ are reached. Therefore, better accuracy will result. This assumes symmetry in the accelerator which is a reasonable assumption.

The XC (automatic cut generator) is used to select the



A4 Tangential Flux Boundaries Set in Edit Boundaries for an Upper-Right-Quarter-Cut of a MHD Accelerator.



A5 Normal Flux Boundaries Set in Edit Boundaries for an Upper-Right-Quarter-Cut of a MHD Accelerator.

points that the current enters and exits the 3-D model.²⁵ (A current of zero must be entered for the iron containment.²²) Twenty thousand Amps were used in both the electrode and the coil. A6 shows a current of 10,000 amps, but this value is doubled when both halves of the MHD accelerator are taken into consideration. The exit through the plasma for the electrode current must be chosen at the base of the tangential boundary of the plasma. The coil exits at the end of the channel (level 23). According to the boundary-condition symmetry, the coil current re-enters at the end of the channel below the inside tangential boundary and re-exits at the beginning or front of the simulated model (producing a one turn coil). A6 shows the procedure to set up one "source node" or point where the current enters or exits the model. A similar procedure is performed for each entrance and exit of the current.

The Mega™ solver can now be used to calculate the current density, magnetic flux density, and magnetic force. A stationary model is solved by entering

SOLVE <filename>.

A moving problem is solved by entering

SOLVE <filename> VEL.

Once the solution is complete, the model may be viewed in two ways. Using either Draw Elements (DE) or Draw Interface (CI 99 DI), Mega™ will display the model.²⁵ The Structure Window (SW) will allow one to zoom in on a

[EL] -- CREATE/ VIEW Z-LEVELS

[EL] MAXIMUM NO LEVELS IS 126

CHECK BASE LEVEL :Y

Y / N :

[C1] Base plane consistency check

[C1] Checking elements. First pass

Check for unconnected nodes :Y

Y / N :

no. unconnected nodes = 0

Check for duplicate nodes :Y

Y / N :

[C1] Calculating default duplicate distance

Duplicate Node Tolerance : 2.582851E-03

-Ve To Abort [?] :

SHOW DUPLICATED NODES :Y

Y / N :

[C1] Checking Please Wait -----

[C1] MESH SEEMS TO BE OK

0 NODES HAVE BEEN DELETED

0 UNCONNECTED

0 DUPLICATED

395 REMAINING

TOTAL NO. OF LEVELS :1

0 TO ABORT :23

LEVEL 1 VALUE : 0.000000E+00

NEW OR <CR> :

LEVEL 2 VALUE : .115300

NEW OR <CR> :

LEVEL 3 VALUE : .228100

NEW OR <CR> :

LEVEL 4 VALUE : .305000

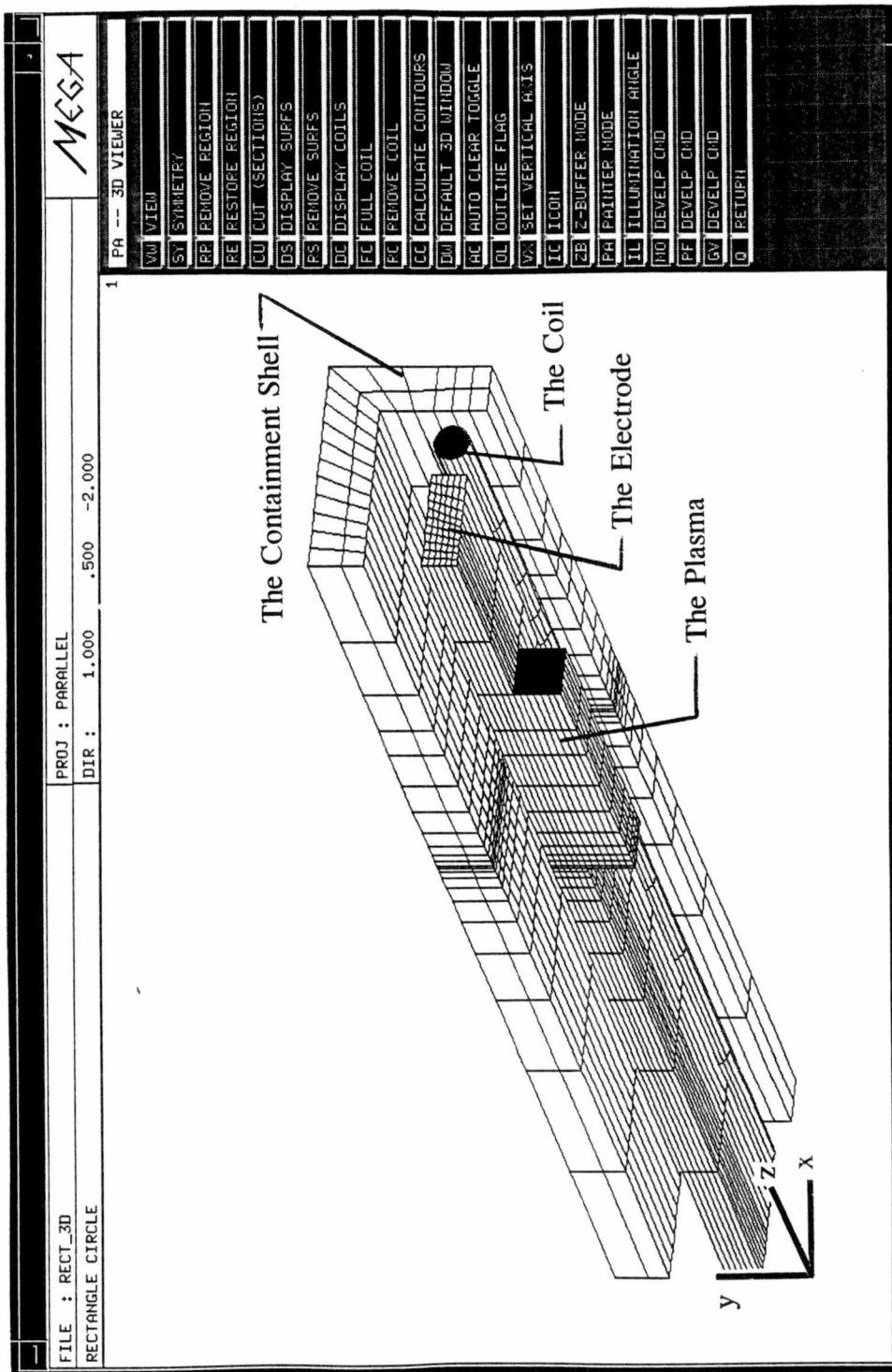
NEW OR <CR> :☐

A6 The Edit Level Procedure.

particular portion of the model or to zoom out and view the whole model.²⁵ This method will display the model in the XY plane. To change to a different level or depth, use Set Level (SL).²⁵ Since the back of the plasma is in level 11, SL 11 <enter> will move to the eleventh level and display the accelerator with the plasma.

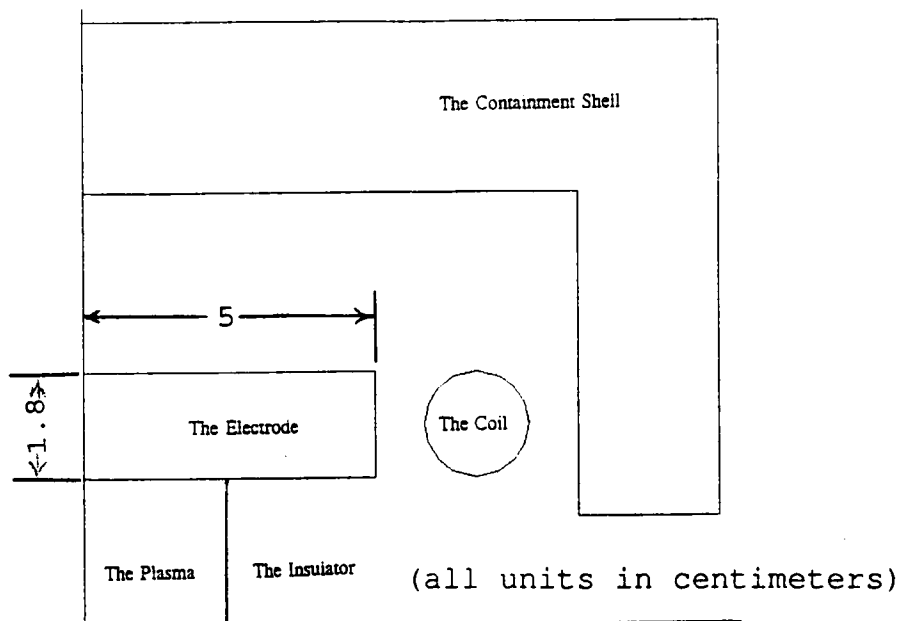
Another way to view the model is in the YZ plane. This is done by entering a Paint (PA) portion of Mega[™].²⁵ After generating the data nodes (GD) and choosing a Full Outline (OL 2), select View (VW) and the point at which the structure is to be viewed.²⁵ A7 shows the accelerator with the plasma from a $x=1$, $y=0.5$, and $z=-2.0$ perspective. Other options in the 3-D paint viewer are listed in A7.

There are several ways to present the vector distributions that result from Mega[™] analysis. Two-dimensional distributions must be in the XY plane, but three-dimensional distributions can be displayed in either XY or YZ planes. The 2-D figures primarily shown so far have been in the XY plane. A7 contains the YZ plane of the rectangular shape.

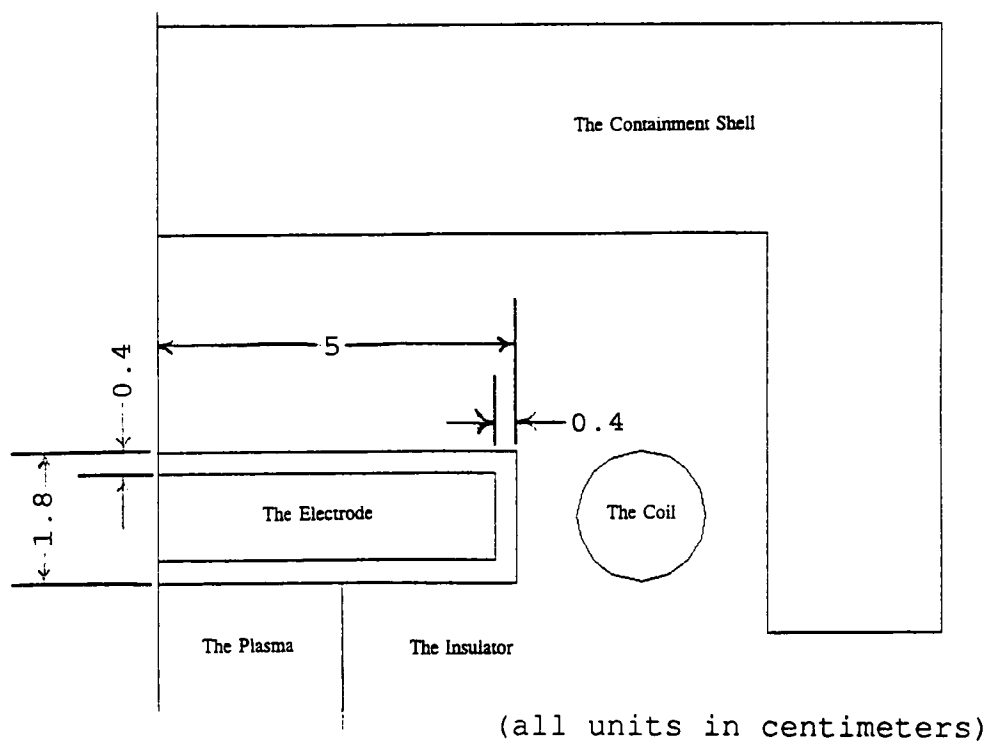


A7 The Main Menu in the 3-D Paint Viewer.

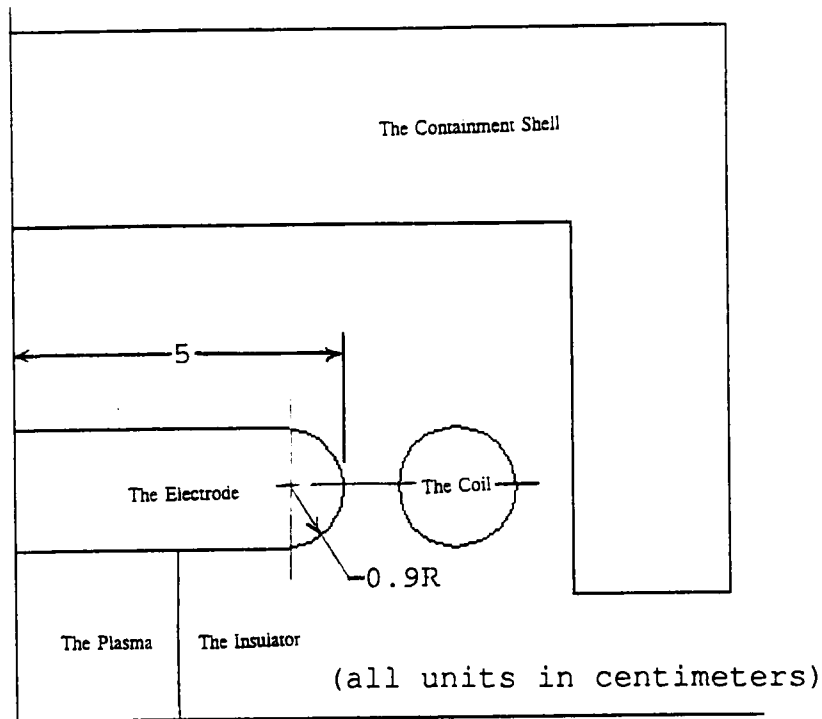
B ELECTRODE SHAPES FROM TABLE 4



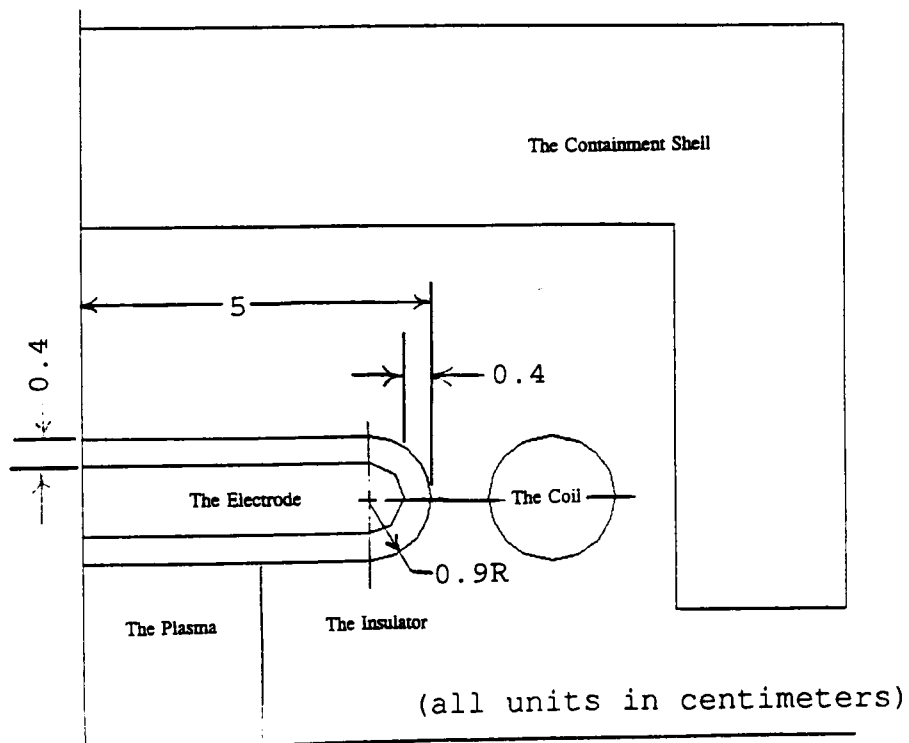
B1 The Quarter of the Solid-Rectangular-Shaped-Electrode, MHD Accelerator



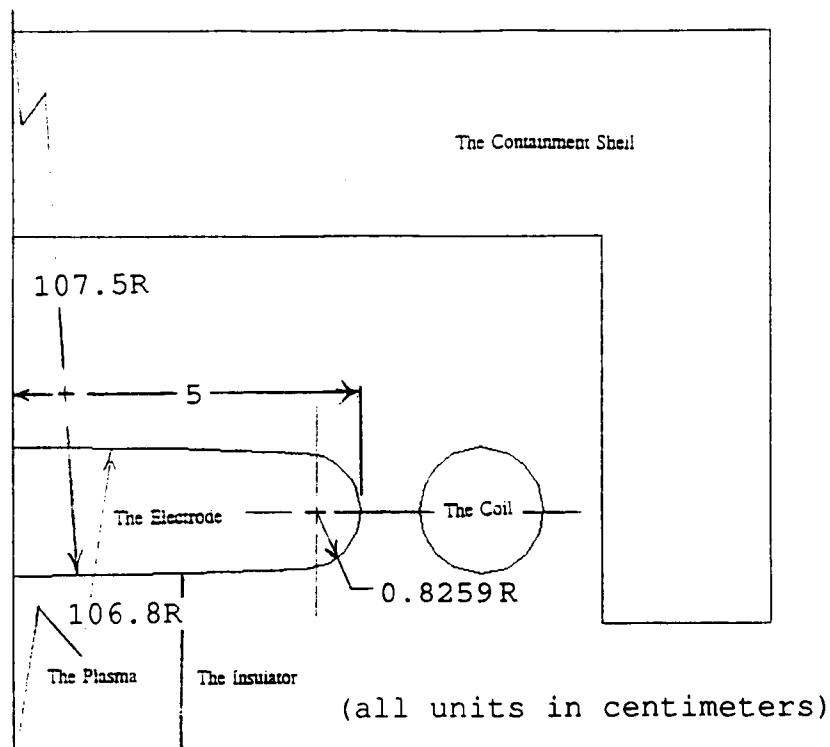
B2 The Quarter of the Hollow-Rectangular-Shaped-Electrode, MHD Accelerator



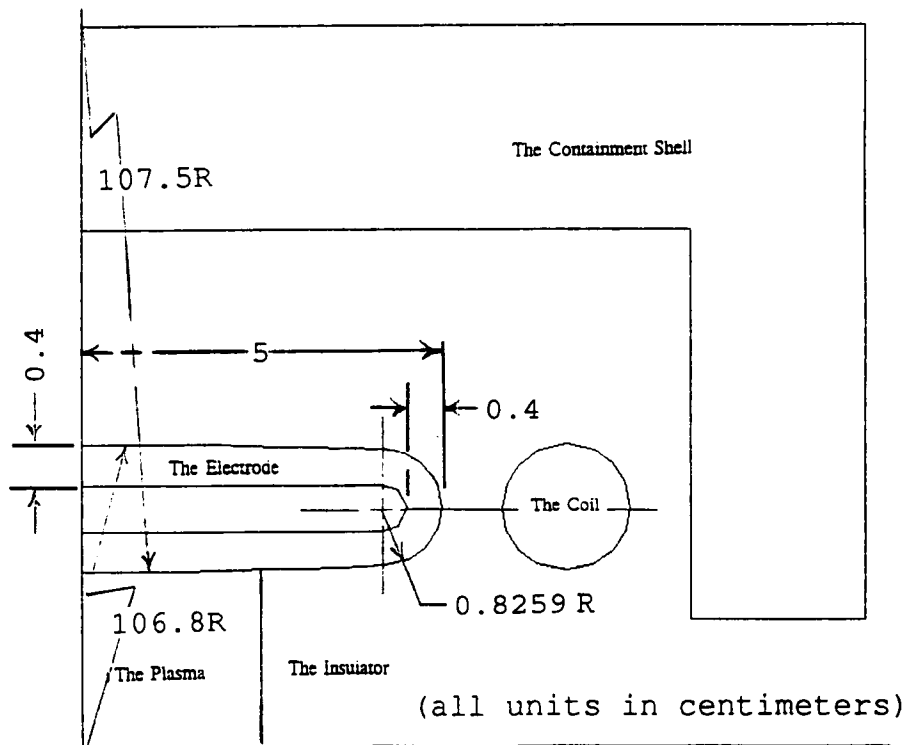
B3 The Quarter of the Solid-Curved-Ended-Shaped-Electrode,
MHD Accelerator



