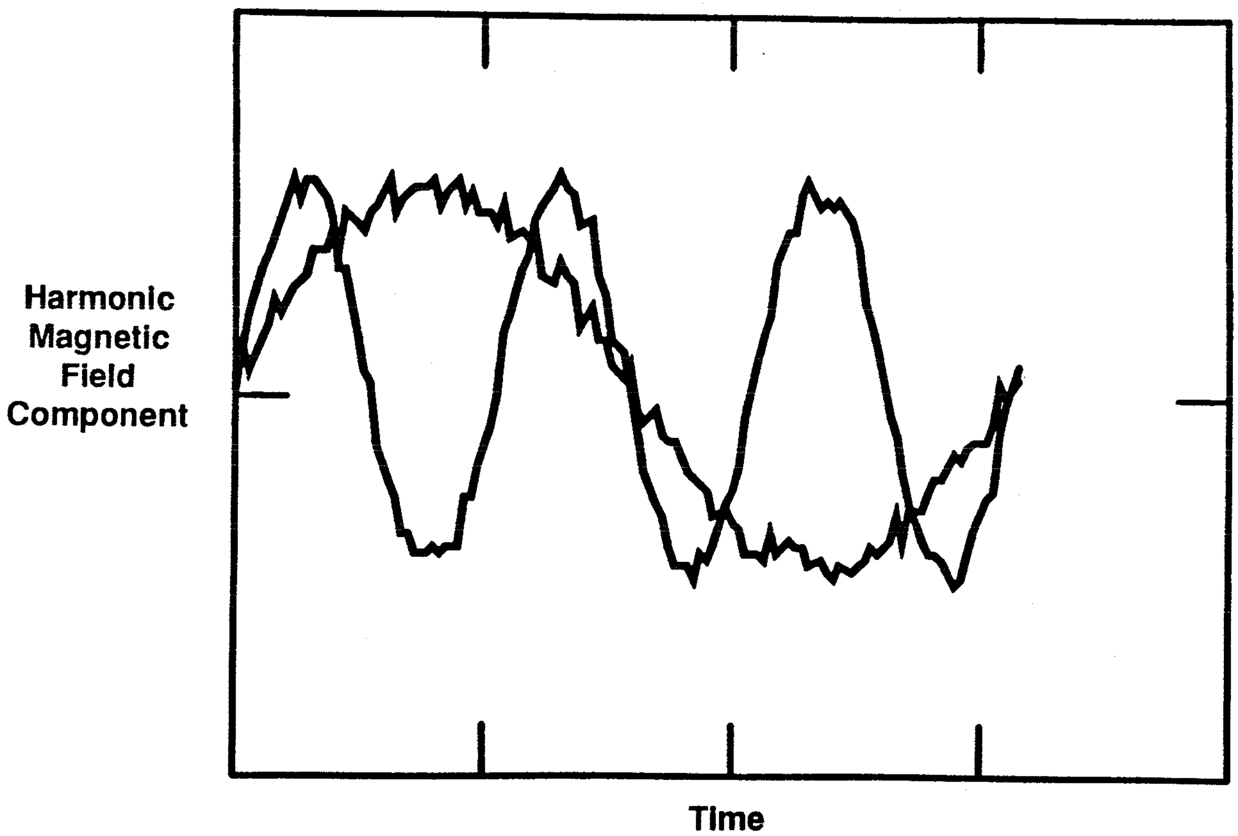
Magnetic Shielding for Electric Vehicles

Program Review

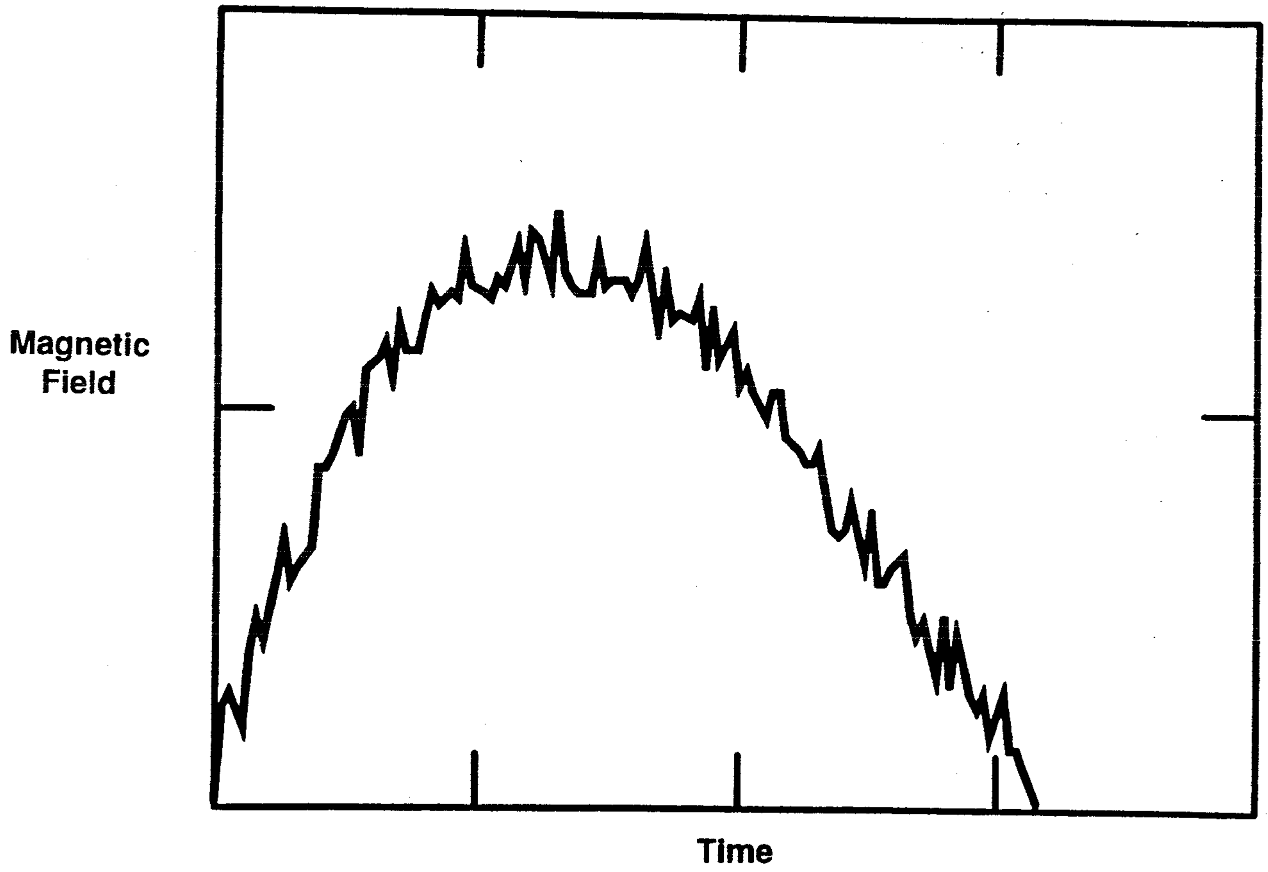
Contract: DAAE07-93-C-R107
COTR: Mr. Marty Snyder, TACOM

16-17 May 1995

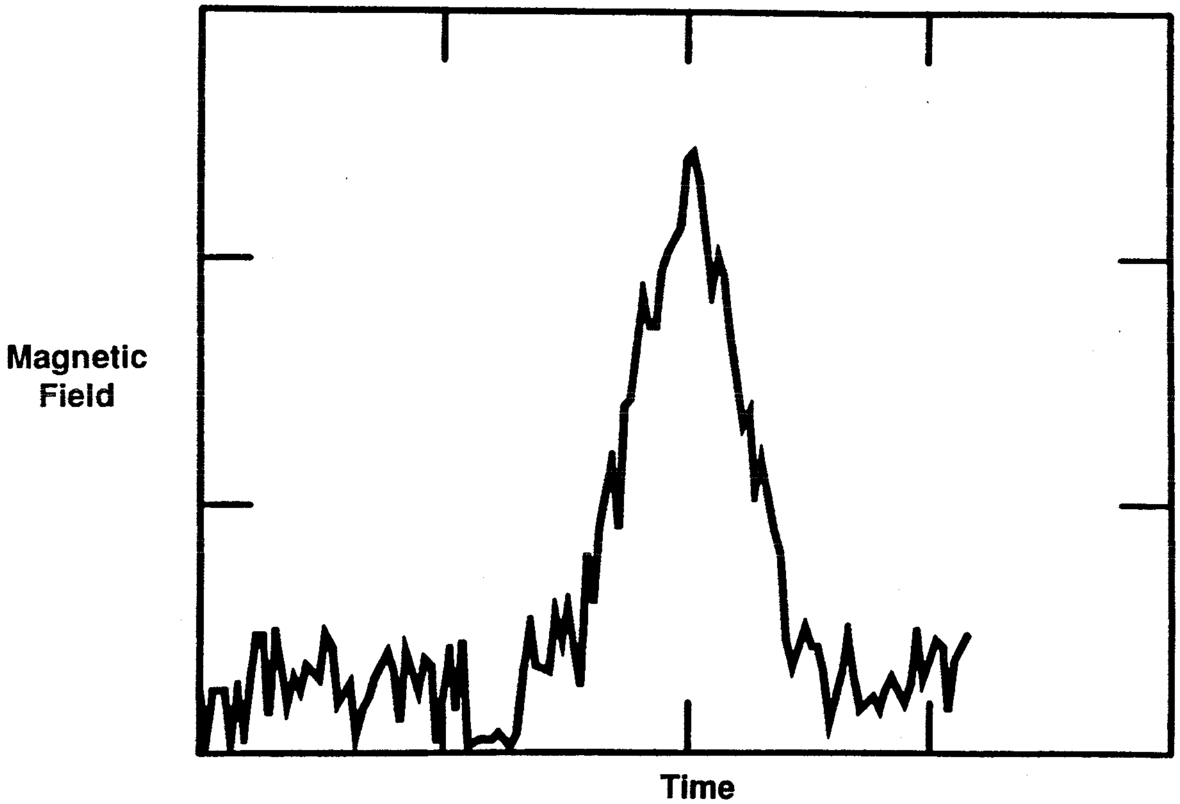
Magnetic Field Frequency



Magnetic Field Intensity

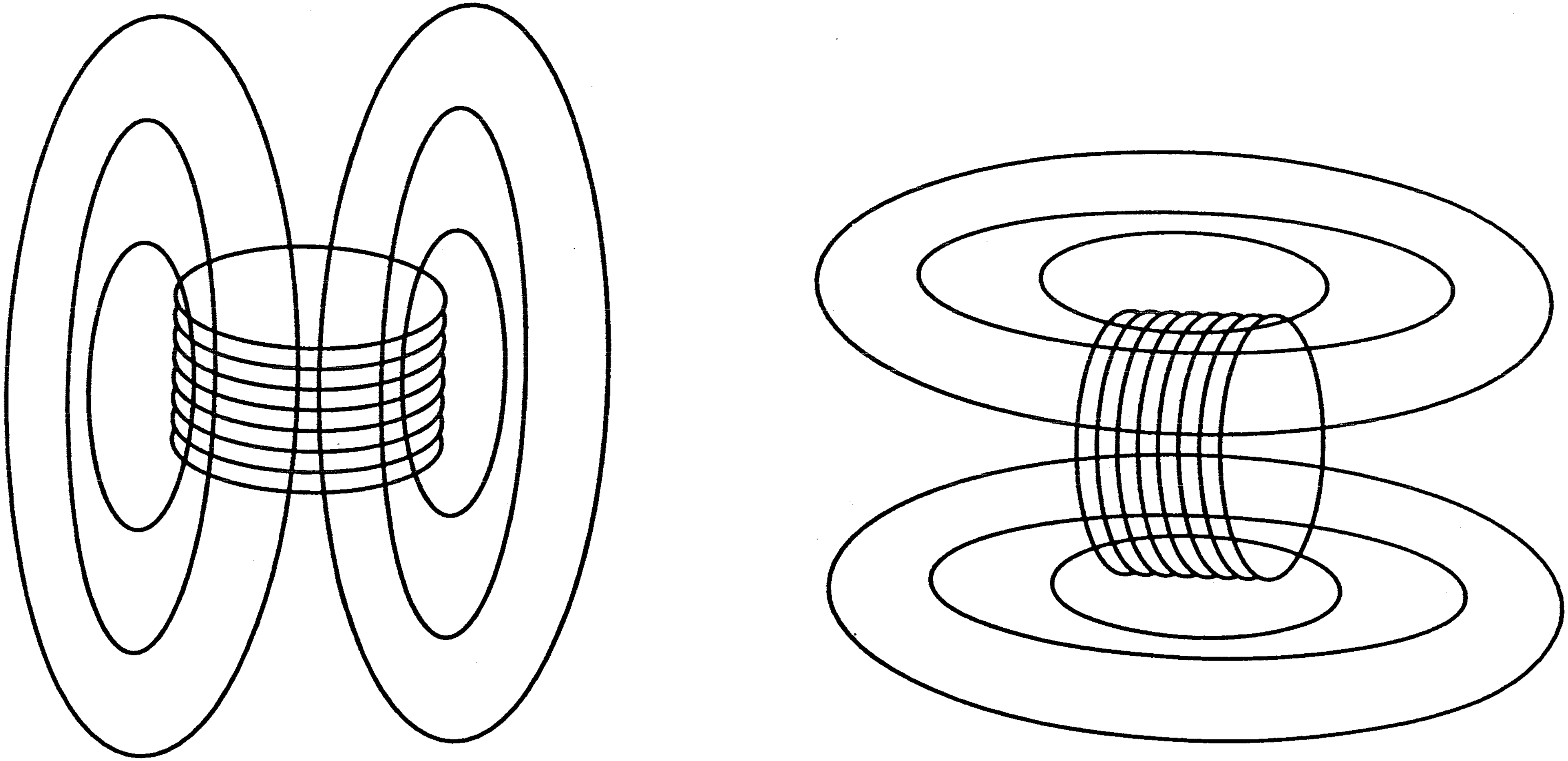


Magnetic Field Event Dependence



Magnetic Field Orientation

Magnetic Solenoid Flux Orientation



Magnetic Shielding of Electric Vehicles

Team Members	• Army TACOM • Chrysler, Corp. • Foster-Miller, Inc.
POC	• Marty Snyder, TACOM • Giovanni Bolgiani, Chrysler • Richard Wiesman and David Cope, Foster-Miller
Vehicles Studied	• Chrysler Corp. DC brush and AC induction electric vehicles
"Threats"	• Military: Magnetically influencd land mines • Commercial: Electromagnetic interference and prudent avoidance
Methodology	• Measurements (full waveform, 0 to 50 kHz, 1 mG to 10G) • Analysis • Design and System Integration • Validation Testing
Results	• Interior: 17 dB reduction in magnetic fields • Exterior: 18 dB reduction in magnetic fields

Sensor Suite

- Magnetic Field Measurements
  - Fluxgates magnetometers for low frequency measurements (0 to 1500 Hz)
  - Search coils for high frequency measurements (50 Hz to 50 kHz)
- Current Measurements
  - Hall effect probes
  - Transformers

Shielding Concepts for Interior Shielding

Component	Shield Classification	Shielding Concepts
Motor	• Active • Passive	• Cancelling current (load and heading dependent) • Passive laminations (flux ducts)
Brushes	• Passive	• Enclosure (high frequency attenuation) • Filter (account for enclosure penetrations)
Switching Harmonics	• Passive	• Smoothing capacitor (filter switching peak currents)

