Contents

5. Viking and STP P78-2 Electrostatic Charging Designs and Testing

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Abstract

Both the Viking and the P78-2 (SCATHA) vehicles must withstand arcing. This paper presents the design provisions of both vehicles and a mathematical analysis of the effect of arcing on typical interface circuits. Results of verification testing of the analysis are presented as well as vehicle testing for tolerance to arcing.

1. ELECTROSTATIC CHARGING DESIGNS

1.1 Viking Electrostatic Charging Design

The Viking lander was designed to survive entry into the Martian atmosphere and landing on Martian soil. Entry deceleration was controlled by aeroshell ablation, followed by parachute deployment and controlled engine flight to the surface. During entry there was a possibility of flight through carbon dioxide clouds, dust devils, and encounter with unknown particles. All of these, as well as engine and parachute charging, could cause arcing on the external surfaces of the vehicle.

Viking was designed to operate with corona and survive any arcing that might occur. Prevention of corona and arcing was not considered practical. The design included the following provisions:

(1) The vehicle body was an rf enclosure bonded together by joints having a resistance of less than 10 mΩ.

(2) All external conductive pieces were bonded to the vehicle structure.

(3) All wiring external to the vehicle body was shielded with the shield grounded at both ends.

(4) The bioshield had a 4-in. grid of conductive paint to minimize charge buildup.

(5) The bioshield cap was supported so that the material could not drape down onto vehicle components.

(6) The antennas were of a dc short design (exposed metal on the antennas and feeds had a direct dc path to ground).

(7) Antennas were designed to operate without corona at critical pressure, with twice the expected rf power. Foaming and/or configuration of the ends of the elements provided acceptable designs.

(8) Separation connectors had deeply recessed female contacts that remained with the lander. These connectors could operate in a hot plasma without arcing.

(9) Command and control interfaces were 50 ohm differential circuits (Harris) driven from a current source (high impedance).

(10) Interfaces with components having voltages over 300 V were provided with corona protection circuitry, where a failure could allow high voltage leakage or corona through the wiring to other components. Fail-short zener diodes provided the protection.

(11) Potting, pressurization, foaming, and vacuum deposited covering of circuit boards were used to allow all landed components to operate at critical pressure.

(12) Communication and radar receiver frequencies, bandwidths, and lock circuits were designed to tolerate signal inputs from corona.

One of the design features that increased the probability of corona and arcing was that the external surface of the lander had to be covered with a rubbery non-conductive substance to protect the vehicle from windblown dust. A tape of the rubbery material was wrapped over all external cable bundles and other parts were painted with the rubbery coating. The coatings were good insulators and would certainly produce corona when exposed to 200 mph wind-blown dust at 5 torr pressure as well as the entry environment.

1.2 STP P78-2 Electrostatic Charging Design

The P78-2 vehicle is being designed to measure plasma parameters at and near synchronous earth orbits. It will be subject to energetic particle charging and subsequent arcing. The design approach is to shield all wiring internal to the lower half of the vehicle (which is to be an rf shielded region) and to double shield all wire external to the shielded region. The single shielding is done by using a braided shielded and jacketed wire. The wire will be the same type used on Viking, which is insulated with 3 mils of Kapton. The second shield will be a bundle shield, achieved by wrapping the bundle with aluminum foil tape that has a conductive adhesive. The outside of the foil will not be insulated or coated in any way, and will be grounded at each cable clamp. Braided shielding will be substituted for the foil wrap where flexibility is important.

The power subsystem is being designed to accept high voltage transients from the solar array without transferring them to the power bus.

The shielding and power subsystem transient suppression are the only design features of P78-2 for protection from arcing. The question, then, is whether these designs represent adequate protection to pass the required testing necessary to verify an interference margin.

2. DESIGN EVALUATION

The design evaluation depends on how large a signal can be coupled into a circuit from an arc discharge. This evaluation will treat only the circuit types and configurations used for Viking and P78-2. Other circuits and configurations will necessarily provide different answers. The method shown here is a general solution, but care must be taken in applying the results. The solution should be exercised completely before a final answer is obtained. That is, the effect of each assumption should be evaluated by varying the value of the assumed parameter over its maximum possible range and observing the variation in the answer. After a few times through the solution in this manner, one feels the effect of variations and begins to understand the relationships between the physical parameters and what is happening in the coupling process.