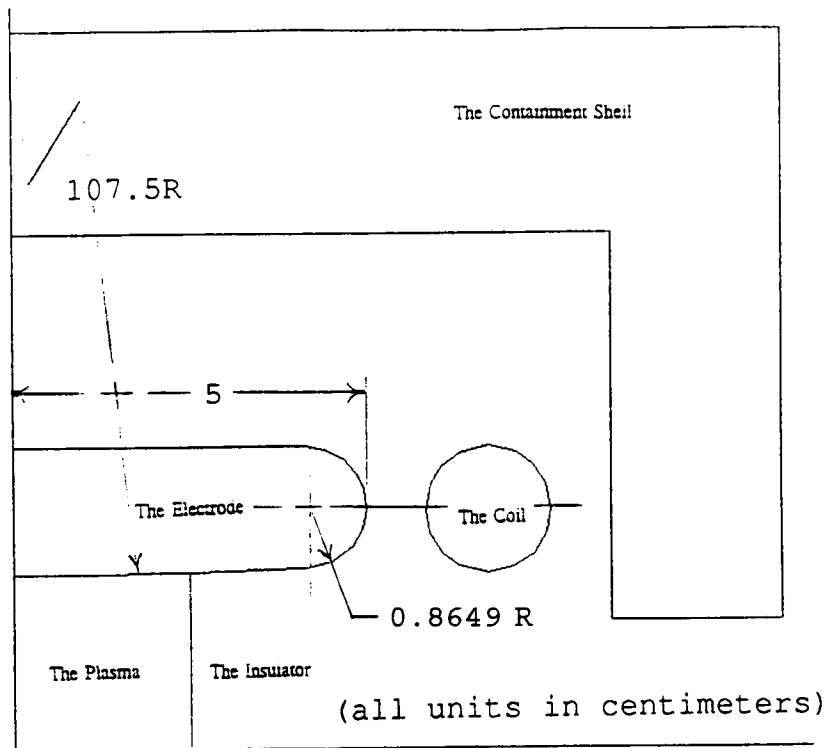
B4 The Quarter of the Hollow-Curve-Ended-Shaped-Electrode,
MHD Accelerator



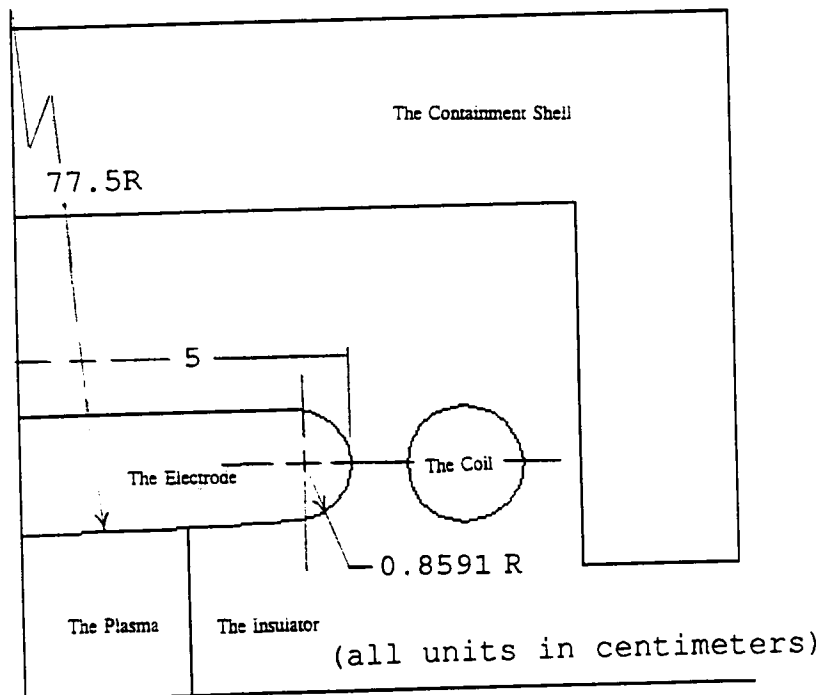
B5 The Quarter of the Solid-Elliptical-Shaped-Electrode, MHD Accelerator



B6 The Quarter of the Hollow-Elliptical-Shaped-Electrode, MHD Accelerator



B.7 The Quarter of the Solid-One-Side-Curved-Large-Radius-Shaped-Electrode, MHD Accelerator



B8 The Quarter of the Solid-One-Side-Curved-Small-Radius-Shaped-Electrode, MHD Accelerator

C MAGNETIC FLUX DENSITY

In C1 through C3, four points are monitored over a time interval from 5 to 100 microseconds. These points are located on the four corners of the channel in the quarter of the MHD accelerator. One is located just under the middle of the electrode. Two is located in the corner where the electrode, the channel, and the channel insulator meet. Three is located in the middle of the channel. Four is located in the middle of the channel insulator. These points are by no means where the maximum or minimum properties occur; they are merely arbitrary points to show trends in the properties.

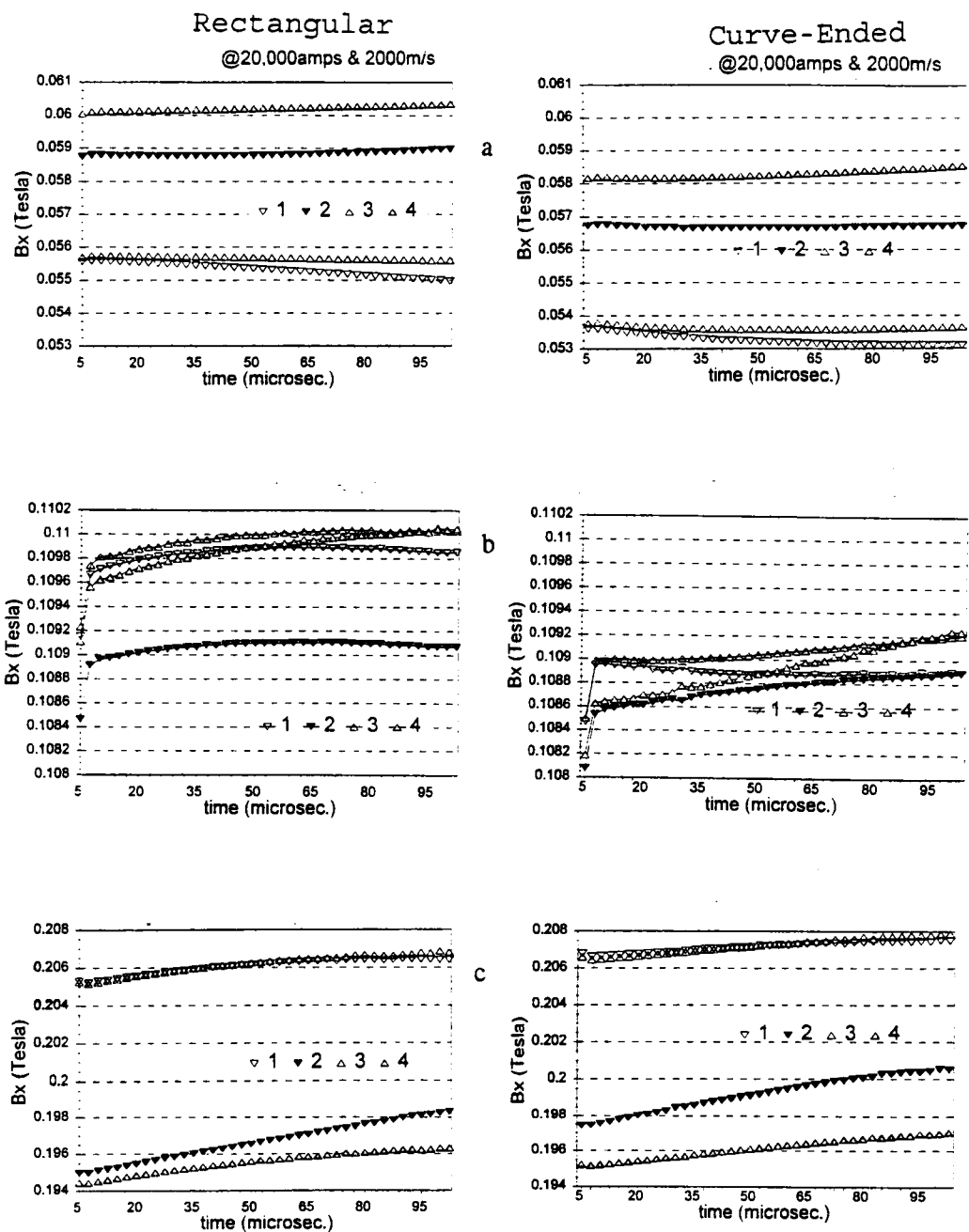
Following a step current input of 20,000 amps, the magnetic flux density shows uniformity by 5 microseconds in all but the y-direction as shown in C1 - C3. C1 - C3 compares the results from a hollow rectangular electrode shape in Figure 6 to that of a hollow curve-ended electrode shown in Figure 7. The magnetic flux density of B1a represents the front of the plasma, C1b represents 9 cm from the back, and C1c represents the back. C2 and C3 show the magnetic flux density in the y- and z-directions, respectively.

C1 contains the simulated, hollow, rectangular-shaped electrode on the left and the simulated, hollow, curve-ended electrode on the right. Appendix B1a simulates

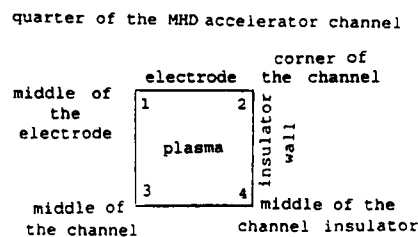
approximately the same trends with the higher magnetic flux densities in the x-direction along the channel insulator wall. The overall values are slightly higher for the hollow, rectangular-shaped electrode. B1b has similar trends, but the magnetic flux density in the x-direction is smallest at the corner of the channel. Eventually this density is strongest along the horizontal middle of the channel. In the back of the plasma, shown in C1c, this density becomes strongest along the vertical middle of the channel.

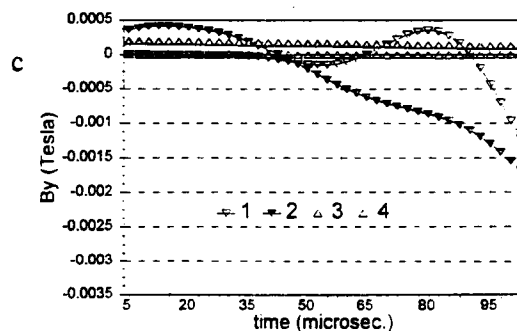
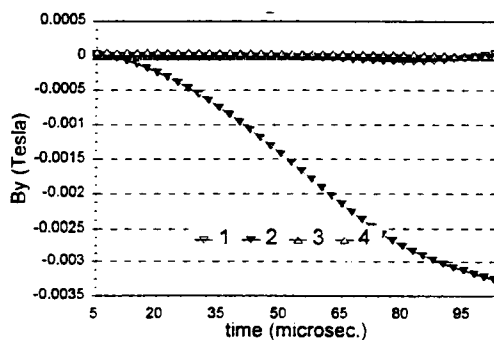
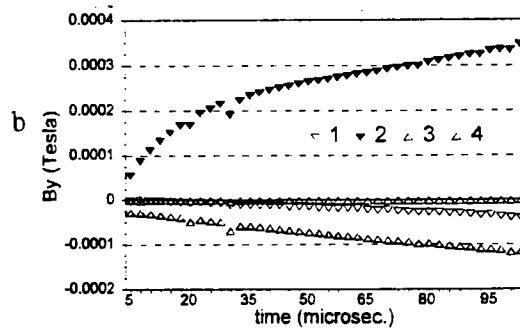
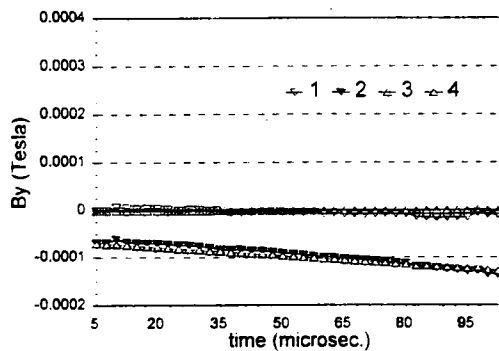
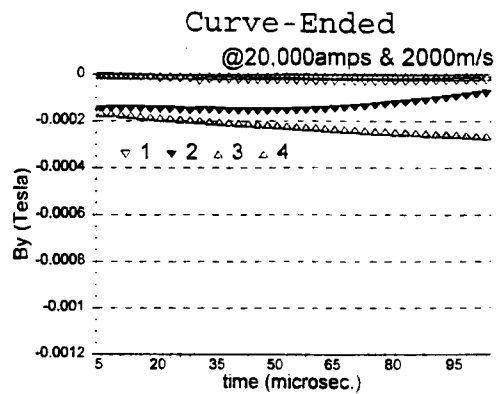
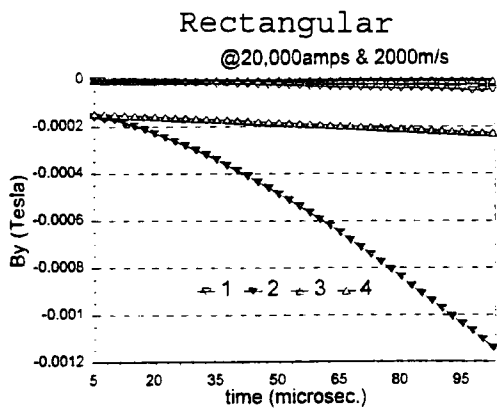
C2 shows most of the activity with the magnetic flux density, although quite small compared to B_x , taking place toward the insulator wall. In C2a for the rectangular electrode, both magnetic flux density points along the insulator wall show a decline, with the corner point having a steeper descent. For the curve-ended electrode, the two points separate as time increases with the corner of the channel point approaching zero with the mid-insulator point having the greater magnitude. In C2b, both insulator points have about the same descent for the rectangular electrode, but the curve-ended electrode increases its values along the insulator wall and exceeds zero in the corner of the channel. In C2c (the back of the plasma), the corner of the channel has an almost continuous decline for both shapes. The middle-of-the-electrode point starts to oscillate as can be seen more clearly in the curve-ended electrode.

C3 for the magnetic flux density in the z-direction sees little change. The z-direction-magnetic-flux-density values are greater in C3 along the insulator wall.



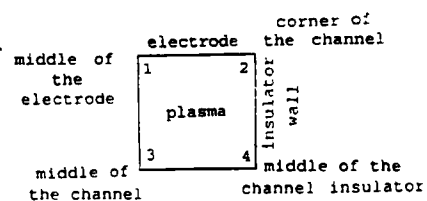
C1 The Magnetic Flux Density in the X-direction vs Time for the Hollow Rectangular (Left) and the Hollow Curve-Ended (Right) Electrode Accelerators at the Front, 9 cm from the Back, and the Back.

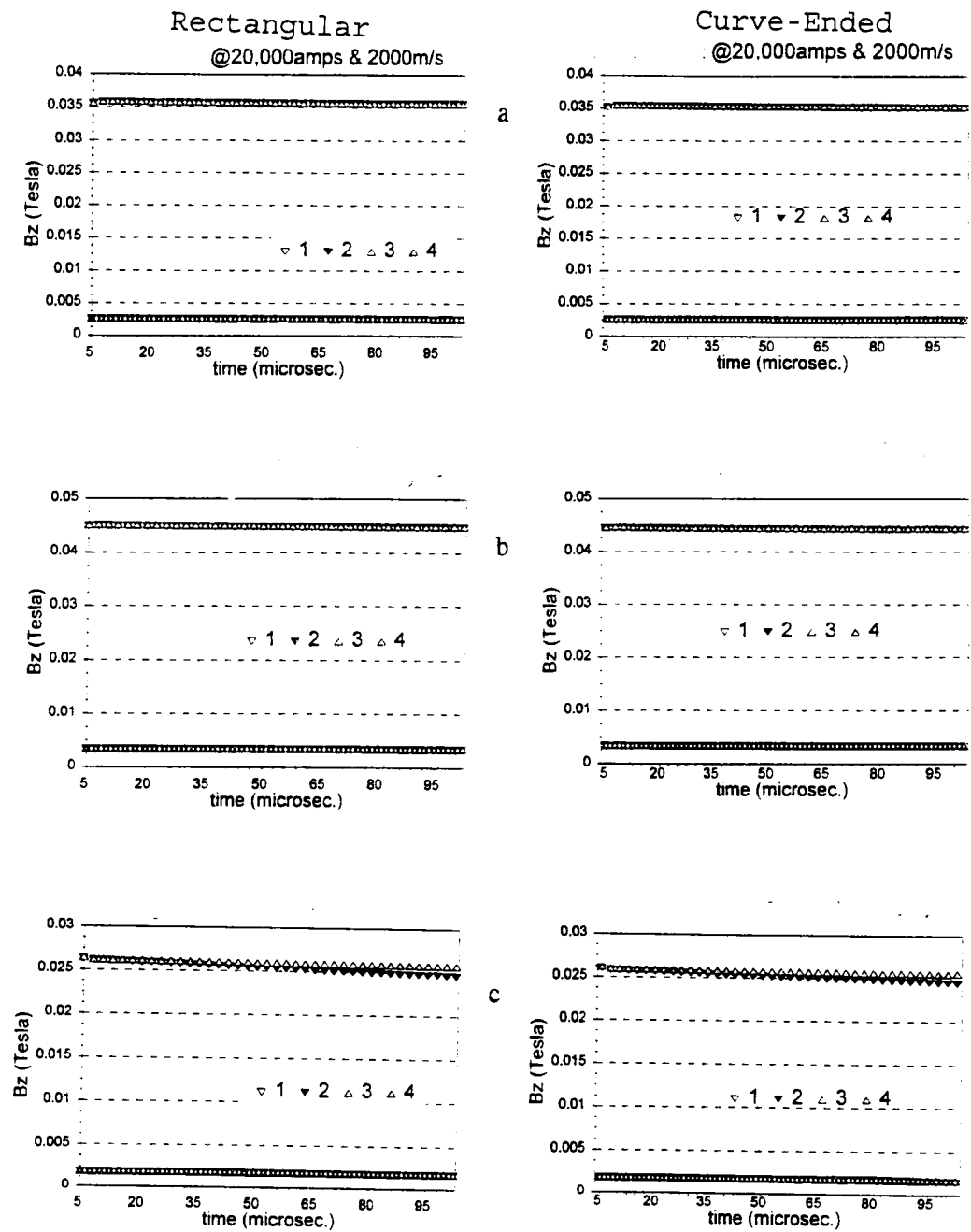




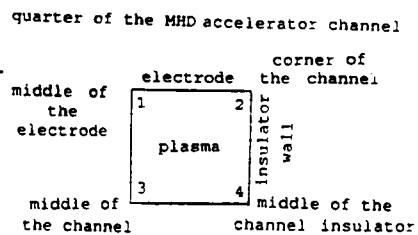
quarter of the MHD accelerator channel

C2 The Magnetic Flux Density in the Y-direction vs Time for the Hollow Rectangular (Left) and the Hollow Curve-Ended (Right) Electrode Accelerators at the Front, 9 cm from the Back, and the Back.





C3 The Magnetic Flux Density in the Z-direction vs Time for the Hollow Rectangular (Left) and the Hollow Curve-Ended (Right) Electrode Accelerators at the Front, 9 cm from the Back, and the Back.