Shielding Concepts for Exterior Shielding

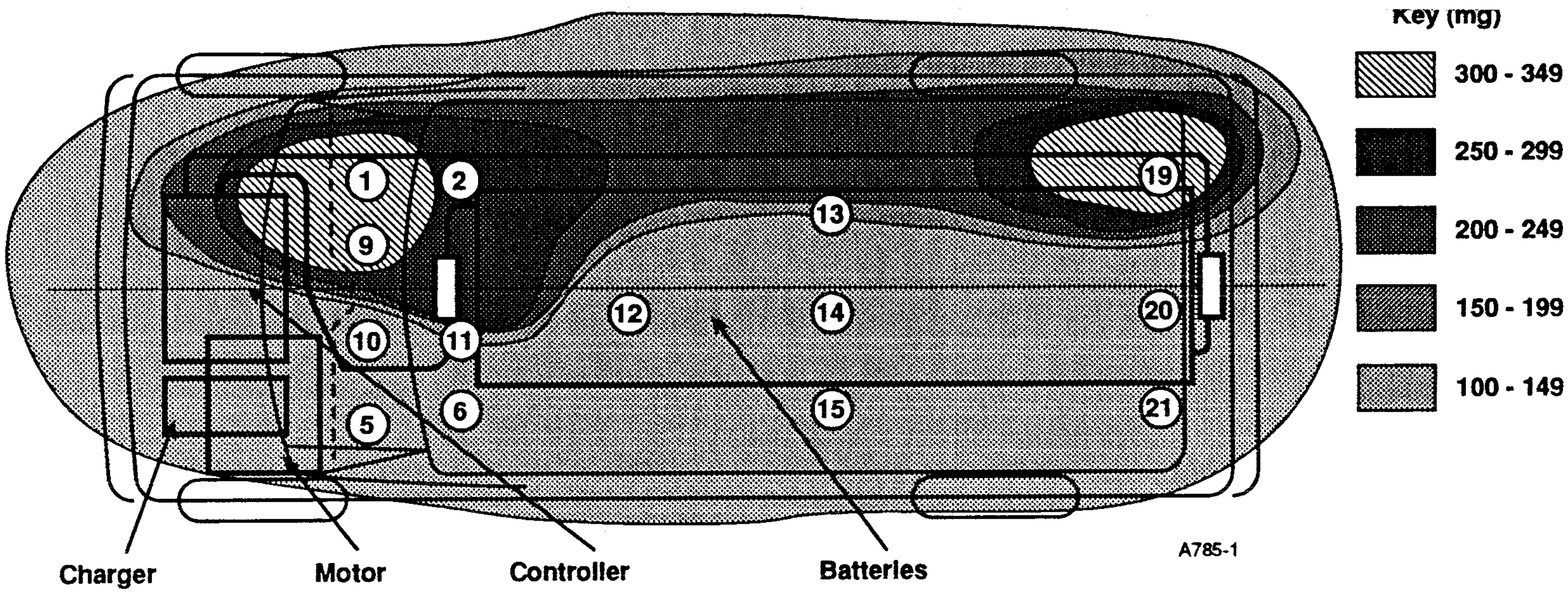
Component	Shield Classification	Shielding Concepts
Battery Permeable Mass and Permanent Moment	• Active • Design change	• Cancellation currents (heading dependent) • Battery-type change (reduce permeability)
Battery Current (Traction and Regeneration)	• Active • Passive (circuit layout)	• Cancellation currents • Battery layout change (reduces enclosed area)
Frame Permeability	• Active	• Cancellation currents (heading dependent)
Motor	• Active	• Cancellation currents (load and heading dependent)

Electric Vehicle Magnetic Shielding Summary of Field Sources and Fixes

Source	Frequency	Scaling	Typical Value	Interior Fix	Exterior Fix
Battery Permeability	DC	constant	~ 1 G	• Use different battery type • May not req'd	• Use different battery type • Elevate batteries • Active shielding
Battery Permanent Moment	DC	varies for different batteries	~1 G	• Use different battery type • May not req'd	• Use different battery type • Elevate batteries • Active shielding
Field Winding	DC	constant	~0.1 G	• Passive cancellation current • May not req'd	• Laminated shell
Armature Winding	4 kHz + harmonics	~2 mG/A	~0.1 G	• Vehicle shell eddy current • May not req'd	• Switch faster • Shield cables • Active shielding
Battery Current	6-20 Hz, 4 kHz + harmonics	~10 mG/A	0.5 G	• Re-wire batteries (see sketch); • Stabilize control circuit • Switch faster	• Re-wire batteries (maybe different configuration - see sketch) • Stabilize control circuit • Switch faster
Brush Noise	~20-25+ kHz	(speed dependent & sporadic)	~10 mG	• Use different motor • Ground vehicle shell • Filter	• Ground vehicle shell • Filter

Chrysler DC Electric Vehicle Reversible Modifications

- MCU changed
- Lead acid batteries replace NiCd
- Non-magnetic (Al, SS) tub straps replace steel straps
- Battery tub fan removed and shielded
- Positive lead wire relocated



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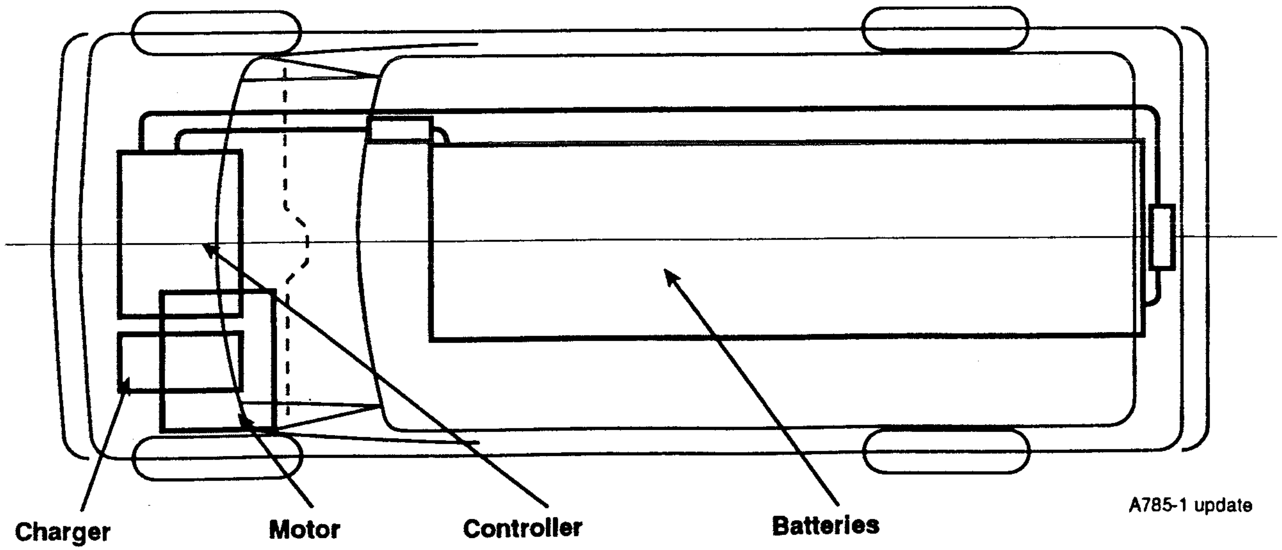

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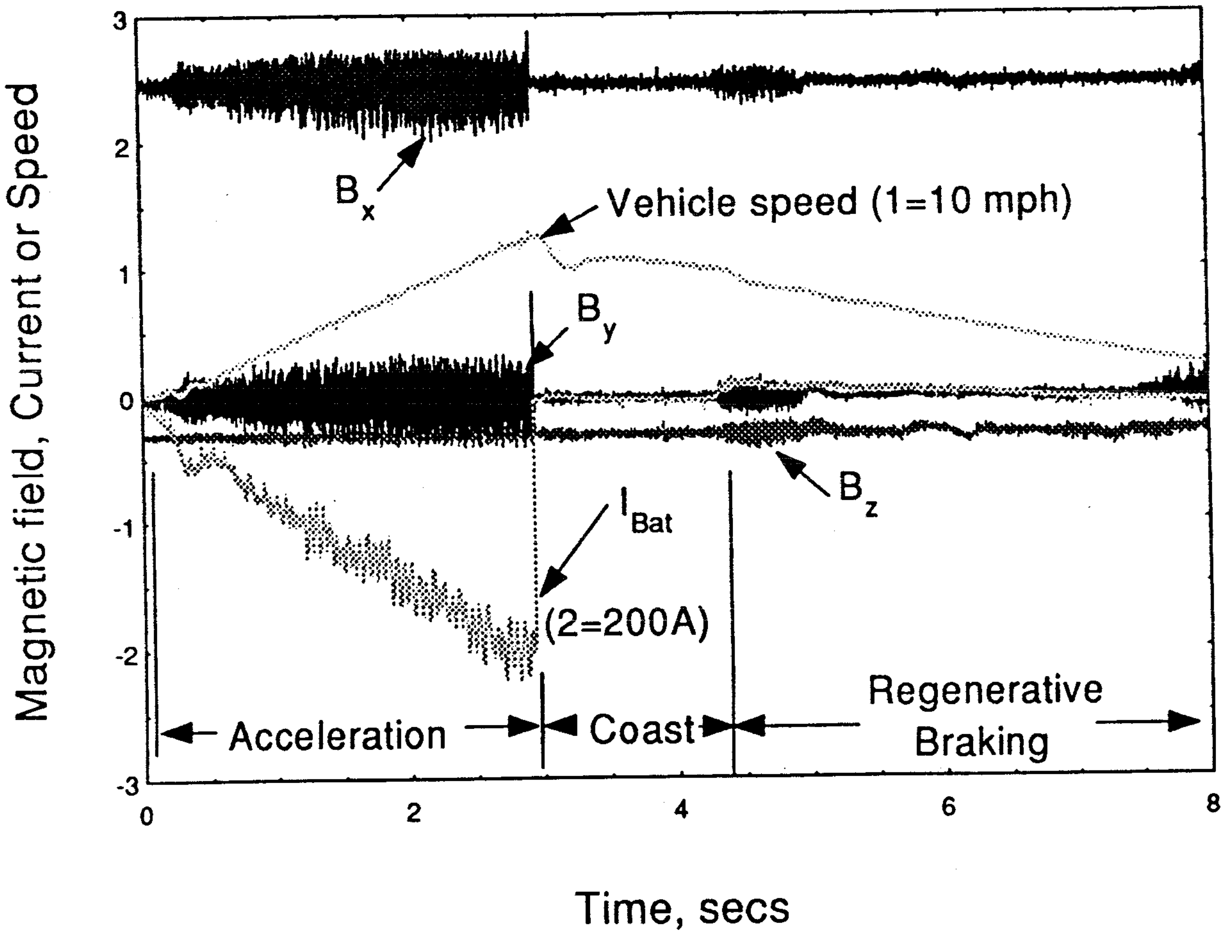
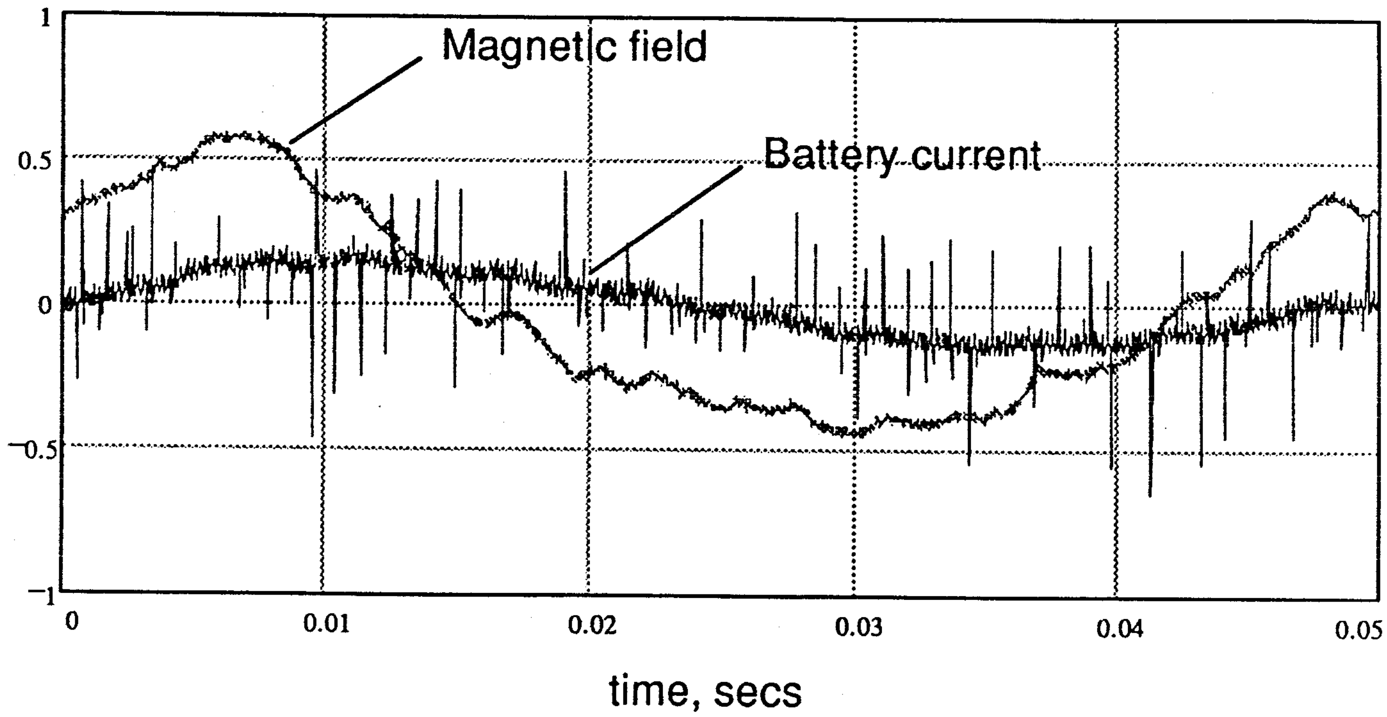
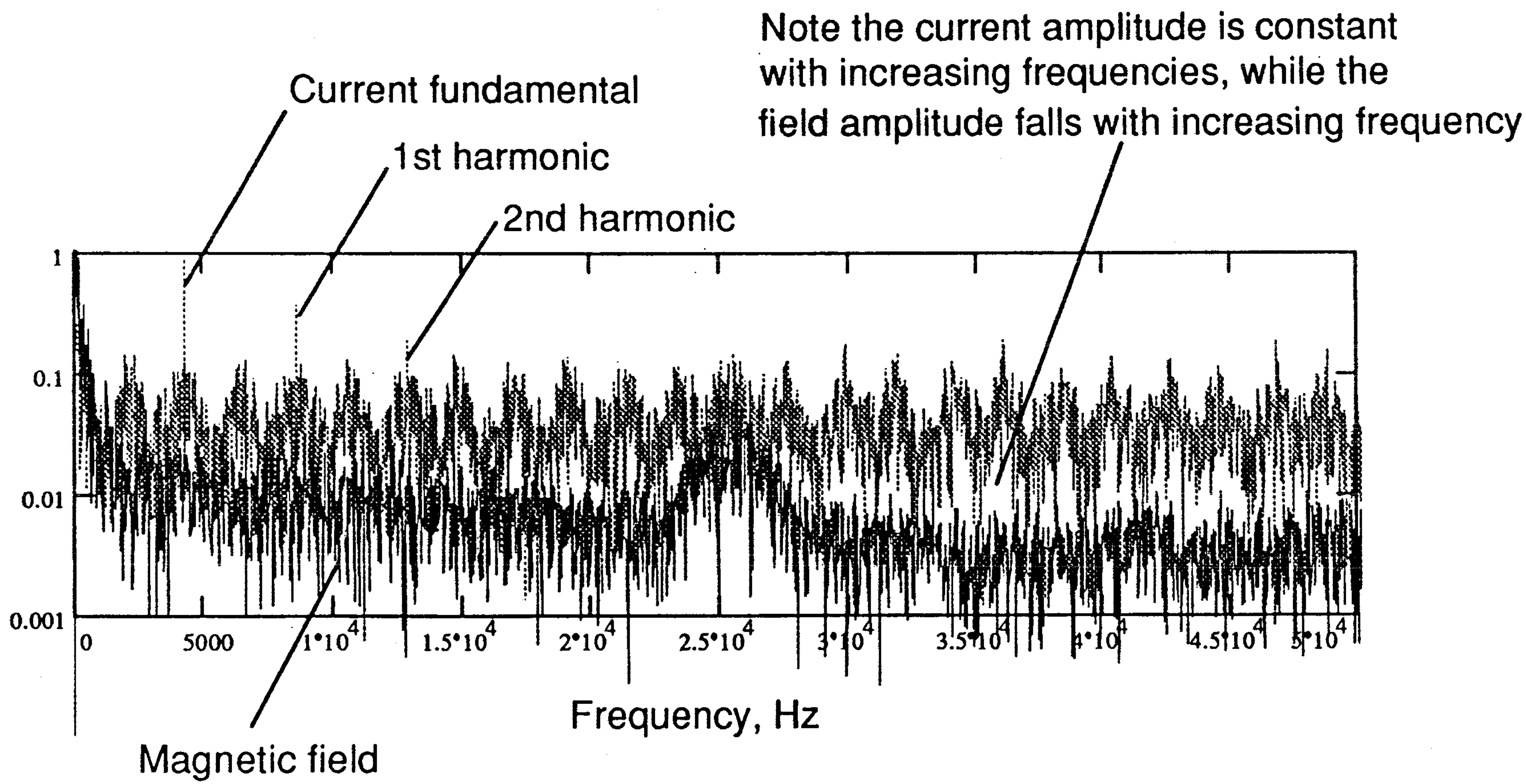
DC Vehicle Acceleration and Regenerative



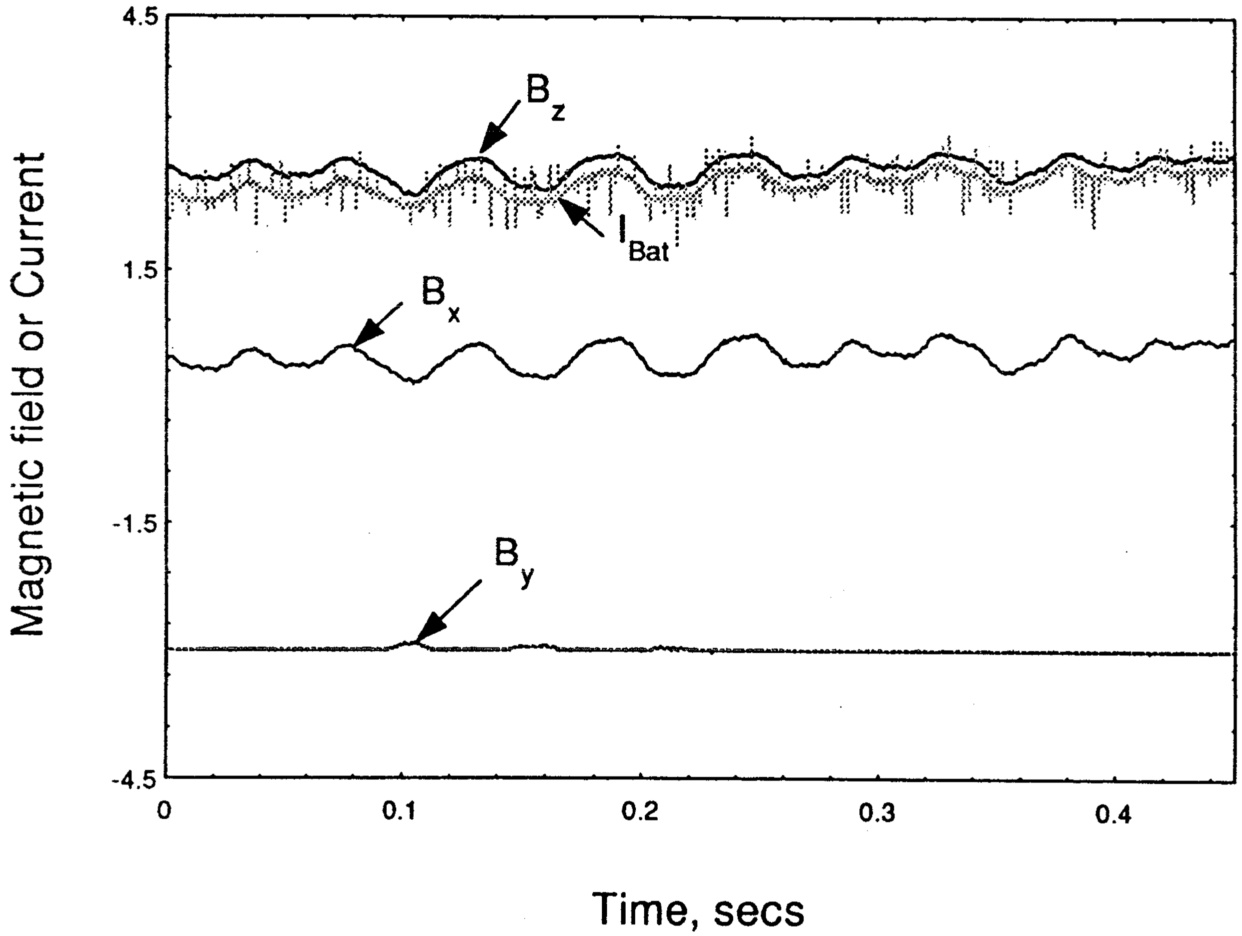
DC Vehicle Battery Current and Magnetic Field - Position No. 1



Battery Current and Magnetic Field FFT

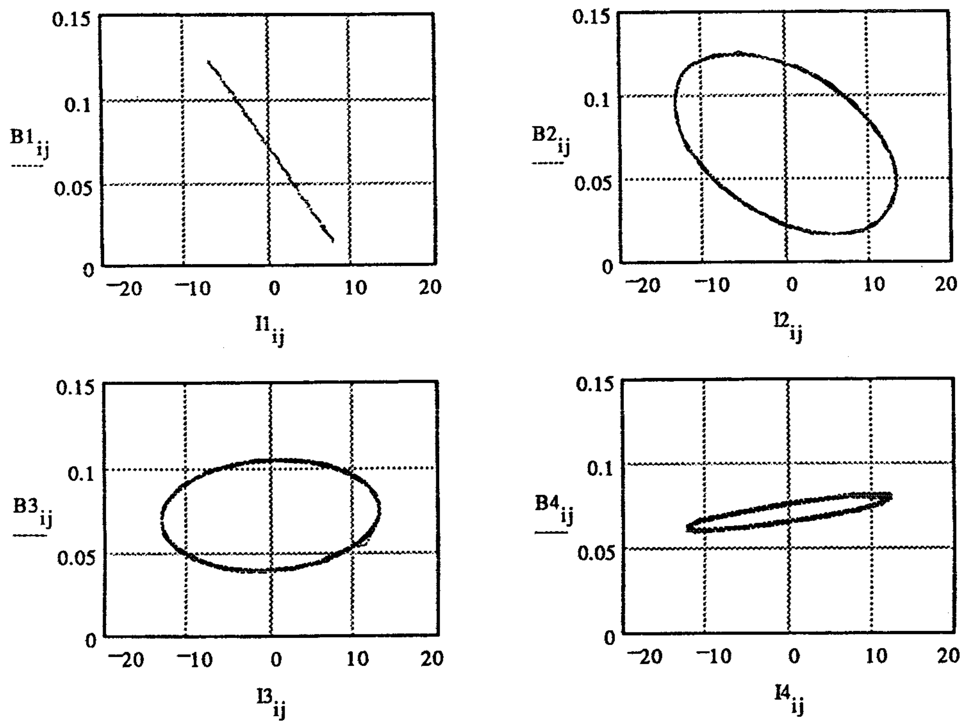


DC Vehicle on Dynamometer - Position No. 19



Floor Panel Eddy Current Shielding

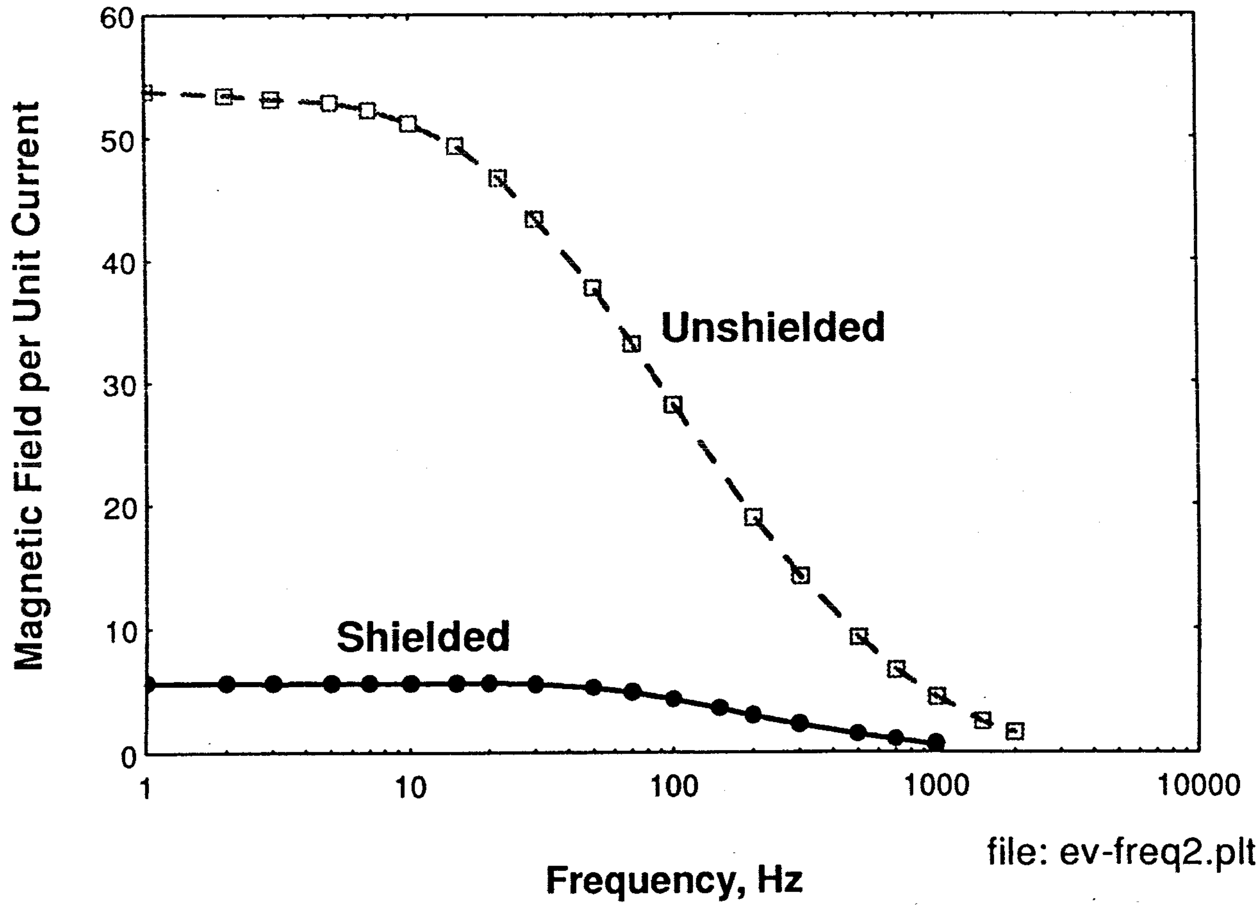
(a.) 1 Hz (b.) 100 Hz



(c.) 200 Hz (d.) 500 Hz

Vehicle Magnetic Field Frequency Response

Shielded versus Unshielded Configurations



Battery Re-Wiring Configuration Development

- Measurement and analysis iterated with each other
- Final configuration limited somewhat by practical realities
- Figures of merit
  - Interior: 7X or 17 dB
  - Exterior: 8 to 9X or 18 to 19 db

Impact of Battery Shield Re-Wiring per Vehicle (6 Tubs)

Parameter	Value
Reduced Magnetic Field	7X = 17 dB
Reduced Connectors	5 pairs (fewer)
Net Extra Length of #2/0 Wire	210 in. = 5.33m
Incremental Wire Resistance	1.3 mΩ*
Incremental Wire Power	13W* (at 100A)
Efficiency Reduction	<0.1%*
Savings in Mass	0.2 lb = 0.1 kg
Savings in Material Cost	$26.00

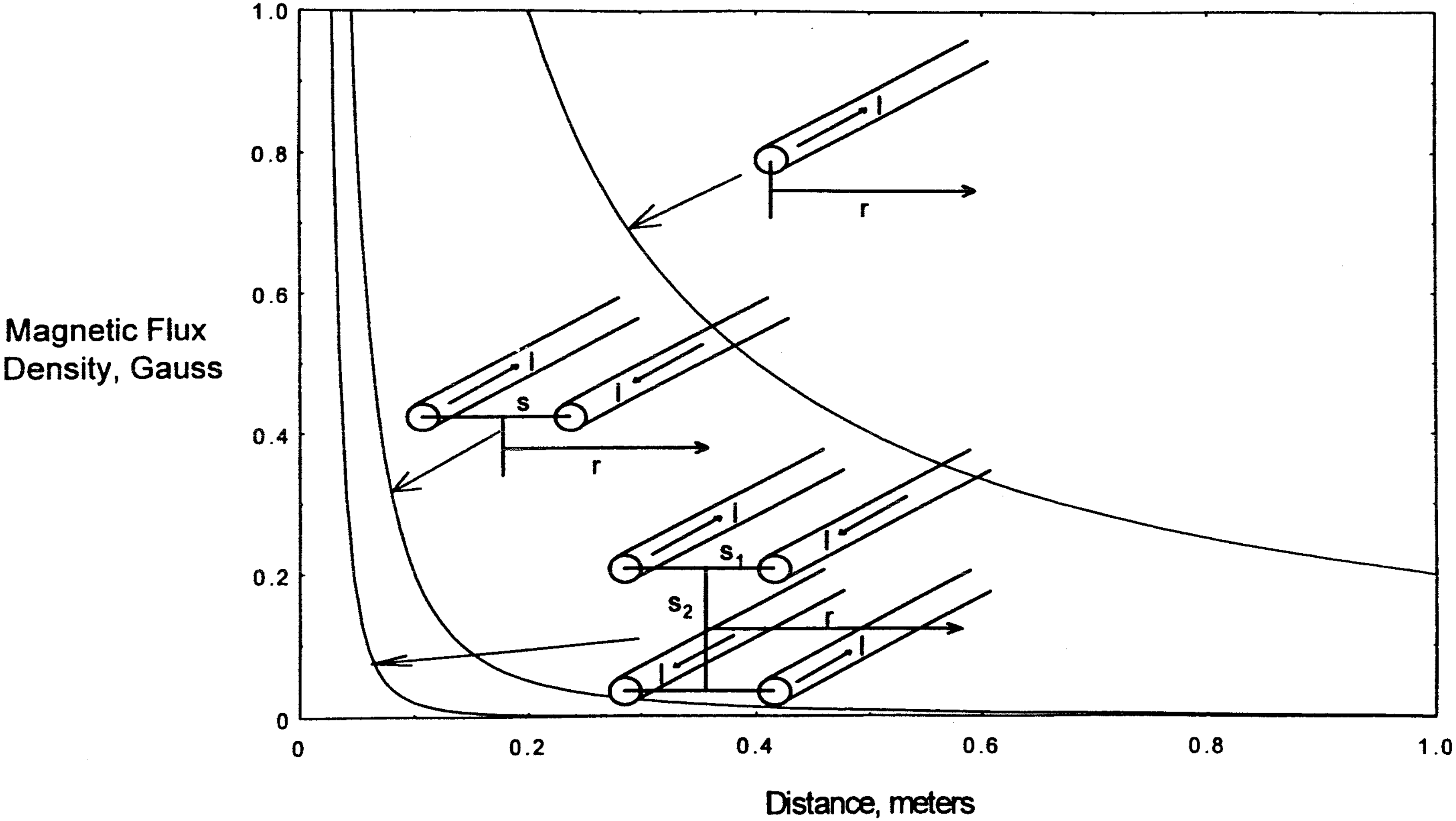
*Neglects savings due to fewer connections