D CURRENT DENSITY

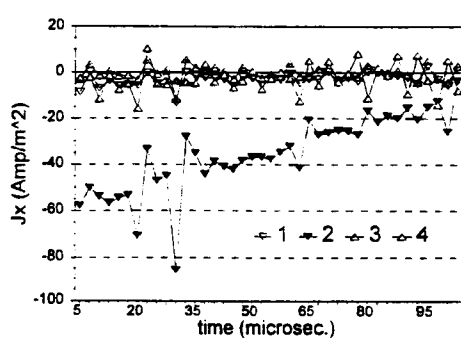
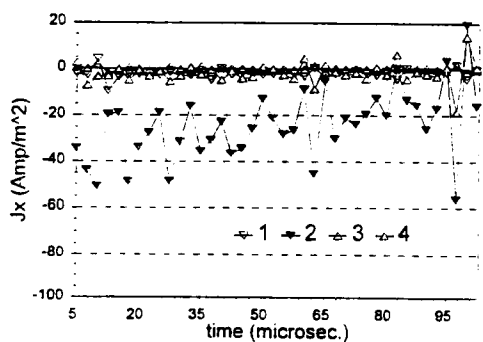
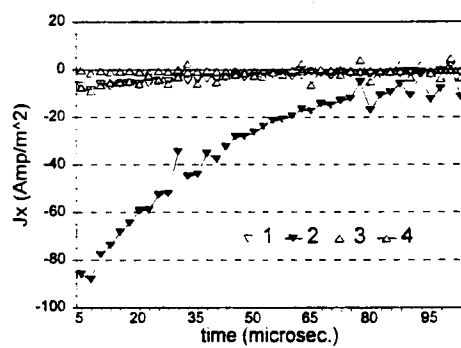
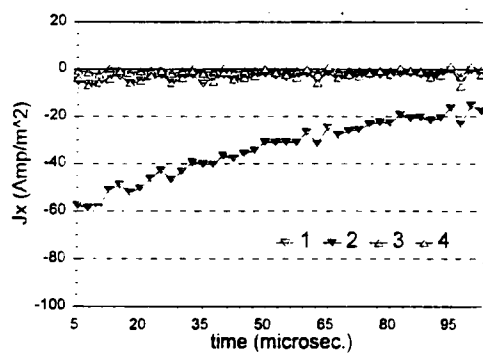
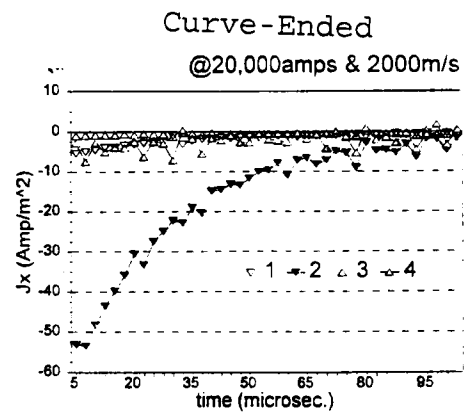
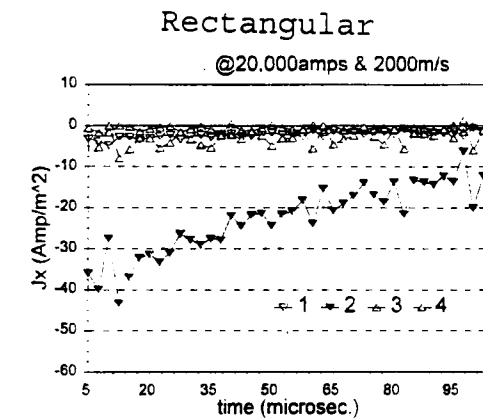
In D1 through D3, four points are monitored over a time interval from 5 to 100 microseconds. These points, like the points of the magnetic flux density, are located on the four corners of the channel in the quarter of the MHD accelerator. One is located just under the middle of the electrode. Two is located in the corner where the electrode, the channel, and the channel insulator meet. Three is located in the middle of the channel. Four is located in the middle of the channel insulator. These points are by no means where the maximum or minimum properties occur; they are merely arbitrary points to show trends in the properties. D1 - D3 compare the results from a hollow rectangular electrode shape to one with curved ends. The current density of D1a represents the front of the plasma; D1b represents 9 cm from the back; and D1c represents the back. D2 and D3 show the current density in the y- and z-directions, respectively.

D1 shows the simulated current density in the x-direction as each of the four points approach zero. In each examined depth of the plasma, the hollow, curve-ended electrode not only approaches zero faster than the hollow, rectangular electrode, but also shows less oscillation. The point of most concern is in the corner of the channel. The hollow, curve-ended electrode has a greater value, but since

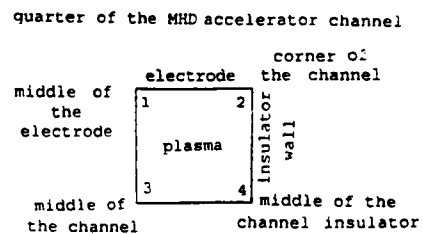
this value is best being close to zero, it reaches zero before the hollow, rectangular electrode. The oscillation in the hollow, curve-ended electrode is partially due to the inability to eliminate small corners in the finite element software.

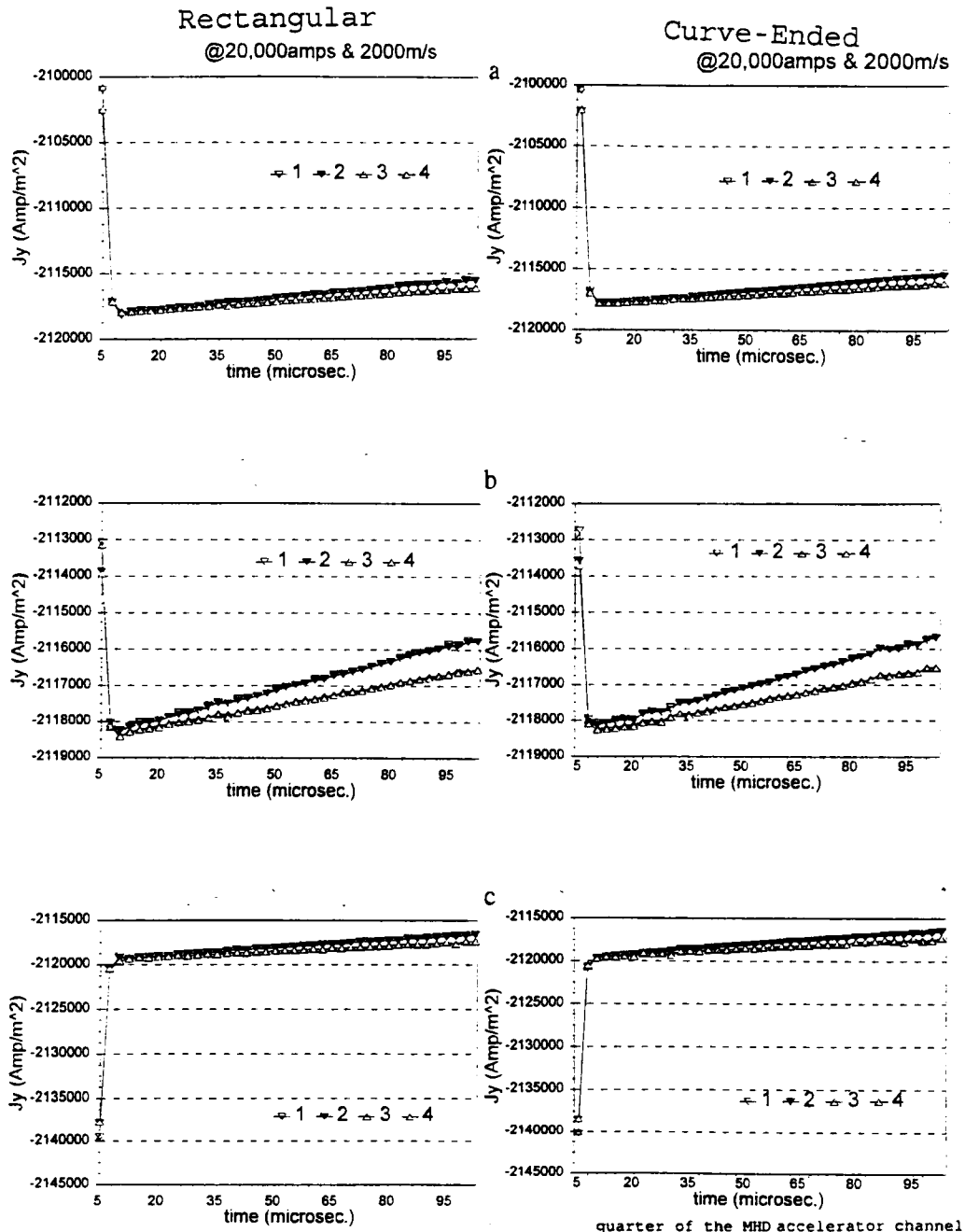
In D2, the current density in the y-direction passing through the plasma is desired to be a large negative number. By 10 microseconds, the system has reached a consistent value. The current density in the y-direction after 10 microseconds steadily decreases as time increases. The larger magnitudes are observed in the back of the plasma. Also at each depth length in the plasma, the values along the electrode are less than they are along the horizontal middle.

D3 shows the result of forcing the current to travel through the plasma. The simulated current density in the z-direction is highest along the electrode wall, particularly in the middle of the electrode. The hollow, rectangular electrode has a constant increase in this direction of the current density, although its values start lower. The hollow, curve-ended electrode, on the other hand, starts at a higher value but declines with time. Also noteworthy is the hollow, curve-ended electrode in D3a. Here, in the front of the plasma, the current density in the z-direction in the corner of the channel is close to zero where it is preferred.

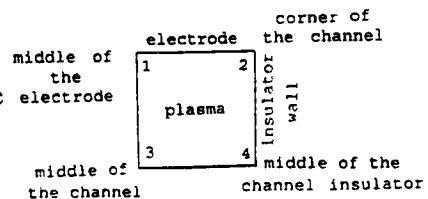


D1 The Current Density in the X-direction vs Time for the Hollow Rectangular (Left) and the Hollow Curve-Ended (Right) Electrode Accelerators at the Front, 9 cm from the Back, and the Back.



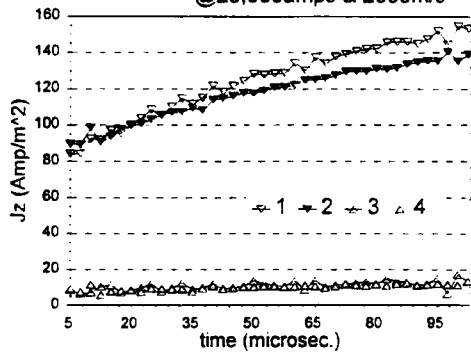


D2 The Current Density in the Y-direction vs Time for the Hollow Rectangular (Left) and the Hollow Curve-Ended (Right) Electrode Accelerators at the Front, 9 cm from the Back, and the Back.



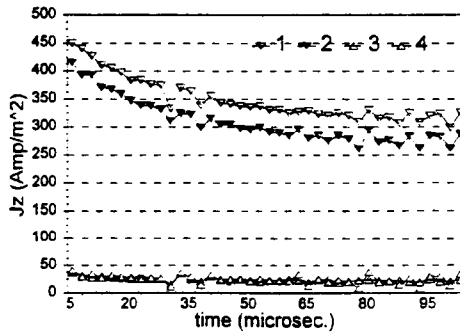
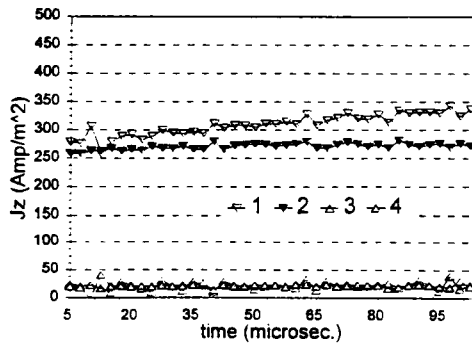
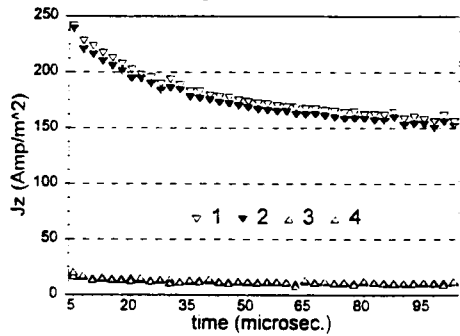
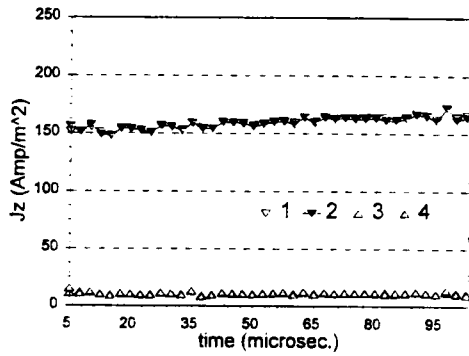
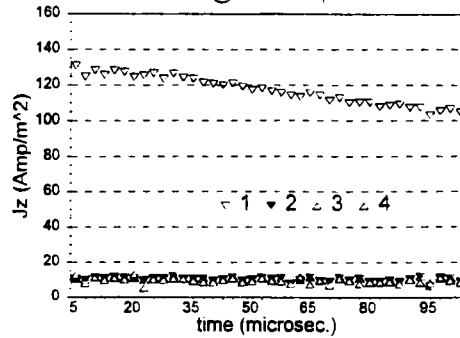
Rectangular

@20,000amps & 2000m/s



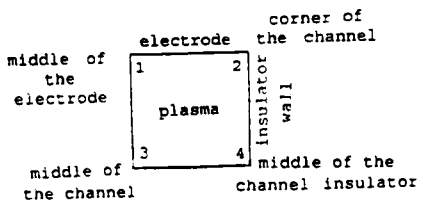
Curve-Ended

@20,000amps & 2000m/s



D3 The Current Density in the Z-direction vs Time for the Hollow Rectangular (Left) and the Hollow Curve-Ended (Right) Electrode Accelerators at the Front, 9 cm from the Back, and the Back.

quarter of the MHD accelerator channel



E MAGNETIC FORCE

Appendix E1 shows the magnetic force in the x-direction. It is calculated from the x component of the $\mathbf{J} \times \mathbf{B}$ equation,

$$F_x = J_y * B_z - J_z * B_y.$$

The results of F_x are fairly constant throughout the depth of the plasma. The points located along the vertical middle remain near zero. The points located along the insulator wall have a larger magnitude, with the exception in the back of the plasma with the hollow, curve-ended electrode. Here the corner-of-the-channel point is close to zero.

In E2, the magnetic force in the y-direction is small. It is calculated from the y-component of the $\mathbf{J} \times \mathbf{B}$ equation,

$$F_y = J_z * B_x - J_x * B_z.$$

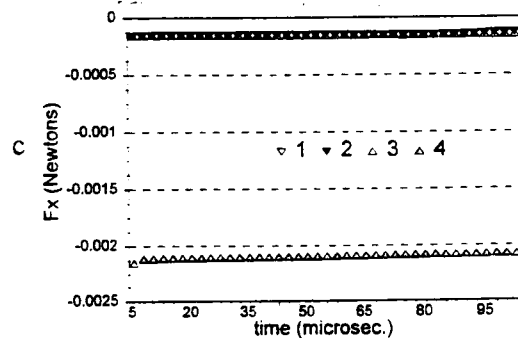
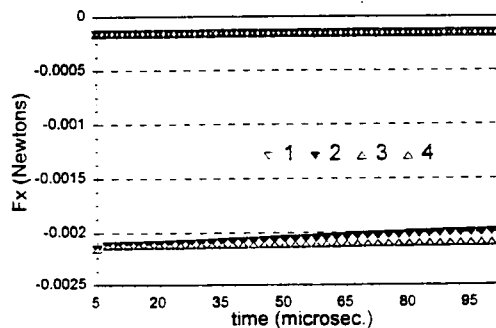
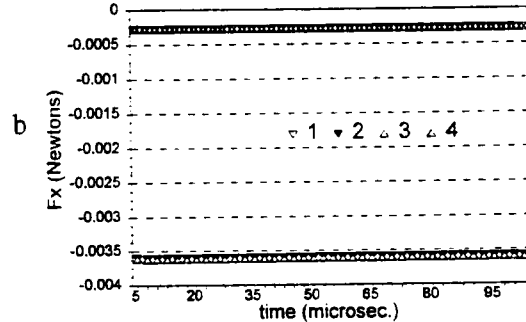
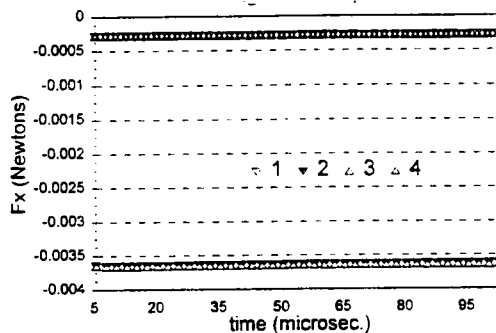
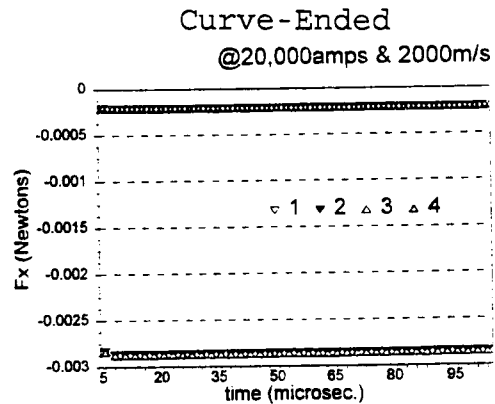
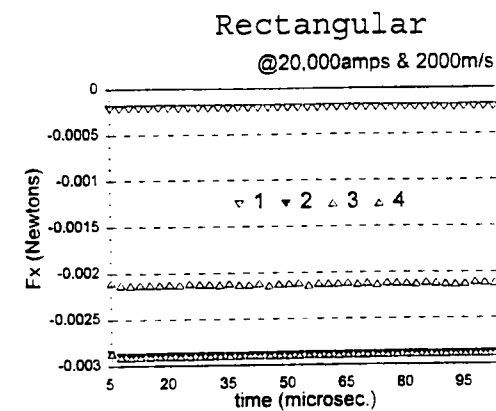
The trend determined by the first term to the right of the equality sign sets the magnitude change because of the relatively larger B_x term and the little change of the other terms. The points along the horizontal middle stay relatively close to zero with one exception on the hollow, curve-ended electrode. The hollow, rectangular electrode has an undesired increase in the simulated values of the magnetic force in the y-direction along the electrode wall as time increases. This value is also greater in the middle of the plasma. Along the electrode wall, the hollow, curve-

ended electrode decreases its magnetic force in the y-direction as time increases.