Battery Re-Wiring Materials Costs

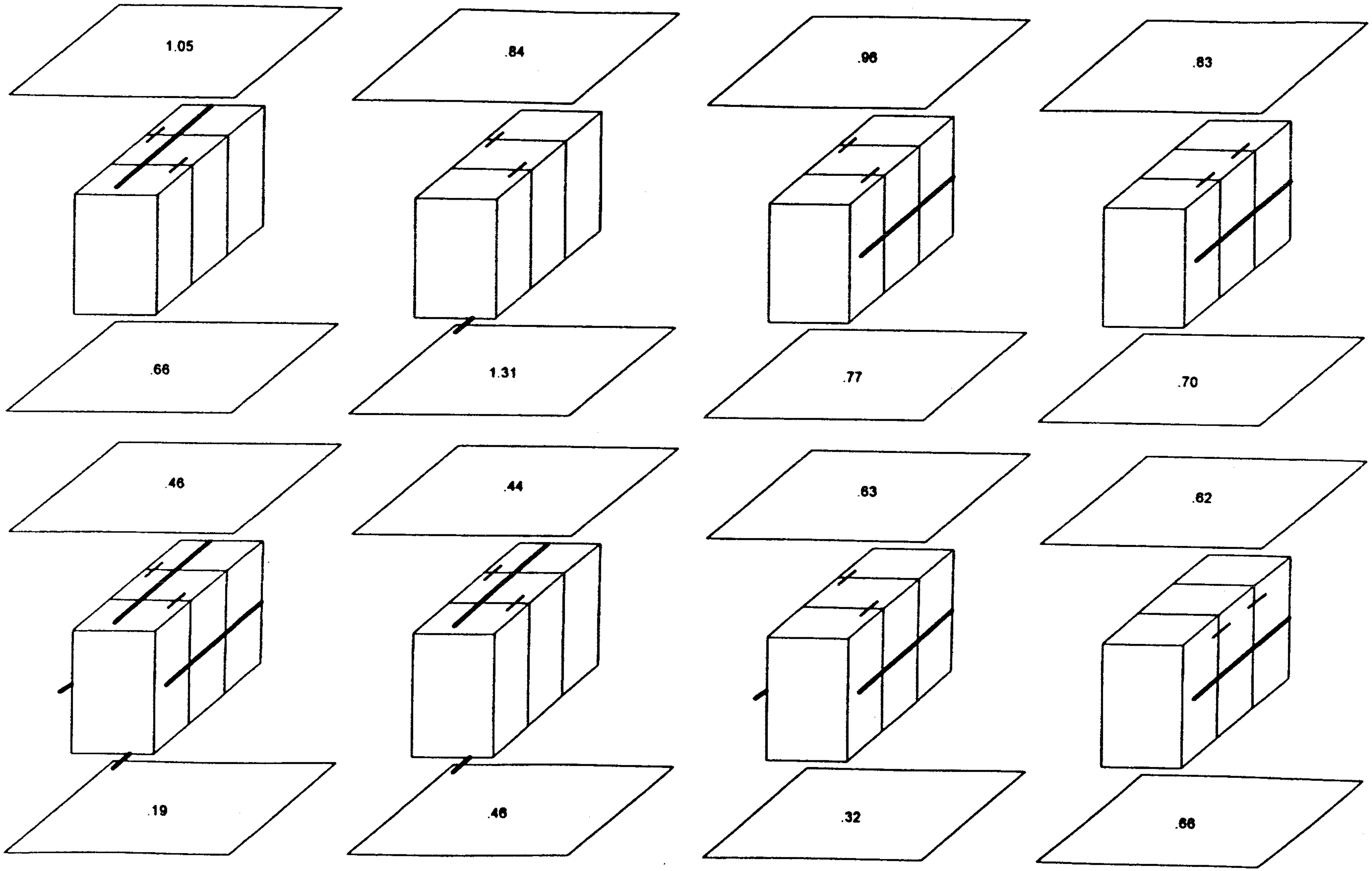
Three-Pack Single Tub
Single Tub Re-Wiring Materials Cost: $31.62

Item	Quantity	Unit Cost	Extended Cost
#2/0 Cu wire	48"	$1.32/ft	$5.28
#2/0 lugs	6	$1.44	$8.64
#2/0 connector	1 pair	$17.70	$17.70

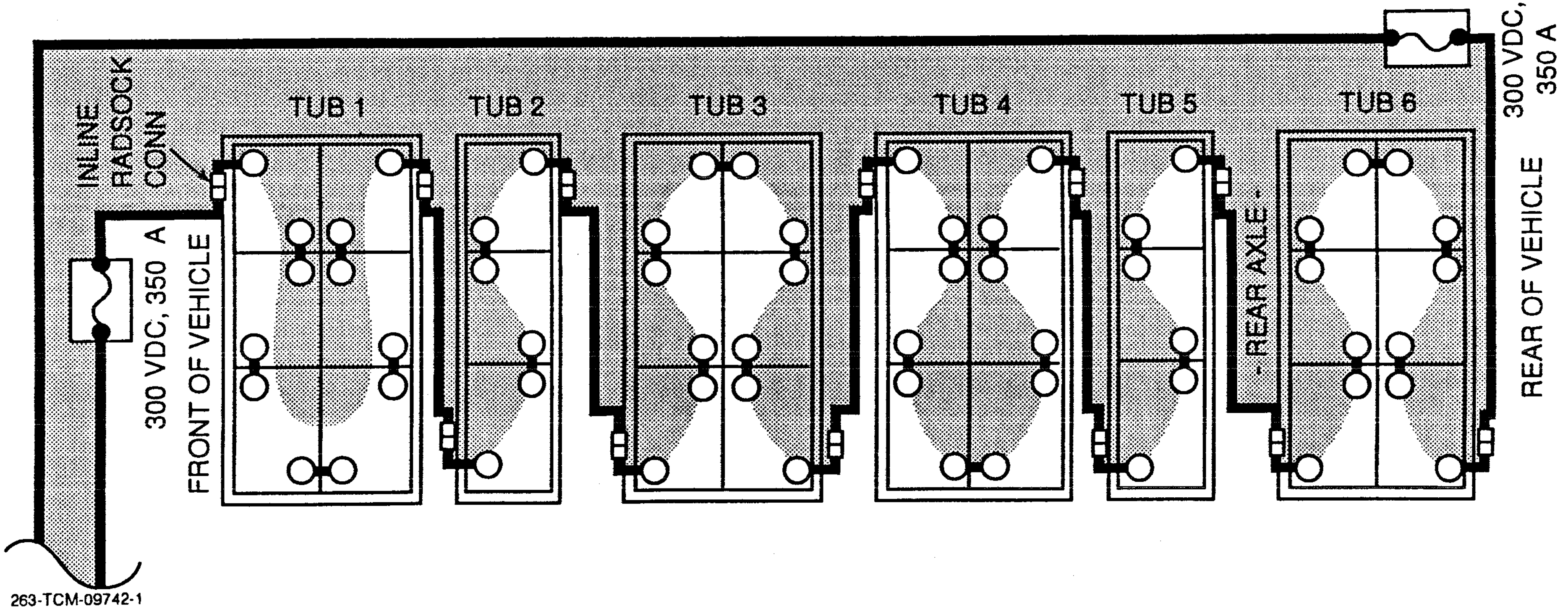
Transmission Line Flux Density Versus Distance



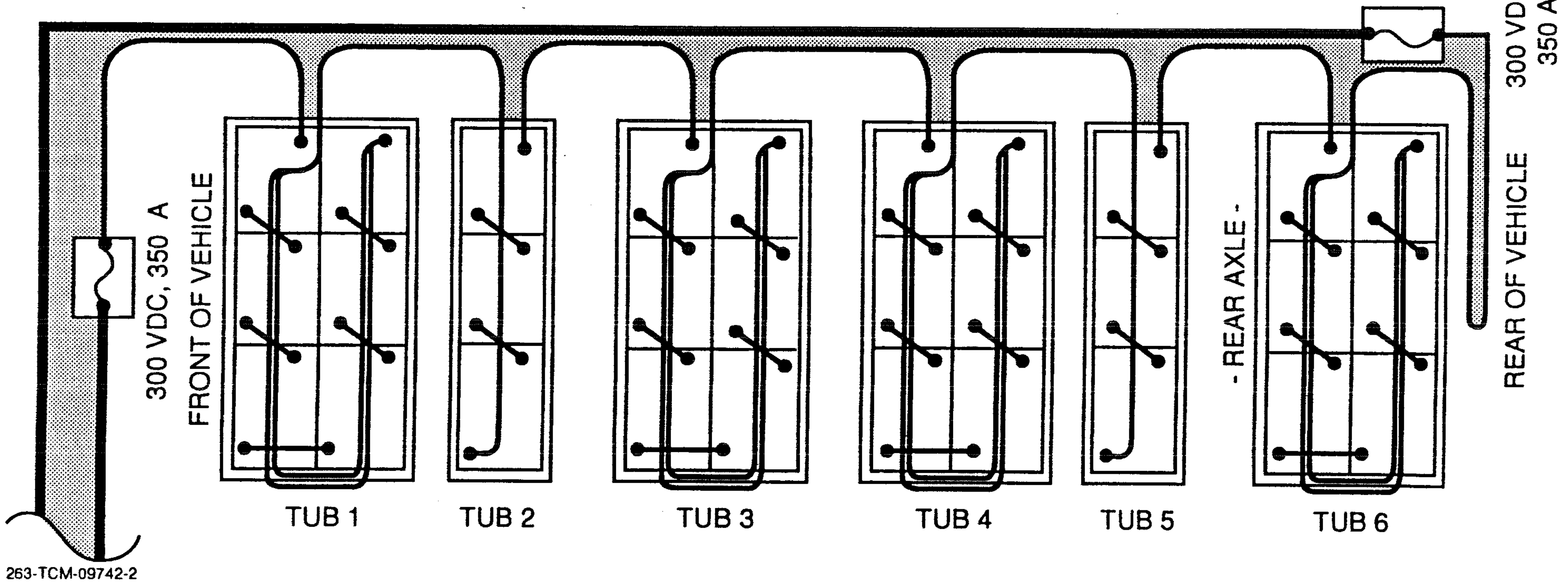
Battery Re-Wiring Configurations Analyzed



Present NiCd Battery Cabling Configuration



New Lead Acid Battery Cabling Configuration

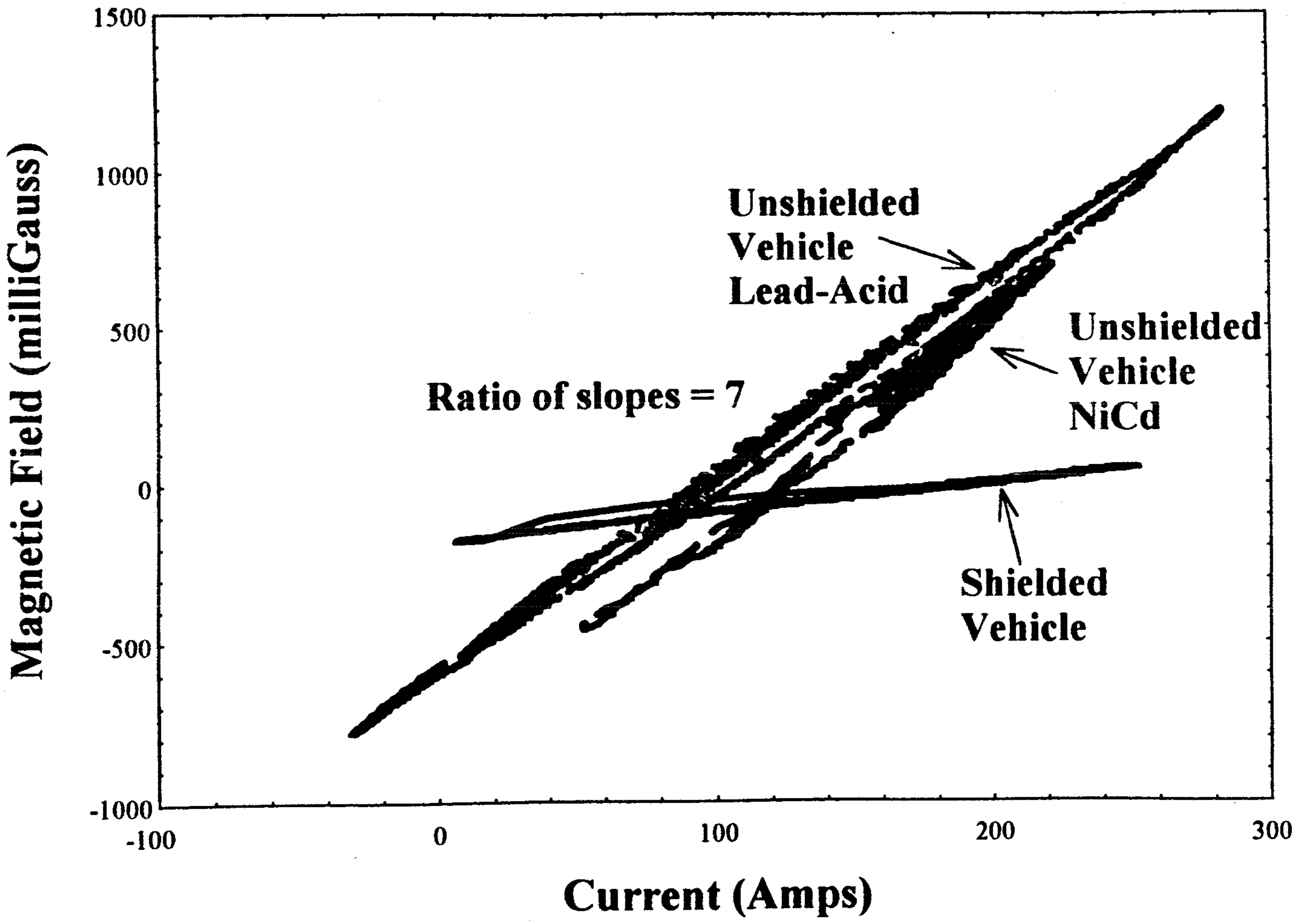


Point Design #1

- Problem
  - Interior electric drive-induced magnetic fields
- Analysis
  - Magnetic fields were proportional to battery current
- Solution
  - Re-wire batteries to reduce emitted field per unit current
- Results
  - Fields reduce 7X = 17 dB