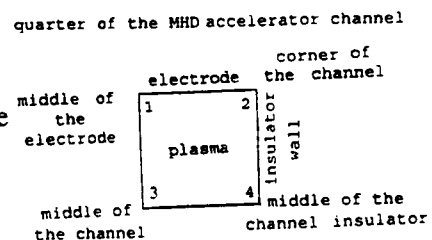
E3 shows the magnetic force in the z-direction that must be uniform. Its $\mathbf{J} \times \mathbf{B}$ equation is

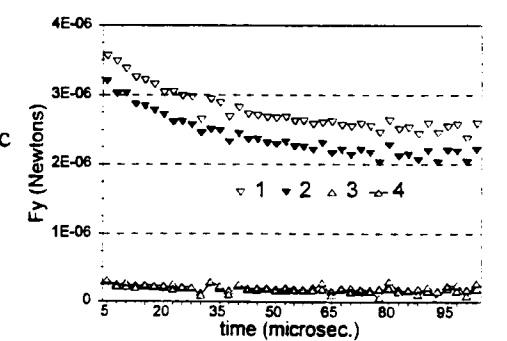
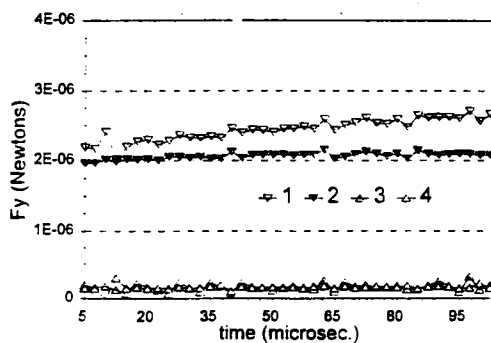
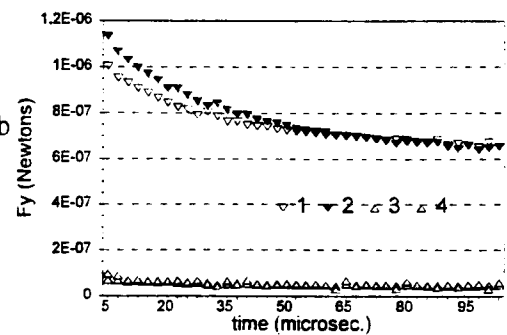
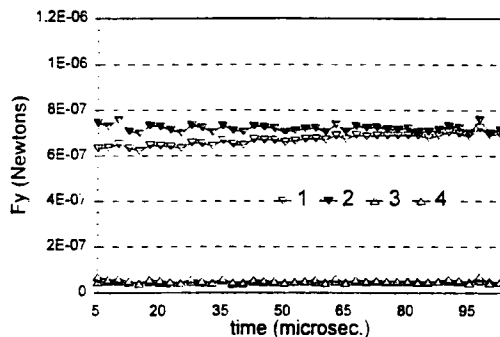
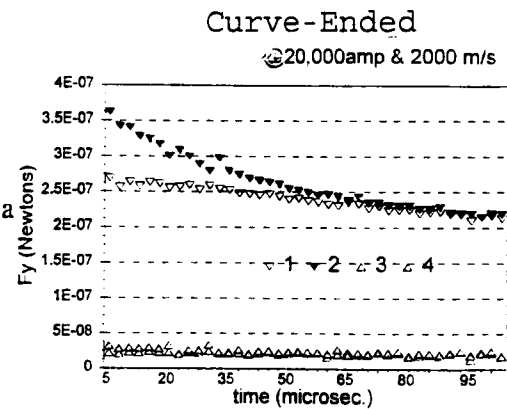
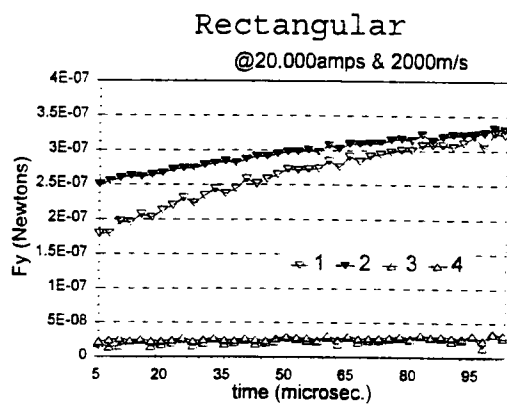
$$F_z = J_x * B_y - J_y * B_x.$$

Both electrode shapes show the same trends. E3a shows the accelerating force highest along the insulator wall, but the force reverses in the plasma to become the lowest value along the insulator wall in the back of the plasma (see E3c). The hollow, rectangular electrode shape has lower accelerating forces in the back of the plasma as compared with the hollow, curve-ended electrode and larger forces in the front. This difference reduces the overall change in the accelerating force, front to back. The force of the hollow, curve-ended electrode shape varies less within the values at the four points throughout the plasma. This produces a more uniform flow in the accelerating force, front to back. Between the front of the plasma and 9 cm from the back of the plasma (see E3a and E3b), the value at the corner of the channel has increased at a much slower rate than the values at the other points. E3b shows the horizontal-middle points increasing the force at a quicker rate than the points along the insulator wall. It reaches its highest value at the back of the plasma.

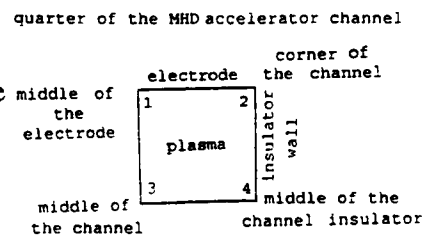


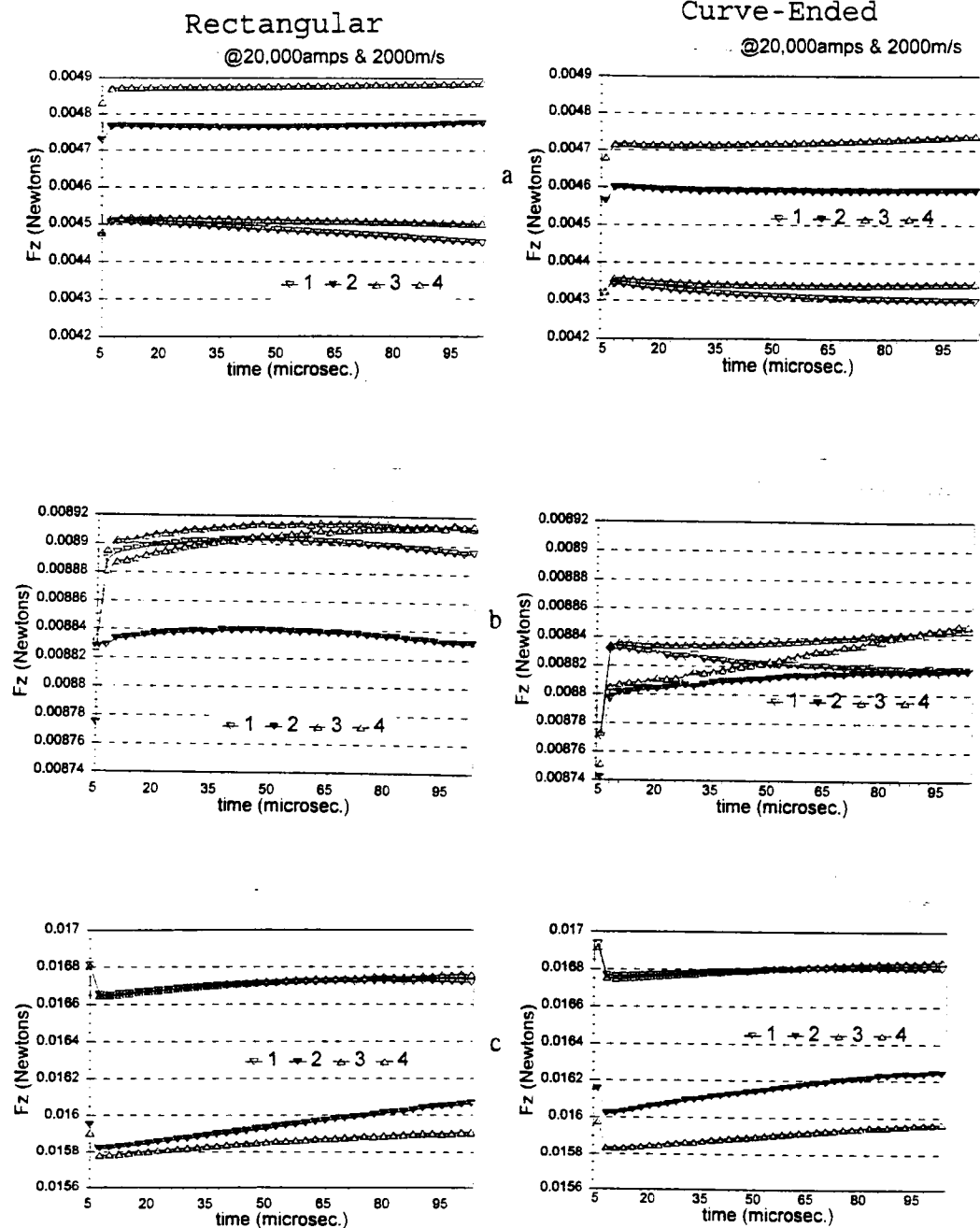
E1 The Magnetic Force in the X-direction vs Time for the Hollow Rectangular (Left) and the Hollow Curve-Ended (Right) Electrode Accelerators at the Front, 9 cm from the Back, and the Back.



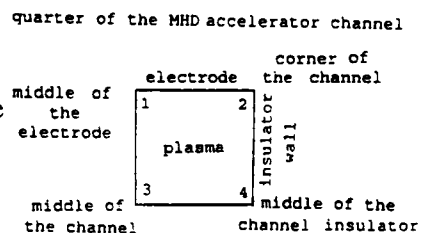


E2 The Magnetic Force in the Y-direction vs Time for the Hollow Rectangular (Left) and the Hollow Curve-Ended (Right) Electrode Accelerators at the Front, 9 cm from the Back, and the Back.





E3 The Magnetic Force in the Z-direction vs Time for the Hollow Rectangular (Left) and the Hollow Curve-Ended (Right) Electrode Accelerators at the Front, 9 cm from the Back, and the Back.



F UNIFORMITY OF THE REMAINING TABLE 3 SHAPES

F1, F3, and F5 show the quartered MHD accelerator with the thin-rectangular, with the solid-rectangular, and with the solid-elliptical electrode shapes, respectively. Only the dimensions of the electrode have been included. The dimensions of Figures 6 and 7 are all constant in these appendices with the exception of the electrode's dimensions.

F2, F4, and F6 show the standard deviation percentage difference (SDPD) of the accelerating force, F_z . In these appendices, the a's (i.e., F2a, F4a) represent the SDPD at a time of 5 microseconds. The b's, c's, and d's represent the SDPD at a time of 10, 25, and 50 microseconds, respectively.

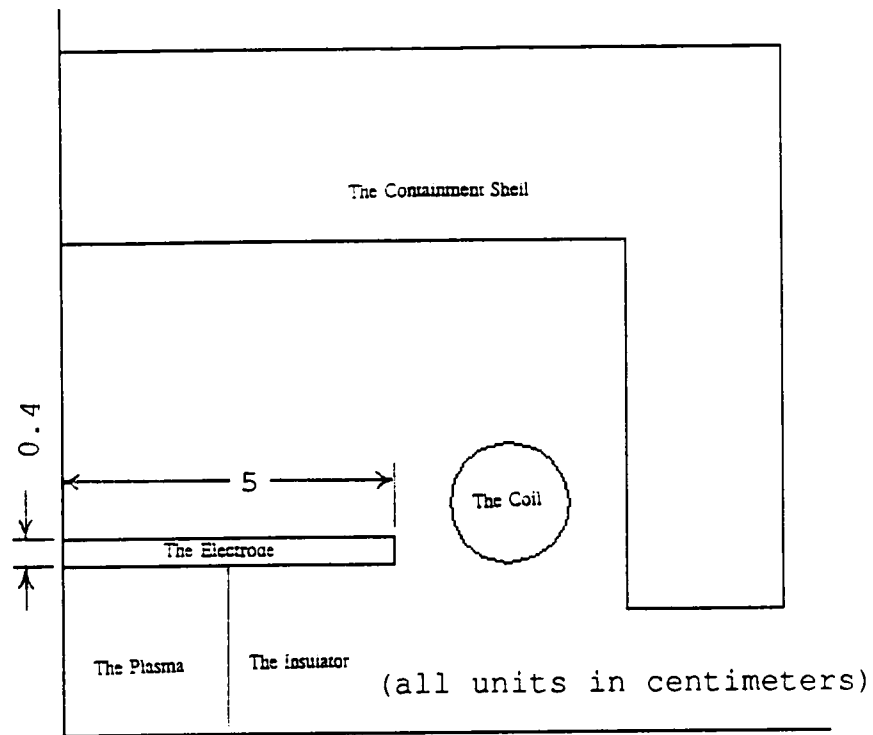
The two columns on the left of each of these even-numbered figures show the distribution of the SDPD at the points examined in each of the levels or depths as it relates to the other points of that level or depth. For example, in F2a of the thin-rectangular-electrode shape at a time of 5 microseconds and at level 11 (or the back of the plasma), a SDPD of 1.81 is observed in the center of the channel next to the electrode. All of the points are compared by an average accelerating force, $(F_z)_{avg}$, using the SDPD equation:

$$\text{SDPD} = \frac{(F_z)_{\text{@ the point}} - (F_z)_{\text{avg}}}{(F_z)_{\text{avg}}} * 100.$$

The average accelerating force is the average of all the forces examined at the level or depth in the plasma. A positive SDPD results from a force greater than the average, and, hence, a negative SDPD results from a force less than the average. A zero SDPD or a negative zero SDPD results in a number equal to or very close to the average accelerating force at that level.

These numbers rate the uniformity simulated by their closeness to zero. For example; in the F2, F4, or F6; levels 17 and 18 (located in the middle of the plasma) are much closer to uniformity than the back (level 11) or the front (level 20) of the plasma.

The right-hand column on the even-numbered appendices gives the average or mean accelerating force represented by each level or depth. The SDPD is also shown for each level.



F1 The Quarter of the Thin-Rectangular-Shaped-Electrode,
MHD Accelerator

Level 11 (15 cm - the Back)	Level 16 (11.06 cm)	Level = 11 (15 cm - the Back)
1.81 1.60 1.18 0.52 -0.41 -1.76 -3.49	0.32 0.28 0.20 0.08 -0.09 -0.30 -0.59	Mean 0.833 N
1.81 1.61 1.19 0.53 -0.39 -1.74 -3.45	0.32 0.28 0.20 0.08 -0.09 -0.30 -0.56	S.D. % Diff 1.773 %
1.83 1.63 1.21 0.56 -0.36 -1.69 -3.38	0.32 0.28 0.21 0.09 -0.07 -0.28 -0.56	
1.84 1.63 1.22 0.56 -0.32 -1.64 -3.30	0.32 0.28 0.20 0.09 -0.07 -0.27 -0.54	Level = 12 (14.7 cm)
1.85 1.64 1.24 0.60 -0.29 -1.58 -3.22	0.31 0.28 0.20 0.09 -0.07 -0.27 -0.52	Mean 0.811 N
1.85 1.65 1.25 0.62 -0.26 -1.54 -3.15	0.32 0.28 0.21 0.09 -0.06 -0.25 -0.51	S.D. % Diff 1.622 %
1.85 1.66 1.25 0.63 -0.25 -1.51 -3.09	0.32 0.28 0.21 0.10 -0.05 -0.24 -0.49	
		Level = 13 (14.25 cm)
		Mean 0.781 N
		S.D. % Diff 1.298 %
Level 12 (14.7 cm)	Level 17 (9.78 cm)	Level = 14 (13.58 cm)
1.69 1.49 1.08 0.44 -0.45 -1.63 -3.16	-0.02 -0.02 -0.02 -0.00 0.03 0.10 0.22	Mean 0.742 N
1.70 1.50 1.09 0.45 -0.44 -1.61 -3.12	-0.03 -0.03 -0.02 -0.01 0.02 0.08 0.20	S.D. % Diff 0.936 %
1.71 1.51 1.11 0.48 -0.40 -1.56 -3.05	-0.03 -0.03 -0.03 -0.02 0.01 0.06 0.16	
1.72 1.52 1.12 0.50 -0.37 -1.51 -2.97	-0.02 -0.03 -0.04 -0.03 -0.01 0.03 0.11	Level = 15 (12.57 cm)
1.73 1.53 1.13 0.52 -0.34 -1.46 -2.89	-0.04 -0.04 -0.05 -0.04 -0.03 -0.00 0.07	Mean 0.69 N
1.74 1.54 1.15 0.54 -0.31 -1.42 -2.82	-0.05 -0.05 -0.05 -0.05 -0.04 -0.02 0.04	S.D. % Diff 0.494 %
1.74 1.54 1.15 0.55 -0.30 -1.39 -2.76	-0.05 -0.05 -0.06 -0.06 -0.06 -0.03 0.02	
		Level = 16 (11.06 cm)
		Mean 0.619 N
		S.D. % Diff 0.296 %
Level 13 (14.25 cm)	Level 18 (6 cm)	Level = 17 (9.78 cm)
1.41 1.23 0.86 0.30 -0.45 -1.39 -2.46	0.15 0.15 0.15 0.15 0.15 0.13 0.10	Mean 0.535 N
1.41 1.23 0.87 0.31 -0.44 -1.37 -2.43	0.14 0.14 0.14 0.13 0.12 0.08 0.02	S.D. % Diff 0.065 %
1.43 1.25 0.86 0.34 -0.40 -1.32 -2.37	0.13 0.13 0.12 0.11 0.07 0.01 -0.09	
1.43 1.26 0.90 0.36 -0.37 -1.27 -2.29	0.11 0.10 0.09 0.06 0.00 -0.09 -0.25	Level = 18 (6 cm)
1.44 1.26 0.91 0.37 -0.34 -1.22 -2.21	0.09 0.08 0.05 0.01 -0.07 -0.20 -0.42	Mean 0.433 N
1.45 1.27 0.92 0.39 -0.31 -1.18 -2.15	0.07 0.06 0.03 -0.02 -0.12 -0.28 -0.54	S.D. % Diff 0.12 %
1.45 1.28 0.93 0.40 -0.30 -1.16 -2.09	0.06 0.05 0.01 -0.05 -0.15 -0.32 -0.62	
		Level = 19 (3.59 cm)
		Mean 0.34 N
		S.D. % Diff 0.836 %
Level 14 (13.58 cm)	Level 19 (3.59 cm)	Level = 20 (Front of Plasma)
1.02 0.88 0.61 0.20 -0.34 -1.01 -1.81	-0.75 -0.64 -0.41 -0.06 0.45 1.18 2.20	Mean 0.212 N
1.02 0.89 0.61 0.21 -0.33 -0.99 -1.78	-0.76 -0.66 -0.44 -0.10 0.40 1.09 2.06	S.D. % Diff 2.517 %
1.04 0.90 0.63 0.23 -0.30 -0.95 -1.72	-0.76 -0.69 -0.48 -0.16 0.30 0.94 1.82	
1.04 0.91 0.64 0.24 -0.27 -0.90 -1.65	-0.83 -0.73 -0.54 -0.25 0.16 0.72 1.49	
1.05 0.91 0.65 0.26 -0.25 -0.86 -1.58	-0.87 -0.78 -0.61 -0.34 0.03 0.51 1.15	
1.05 0.92 0.66 0.28 -0.22 -0.82 -1.52	-0.89 -0.81 -0.65 -0.41 -0.08 0.34 0.90	
1.05 0.92 0.66 0.28 -0.21 -0.79 -1.47	-0.91 -0.83 -0.68 -0.45 -0.15 0.25 0.73	
Level 15 (12.57 cm)	Level 20 (the Front)	
0.56 0.47 0.31 0.08 -0.23 -0.58 -0.95	-2.64 -2.22 -1.39 -0.15 1.47 3.45 5.72	
0.56 0.48 0.32 0.08 -0.22 -0.57 -0.93	-2.67 -2.26 -1.44 -0.23 1.35 3.25 5.42	
0.57 0.49 0.33 0.10 -0.20 -0.53 -0.86	-2.73 -2.33 -1.54 -0.38 1.12 2.91 4.89	
0.57 0.49 0.34 0.11 -0.18 -0.50 -0.83	-2.81 -2.43 -1.67 -0.57 0.84 2.47 4.20	
0.57 0.50 0.34 0.12 -0.15 -0.47 -0.78	-2.90 -2.53 -1.81 -0.76 0.55 2.02 3.50	
0.58 0.50 0.35 0.14 -0.13 -0.43 -0.73	-2.96 -2.60 -1.90 -0.90 0.33 1.67 2.96	
0.58 0.50 0.35 0.14 -0.13 -0.42 -0.70	-3.00 -2.65 -1.96 -0.99 0.19 1.48 2.63	

F2 The Uniformity of the Magnetic Force or Accelerating Force for the Thin-Rectangular Electrode at 20,000 amps and 2,000 m/s at each Depth Simulated Using the Standard Deviation Percentage Difference Method. (The Numbers in Each block represents a percentage.)
a) At 5 Microseconds.