Interior Magnetic Field Shielding Results

Floor Level



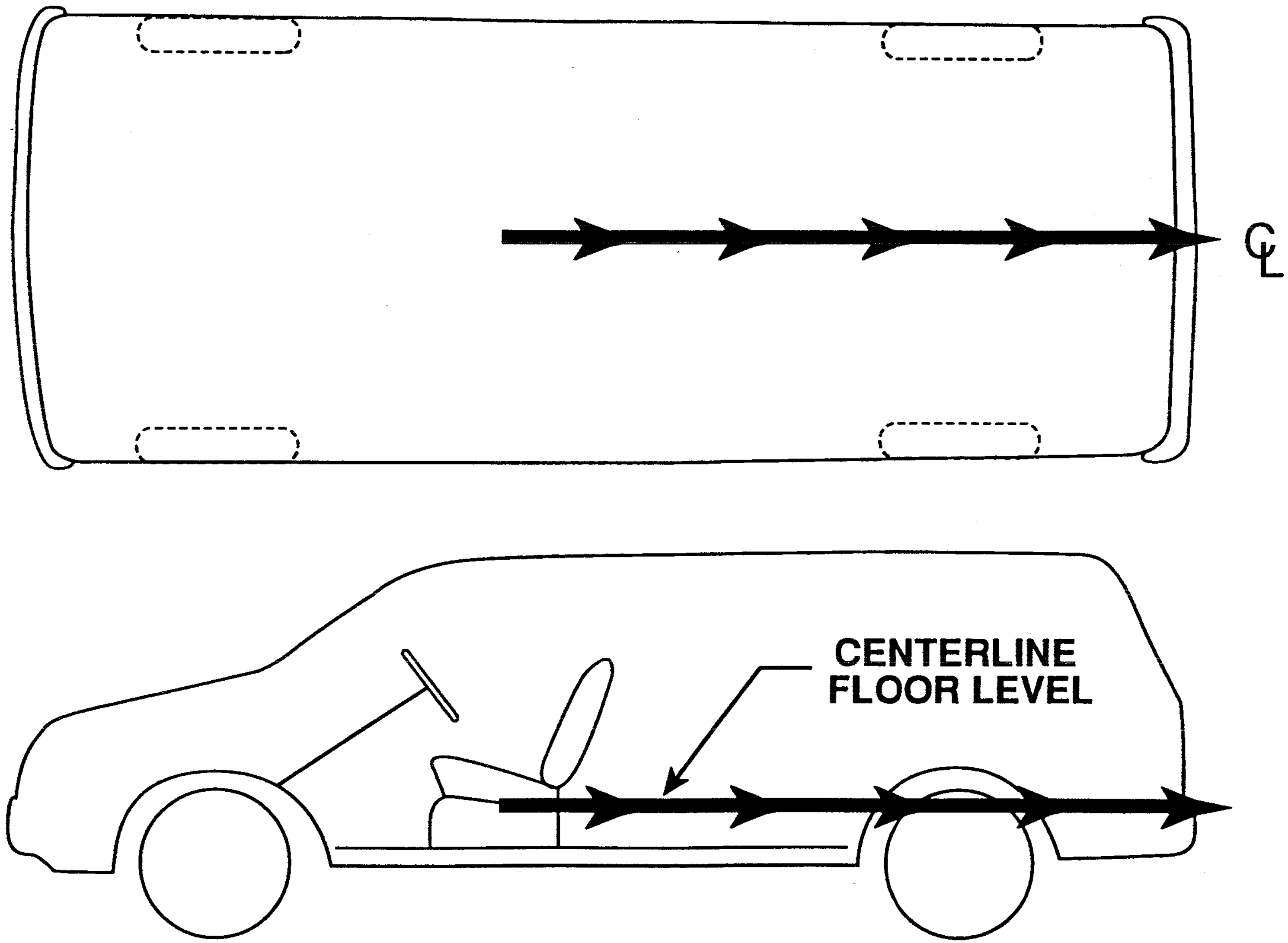


DIAGRAM 2

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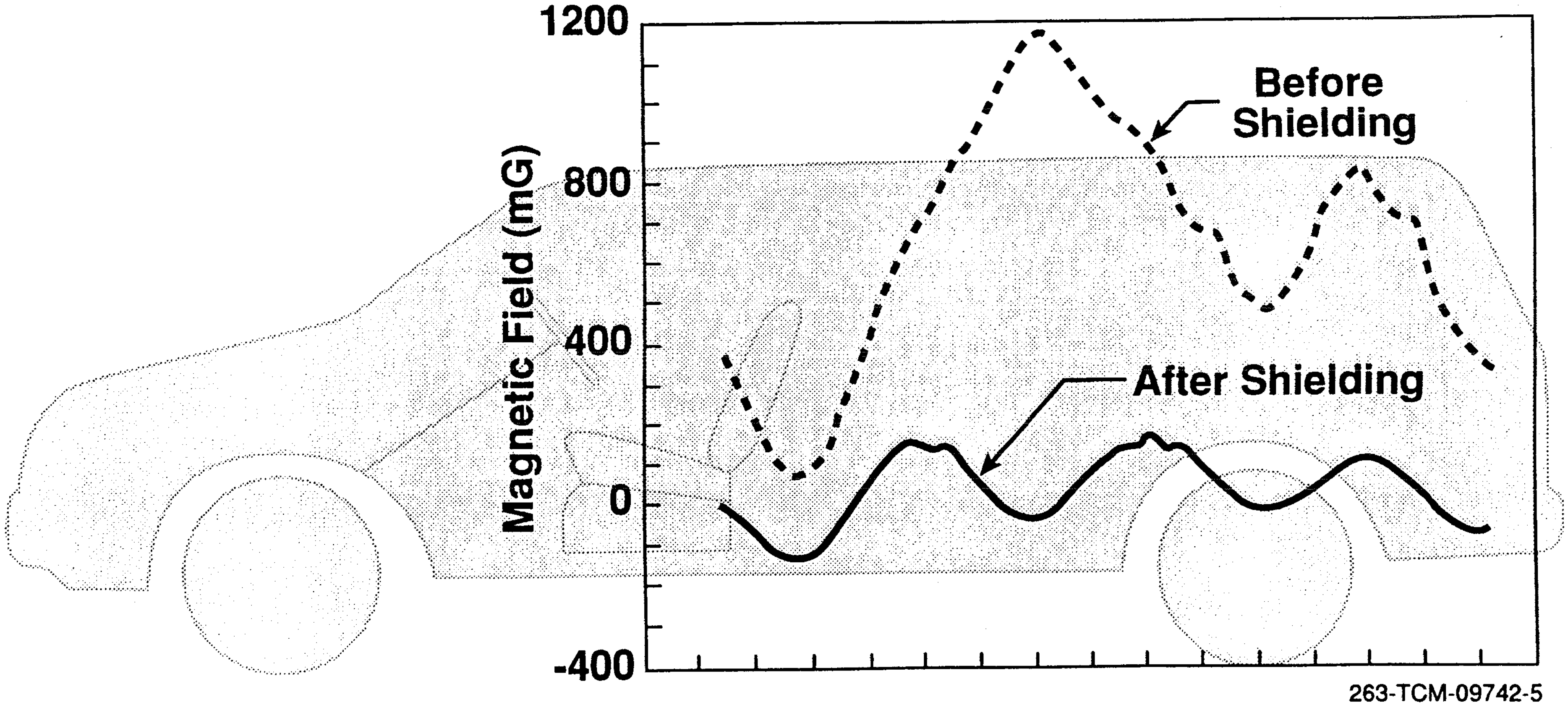
Interior Magnetic Field

Vehicle Center Line at Floor Level

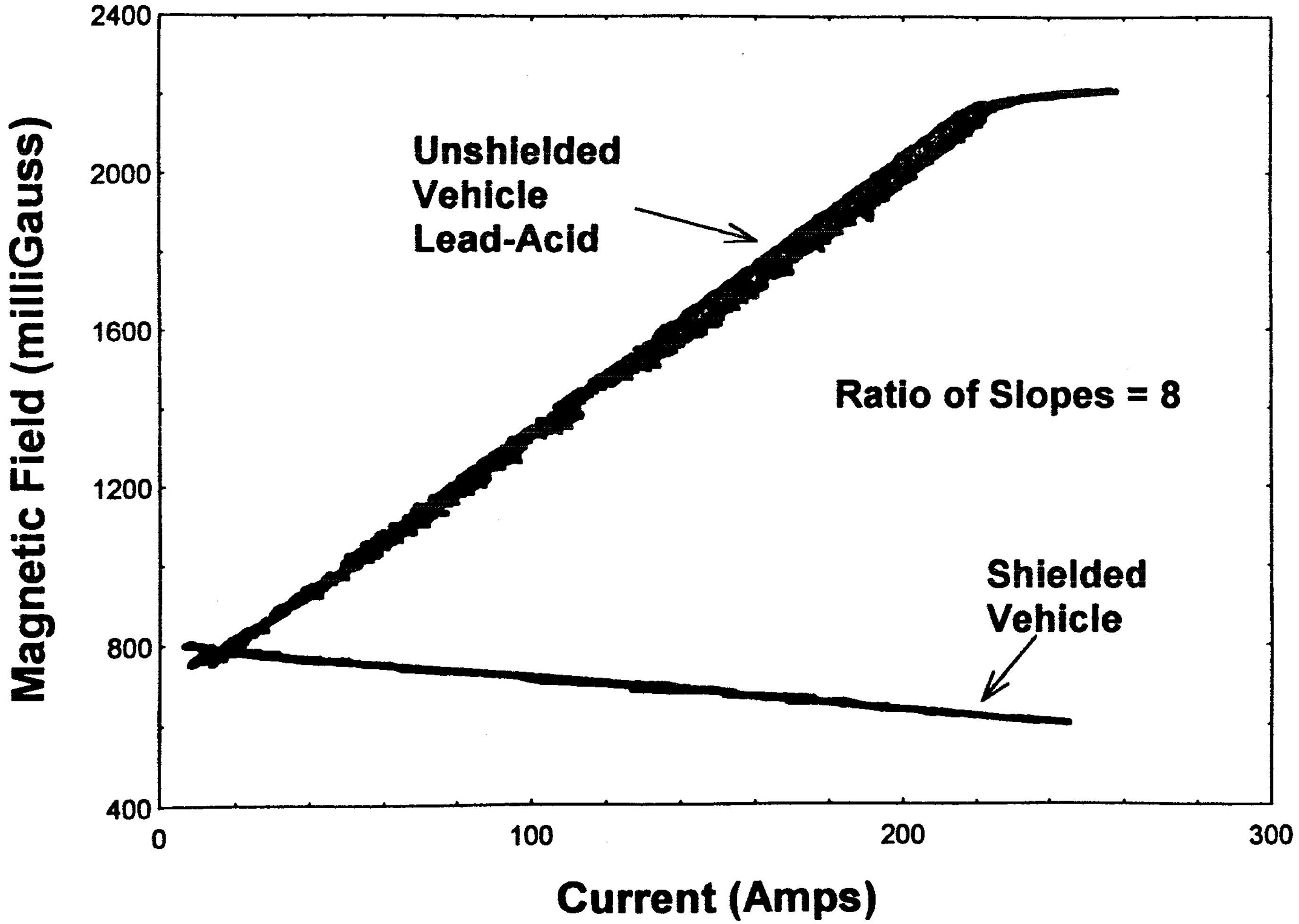


Point Design #2

- Problem
  - Exterior electric drive-induced fields
- Analysis
  - Fields were proportional to battery current
- Solution
  - Re-wire batteries to reduce emitted field per amp
- Results
  - Fields reduce 8X to 9X (18 to 19 dB)

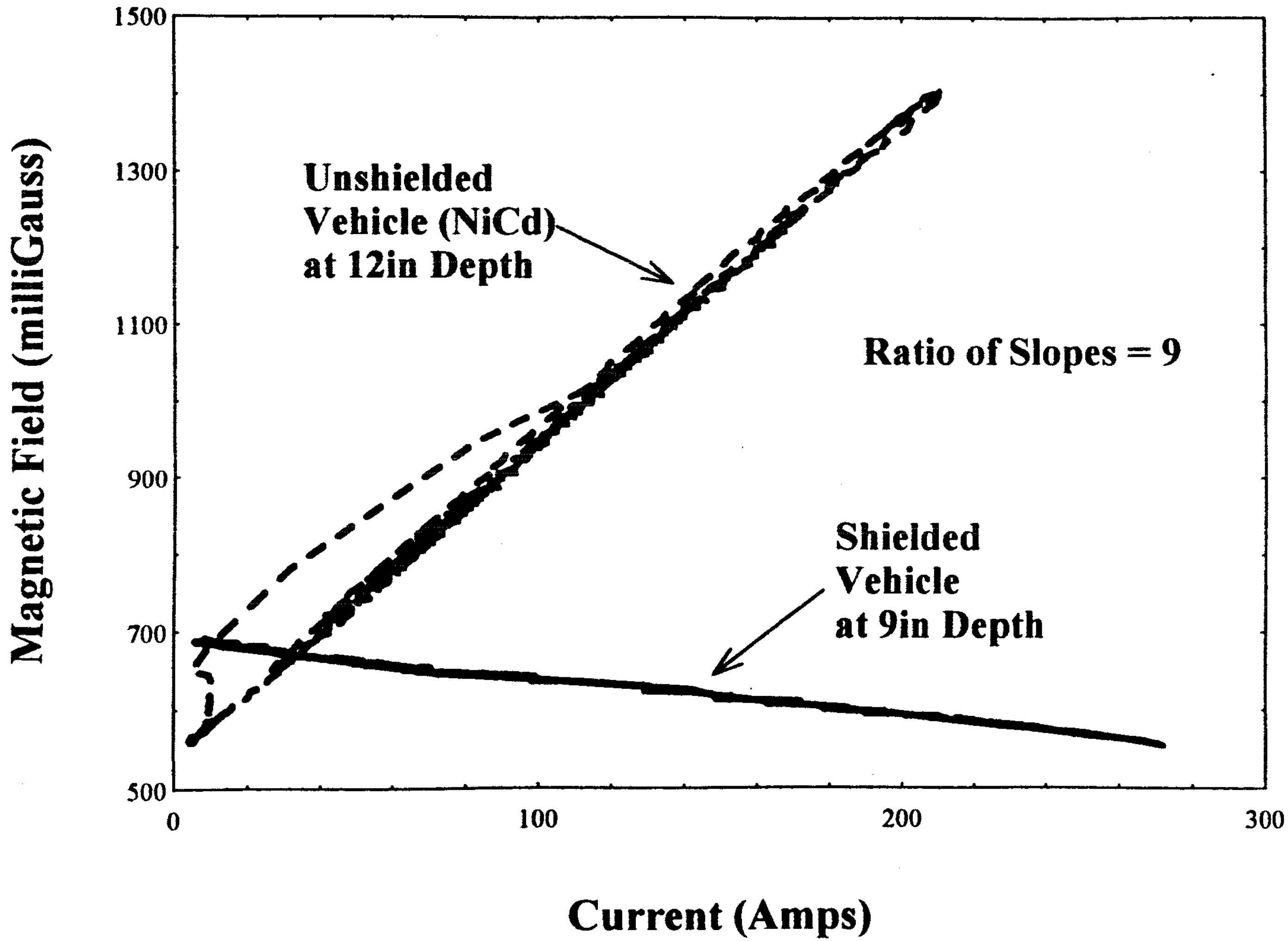
Exterior Magnetic Field Shielding Results

Ground Level



Exterior Magnetic Field Shielding Results

Simulated Mine Depth



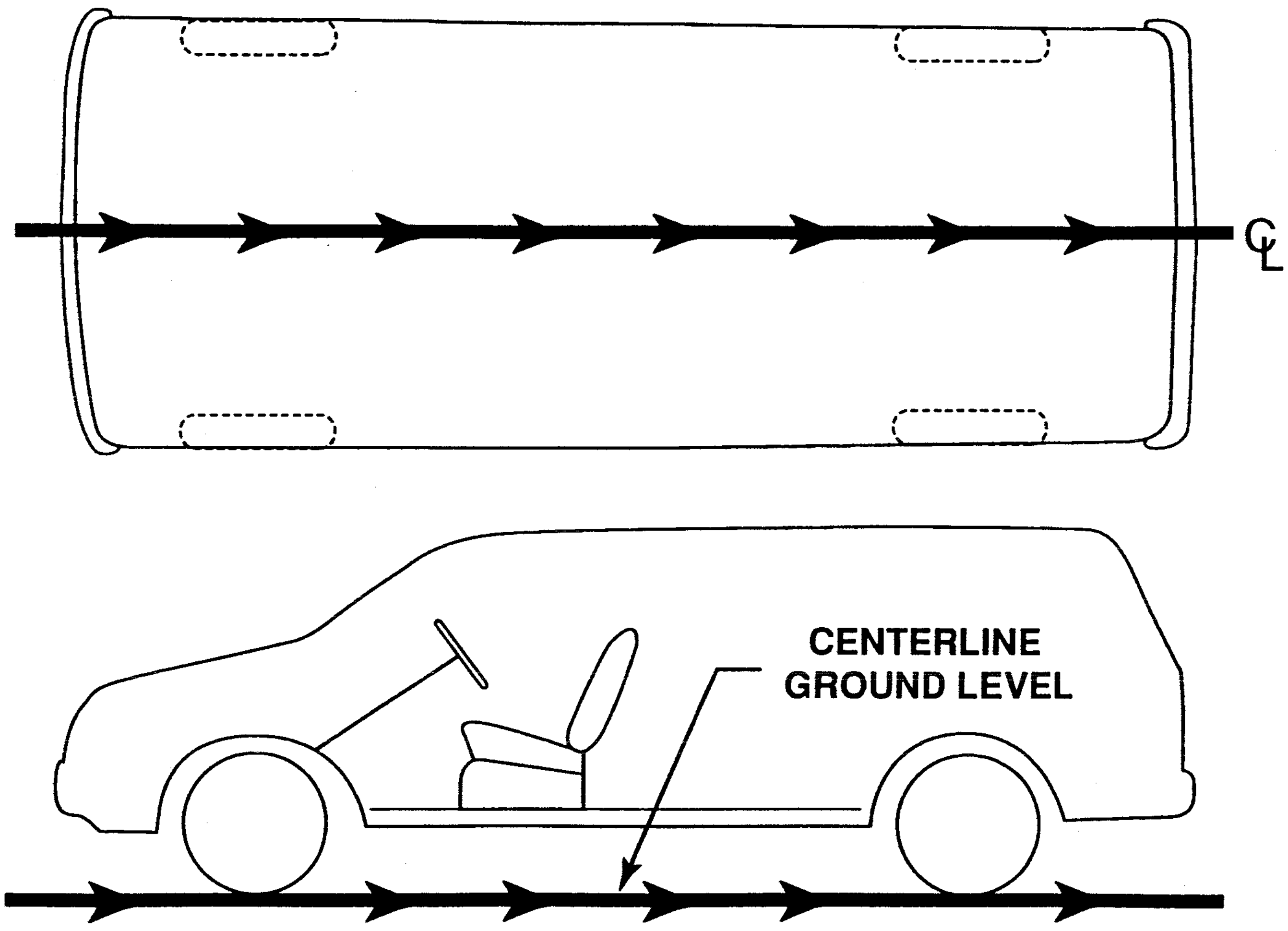
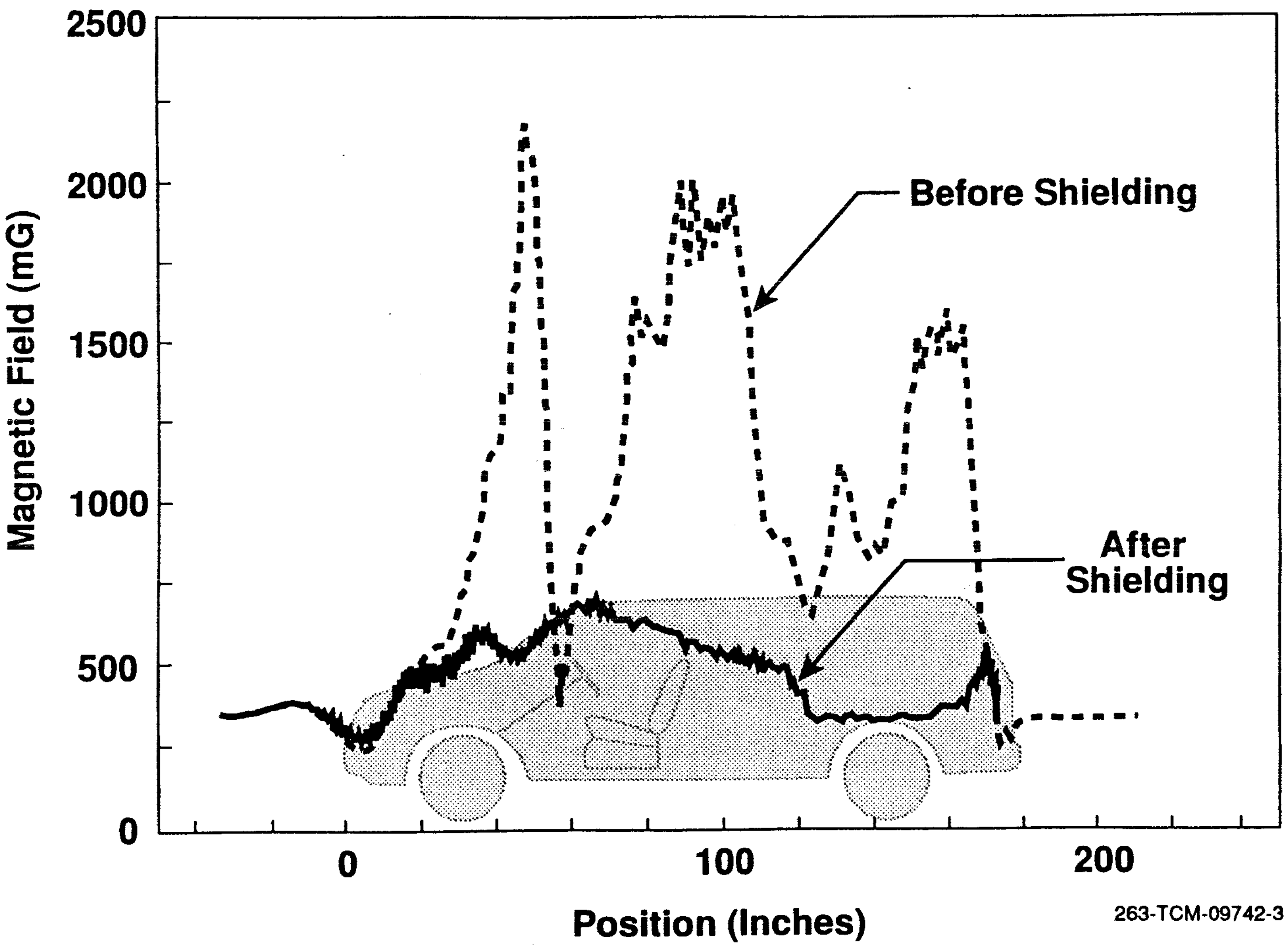