Level 11 (15 cm - the Back)

1.77	1.57	1.15	0.51	-0.39	-1.72	-3.41
1.77	1.57	1.16	0.52	-0.38	-1.70	-3.37
1.79	1.59	1.19	0.55	-0.34	-1.64	-3.30
1.79	1.59	1.20	0.57	-0.32	-1.60	-3.22
1.79	1.60	1.20	0.58	-0.28	-1.55	-3.14
1.80	1.61	1.22	0.60	-0.25	-1.49	-3.07
1.79	1.60	1.21	0.60	-0.25	-1.48	-3.00

Level 12 (14.7 cm)

1.65	1.45	1.05	0.43	-0.44	-1.55	-3.07
1.65	1.46	1.06	0.44	-0.43	-1.57	-3.04
1.67	1.48	1.09	0.48	-0.38	-1.51	-2.96
1.67	1.48	1.09	0.49	-0.36	-1.47	-2.89
1.67	1.48	1.10	0.50	-0.33	-1.42	-2.81
1.69	1.50	1.11	0.52	-0.30	-1.37	-2.74
1.68	1.49	1.11	0.52	-0.30	-1.36	-2.67

Level 13 (14.25 cm)

1.36	1.19	0.83	0.29	-0.44	-1.35	-2.39
1.37	1.19	0.84	0.30	-0.42	-1.33	-2.36
1.39	1.21	0.86	0.33	-0.38	-1.27	-2.28
1.39	1.22	0.87	0.35	-0.36	-1.23	-2.21
1.38	1.22	0.88	0.36	-0.33	-1.19	-2.13
1.40	1.23	0.89	0.38	-0.30	-1.13	-2.06
1.39	1.22	0.88	0.38	-0.30	-1.11	-2.00

Level 14 (13.58 cm)

0.98	0.85	0.58	0.19	-0.33	-0.97	-1.74
0.98	0.85	0.59	0.20	-0.32	-0.95	-1.71
1.00	0.87	0.61	0.22	-0.28	-0.90	-1.64
1.00	0.87	0.61	0.23	-0.26	-0.87	-1.58
1.00	0.87	0.62	0.24	-0.24	-0.83	-1.52
1.01	0.88	0.63	0.27	-0.21	-0.78	-1.45
1.00	0.87	0.63	0.27	-0.20	-0.75	-1.39

Level 15 (12.57 cm)

0.53	0.45	0.29	0.07	-0.22	-0.55	-0.91
0.53	0.45	0.30	0.07	-0.21	-0.54	-0.88
0.55	0.47	0.32	0.10	-0.18	-0.50	-0.83
0.54	0.47	0.32	0.10	-0.17	-0.47	-0.79
0.54	0.47	0.32	0.11	-0.15	-0.44	-0.73
0.55	0.48	0.33	0.13	-0.12	-0.40	-0.68
0.54	0.47	0.32	0.12	-0.12	-0.39	-0.64

Level 16 (11.06 cm)

0.31	0.27	0.19	0.07	-0.09	-0.30	-0.57
0.31	0.27	0.19	0.07	-0.09	-0.29	-0.56
0.32	0.28	0.21	0.09	-0.06	-0.27	-0.53
0.31	0.27	0.20	0.09	-0.06	-0.26	-0.52
0.30	0.26	0.19	0.08	-0.07	-0.26	-0.51
0.31	0.27	0.20	0.09	-0.05	-0.24	-0.50
0.30	0.27	0.20	0.09	-0.05	-0.23	-0.47

Level 17 (9.78 cm)

-0.02	-0.02	-0.01	-0.00	0.02	0.08	0.20
-0.02	-0.02	-0.02	-0.01	0.02	0.07	0.18
-0.01	-0.01	-0.02	-0.01	0.01	0.05	0.15
-0.02	-0.02	-0.03	-0.03	-0.02	0.01	0.09
-0.03	-0.03	-0.04	-0.04	-0.04	-0.01	0.04
-0.03	-0.03	-0.04	-0.04	-0.04	-0.02	0.02
-0.04	-0.04	-0.05	-0.06	-0.06	-0.03	0.00

Level 18 (6 cm)

0.18	0.18	0.17	0.16	0.14	0.11	0.05
0.17	0.17	0.16	0.14	0.11	0.06	-0.03
0.18	0.17	0.16	0.13	0.07	-0.01	-0.14
0.15	0.14	0.11	0.07	-0.00	-0.12	-0.31
0.12	0.11	0.07	0.01	-0.08	-0.23	-0.48
0.11	0.09	0.06	-0.01	-0.13	-0.31	-0.61
0.09	0.07	0.03	-0.05	-0.17	-0.36	-0.69

Level 17 (9.78 cm)

-0.70	-0.59	-0.38	-0.04	0.45	1.15	2.14
-0.71	-0.61	-0.40	-0.07	0.40	1.07	2.01
-0.73	-0.64	-0.44	-0.13	0.30	0.92	1.76
-0.79	-0.70	-0.51	-0.24	0.15	0.69	1.41
-0.83	-0.74	-0.58	-0.33	0.01	0.46	1.06
-0.85	-0.78	-0.63	-0.41	-0.10	0.30	0.81
-0.88	-0.81	-0.67	-0.46	-0.18	0.20	0.63

Level 20 (the Front)

-2.61	-2.19	-1.36	-0.12	1.50	3.48	5.76
-2.65	-2.24	-1.42	-0.21	1.37	3.27	5.44
-2.71	-2.31	-1.52	-0.36	1.14	2.92	4.89
-2.80	-2.42	-1.67	-0.57	0.83	2.45	4.18
-2.90	-2.53	-1.81	-0.77	0.53	1.99	3.45
-2.96	-2.61	-1.91	-0.92	0.31	1.64	2.91
-3.01	-2.66	-1.98	-1.01	0.16	1.44	2.57

Level = 11 (15 cm - the Back)

Mean 0.825 N
S.D. % Diff 1.728 %

Level = 12 (14.7 cm)

Mean 0.803 N
S.D. % Diff 1.575 %

Level = 13 (14.25 cm)

Mean 0.774 N
S.D. % Diff 1.253 %

Level = 14 (13.58 cm)

Mean 0.735 N
S.D. % Diff 0.895 %

Level = 15 (12.57 cm)

Mean 0.685 N
S.D. % Diff 0.465 %

Level = 16 (11.06 cm)

Mean 0.617 N
S.D. % Diff 0.287 %

Level = 17 (9.78 cm)

Mean 0.536 N
S.D. % Diff 0.056 %

Level = 18 (6 cm)

Mean 0.436 N
S.D. % Diff 0.206 %

Level = 19 (3.59 cm)

Mean 0.343 N
S.D. % Diff 0.801 %

Level = 20 (Front of Plasma)

Mean 0.214 N
S.D. % Diff 2.513 %

F2 Continued.

b) At 10 Microseconds.

Level 11 (15 cm - the Back)

1.75	1.56	1.15	0.52	-0.39	-1.71	-3.39
1.78	1.58	1.17	0.54	-0.36	-1.68	-3.35
1.80	1.61	1.21	0.57	-0.32	-1.62	-3.26
1.78	1.59	1.20	0.55	-0.32	-1.59	-3.22
1.77	1.58	1.18	0.56	-0.29	-1.55	-3.14
1.78	1.59	1.20	0.59	-0.26	-1.48	-3.07
1.77	1.58	1.18	0.57	-0.27	-1.51	-2.94

Level 16 (11.06 cm)

0.31	0.27	0.19	0.07	-0.09	-0.29	-0.56
0.32	0.28	0.20	0.08	-0.08	-0.28	-0.55
0.34	0.30	0.23	0.12	-0.04	-0.24	-0.50
0.30	0.27	0.19	0.08	-0.06	-0.26	-0.53
0.28	0.24	0.16	0.05	-0.09	-0.28	-0.54
0.30	0.27	0.19	0.08	-0.06	-0.25	-0.51
0.29	0.26	0.19	0.09	-0.05	-0.21	-0.47

Level = 11 (15 cm - the Back)

Mean 0.826 N
S.D. % Diff 1.719 %

Level = 12 (14.7 cm)

Mean 0.804 N
S.D. % Diff 1.562 %

Level = 13 (14.25 cm)

Mean 0.774 N
S.D. % Diff 1.243 %

Level 12 (14.7 cm)

1.64	1.45	1.06	0.43	-0.44	-1.58	-3.05
1.65	1.46	1.07	0.45	-0.41	-1.55	-3.01
1.68	1.49	1.10	0.50	-0.36	-1.48	-2.93
1.66	1.47	1.08	0.49	-0.35	-1.46	-2.88
1.65	1.46	1.07	0.48	-0.34	-1.42	-2.80
1.67	1.48	1.10	0.51	-0.30	-1.36	-2.71
1.64	1.45	1.07	0.48	-0.33	-1.37	-2.61

Level 17 (9.78 cm)

-0.03	-0.02	-0.02	-0.00	0.03	0.10	0.23
-0.03	-0.02	-0.02	0.00	0.03	0.09	0.21
-0.01	-0.01	-0.01	-0.01	0.02	0.07	0.18
-0.03	-0.03	-0.03	-0.04	-0.03	0.01	0.08
-0.04	-0.04	-0.04	-0.05	-0.04	-0.03	0.02
-0.03	-0.03	-0.04	-0.04	-0.03	-0.02	0.02
-0.05	-0.05	-0.05	-0.06	-0.06	-0.03	-0.01

Level = 14 (13.58 cm)

Mean 0.736 N
S.D. % Diff 0.884 %

Level = 15 (12.57 cm)

Mean 0.686 N
S.D. % Diff 0.458 %

Level = 16 (11.06 cm)

Mean 0.618 N
S.D. % Diff 0.285 %

Level 13 (14.25 cm)

1.36	1.18	0.83	0.30	-0.43	-1.34	-2.37
1.37	1.20	0.84	0.31	-0.41	-1.31	-2.34
1.40	1.23	0.88	0.35	-0.37	-1.25	-2.25
1.38	1.21	0.86	0.34	-0.36	-1.23	-2.20
1.36	1.20	0.86	0.34	-0.34	-1.19	-2.13
1.38	1.21	0.87	0.37	-0.31	-1.12	-2.04
1.35	1.18	0.85	0.35	-0.32	-1.11	-1.95

Level 18 (6 cm)

0.18	0.18	0.18	0.17	0.16	0.13	0.09
0.18	0.18	0.17	0.15	0.12	0.08	0.01
0.20	0.20	0.19	0.16	0.11	0.03	-0.09
0.15	0.14	0.12	0.07	0.00	-0.11	-0.30
0.11	0.09	0.06	-0.00	-0.10	-0.25	-0.51
0.10	0.09	0.05	-0.03	-0.15	-0.34	-0.65
0.07	0.05	-0.00	-0.08	-0.21	-0.39	-0.75

Level = 17 (9.78 cm)

Mean 0.536 N
S.D. % Diff 0.064 %

Level = 18 (6 cm)

Mean 0.436 N
S.D. % Diff 0.222 %

Level = 19 (3.59 cm)

Mean 0.343 N
S.D. % Diff 0.83 %

Level 14 (13.58 cm)

0.97	0.84	0.58	0.19	-0.32	-0.96	-1.73
0.99	0.85	0.59	0.21	-0.30	-0.93	-1.68
1.01	0.88	0.63	0.24	-0.26	-0.88	-1.61
0.99	0.86	0.61	0.23	-0.26	-0.86	-1.58
0.98	0.85	0.60	0.23	-0.25	-0.83	-1.52
0.98	0.86	0.61	0.26	-0.21	-0.77	-1.44
0.95	0.84	0.59	0.24	-0.21	-0.73	-1.35

Level 19 (3.59 cm)

-0.69	-0.59	-0.37	-0.02	0.49	1.21	2.22
-0.70	-0.60	-0.39	-0.05	0.45	1.14	2.11
-0.73	-0.63	-0.43	-0.11	0.35	0.97	1.85
-0.81	-0.72	-0.53	-0.24	0.16	0.70	1.44
-0.86	-0.77	-0.61	-0.35	-0.01	0.45	1.05
-0.88	-0.81	-0.66	-0.43	-0.12	0.28	0.80
-0.95	-0.88	-0.73	-0.52	-0.23	0.16	0.58

Level = 20 (Front of Plasma)

Mean 0.214 N
S.D. % Diff 2.552 %

Level 15 (12.57 cm)

0.52	0.45	0.29	0.07	-0.22	-0.54	-0.89
0.53	0.46	0.30	0.08	-0.20	-0.53	-0.86
0.56	0.48	0.33	0.11	-0.16	-0.48	-0.80
0.53	0.45	0.31	0.10	-0.17	-0.47	-0.79
0.52	0.45	0.31	0.10	-0.15	-0.44	-0.74
0.53	0.46	0.33	0.13	-0.12	-0.39	-0.67
0.51	0.44	0.30	0.11	-0.14	-0.38	-0.63

Level 20 (the Front)

-2.59	-2.16	-1.32	-0.06	1.58	3.60	5.94
-2.63	-2.21	-1.38	-0.16	1.44	3.38	5.60
-2.69	-2.29	-1.49	-0.32	1.20	3.01	5.02
-2.83	-2.44	-1.69	-0.58	0.83	2.47	4.21
-2.97	-2.60	-1.87	-0.82	0.49	1.95	3.41
-3.04	-2.68	-1.97	-0.98	0.25	1.58	2.84
-3.09	-2.74	-2.06	-1.09	0.08	1.38	2.50

F2 Continued.

c) At 25 Microseconds.

Level 11 (15 cm - the Back)

1.76	1.56	1.14	0.54	-0.37	-1.70	-3.35
1.78	1.58	1.16	0.54	-0.34	-1.65	-3.32
1.83	1.65	1.22	0.61	-0.28	-1.56	-3.20
1.77	1.57	1.17	0.56	-0.29	-1.57	-3.17
1.74	1.54	1.13	0.55	-0.29	-1.56	-3.15
1.77	1.59	1.17	0.57	-0.27	-1.47	-3.04
1.70	1.53	1.11	0.50	-0.35	-1.57	-2.82

Level 16 (11.06 cm)

0.32	0.27	0.19	0.08	-0.08	-0.28	-0.53
0.33	0.29	0.21	0.09	-0.07	-0.26	-0.51
0.37	0.34	0.27	0.16	0.01	-0.19	-0.44
0.29	0.26	0.19	0.09	-0.06	-0.26	-0.52
0.23	0.20	0.12	0.01	-0.13	-0.32	-0.57
0.29	0.25	0.17	0.07	-0.07	-0.26	-0.51
0.26	0.23	0.16	0.07	-0.06	-0.20	-0.51

Level=11 (15 cm - the Back)

Mean 0.827 N
S.D. % Diff 1.7 %

Level = 12 (14.7 cm)

Mean 0.805 N
S.D. % Diff 1.538 %

Level = 13 (14.25 cm)

Mean 0.776 N
S.D. % Diff 1.219 %

Level = 14 (13.58 cm)

Mean 0.737 N
S.D. % Diff 0.86 %

Level = 15 (12.57 cm)

Mean 0.686 N
S.D. % Diff 0.441 %

Level = 16 (11.06 cm)

Mean 0.618 N
S.D. % Diff 0.281 %

Level = 17 (9.78 cm)

Mean 0.536 N
S.D. % Diff 0.083 %

Level = 18 (6 cm)

Mean 0.436 N
S.D. % Diff 0.249 %

Level = 19 (3.59 cm)

Mean 0.342 N
S.D. % Diff 0.878 %

Level = 20 (Front of Plasma)

Mean 0.213 N
S.D. % Diff 2.604 %

Level 12 (14.7 cm)

1.64	1.46	1.07	0.45	-0.42	-1.54	-3.01
1.66	1.47	1.08	0.47	-0.40	-1.51	-2.95
1.71	1.52	1.13	0.54	-0.31	-1.43	-2.86
1.63	1.44	1.06	0.48	-0.34	-1.44	-2.85
1.61	1.41	1.02	0.45	-0.37	-1.43	-2.79
1.63	1.44	1.07	0.48	-0.32	-1.36	-2.66
1.57	1.39	1.01	0.42	-0.40	-1.40	-2.50

Level 17 (9.78 cm)

-0.05	-0.04	-0.03	-0.00	0.05	0.13	0.28
-0.04	-0.03	-0.02	0.01	0.06	0.13	0.27
0.00	-0.00	-0.00	0.01	0.04	0.10	0.23
-0.03	-0.04	-0.05	-0.04	-0.03	0.00	0.06
-0.07	-0.07	-0.06	-0.06	-0.05	-0.05	-0.02
-0.04	-0.04	-0.03	-0.03	-0.02	-0.01	0.03
-0.07	-0.07	-0.07	-0.07	-0.07	-0.01	-0.06

Level 13 (14.25 cm)

1.35	1.18	0.83	0.31	-0.41	-1.30	-2.34
1.37	1.20	0.85	0.33	-0.39	-1.28	-2.30
1.42	1.25	0.92	0.39	-0.32	-1.19	-2.19
1.36	1.20	0.86	0.33	-0.35	-1.20	-2.18
1.31	1.14	0.82	0.32	-0.35	-1.19	-2.13
1.33	1.17	0.84	0.35	-0.30	-1.09	-1.99
1.28	1.11	0.77	0.27	-0.37	-1.09	-1.88

Level 18 (6 cm)

0.18	0.18	0.16	0.18	0.18	0.18	0.16
0.19	0.19	0.18	0.17	0.14	0.11	0.07
0.25	0.25	0.24	0.21	0.16	0.09	-0.02
0.16	0.15	0.13	0.09	0.02	-0.09	-0.29
0.08	0.07	0.03	-0.03	-0.12	-0.28	-0.55
0.09	0.07	0.03	-0.05	-0.17	-0.38	-0.70
0.02	-0.01	-0.05	-0.14	-0.27	-0.44	-0.87

Level 14 (13.58 cm)

0.96	0.84	0.59	0.20	-0.31	-0.93	-1.68
0.98	0.86	0.60	0.22	-0.28	-0.90	-1.63
1.04	0.91	0.66	0.28	-0.21	-0.82	-1.54
0.97	0.84	0.60	0.23	-0.25	-0.85	-1.55
0.93	0.80	0.56	0.19	-0.27	-0.84	-1.52
0.94	0.81	0.58	0.23	-0.21	-0.75	-1.39
0.87	0.75	0.53	0.19	-0.23	-0.71	-1.31

Level 19 (3.59 cm)

-0.70	-0.59	-0.36	0.00	0.54	1.29	2.35
-0.70	-0.59	-0.37	-0.01	0.52	1.24	2.25
-0.71	-0.61	-0.40	-0.05	0.42	1.08	1.98
-0.86	-0.75	-0.55	-0.24	0.17	0.72	1.47
-0.91	-0.82	-0.65	-0.38	-0.02	0.44	1.03
-0.94	-0.87	-0.72	-0.47	-0.14	0.28	0.80
-1.07	-1.00	-0.84	-0.60	-0.29	0.12	0.51

Level 15 (12.57 cm)

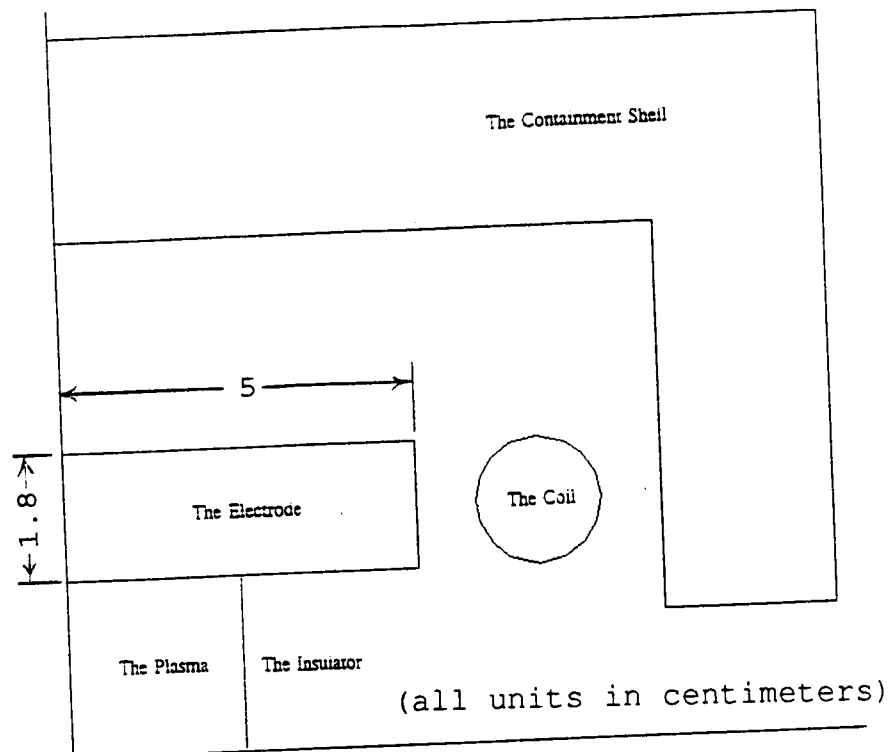
0.52	0.44	0.29	0.08	-0.20	-0.51	-0.85
0.53	0.46	0.31	0.10	-0.18	-0.49	-0.82
0.58	0.50	0.36	0.15	-0.12	-0.43	-0.74
0.51	0.43	0.29	0.09	-0.17	-0.46	-0.78
0.47	0.41	0.28	0.09	-0.16	-0.45	-0.75
0.50	0.44	0.31	0.12	-0.11	-0.37	-0.63
0.45	0.38	0.25	0.07	-0.15	-0.37	-0.64

Level 20 (the Front)

-2.55	-2.12	-1.26	0.01	1.70	3.76	6.18
-2.60	-2.17	-1.33	-0.09	1.53	3.52	5.80
-2.67	-2.25	-1.45	-0.26	1.28	3.12	5.18
-2.87	-2.48	-1.72	-0.61	0.83	2.49	4.25
-3.06	-2.69	-1.96	-0.90	0.42	1.89	3.34
-3.13	-2.77	-2.06	-1.05	0.19	1.51	2.75
-3.20	-2.85	-2.16	-1.19	-0.03	1.34	2.41

F2 Continued.

d) At 50 Microseconds.



F3 The Quarter of the Solid-Rectangular-Shaped-Electrode,
MHD Accelerator

Level 11 (15 cm - the Back) 1.90 1.68 1.25 0.57 -0.39 -1.76 -3.55 1.89 1.68 1.25 0.57 -0.38 -1.77 -3.53 1.91 1.70 1.26 0.58 -0.36 -1.74 -3.48 1.91 1.70 1.27 0.60 -0.34 -1.71 -3.44 1.91 1.70 1.27 0.61 -0.32 -1.67 -3.38 1.92 1.71 1.29 0.63 -0.30 -1.64 -3.33 1.92 1.72 1.30 0.64 -0.29 -1.62 -3.29	Level 16 (11.05 cm) 0.35 0.30 0.22 0.09 -0.08 -0.30 -0.58 0.34 0.30 0.21 0.09 -0.08 -0.30 -0.59 0.35 0.30 0.22 0.10 -0.07 -0.29 -0.57 0.34 0.30 0.22 0.09 -0.08 -0.30 -0.58 0.33 0.29 0.21 0.08 -0.08 -0.30 -0.58 0.34 0.30 0.22 0.09 -0.07 -0.29 -0.57 0.34 0.30 0.22 0.10 -0.07 -0.28 -0.56	Level = 11 (15 cm - the Back) Mean 0.808 N S.D. % Diff 1.843 % Level = 12 (14.7 cm) Mean 0.786 N S.D. % Diff 1.687 % Level = 13 (14.25 cm) Mean 0.758 N S.D. % Diff 1.356 % Level = 14 (13.58 cm) Mean 0.72 N S.D. % Diff 0.979 % Level = 15 (12.57 cm) Mean 0.67 N S.D. % Diff 0.528 % Level = 16 (11.06 cm) Mean 0.604 N S.D. % Diff 0.316 % Level = 17 (9.78 cm) Mean 0.526 N S.D. % Diff 0.057 % Level = 18 (6 cm) Mean 0.432 N S.D. % Diff 0.159 % Level = 19 (3.59 cm) Mean 0.346 N S.D. % Diff 0.836 % Level = 20 (Front of Plasma) Mean 0.225 N S.D. % Diff 2.371 %
Level 12 (14.7 cm) 1.78 1.57 1.15 0.49 -0.43 -1.65 -3.20 1.77 1.57 1.14 0.49 -0.43 -1.64 -3.19 1.79 1.58 1.16 0.50 -0.41 -1.61 -3.14 1.79 1.58 1.16 0.52 -0.39 -1.58 -3.10 1.79 1.59 1.17 0.53 -0.37 -1.55 -3.04 1.80 1.60 1.18 0.54 -0.35 -1.51 -3.00 1.80 1.60 1.19 0.55 -0.34 -1.49 -2.95	Level 17 (9.78 cm) -0.00 -0.00 -0.00 0.01 0.03 0.09 0.20 -0.01 -0.01 -0.01 -0.00 0.02 0.07 0.18 -0.01 -0.01 -0.01 -0.01 0.01 0.06 0.15 -0.02 -0.03 -0.03 -0.03 -0.02 0.02 0.09 -0.04 -0.04 -0.05 -0.05 -0.05 -0.02 0.04 -0.03 -0.04 -0.04 -0.05 -0.05 -0.03 0.01 -0.03 -0.04 -0.05 -0.05 -0.06 -0.04 -0.00	
Level 13 (14.25 cm) 1.49 1.30 0.92 0.34 -0.43 -1.40 -2.50 1.48 1.29 0.92 0.34 -0.43 -1.39 -2.49 1.49 1.31 0.93 0.36 -0.41 -1.36 -2.44 1.49 1.31 0.94 0.37 -0.39 -1.33 -2.40 1.49 1.31 0.94 0.38 -0.37 -1.30 -2.35 1.50 1.32 0.95 0.40 -0.35 -1.27 -2.30 1.51 1.33 0.96 0.40 -0.34 -1.25 -2.26	Level 18 (6 cm) 0.13 0.13 0.14 0.14 0.13 0.11 0.06 0.11 0.12 0.12 0.11 0.09 0.06 -0.01 0.12 0.12 0.11 0.09 0.06 0.00 -0.10 0.10 0.10 0.08 0.05 0.00 -0.09 -0.24 0.08 0.07 0.05 0.01 -0.06 -0.18 -0.38 0.07 0.06 0.04 -0.01 -0.09 -0.23 -0.48 0.06 0.05 0.02 -0.03 -0.12 -0.27 -0.53	
Level 14 (13.58 cm) 1.08 0.94 0.65 0.23 -0.33 -1.01 -1.82 1.08 0.94 0.66 0.23 -0.32 -1.00 -1.81 1.09 0.95 0.67 0.25 -0.30 -0.97 -1.77 1.09 0.95 0.67 0.25 -0.29 -0.95 -1.73 1.09 0.95 0.67 0.26 -0.28 -0.93 -1.69 1.10 0.96 0.68 0.28 -0.25 -0.90 -1.65 1.10 0.96 0.69 0.28 -0.24 -0.87 -1.61	Level 19 (3.59 cm) -0.79 -0.68 -0.47 -0.12 0.38 1.09 2.07 -0.80 -0.69 -0.48 -0.14 0.34 1.02 1.96 -0.81 -0.71 -0.51 -0.19 0.27 0.91 1.77 -0.85 -0.76 -0.56 -0.26 0.17 0.74 1.52 -0.88 -0.79 -0.61 -0.33 0.06 0.58 1.26 -0.89 -0.80 -0.63 -0.37 -0.02 0.45 1.06 -0.90 -0.82 -0.65 -0.40 -0.06 0.38 0.94	
Level 15 (12.57 cm) 0.61 0.52 0.35 0.10 -0.21 -0.57 -0.95 0.61 0.52 0.35 0.10 -0.21 -0.57 -0.95 0.61 0.53 0.36 0.12 -0.19 -0.55 -0.92 0.61 0.52 0.36 0.12 -0.19 -0.54 -0.90 0.61 0.52 0.36 0.12 -0.18 -0.52 -0.87 0.61 0.53 0.37 0.13 -0.16 -0.50 -0.84 0.62 0.53 0.37 0.13 -0.16 -0.48 -0.82	Level 20 (the Front) -2.55 -2.16 -1.38 -0.23 1.27 3.08 5.12 -2.59 -2.20 -1.43 -0.30 1.17 2.92 4.88 -2.63 -2.25 -1.50 -0.40 1.01 2.67 4.49 -2.68 -2.31 -1.59 -0.53 0.80 2.35 3.98 -2.75 -2.39 -1.59 -0.68 0.59 2.02 3.47 -2.79 -2.44 -1.76 -0.78 0.43 1.77 3.07 -2.81 -2.47 -1.80 -0.84 0.34 1.64 2.86	

F4 The Uniformity of the Magnetic Force or Accelerating Force for the Solid-Rectangular Electrode at 20,000 amps and 2,000 m/s at each Depth Simulated Using the Standard Deviation Percentage Difference Method. (The Numbers in Each block represents a percentage.)
a) At 5 Microseconds.

Level 11 (15 cm - the Back) 1.85 1.64 1.22 0.55 -0.38 -1.74 -3.47 1.85 1.64 1.22 0.56 -0.37 -1.73 -3.45 1.86 1.66 1.24 0.58 -0.34 -1.68 -3.39 1.86 1.65 1.24 0.59 -0.33 -1.66 -3.35 1.86 1.66 1.24 0.60 -0.31 -1.63 -3.31 1.87 1.67 1.26 0.61 -0.28 -1.60 -3.26 1.87 1.67 1.25 0.61 -0.28 -1.59 -3.21	Level 16 (11.06 cm) 0.33 0.29 0.21 0.09 -0.08 -0.29 -0.56 0.33 0.29 0.21 0.09 -0.08 -0.29 -0.56 0.34 0.30 0.22 0.10 -0.06 -0.28 -0.55 0.33 0.29 0.21 0.09 -0.07 -0.29 -0.56 0.32 0.28 0.20 0.08 -0.08 -0.30 -0.57 0.33 0.29 0.21 0.09 -0.07 -0.28 -0.56 0.33 0.29 0.21 0.09 -0.07 -0.27 -0.54	Level = 11 (15 cm - the Back) Mean 0.801 N S.D. % Diff 1.798 % Level = 12 (14.7 cm) Mean 0.779 N S.D. % Diff 1.64 % Level = 13 (14.25 cm) Mean 0.751 N S.D. % Diff 1.31 % Level = 14 (13.58 cm) Mean 0.714 N S.D. % Diff 0.939 % Level = 15 (12.57 cm) Mean 0.666 N S.D. % Diff 0.499 % Level = 16 (11.06 cm) Mean 0.603 N S.D. % Diff 0.306 % Level = 17 (9.78 cm) Mean 0.527 N S.D. % Diff 0.049 % Level = 18 (6 cm) Mean 0.435 N S.D. % Diff 0.186 % Level = 19 (3.59 cm) Mean 0.35 N S.D. % Diff 0.798 % Level = 20 (Front of Plasma) Mean 0.227 N S.D. % Diff 2.356 %
Level 12 (14.7 cm) 1.72 1.52 1.11 0.47 -0.43 -1.61 -3.12 1.73 1.52 1.12 0.48 -0.42 -1.60 -3.10 1.74 1.54 1.13 0.50 -0.39 -1.56 -3.05 1.74 1.54 1.13 0.51 -0.37 -1.53 -3.01 1.74 1.54 1.14 0.51 -0.36 -1.51 -2.96 1.75 1.55 1.15 0.53 -0.33 -1.47 -2.92 1.74 1.55 1.15 0.53 -0.34 -1.46 -2.87	Level 17 (9.78 cm) -0.00 -0.00 -0.00 0.00 0.02 0.07 0.18 -0.00 -0.01 -0.01 -0.00 0.02 0.06 0.16 0.00 -0.00 -0.01 -0.01 0.00 0.04 0.13 -0.01 -0.01 -0.02 -0.03 -0.02 -0.00 0.06 -0.02 -0.03 -0.03 -0.04 -0.05 -0.03 0.01 -0.01 -0.02 -0.03 -0.04 -0.04 -0.04 -0.01 -0.02 -0.02 -0.03 -0.05 -0.06 -0.05 -0.02	
Level 13 (14.25 cm) 1.43 1.25 0.88 0.33 -0.42 -1.36 -2.42 1.43 1.25 0.89 0.33 -0.42 -1.35 -2.40 1.45 1.27 0.91 0.35 -0.39 -1.31 -2.35 1.45 1.27 0.91 0.36 -0.38 -1.29 -2.31 1.44 1.27 0.91 0.37 -0.36 -1.26 -2.27 1.46 1.28 0.92 0.38 -0.34 -1.23 -2.22 1.45 1.27 0.92 0.38 -0.34 -1.21 -2.18	Level 18 (6 cm) 0.16 0.16 0.15 0.14 0.12 0.08 0.01 0.16 0.15 0.14 0.12 0.09 0.03 -0.06 0.16 0.16 0.14 0.12 0.07 -0.02 -0.15 0.14 0.13 0.11 0.07 0.00 -0.11 -0.29 0.11 0.10 0.07 0.02 -0.07 -0.21 -0.44 0.11 0.09 0.06 -0.00 -0.11 -0.27 -0.55 0.09 0.07 0.03 -0.03 -0.14 -0.31 -0.60	
Level 14 (13.58 cm) 1.03 0.90 0.63 0.22 -0.32 -0.97 -1.75 1.04 0.90 0.63 0.22 -0.31 -0.96 -1.74 1.05 0.92 0.65 0.24 -0.28 -0.93 -1.69 1.05 0.92 0.64 0.25 -0.28 -0.91 -1.66 1.05 0.91 0.64 0.25 -0.27 -0.89 -1.62 1.05 0.92 0.65 0.26 -0.25 -0.86 -1.59 1.04 0.91 0.65 0.26 -0.24 -0.84 -1.54	Level 17 (9.78 cm) -0.73 -0.63 -0.42 -0.09 0.39 1.06 2.01 -0.74 -0.64 -0.44 -0.12 0.35 1.00 1.90 -0.76 -0.67 -0.48 -0.17 0.27 0.87 1.71 -0.81 -0.72 -0.53 -0.25 0.15 0.70 1.44 -0.84 -0.75 -0.58 -0.32 0.04 0.53 1.17 -0.85 -0.77 -0.61 -0.37 -0.04 0.40 0.98 -0.87 -0.79 -0.64 -0.41 -0.09 0.33 0.85	
Level 15 (12.57 cm) 0.57 0.49 0.33 0.09 -0.21 -0.55 -0.91 0.57 0.49 0.33 0.09 -0.20 -0.55 -0.90 0.58 0.50 0.34 0.11 -0.18 -0.52 -0.86 0.58 0.50 0.34 0.11 -0.18 -0.51 -0.85 0.57 0.50 0.34 0.12 -0.17 -0.49 -0.82 0.58 0.50 0.35 0.13 -0.15 -0.46 -0.78 0.58 0.50 0.34 0.12 -0.15 -0.46 -0.76	Level 20 (the Front) -2.53 -2.14 -1.36 -0.21 1.28 3.07 5.10 -2.56 -2.17 -1.40 -0.28 1.18 2.93 4.87 -2.59 -2.21 -1.47 -0.38 1.02 2.67 4.48 -2.67 -2.30 -1.58 -0.53 0.80 2.33 3.95 -2.74 -2.39 -1.69 -0.69 0.57 1.99 3.41 -2.78 -2.43 -1.76 -0.79 0.41 1.74 3.02 -2.80 -2.46 -1.80 -0.85 0.31 1.61 2.80	

F4 Continued.
b) At 10 Microseconds.

Level 11 (15 cm - the Back)

1.85	1.64	1.20	0.54	-0.36	-1.73	-3.45
1.85	1.65	1.22	0.57	-0.36	-1.71	-3.42
1.89	1.68	1.26	0.61	-0.32	-1.67	-3.36
1.86	1.64	1.23	0.59	-0.32	-1.65	-3.34
1.84	1.64	1.22	0.57	-0.33	-1.64	-3.31
1.86	1.66	1.24	0.61	-0.30	-1.59	-3.26
1.83	1.64	1.23	0.59	-0.31	-1.60	-3.16

Level 16 (11.06 cm)

0.33	0.29	0.21	0.09	-0.08	-0.29	-0.56
0.34	0.30	0.22	0.09	-0.07	-0.28	-0.55
0.36	0.32	0.24	0.12	-0.04	-0.25	-0.52
0.32	0.28	0.21	0.09	-0.07	-0.28	-0.56
0.29	0.25	0.17	0.05	-0.10	-0.31	-0.59
0.32	0.28	0.20	0.08	-0.08	-0.29	-0.57
0.31	0.28	0.20	0.08	-0.07	-0.26	-0.53

Level = 11 (15 cm - the Back)

Mean 0.802 N
S.D. % Diff 1.789 %

Level = 12 (14.7 cm)

Mean 0.781 N
S.D. % Diff 1.63 %

Level = 13 (14.25 cm)

Mean 0.752 N
S.D. % Diff 1.3 %

Level = 14 (13.58 cm)

Mean 0.715 N
S.D. % Diff 0.929 %

Level = 15 (12.57 cm)

Mean 0.668 N
S.D. % Diff 0.492 %

Level = 16 (11.06 cm)

Mean 0.604 N
S.D. % Diff 0.304 %

Level = 17 (9.78 cm)

Mean 0.528 N
S.D. % Diff 0.055 %

Level = 18 (6 cm)

Mean 0.436 N
S.D. % Diff 0.196 %

Level = 19 (3.59 cm)

Mean 0.35 N
S.D. % Diff 0.817 %

Level = 20 (Front of Plasma)

Mean 0.227 N
S.D. % Diff 2.374 %

Level 12 (14.7 cm)

1.72	1.52	1.12	0.47	-0.43	-1.60	-3.10
1.72	1.52	1.12	0.48	-0.41	-1.58	-3.08
1.75	1.56	1.15	0.52	-0.36	-1.53	-3.02
1.73	1.53	1.13	0.50	-0.36	-1.52	-3.01
1.72	1.52	1.11	0.50	-0.37	-1.51	-2.96
1.74	1.54	1.14	0.52	-0.34	-1.46	-2.90
1.72	1.52	1.12	0.50	-0.36	-1.46	-2.82

Level 17 (9.78 cm)

-0.02	-0.01	-0.01	-0.00	0.03	0.09	0.20
-0.01	-0.01	-0.01	0.00	0.03	0.08	0.18
0.01	0.00	-0.00	-0.00	0.01	0.06	0.15
-0.01	-0.02	-0.02	-0.03	-0.03	-0.01	0.05
-0.03	-0.03	-0.04	-0.05	-0.05	-0.04	-0.01
-0.02	-0.02	-0.03	-0.03	-0.03	-0.03	-0.00
-0.03	-0.03	-0.04	-0.05	-0.06	-0.03	-0.02

Level 13 (14.25 cm)