DIAGRAM 1

Exterior Magnetic Field

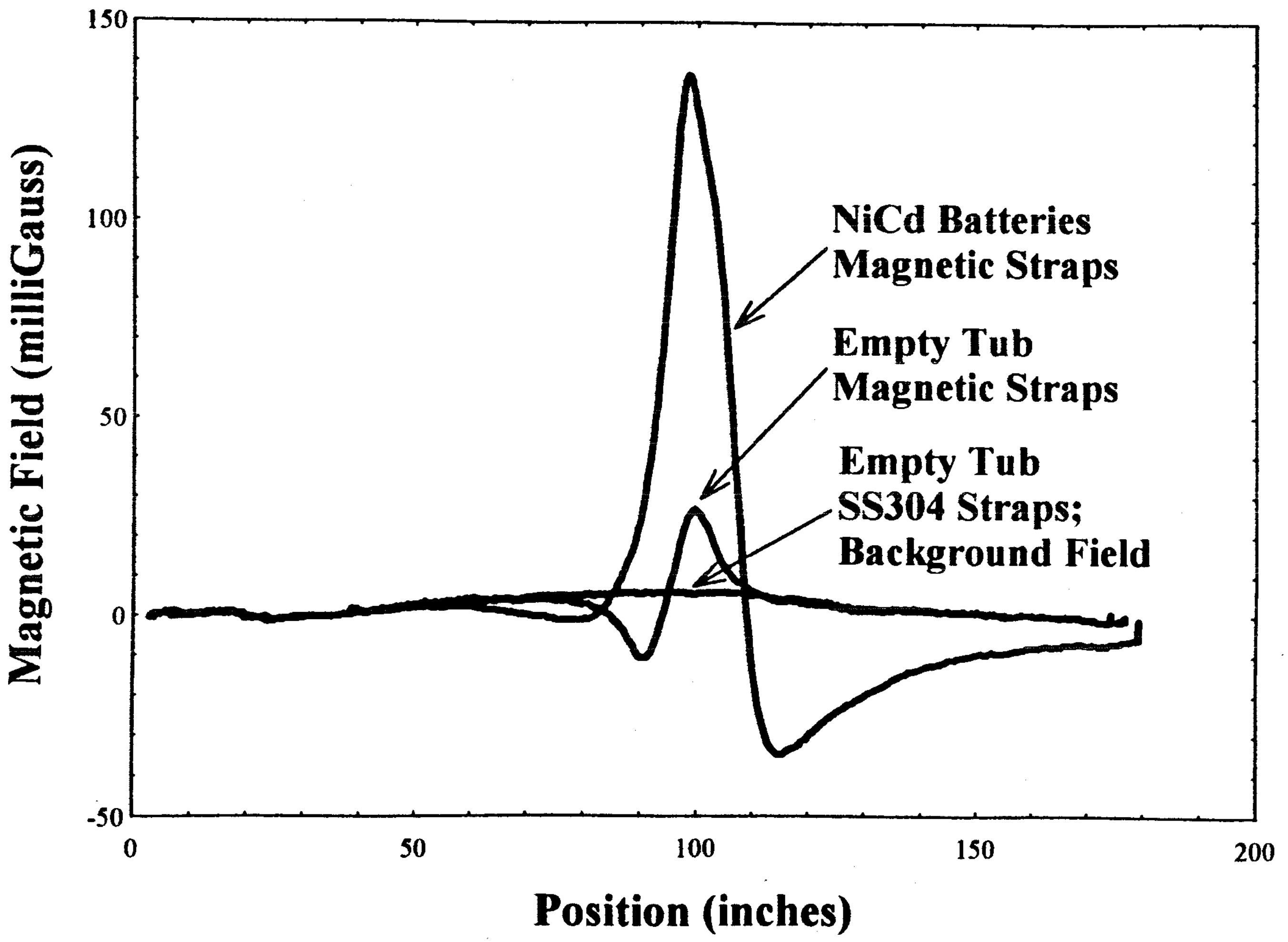
Vehicle Center Line at Ground Level



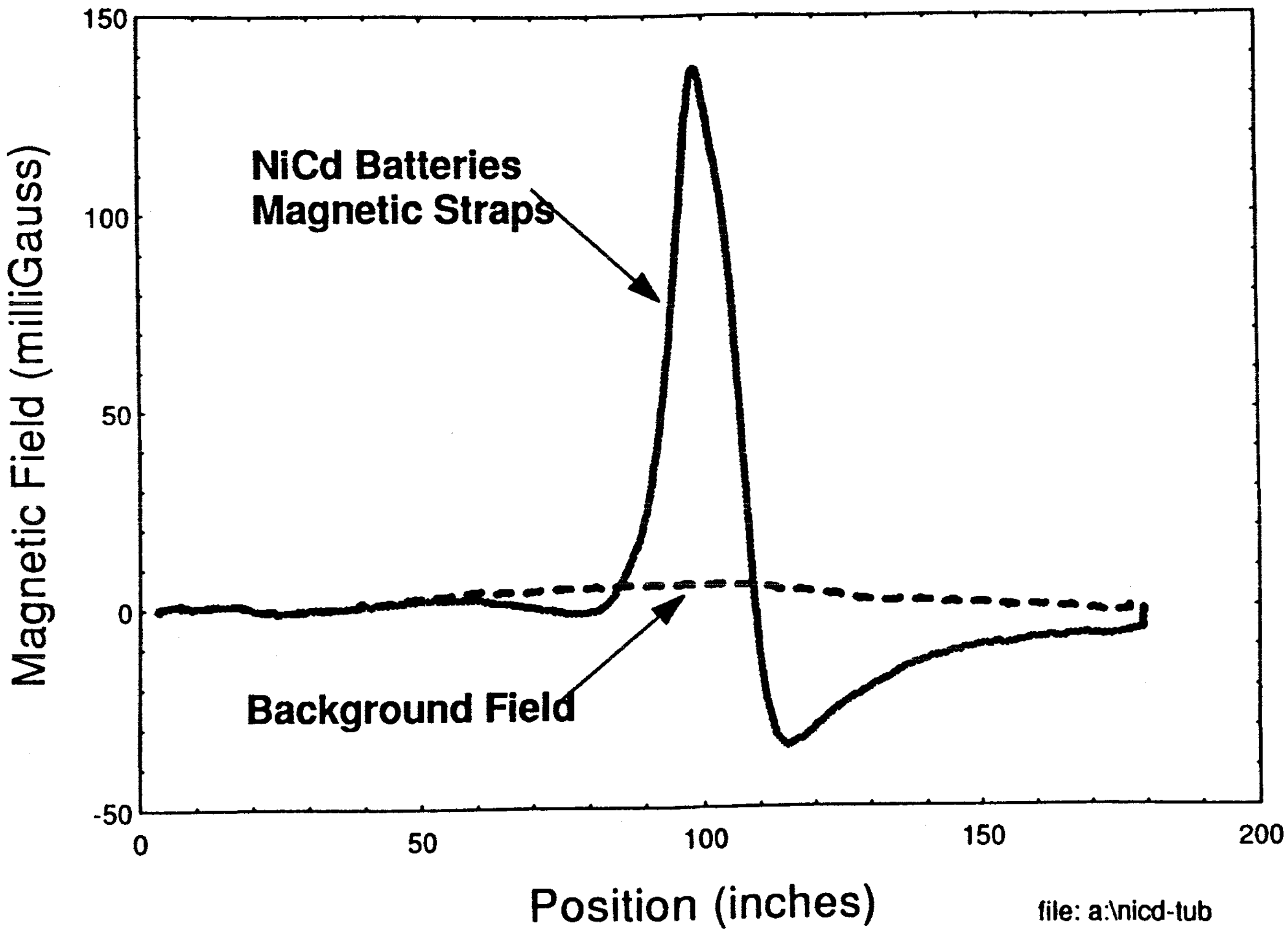
Point Design #3

- Problem
  - Exterior earth-induced fields
- Analysis
  - Interaction with earth background field
- Solution
  - Replace permeable NiCd batteries and straps with non-permeable lead acid batteries and aluminum or stainless steel straps
- Results
  - Fields reduce by 140 mG

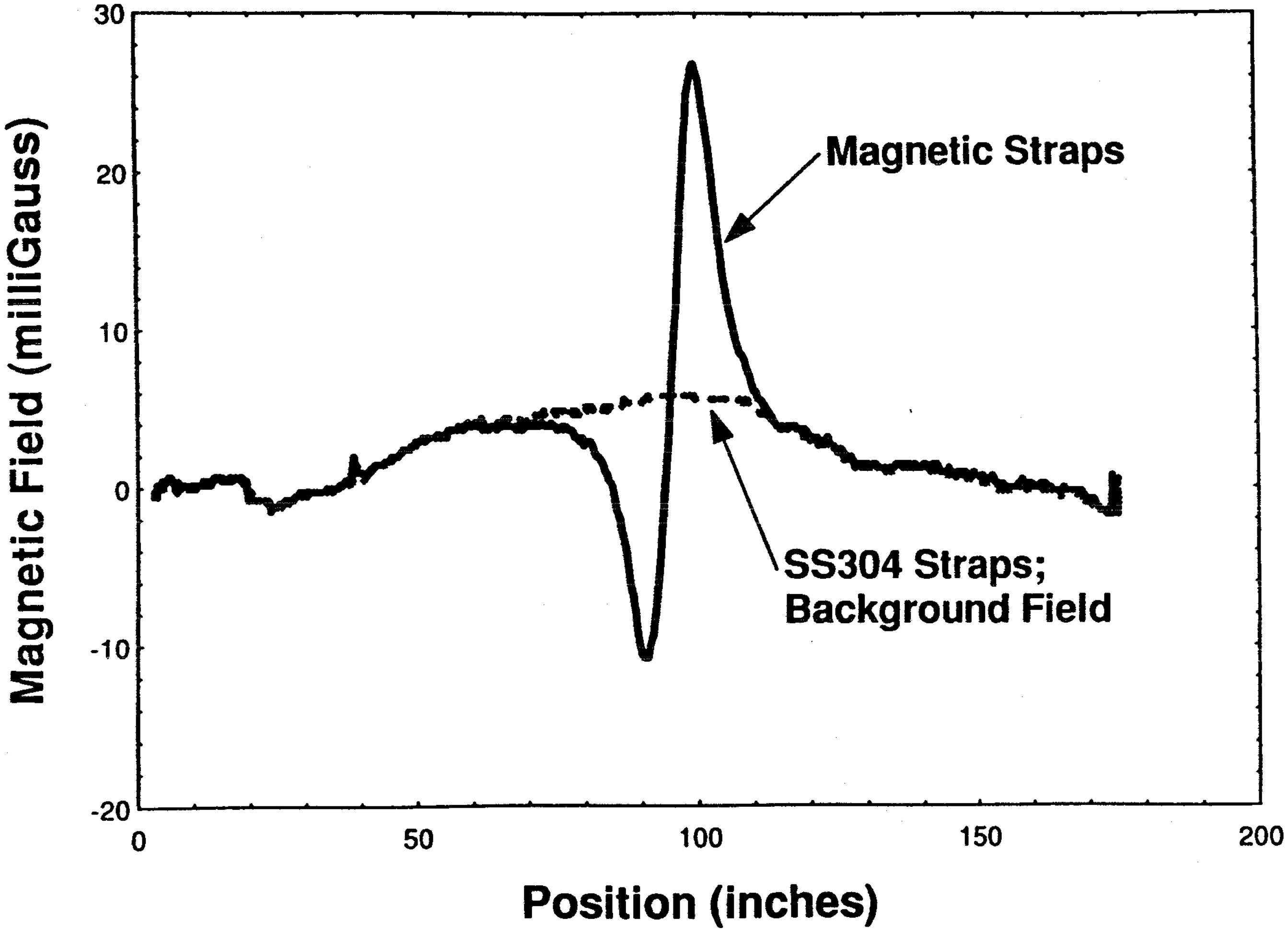
Magentic Field of Battery Assembly Components