1.42	1.25	0.88	0.33	-0.41	-1.35	-2.41
1.43	1.26	0.89	0.34	-0.41	-1.33	-2.38
1.47	1.29	0.92	0.37	-0.37	-1.29	-2.32
1.44	1.26	0.90	0.35	-0.38	-1.28	-2.31
1.42	1.24	0.89	0.35	-0.37	-1.26	-2.27
1.44	1.27	0.91	0.38	-0.34	-1.21	-2.20
1.42	1.24	0.88	0.35	-0.35	-1.20	-2.14

Level 18 (6 cm)

0.16	0.16	0.15	0.15	0.13	0.09	0.04
0.16	0.16	0.15	0.13	0.10	0.05	-0.04
0.19	0.19	0.17	0.14	0.10	0.01	-0.11
0.14	0.13	0.11	0.07	0.01	-0.10	-0.29
0.10	0.09	0.06	0.01	-0.08	-0.22	-0.46
0.10	0.09	0.05	-0.01	-0.12	-0.29	-0.58
0.07	0.05	0.01	-0.06	-0.17	-0.33	-0.64

Level 14 (13.58 cm)

1.03	0.89	0.62	0.22	-0.31	-0.96	-1.74
1.04	0.90	0.63	0.23	-0.30	-0.94	-1.71
1.07	0.93	0.66	0.26	-0.26	-0.90	-1.66
1.04	0.91	0.64	0.25	-0.27	-0.90	-1.65
1.03	0.89	0.62	0.23	-0.28	-0.90	-1.63
1.03	0.90	0.64	0.25	-0.25	-0.85	-1.57
1.01	0.88	0.62	0.24	-0.25	-0.82	-1.50

Level 19 (3.59 cm)

-0.73	-0.62	-0.41	-0.08	0.41	1.10	2.06
-0.74	-0.64	-0.43	-0.10	0.38	1.04	1.97
-0.75	-0.66	-0.46	-0.14	0.30	0.92	1.77
-0.83	-0.74	-0.54	-0.25	0.15	0.70	1.45
-0.86	-0.77	-0.60	-0.33	0.03	0.52	1.16
-0.88	-0.80	-0.64	-0.39	-0.05	0.40	0.98
-0.94	-0.85	-0.70	-0.45	-0.13	0.31	0.83

Level 15 (12.57 cm)

0.56	0.48	0.33	0.09	-0.20	-0.54	-0.90
0.57	0.49	0.33	0.10	-0.19	-0.53	-0.89
0.60	0.52	0.36	0.13	-0.16	-0.50	-0.83
0.56	0.49	0.33	0.11	-0.18	-0.51	-0.85
0.55	0.48	0.33	0.11	-0.17	-0.49	-0.82
0.57	0.50	0.35	0.13	-0.14	-0.45	-0.77
0.55	0.47	0.32	0.10	-0.17	-0.45	-0.75

Level 20 (the Front)

-2.50	-2.11	-1.33	-0.17	1.33	3.14	5.21
-2.53	-2.14	-1.37	-0.24	1.23	2.99	4.96
-2.57	-2.19	-1.44	-0.35	1.06	2.73	4.55
-2.68	-2.31	-1.60	-0.55	0.79	2.33	3.95
-2.79	-2.43	-1.74	-0.73	0.53	1.95	3.37
-2.82	-2.47	-1.79	-0.82	0.38	1.70	2.97
-2.85	-2.50	-1.86	-0.90	0.26	1.58	2.76

F4 Continued.

c) At 25 Microseconds.

Level 11 (15 cm - the Back)

1.83	1.63	1.23	0.56	-0.36	-1.73	-3.40
1.85	1.66	1.23	0.59	-0.32	-1.67	-3.38
1.91	1.70	1.29	0.64	-0.27	-1.62	-3.29
1.84	1.64	1.22	0.58	-0.31	-1.63	-3.33
1.78	1.59	1.19	0.54	-0.34	-1.66	-3.32
1.82	1.62	1.23	0.58	-0.32	-1.56	-3.21
1.78	1.57	1.17	0.54	-0.35	-1.64	-3.05

Level 16 (11.06 cm)

0.34	0.30	0.21	0.09	-0.08	-0.28	-0.53
0.36	0.31	0.23	0.10	-0.06	-0.26	-0.52
0.39	0.36	0.28	0.17	0.01	-0.20	-0.46
0.31	0.27	0.20	0.09	-0.07	-0.28	-0.56
0.25	0.21	0.13	0.01	-0.14	-0.35	-0.62
0.30	0.26	0.19	0.07	-0.08	-0.30	-0.58
0.28	0.25	0.18	0.07	-0.08	-0.23	-0.55

Level=11 (15 cm - the Back)

Mean 0.804 N
S.D. % Diff 1.769 %

Level = 12 (14.7 cm)

Mean 0.782 N
S.D. % Diff 1.608 %

Level = 13 (14.25 cm)

Mean 0.754 N
S.D. % Diff 1.279 %

Level = 14 (13.58 cm)

Mean 0.717 N
S.D. % Diff 0.908 %

Level = 15 (12.57 cm)

Mean 0.669 N
S.D. % Diff 0.477 %

Level = 16 (11.06 cm)

Mean 0.605 N
S.D. % Diff 0.3 %

Level = 17 (9.78 cm)

Mean 0.529 N
S.D. % Diff 0.071 %

Level = 18 (6 cm)

Mean 0.436 N
S.D. % Diff 0.215 %

Level = 19 (3.59 cm)

Mean 0.35 N
S.D. % Diff 0.857 %

Level = 20 (Front of Plasma)

Mean 0.227 N
S.D. % Diff 2.404 %

Level 12 (14.7 cm)

1.71	1.53	1.11	0.47	-0.41	-1.56	-3.06
1.73	1.53	1.14	0.49	-0.40	-1.55	-3.03
1.78	1.58	1.19	0.55	-0.32	-1.47	-2.95
1.71	1.51	1.11	0.50	-0.36	-1.50	-2.98
1.68	1.47	1.07	0.46	-0.40	-1.51	-2.95
1.70	1.51	1.10	0.49	-0.35	-1.44	-2.85
1.65	1.45	1.06	0.44	-0.41	-1.48	-2.74

Level 17 (9.78 cm)

-0.03	-0.03	-0.02	-0.00	0.04	0.11	0.24
-0.03	-0.02	-0.01	0.01	0.05	0.11	0.23
0.02	0.01	0.01	0.01	0.04	0.09	0.20
-0.02	-0.03	-0.03	-0.04	-0.04	-0.02	0.04
-0.06	-0.06	-0.06	-0.05	-0.06	-0.06	-0.04
-0.03	-0.03	-0.03	-0.02	-0.02	-0.01	0.01
-0.06	-0.05	-0.05	-0.06	-0.06	-0.02	-0.04

Level 13 (14.25 cm)

1.42	1.24	0.88	0.34	-0.40	-1.32	-2.37
1.43	1.25	0.89	0.35	-0.39	-1.31	-2.35
1.49	1.31	0.95	0.41	-0.33	-1.23	-2.26
1.43	1.25	0.90	0.35	-0.37	-1.26	-2.29
1.37	1.21	0.85	0.32	-0.38	-1.26	-2.27
1.40	1.23	0.88	0.35	-0.34	-1.18	-2.15
1.36	1.17	0.82	0.30	-0.39	-1.19	-2.08

Level 18 (6 cm)

0.16	0.16	0.16	0.16	0.15	0.13	0.10
0.17	0.17	0.16	0.14	0.11	0.08	0.02
0.23	0.23	0.23	0.20	0.15	0.08	-0.04
0.15	0.14	0.12	0.08	0.02	-0.08	-0.27
0.07	0.06	0.03	-0.02	-0.10	-0.25	-0.50
0.08	0.07	0.03	-0.03	-0.14	-0.32	-0.62
0.02	-0.00	-0.05	-0.12	-0.23	-0.37	-0.72

Level 14 (13.58 cm)

1.02	0.89	0.62	0.23	-0.30	-0.94	-1.70
1.03	0.90	0.64	0.25	-0.28	-0.91	-1.67
1.09	0.95	0.69	0.30	-0.21	-0.84	-1.60
1.03	0.89	0.63	0.24	-0.27	-0.89	-1.63
0.98	0.85	0.58	0.20	-0.30	-0.90	-1.63
0.99	0.86	0.60	0.23	-0.24	-0.83	-1.53
0.93	0.81	0.55	0.19	-0.26	-0.79	-1.45

Level 19 (3.59 cm)

-0.74	-0.63	-0.41	-0.06	0.45	1.16	2.15
-0.74	-0.63	-0.41	-0.06	0.44	1.13	2.08
-0.74	-0.64	-0.43	-0.10	0.37	1.01	1.89
-0.87	-0.77	-0.56	-0.25	0.17	0.73	1.47
-0.92	-0.82	-0.63	-0.36	0.01	0.51	1.15
-0.93	-0.85	-0.68	-0.43	-0.06	0.41	0.99
-1.05	-0.96	-0.80	-0.54	-0.19	0.29	0.81

Level 15 (12.57 cm)

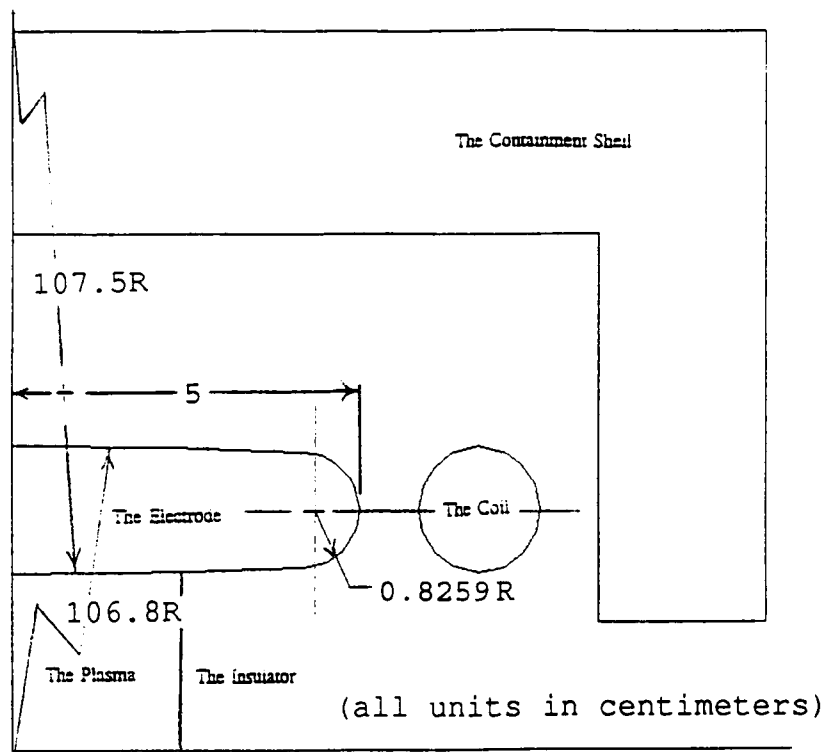
0.56	0.49	0.33	0.10	-0.19	-0.52	-0.87
0.57	0.50	0.34	0.12	-0.17	-0.51	-0.85
0.62	0.54	0.38	0.16	-0.13	-0.45	-0.78
0.54	0.47	0.32	0.09	-0.19	-0.51	-0.85
0.51	0.44	0.30	0.09	-0.19	-0.50	-0.83
0.54	0.47	0.33	0.12	-0.14	-0.43	-0.74
0.50	0.42	0.27	0.06	-0.19	-0.44	-0.75

Level 20 (the Front)

-2.46	-2.06	-1.28	-0.11	1.42	3.26	5.38
-2.50	-2.11	-1.32	-0.18	1.30	3.09	5.11
-2.53	-2.14	-1.40	-0.30	1.13	2.81	4.66
-2.70	-2.33	-1.62	-0.57	0.78	2.33	3.96
-2.86	-2.50	-1.81	-0.80	0.47	1.89	3.29
-2.89	-2.54	-1.86	-0.89	0.33	1.64	2.90
-2.93	-2.57	-1.94	-0.97	0.18	1.57	2.69

F4 Continued.

d) At 50 Microseconds.



F5 The Quarter of the Solid-Elliptical-Shaped-Electrode,
MHD Accelerator

Level 11 (15 cm - the Back)	Level 16 (11.06 cm)	Level = 11 (15 cm - the Back)
2.19 1.88 1.27 0.31 -0.99 -2.80 -5.12	0.69 0.55 0.28 -0.13 -0.68 -1.37 -2.22	Mean 0.822 N
2.24 1.94 1.32 0.37 -0.93 -2.72 -5.04	0.74 0.60 0.33 -0.08 -0.63 -1.32 -2.17	S.D. % Diff 2.5 %
2.35 2.05 1.44 0.49 -0.80 -2.58 -4.88	0.85 0.71 0.44 0.03 -0.52 -1.21 -2.06	
2.51 2.21 1.60 0.66 -0.61 -2.38 -4.65	1.00 0.87 0.59 0.18 -0.36 -1.05 -1.90	Level = 12 (14.7 cm)
2.71 2.41 1.81 0.87 -0.39 -2.13 -4.37	1.20 1.06 0.79 0.38 -0.17 -0.85 -1.69	Mean 0.799 N
3.00 2.71 2.10 1.17 -0.08 -1.81 -4.02	1.49 1.35 1.07 0.66 0.12 -0.56 -1.38	S.D. % Diff 2.367 %
3.23 2.93 2.33 1.39 0.14 -1.57 -3.74	1.70 1.56 1.29 0.88 0.34 -0.33 -1.11	
		Level = 13 (14.25 cm)
		Mean 0.77 N
		S.D. % Diff 2.053 %
Level 12 (14.7 cm)	Level 17 (9.78 cm)	Level = 14 (13.58 cm)
2.08 1.78 1.17 0.24 -1.04 -2.71 -4.82	0.35 0.25 0.07 -0.20 -0.54 -0.94 -1.38	Mean 0.731 N
2.13 1.83 1.23 0.30 -0.98 -2.63 -4.74	0.40 0.30 0.12 -0.16 -0.50 -0.92 -1.36	S.D. % Diff 1.695 %
2.25 1.95 1.35 0.42 -0.84 -2.49 -4.58	0.50 0.40 0.21 -0.07 -0.43 -0.85 -1.32	
2.41 2.11 1.51 0.59 -0.66 -2.29 -4.35	0.65 0.55 0.35 0.07 -0.30 -0.74 -1.24	Level = 15 (12.57 cm)
2.62 2.32 1.72 0.81 -0.44 -2.04 -4.06	0.84 0.74 0.54 0.25 -0.14 -0.59 -1.10	Mean 0.681 N
2.91 2.61 2.01 1.11 -0.13 -1.72 -3.70	1.12 1.02 0.81 0.51 0.12 -0.34 -0.87	S.D. % Diff 1.265 %
3.13 2.84 2.24 1.33 0.10 -1.48 -3.41	1.33 1.23 1.02 0.72 0.32 -0.14 -0.66	
		Level = 16 (11.06 cm)
		Mean 0.612 N
		S.D. % Diff 1.065 %
Level 13 (14.25 cm)	Level 18 (6 cm)	Level = 17 (9.78 cm)
1.80 1.52 0.95 0.10 -1.05 -2.48 -4.13	0.50 0.41 0.23 -0.04 -0.40 -0.86 -1.42	Mean 0.531 N
1.85 1.57 1.01 0.16 -0.98 -2.41 -4.05	0.54 0.45 0.27 -0.01 -0.39 -0.87 -1.47	S.D. % Diff 0.727 %
1.96 1.69 1.12 0.28 -0.86 -2.27 -3.89	0.64 0.55 0.35 0.06 -0.34 -0.87 -1.52	
2.13 1.85 1.29 0.45 -0.67 -2.06 -3.66	0.77 0.67 0.47 0.15 -0.28 -0.85 -1.57	Level = 18 (6 cm)
2.33 2.06 1.50 0.67 -0.44 -1.82 -3.37	0.95 0.84 0.62 0.29 -0.18 -0.79 -1.58	Mean 0.433 N
2.62 2.35 1.80 0.97 -0.13 -1.48 -3.01	1.22 1.11 0.88 0.53 0.04 -0.61 -1.46	S.D. % Diff 0.846 %
2.85 2.57 2.02 1.19 0.09 -1.24 -2.72	1.42 1.30 1.07 0.71 0.21 -0.46 -1.31	
		Level = 19 (3.59 cm)
		Mean 0.343 N
		S.D. % Diff 0.265 %
Level 14 (13.58 cm)	Level 19 (3.59 cm)	Level = 20 (Front of Plasma)
1.40 1.17 0.69 -0.01 -0.94 -2.10 -3.47	-0.39 -0.37 -0.32 -0.22 -0.05 0.25 0.77	Mean 0.219 N
1.46 1.22 0.75 0.05 -0.88 -2.03 -3.40	-0.36 -0.34 -0.30 -0.22 -0.07 0.20 0.66	S.D. % Diff 1.741 %
1.57 1.34 0.87 0.17 -0.75 -1.89 -3.24	-0.28 -0.27 -0.24 -0.19 -0.09 0.10 0.45	
1.73 1.50 1.03 0.34 -0.57 -1.69 -3.02	-0.17 -0.17 -0.16 -0.15 -0.11 -0.01 0.19	
1.94 1.71 1.24 0.55 -0.35 -1.45 -2.74	-0.01 -0.02 -0.04 -0.07 -0.09 -0.10 -0.04	
2.23 2.00 1.54 0.85 -0.04 -1.12 -2.38	0.24 0.22 0.18 0.12 0.04 -0.04 -0.12	
2.46 2.22 1.76 1.07 0.19 -0.88 -2.09	0.43 0.41 0.36 0.28 0.17 0.04 -0.10	
Level 15 (12.57 cm)	Level 20 (the Front)	
0.94 0.76 0.40 -0.13 -0.82 -1.66 -2.61	-2.19 -1.87 -1.23 -0.28 0.97 2.47 4.19	
0.99 0.81 0.45 -0.08 -0.77 -1.60 -2.55	-2.18 -1.86 -1.24 -0.32 0.87 2.30 3.90	
1.10 0.92 0.57 0.04 -0.65 -1.47 -2.41	-2.14 -1.83 -1.24 -0.38 0.72 2.00 3.39	
1.26 1.08 0.73 0.20 -0.47 -1.29 -2.20	-2.06 -1.78 -1.23 -0.44 0.54 1.64 2.75	
1.46 1.29 0.93 0.42 -0.25 -1.05 -1.94	-1.95 -1.69 -1.18 -0.46 0.41 1.32 2.13	
1.76 1.58 1.23 0.71 0.05 -0.73 -1.60	-1.73 -1.48 -1.01 -0.35 0.42 1.18 1.73	
1.98 1.80 1.45 0.93 0.27 -0.49 -1.32	-1.57 -1.33 -0.86 -0.23 0.48 1.16 1.56	

F6 The Uniformity of the Magnetic Force or Accelerating Force for the Solid-Elliptical Electrode at 20,000 amps and 2,000 m/s at each Depth Simulated Using the Standard Deviation Percentage Difference Method. (The Numbers in Each block represents a percentage.)
a) At 5 Microseconds.

Level 11 (15 cm - the Back)

2.14	1.84	1.24	0.29	-0.97	-2.73	-5.06
2.19	1.89	1.29	0.35	-0.90	-2.65	-4.96
2.31	2.01	1.42	0.48	-0.77	-2.50	-4.81
2.47	2.17	1.57	0.65	-0.59	-2.30	-4.58
2.65	2.36	1.77	0.85	-0.37	-2.06	-4.31
2.86	2.68	2.09	1.17	-0.04	-1.70	-3.93
3.13	2.83	2.25	1.33	0.13	-1.54	-3.71

Level 16 (11.06 cm)

0.70	0.56	0.28	-0.13	-0.69	-1.38	-2.23
0.75	0.61	0.33	-0.08	-0.63	-1.33	-2.18
0.86	0.72	0.45	0.04	-0.51	-1.21	-2.06
1.01	0.87	0.60	0.19	-0.35	-1.04	-1.89
1.19	1.05	0.77	0.37	-0.17	-0.85	-1.68
1.49	1.36	1.09	0.69	0.15	-0.52	-1.33
1.65	1.52	1.25	0.85	0.32	-0.34	-1.13

Level = 11 (15 cm - the Back)

Mean 0.814 N
S.D. % Diff 2.452 %

Level = 12 (14.7 cm)

Mean 0.792 N
S.D. % Diff 2.33 %

Level = 13 (14.25 cm)

Mean 0.764 N
S.D. % Diff 2.019 %

Level = 14 (13.58 cm)

Mean 0.726 N
S.D. % Diff 1.666 %

Level = 15 (12.57 cm)

Mean 0.677 N
S.D. % Diff 1.246 %

Level = 16 (11.06 cm)

Mean 0.611 N
S.D. % Diff 1.061 %

Level = 17 (9.78 cm)

Mean 0.532 N
S.D. % Diff 0.742 %

Level = 18 (6 cm)

Mean 0.436 N
S.D. % Diff 0.882 %

Level = 19 (3.59 cm)

Mean 0.347 N
S.D. % Diff 0.24 %

Level = 20 (Front of Plasma)

Mean 0.221 N
S.D. % Diff 1.724 %

Level 12 (14.7 cm)

2.04	1.75	1.15	0.23	-1.02	-2.67	-4.77
2.10	1.80	1.21	0.29	-0.96	-2.60	-4.69
2.21	1.92	1.33	0.43	-0.82	-2.44	-4.52
2.37	2.08	1.49	0.59	-0.64	-2.24	-4.29
2.57	2.27	1.69	0.80	-0.42	-2.00	-4.00
2.88	2.59	2.01	1.12	-0.08	-1.64	-3.61
3.04	2.76	2.17	1.29	0.08	-1.47	-3.39

Level 17 (9.78 cm)

0.38	0.28	0.09	-0.20	-0.56	-0.98	-1.43
0.43	0.33	0.13	-0.15	-0.51	-0.94	-1.41
0.53	0.43	0.23	-0.06	-0.43	-0.87	-1.35
0.67	0.57	0.37	0.07	-0.31	-0.76	-1.27
0.85	0.75	0.55	0.25	-0.14	-0.60	-1.13
1.15	1.05	0.85	0.54	0.15	-0.32	-0.85
1.31	1.21	1.00	0.69	0.30	-0.17	-0.70

Level 13 (14.25 cm)

1.76	1.49	0.93	0.09	-1.04	-2.45	-4.08
1.82	1.54	0.99	0.15	-0.97	-2.38	-4.01
1.94	1.66	1.11	0.28	-0.84	-2.23	-3.83
2.09	1.82	1.28	0.45	-0.65	-2.02	-3.60
2.29	2.02	1.48	0.66	-0.43	-1.78	-3.32
2.60	2.34	1.80	0.99	-0.09	-1.42	-2.92
2.77	2.50	1.96	1.15	0.07	-1.24	-2.69

Level 18 (6 cm)

0.56	0.46	0.27	-0.03	-0.42	-0.92	-1.52
0.60	0.50	0.30	0.00	-0.41	-0.92	-1.55
0.70	0.60	0.39	0.08	-0.35	-0.90	-1.59
0.82	0.71	0.50	0.16	-0.29	-0.88	-1.64
0.98	0.86	0.64	0.29	-0.19	-0.83	-1.65
1.28	1.16	0.93	0.57	0.06	-0.60	-1.48
1.41	1.30	1.06	0.69	0.18	-0.50	-1.39

Level 14 (13.58 cm)

1.38	1.14	0.67	-0.02	-0.94	-2.08	-3.43
1.43	1.20	0.73	0.04	-0.88	-2.01	-3.35
1.55	1.32	0.86	0.17	-0.74	-1.86	-3.19
1.71	1.48	1.02	0.34	-0.56	-1.66	-2.96
1.90	1.67	1.22	0.54	-0.34	-1.42	-2.69
2.22	1.99	1.54	0.87	-0.00	-1.06	-2.29
2.38	2.15	1.70	1.03	0.17	-0.87	-2.06

Level 17 (9.78 cm)

-0.32	-0.31	-0.28	-0.21	-0.07	0.20	0.67
-0.29	-0.28	-0.25	-0.19	-0.08	0.15	0.57
-0.21	-0.21	-0.20	-0.17	-0.10	0.06	0.37
-0.12	-0.13	-0.14	-0.14	-0.12	-0.06	0.11
0.02	0.00	-0.03	-0.07	-0.11	-0.14	-0.12
0.30	0.27	0.22	0.15	0.06	-0.05	-0.16
0.44	0.42	0.36	0.27	0.14	-0.01	-0.19

Level 15 (12.57 cm)

0.92	0.74	0.38	-0.14	-0.83	-1.66	-2.60
0.98	0.80	0.44	-0.08	-0.77	-1.59	-2.53
1.09	0.91	0.56	0.04	-0.64	-1.45	-2.37
1.24	1.07	0.72	0.20	-0.46	-1.26	-2.17
1.43	1.26	0.92	0.41	-0.25	-1.03	-1.91
1.75	1.58	1.24	0.73	0.09	-0.67	-1.52
1.92	1.74	1.40	0.90	0.26	-0.49	-1.30

Level 20 (the Front)

-2.14	-1.82	-1.19	-0.25	0.98	2.46	4.16
-2.13	-1.82	-1.20	-0.29	0.88	2.29	3.87
-2.09	-1.79	-1.21	-0.36	0.73	2.00	3.37
-2.03	-1.76	-1.21	-0.43	0.54	1.63	2.72
-1.95	-1.69	-1.18	-0.47	0.39	1.29	2.09
-1.73	-1.48	-1.00	-0.34	0.43	1.18	1.72
-1.62	-1.38	-0.92	-0.29	0.43	1.11	1.49

F6 Continued.

b) At 10 Microseconds.

Level 11 (15 cm - the Back)

2.11	1.80	1.22	0.27	-0.94	-2.61	-5.08
2.17	1.87	1.28	0.33	-0.86	-2.52	-4.99
2.30	2.00	1.42	0.47	-0.71	-2.36	-4.81
2.43	2.14	1.57	0.63	-0.54	-2.18	-4.60
2.60	2.31	1.74	0.81	-0.36	-1.96	-4.36
3.00	2.71	2.14	1.21	0.07	-1.53	-3.91
3.01	2.70	2.13	1.21	0.05	-1.55	-3.81

Level 12 (14.7 cm)

2.04	1.75	1.16	0.25	-0.99	-2.65	-4.81
2.11	1.81	1.22	0.31	-0.92	-2.57	-4.72
2.24	1.95	1.36	0.47	-0.76	-2.40	-4.55
2.38	2.09	1.50	0.62	-0.59	-2.21	-4.33
2.55	2.26	1.67	0.80	-0.41	-2.01	-4.08
2.95	2.66	2.08	1.20	0.01	-1.57	-3.61
2.94	2.66	2.08	1.19	-0.01	-1.58	-3.51

Level 13 (14.25 cm)

1.78	1.50	0.95	0.10	-1.03	-2.46	-4.12
1.84	1.57	1.01	0.17	-0.96	-2.39	-4.04
1.98	1.70	1.15	0.32	-0.81	-2.22	-3.85
2.12	1.85	1.30	0.48	-0.64	-2.03	-3.64
2.28	2.02	1.48	0.66	-0.44	-1.81	-3.39
2.68	2.42	1.88	1.07	-0.02	-1.36	-2.91
2.68	2.41	1.87	1.06	-0.03	-1.35	-2.82

Level 14 (13.58 cm)

1.39	1.16	0.69	-0.01	-0.94	-2.09	-3.45
1.46	1.22	0.75	0.06	-0.87	-2.01	-3.37
1.59	1.36	0.89	0.20	-0.72	-1.85	-3.20
1.74	1.51	1.04	0.36	-0.55	-1.67	-2.99
1.91	1.68	1.21	0.53	-0.37	-1.46	-2.75
2.31	2.08	1.62	0.94	0.06	-1.01	-2.27
2.30	2.07	1.62	0.94	0.06	-0.98	-2.20

Level 15 (12.57 cm)

0.93	0.75	0.39	-0.14	-0.83	-1.66	-2.60
1.00	0.82	0.46	-0.07	-0.76	-1.59	-2.53
1.13	0.95	0.59	0.06	-0.62	-1.44	-2.37
1.27	1.09	0.74	0.22	-0.46	-1.27	-2.19
1.43	1.26	0.92	0.40	-0.26	-1.06	-1.96
1.84	1.67	1.32	0.81	0.16	-0.62	-1.49
1.84	1.67	1.31	0.80	0.15	-0.60	-1.45

Level 16 (11.06 cm)

0.72	0.56	0.30	-0.12	-0.66	-1.39	-2.23
0.78	0.64	0.35	-0.07	-0.63	-1.32	-2.18
0.90	0.77	0.49	0.07	-0.48	-1.18	-2.04
1.03	0.90	0.62	0.21	-0.34	-1.05	-1.90
1.18	1.04	0.76	0.35	-0.20	-0.89	-1.74
1.58	1.44	1.16	0.75	0.21	-0.48	-1.32
1.57	1.44	1.17	0.76	0.22	-0.45	-1.29

Level 17 (9.78 cm)

0.38	0.28	0.09	-0.19	-0.55	-0.97	-1.42
0.43	0.33	0.14	-0.14	-0.50	-0.93	-1.39
0.55	0.45	0.25	-0.04	-0.42	-0.86	-1.34
0.69	0.59	0.39	0.08	-0.30	-0.76	-1.29
0.85	0.75	0.55	0.25	-0.15	-0.63	-1.18
1.24	1.13	0.93	0.62	0.22	-0.27	-0.83
1.25	1.14	0.93	0.61	0.19	-0.29	-0.87

Level 18 (6 cm)

0.57	0.47	0.28	-0.02	-0.41	-0.90	-1.50
0.63	0.53	0.32	0.01	-0.40	-0.92	-1.54
0.75	0.64	0.43	0.11	-0.32	-0.88	-1.57
0.85	0.74	0.52	0.18	-0.28	-0.88	-1.65
0.98	0.86	0.63	0.27	-0.22	-0.88	-1.71
1.37	1.25	1.01	0.64	0.12	-0.57	-1.48
1.34	1.22	0.98	0.60	0.07	-0.63	-1.58

Level 19 (3.59 cm)

-0.32	-0.30	-0.27	-0.19	-0.04	0.24	0.74
-0.28	-0.27	-0.24	-0.17	-0.04	0.20	0.64
-0.21	-0.20	-0.19	-0.15	-0.07	0.10	0.44
-0.14	-0.14	-0.14	-0.14	-0.12	-0.05	0.12
-0.02	-0.03	-0.06	-0.09	-0.14	-0.17	-0.16
0.35	0.32	0.28	0.21	0.12	-0.00	-0.13
0.36	0.33	0.27	0.17	0.04	-0.12	-0.35

Level 20 (the Front)

-2.11	-1.79	-1.15	-0.19	1.05	2.58	4.34
-2.11	-1.79	-1.17	-0.24	0.95	2.39	4.03
-2.06	-1.76	-1.18	-0.32	0.79	2.08	3.50
-2.03	-1.75	-1.21	-0.43	0.56	1.66	2.78
-1.98	-1.73	-1.23	-0.51	0.34	1.25	2.04
-1.69	-1.45	-0.97	-0.32	0.43	1.17	1.69
-1.76	-1.52	-1.08	-0.46	0.23	0.91	1.24

Level = 11 (15 cm - the Back)

Mean 0.817 N
S.D. % Diff 2.428 %

Level = 12 (14.7 cm)

Mean 0.795 N
S.D. % Diff 2.339 %

Level = 13 (14.25 cm)

Mean 0.766 N
S.D. % Diff 2.035 %

Level = 14 (13.58 cm)

Mean 0.727 N
S.D. % Diff 1.679 %

Level = 15 (12.57 cm)

Mean 0.678 N
S.D. % Diff 1.255 %

Level = 16 (11.06 cm)

Mean 0.612 N
S.D. % Diff 1.069 %

Level = 17 (9.78 cm)

Mean 0.533 N
S.D. % Diff 0.746 %

Level = 18 (6 cm)

Mean 0.437 N
S.D. % Diff 0.895 %

Level = 19 (3.59 cm)

Mean 0.347 N
S.D. % Diff 0.25 %

Level = 20 (Front of Plasma)

Mean 0.22 N
S.D. % Diff 1.753 %

F6 Continued.

c) At 25 Microseconds.

Level 11 (15 cm - the Back)

2.06	1.75	1.20	0.24	-0.86	-2.37	-5.04
2.12	1.86	1.27	0.33	-0.76	-2.28	-4.97
2.29	1.98	1.43	0.48	-0.61	-2.10	-4.77
2.38	2.10	1.55	0.60	-0.46	-1.94	-4.59
2.48	2.20	1.66	0.73	-0.33	-1.81	-4.42
3.02	2.72	2.19	1.26	0.19	-1.25	-3.86
2.75	2.44	1.88	0.99	-0.11	-1.67	-3.99

Level 12 (14.7 cm)

2.04	1.76	1.17	0.29	-0.92	-2.56	-4.82
2.11	1.83	1.25	0.37	-0.84	-2.48	-4.73
2.27	1.99	1.41	0.54	-0.67	-2.30	-4.54
2.38	2.10	1.53	0.65	-0.53	-2.16	-4.38
2.51	2.21	1.64	0.77	-0.41	-2.01	-4.19
3.05	2.76	2.18	1.29	0.13	-1.45	-3.61
2.74	2.47	1.89	1.01	-0.19	-1.80	-3.74

Level 13 (14.25 cm)

1.81	1.53	0.98	0.16	-0.98	-2.43	-4.10
1.89	1.61	1.05	0.22	-0.91	-2.35	-4.03
2.04	1.76	1.22	0.38	-0.74	-2.18	-3.83
2.16	1.89	1.34	0.51	-0.61	-2.02	-3.68
2.26	2.00	1.46	0.64	-0.47	-1.86	-3.47
2.79	2.52	1.99	1.18	0.07	-1.30	-2.89
2.50	2.22	1.70	0.86	-0.25	-1.57	-3.06

Level 14 (13.58 cm)

1.42	1.19	0.72	0.02	-0.91	-2.06	-3.41
1.50	1.26	0.80	0.10	-0.83	-1.97	-3.32
1.66	1.42	0.95	0.26	-0.66	-1.80	-3.16
1.78	1.55	1.08	0.39	-0.53	-1.65	-2.99
1.89	1.65	1.18	0.50	-0.41	-1.52	-2.83
2.42	2.18	1.71	1.03	0.15	-0.94	-2.23
2.12	1.89	1.43	0.74	-0.14	-1.19	-2.44

Level 15 (12.57 cm)

0.97	0.79	0.43	-0.11	-0.80	-1.63	-2.56
1.03	0.86	0.50	-0.04	-0.72	-1.55	-2.48
1.18	1.00	0.64	0.11	-0.57	-1.39	-2.31
1.29	1.11	0.76	0.23	-0.45	-1.27	-2.19
1.40	1.23	0.89	0.37	-0.30	-1.11	-2.03
1.95	1.77	1.43	0.92	0.26	-0.54	-1.44
1.69	1.51	1.15	0.62	-0.04	-0.80	-1.72

Level 16 (11.06 cm)

0.76	0.61	0.33	-0.09	-0.65	-1.34	-2.17
0.83	0.68	0.40	-0.03	-0.59	-1.28	-2.12
0.97	0.83	0.55	0.14	-0.42	-1.12	-1.97
1.06	0.93	0.65	0.24	-0.31	-1.02	-1.89
1.15	1.01	0.72	0.30	-0.25	-0.95	-1.82
1.67	1.53	1.25	0.83	0.28	-0.43	-1.29
1.40	1.27	0.99	0.57	0.02	-0.67	-1.58

Level 17 (9.78 cm)

0.38	0.29	0.11	-0.17	-0.51	-0.91	-1.34
0.45	0.35	0.17	-0.10	-0.45	-0.86	-1.31
0.58	0.48	0.28	-0.01	-0.38	-0.81	-1.27
0.73	0.63	0.42	0.12	-0.27	-0.75	-1.28
0.82	0.72	0.53	0.23	-0.17	-0.67	-1.24
1.35	1.24	1.03	0.72	0.30	-0.21	-0.79
1.10	0.98	0.76	0.42	-0.02	-0.52	-1.16

Level 18 (6 cm)

0.60	0.49	0.30	0.01	-0.37	-0.85	-1.41
0.65	0.55	0.34	0.03	-0.37	-0.87	-1.48
0.81	0.70	0.49	0.17	-0.27	-0.83	-1.50
0.91	0.79	0.56	0.22	-0.25	-0.86	-1.64
0.96	0.84	0.60	0.23	-0.27	-0.94	-1.80
1.49	1.37	1.13	0.74	0.22	-0.51	-1.46
1.17	1.05	0.80	0.40	-0.15	-0.86	-1.92

Level 19 (3.59 cm)

-0.35	-0.33	-0.28	-0.18	0.01	0.34	0.89
-0.29	-0.27	-0.22	-0.13	0.04	0.32	0.82
-0.20	-0.19	-0.16	-0.09	0.02	0.23	0.62
-0.18	-0.17	-0.15	-0.13	-0.09	-0.01	0.20
-0.11	-0.11	-0.13	-0.16	-0.19	-0.21	-0.19
0.42	0.39	0.35	0.29	0.20	0.08	-0.06
0.20	0.16	0.09	-0.01	-0.15	-0.32	-0.62

Level 20 (the Front)

-2.07	-1.74	-1.08	-0.09	1.20	2.80	4.66
-2.06	-1.74	-1.10	-0.15	1.09	2.60	4.33
-2.01	-1.70	-1.11	-0.23	0.91	2.26	3.75
-2.03	-1.76	-1.22	-0.42	0.58	1.73	2.90
-2.08	-1.82	-1.31	-0.60	0.27	1.19	2.01
-1.69	-1.44	-0.97	-0.32	0.43	1.16	1.66
-2.05	-1.82	-1.38	-0.78	-0.14	0.56	0.82

Level=11 (15 cm - the Back)

Mean 0.82 N
S.D. % Diff 2.377 %

Level = 12 (14.7 cm)

Mean 0.797 N
S.D. % Diff 2.34 %

Level = 13 (14.25 cm)

Mean 0.768 N
S.D. % Diff 2.046 %

Level = 14 (13.58 cm)

Mean 0.729 N
S.D. % Diff 1.683 %

Level = 15 (12.57 cm)

Mean 0.68 N
S.D. % Diff 1.258 %

Level = 16 (11.06 cm)

Mean 0.613 N
S.D. % Diff 1.066 %

Level = 17 (9.78 cm)

Mean 0.533 N
S.D. % Diff 0.743 %

Level = 18 (6 cm)

Mean 0.437 N
S.D. % Diff 0.907 %

Level = 19 (3.59 cm)

Mean 0.347 N
S.D. % Diff 0.299 %

Level = 20 (Front of Plasma)

Mean 0.219 N
S.D. % Diff 1.827 %

F5 Continued.

d) At 50 Microseconds.

VITA

The author, Robert A. Yeargin, Jr. was born in Murfreesboro, Tennessee on February 11, 1966. He attended a private school in Nashville, Tennessee, through his high school years. In Cookeville, Tennessee, he obtained a Bachelor of Science Degree in Mechanical Engineering at Tennessee Technological University in March 1989 with a minor in Computer Science.

From 1989 to 1991, he worked in several cities in Brazil, applying the principles that he learned while earning his undergraduate degree. In 1994, he obtained a Master's Degree in Aerospace Engineering from the University of Tennessee Space Institute in Tullahoma, Tennessee.