Magnetic Field of NiCd Battery Tub



Magnetic Field Reduction Due to Support Straps

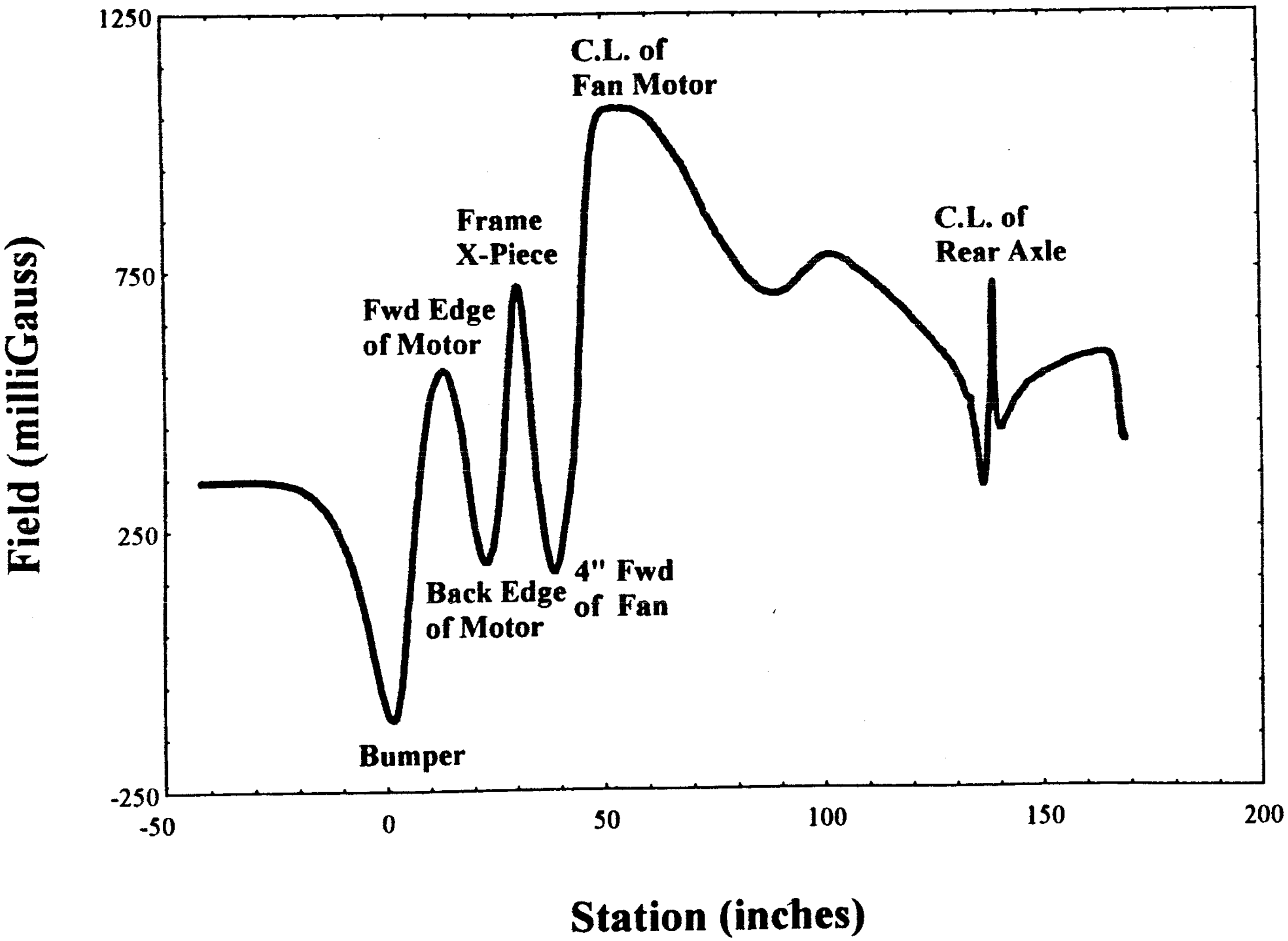


Point Design #4

- Problem
  - Exterior magnetic field: battery tub fan motor
- Analysis
  - DC field due to motor permanent magnets, analysis shows the field to be dipole in nature
- Solution
  - Single coil (inherent dipole) produces cancellation field
- Results
  - Fields significantly reduced (work in progress)

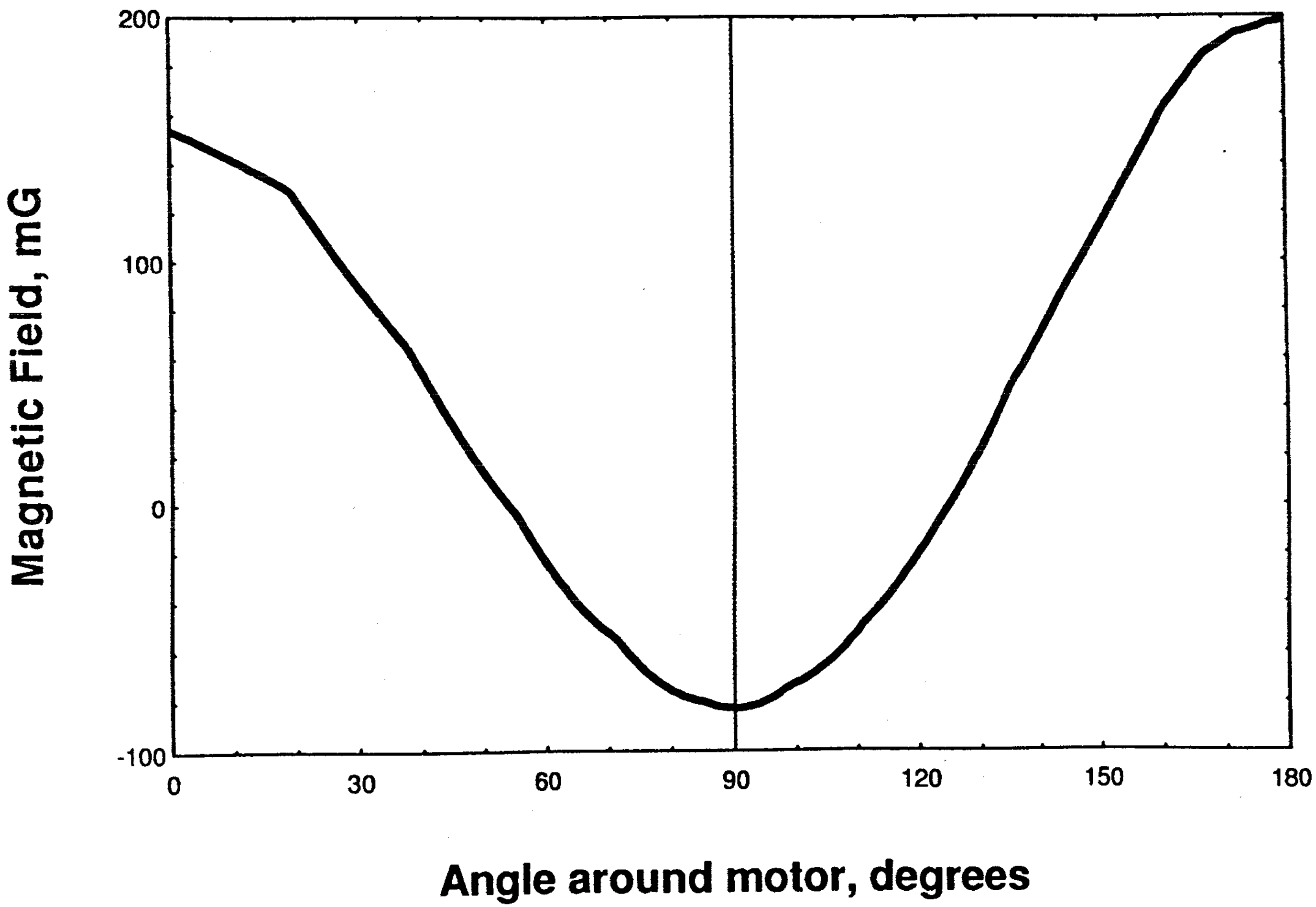
Exterior Magnetic Field of Vehicle

Batteries Removed



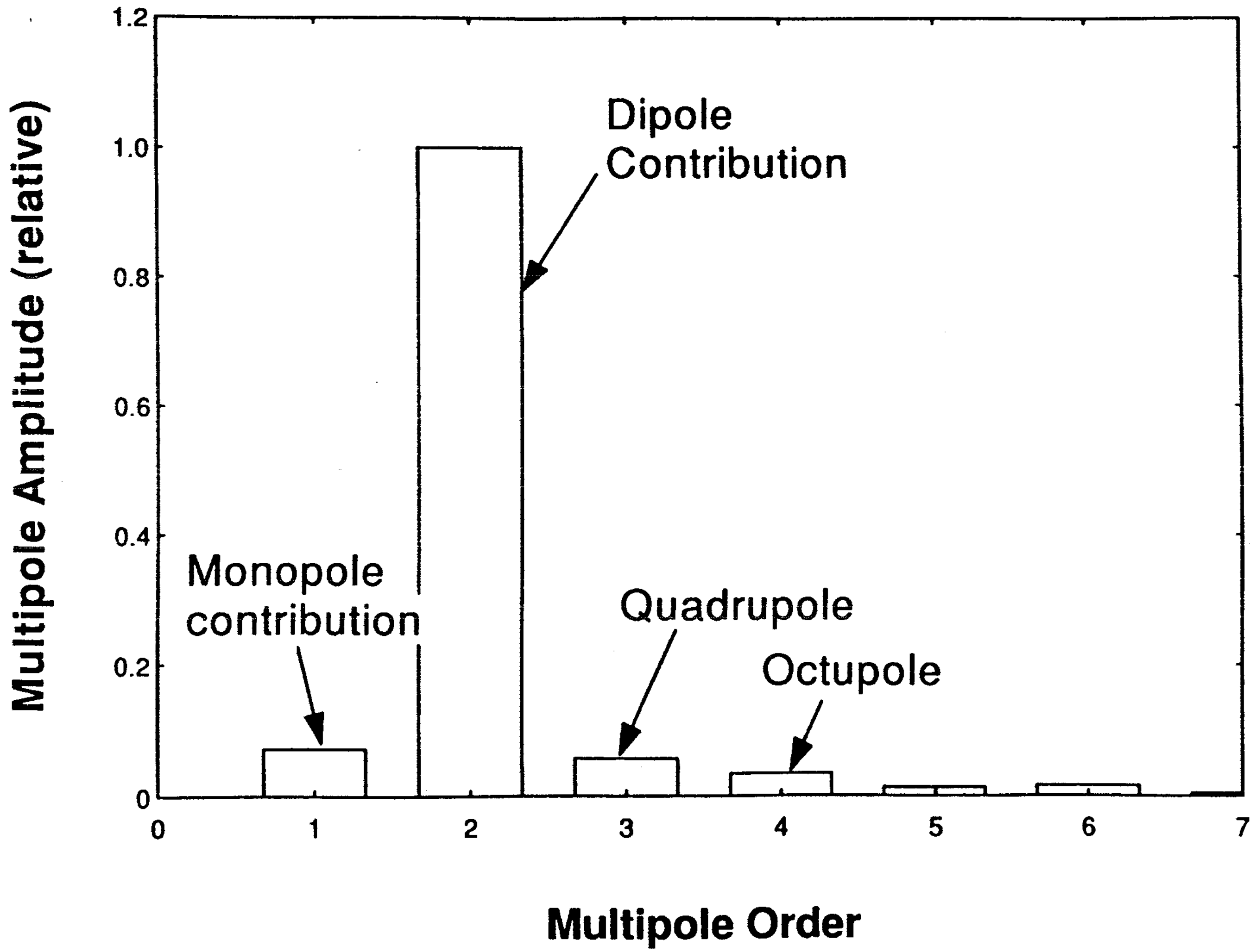
DC Motor Magnetic Field

Battery Tub Fan



DC Motor Multipole Contributions

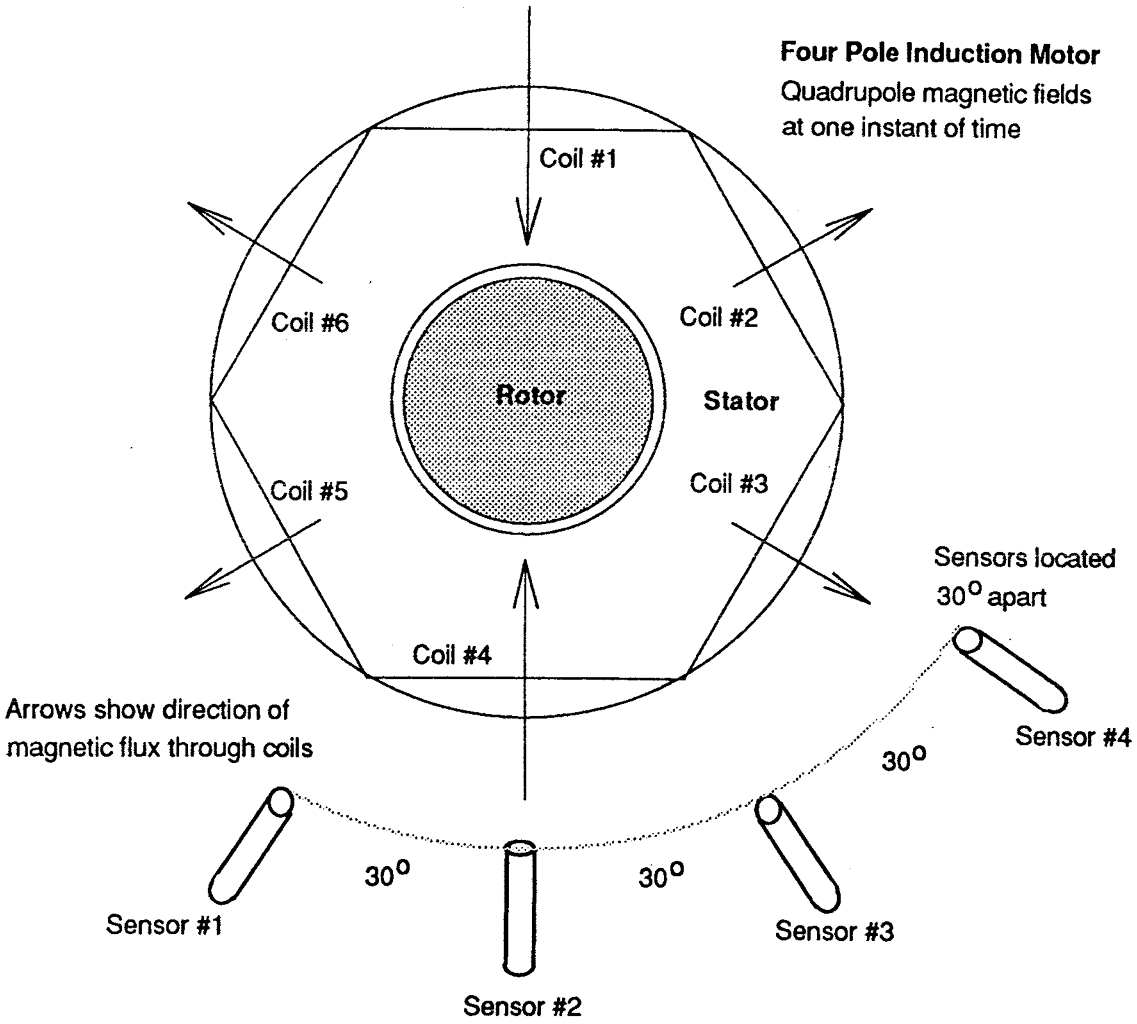
Battery Tub Fan



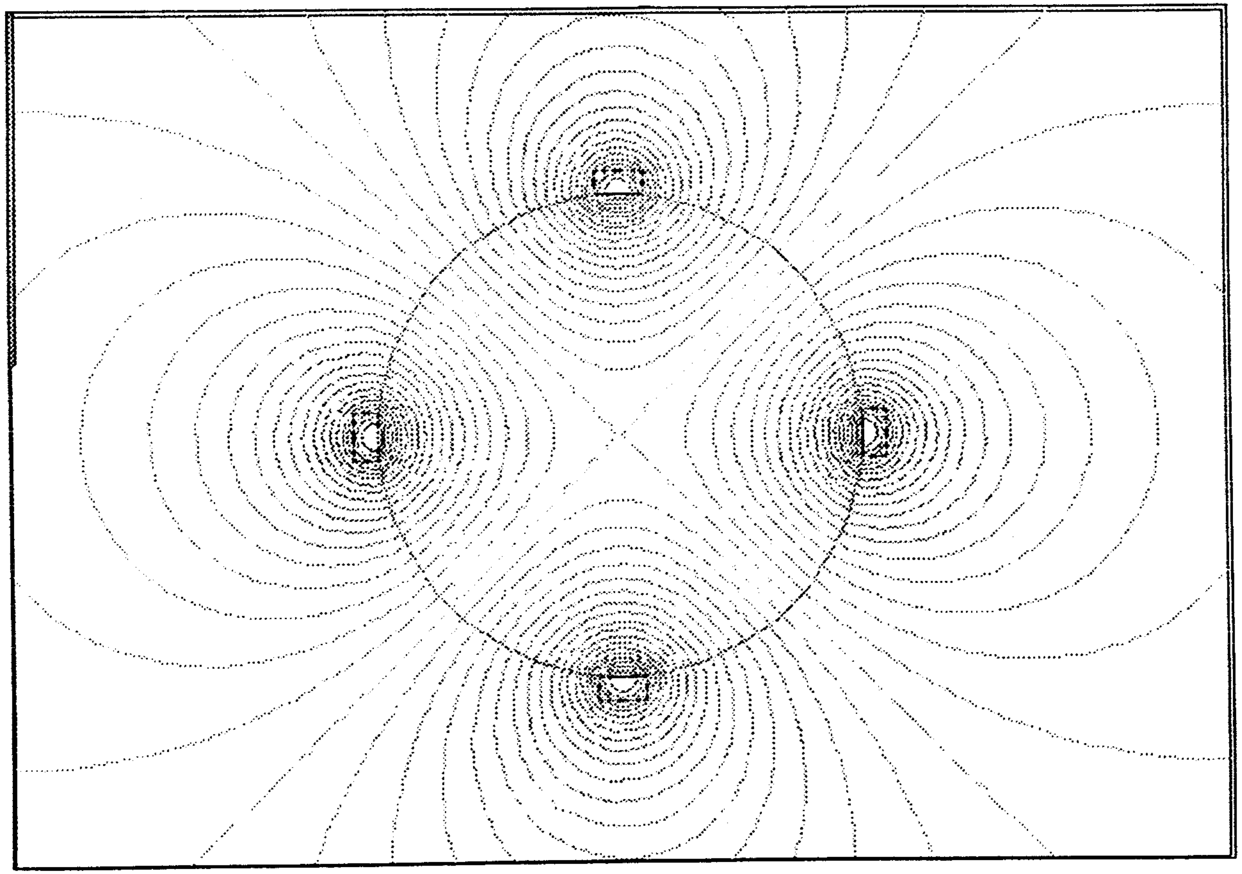
Point Design #5

- Problem
  - Exterior magnetic field: Traction AC induction motor, AC fields due to motor traveling magnetic field wave
- Analysis
  - Measurements and analyses show field to be quadrupole in nature
- Solution
  - Active quadrupole cancellation currents for ironless shield design (low added-weight)
- Results
  - Shield designed but not implemented

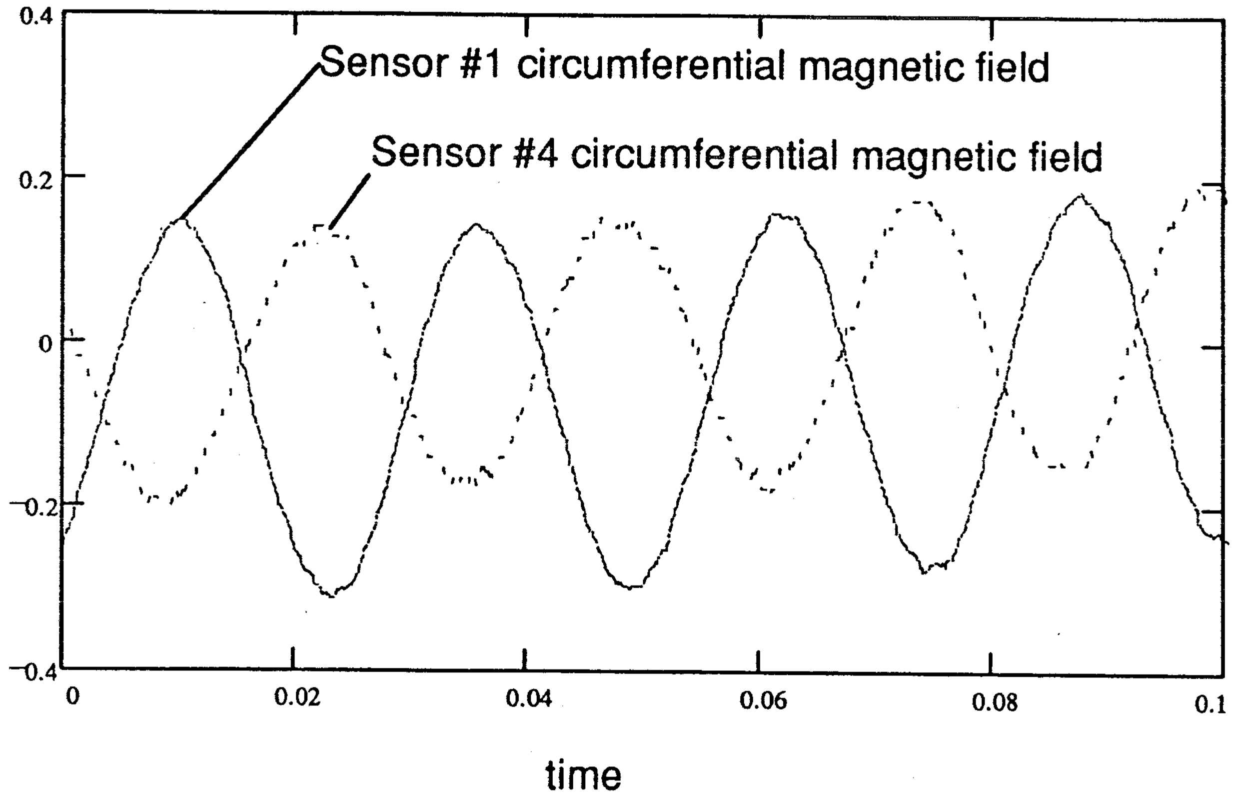
Four Pole Induction Motor Setup



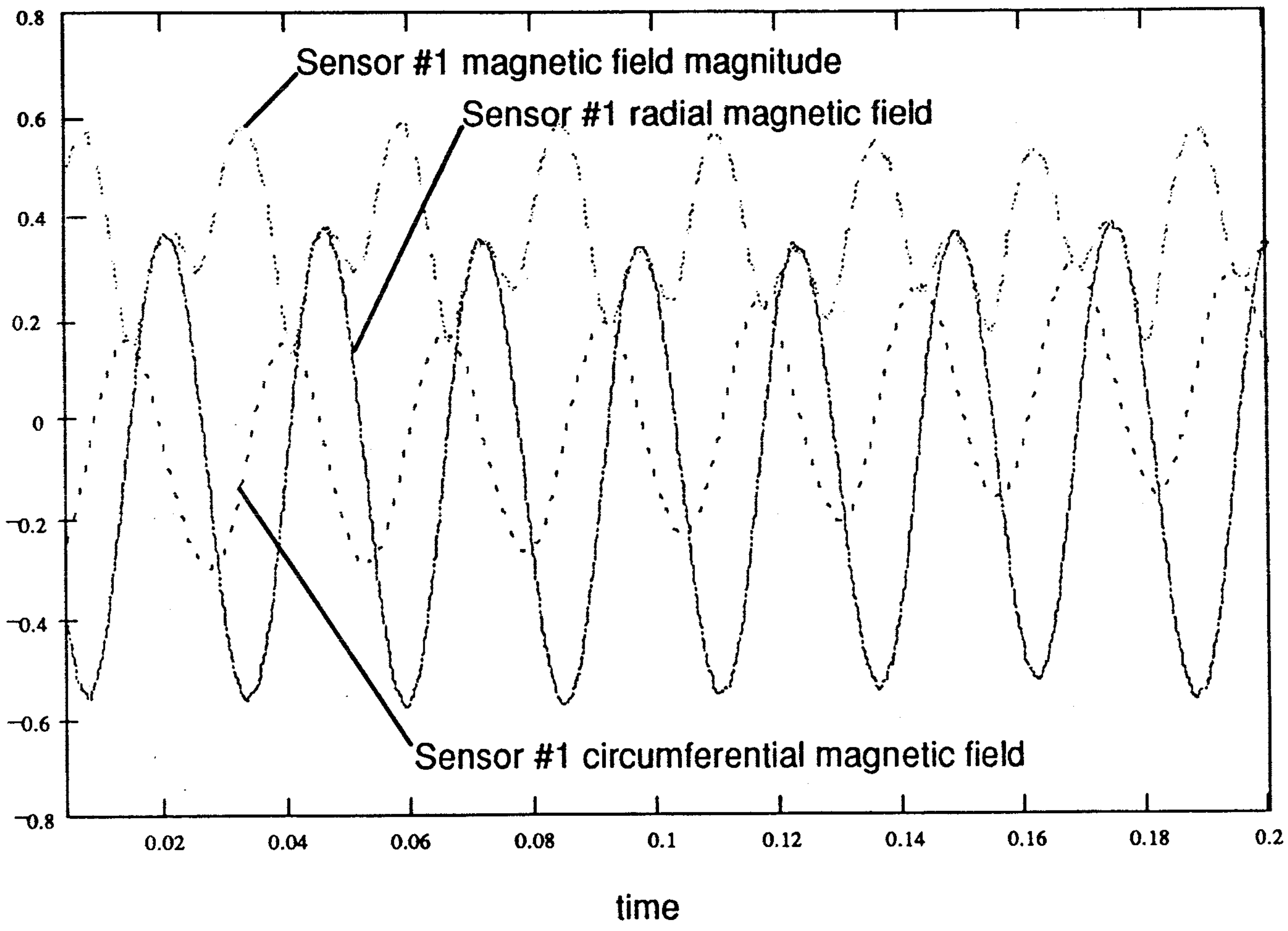
Four Pole Rotor Magnetic Flux Pattern



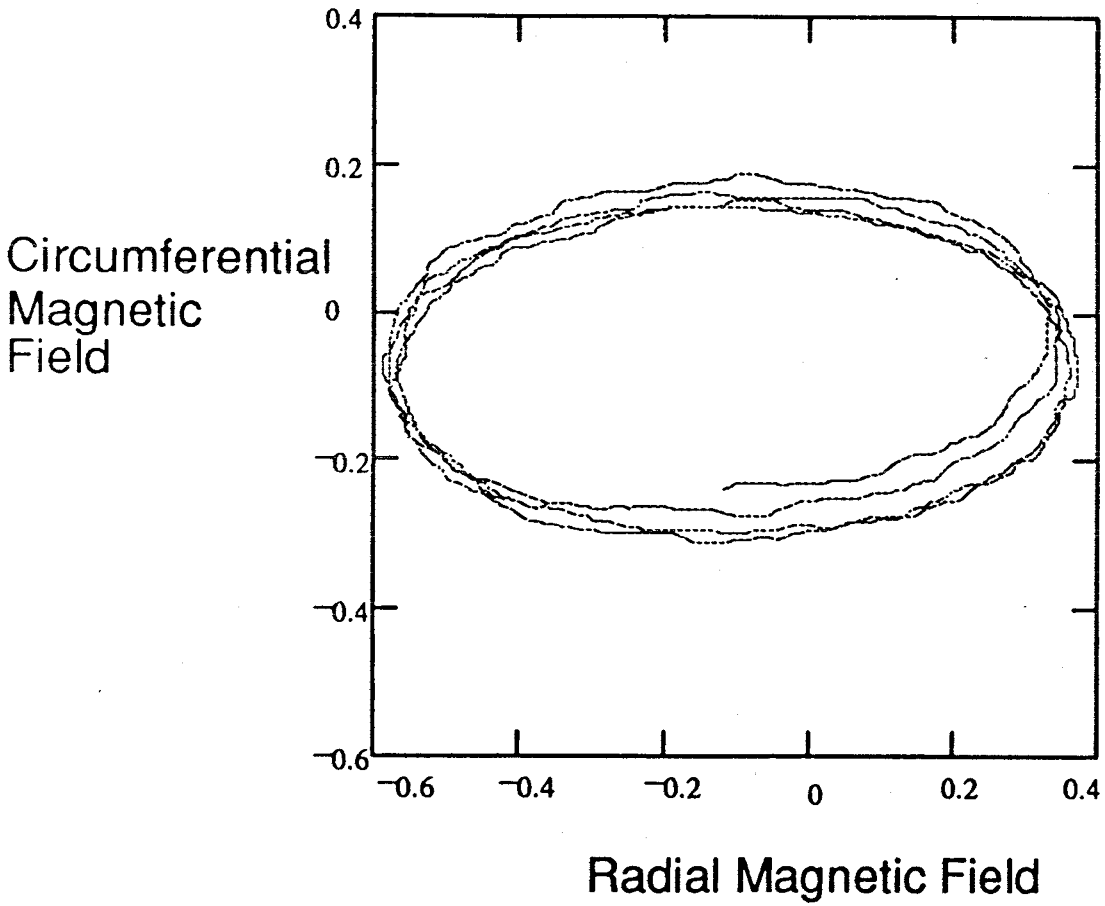
Time Plot of Magnetic Sensor Data



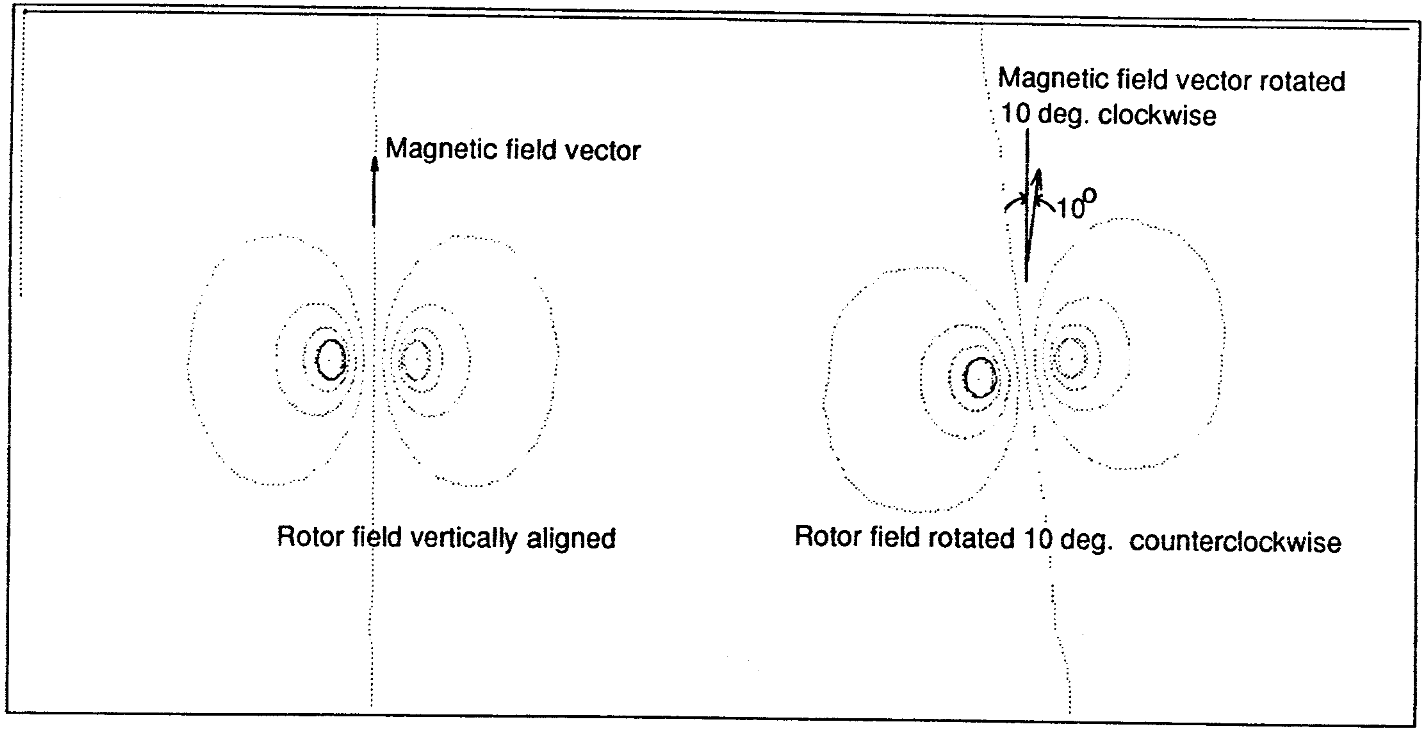
Sensor No. 1 Magnetic Field Measurements



Lissajous Plot of Sensor No. 1 Fields



Magnetic Field Rotates Opposite to Rotor



AC Induction Motor Shield Design Features

Design Feature	Rationale
Quadrupole	Four-pole motor
Negative current in shield coils	Cancellation currents
Same rotation sense, frequency, and phase as motor	Cancellation by superposition with source field
Active/passive coils depending upon shielding requirements	Active shielding provides better signature reduction; passive shielding is simpler, more robust and less expensive
Iron-free design	Weight savings consistent with four-pole design

Summary

- Interior fields
  - Electric drive-induced field proportional to battery current
  - Reduced by 7X or 17 dB due to battery re-wiring
  - Amounts to a reduction from 700 mG to approximately 100 mG at 200A
  - Frequency content of the field peaks between 6 and 20 Hz. The source of this frequency is an oscillation within the MCU. This can be fixed by proper design.

Summary (continued)

- Exterior fields
  - Non-permeable batteries reduce Earth-induced field by 140 mG
  - Electric drive-induced field proportional to battery current
  - Reduced by a factor of greater than 8X or 18 dB due to battery wiring
  - Amounts to a reduction from ~1700 mG to ~120 mG at 200A
  - Frequency content is that of battery current. Significant components at MCU oscillation frequency and PWM frequency (~4.2 kHz) and harmonics