2.1 Defining the Source

First, consider the source characteristics. The arc voltage has been estimated to be between 10 and 25 kV and the arc current to be between 10 and 1000 A. This would then suggest that the source could be characterized as a 10- to 25-kV voltage source with a source impedance of 2.5 to 1000 ohms. This source must be simulated during electromagnetic compatibility (EMC) testing to determine the susceptibility of the vehicle and external components. MIL-STD-1541 has an electrostatic sensitivity test that consists of a 10-kV arc containing 2.5 mJ. Laboratory tests with a 3.5-mJ, 10-kV source in air at Denver altitude has shown the source impedance to be approximately 370 ohms and the pulse to have a rise time of 3 nsec and an average duration of 7 nsec. The arc was formed by gradually increasing the voltage of the source until arcing occurred at a 60 Hz repetition rate.

With a test arc established that is fairly representative of a space arc, let us analyze its effect upon a circuit. Assume that there is an arc to the center of a 5-ft shielded circuit. Since the rise time of the arc is less than the transmission time down the shield and back, the shield acts like a long transmission line with Z_o impedance. The voltage on the shield is then a strong function of the shield configuration with respect to the ground plane. Z_o can vary from approximately 11 to 181 ohms, this being one half of the characteristic impedance of the transmission line (because there are effectively two in parallel at the point of the arc discharge, see Appendix A). Eleven ohms represents a kapton-covered shield adjacent to the ground plane or adjacent to other shields in a bundle, and 181 ohms represents a shield 10 in. above the ground plane. The above values are based upon a twisted shielded pair wire insulated with 3 mils of kapton. If the design restricts single shields to being next to structure, then the calculated voltage on the shield, due to a 10 kV arc would be 289 volts. The calculations are shown in Appendix A. The measured voltage on the shield was 256 volts. This represents approximately half the error of the measuring system (2 dB).

2.2 Electric Field Coupling

The task of determining how much of the voltage on the exterior surface of the shield is coupled to the internal circuit wires requires the circuit model shown in Figure 1 and its transient solution.

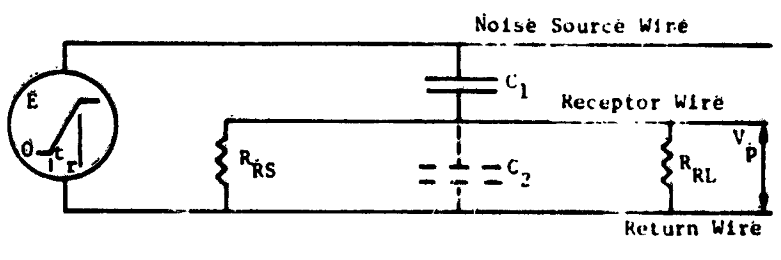


Figure 1. Electric Coupling Model

C_1 then represents the capacity between the outside of the shield and the internal circuit wire, and C_2 represents the capacity between the internal circuit wire and the internal return wire. The transient solution to this circuit is

$$V_p = \frac{E}{t_r} R_T C_1 \left[1 - \exp\left(-\frac{t}{R_T(C_1 + C_2)}\right)\right] \tag{1}$$

and

$$V_{pmax} = \frac{E C_1}{C_1 + C_2} \tag{2}$$

where R_T = parallel resistance of R_{RS} and R_{RL}. The maximum value of V_p occurs when $t = t_r$. The complete definition of parameters appears in Appendix B.

Applying the solution to the circuits of Figures 2 and 3, yields the following results for Tables 1 and 2:

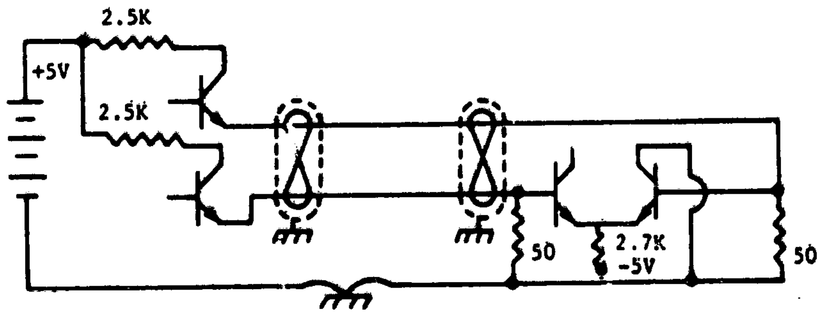


Figure 2. Viking Interface Circuit

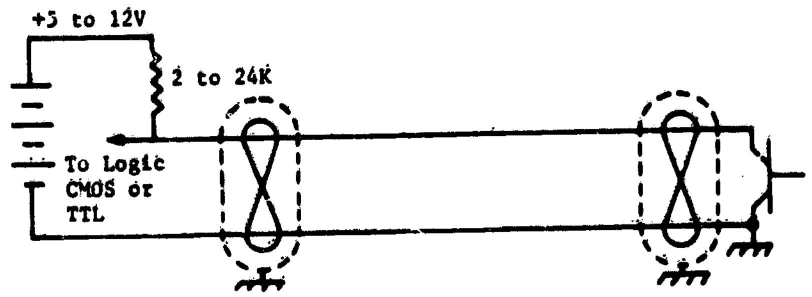


Figure 3. P78-2 Interface Circuit

Table 1. Viking Design

t_r	(e factor)	V_p
1×10^{-9}	4.5×10^{-2}	13.49
3×10^{-9}	1.3×10^{-1}	12.89
10×10^{-9}	0.368	11.07
100×10^{-9}	0.99	2.98
1×10^{-6}	1.0	0.301
10×10^{-6}	1.0	0.03

$C_1 = 20.8 \times 10^{-12}$ F
$C_2 = 415 \times 10^{-12}$ F
$R_T = 50$ ohms

Table 2. P78-2 Design (Preliminary)

t_r	(e factor)	V_p
1×10^{-9}	1.1×10^{-4}	13.79
3×10^{-9}	3.4×10^{-3}	13.79
10×10^{-9}	1.1×10^{-3}	13.79
100×10^{-9}	1.1×10^{-2}	13.72
1×10^{-6}	1.1×10^{-1}	13.04
10×10^{-6}	0.6801	8.23

$C_1 = 20.8 \times 10^{-12}$ F
$C_2 = 415 \times 10^{-12}$ F
$R_T = 20,134$ ohms

These data show that the electric field coupling differs only as to rise time of the interference pulse. The P78-2 design is susceptible to longer rise time pulses than the Viking design. Since the arc rise time is very short, the response to the arc is quite similar. The measured coupling to the Viking circuit was 12.4 volts and to the P78-2 circuit was 12.0 volts.

The value of C_1 is obtained by multiplying the capacity between the wire and the internal surface of the shield (415 pF) by the lack of coverage of the shield (95 percent coverage and therefore 0.05 lack of coverage) or by actual measurement. The measured value was 18 pF while the calculated value was 20.8 pF.

2.3 Inductive Coupling

The previous analysis has defined the capacitive coupling to the circuits. The inductive coupling must also be determined. This task required the following circuit (Figure 4) model and its transient solution:

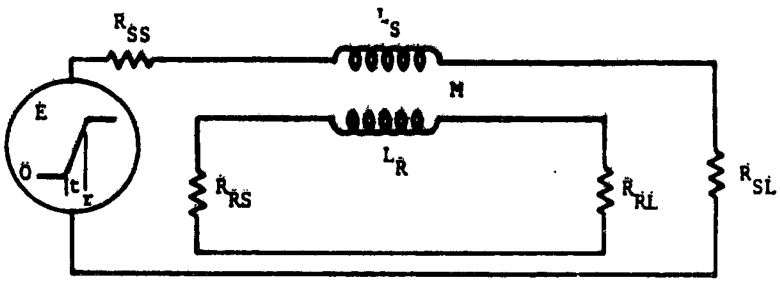


Figure 4. Inductive Coupling

L_S is the inductance in the source circuit, L_R is the inductance in the receptor circuit, and M is the mutual inductance between circuits. A more complete definition of parameters and the complete transient solution appear in Appendix B.

The simplified transient solution to this circuit is as follows:

$$V_p = \frac{E\,M\,R_{RL}}{t_r\,R_S\,R_R}\left[1 - \exp\left(-\frac{t\,R_S\,R_R}{L_S(R_S + R_R)}\right)\right] \quad (3)$$

and

$$V_{pmax} = \frac{E\,M\,R_{RL}}{L_S(R_S + R_R)} \quad (4)$$

where $R_S = R_{SS} + R_{SL}$ and $R_R = R_{RS} + R_{RL}$. Applying the solutions to the interface circuits of Figures 2 and 3, yields the following results for Tables 3 and 4:

Table 3. Viking Design

t_r	(e factor)	V_p
1×10^{-9}	4.7×10^{-2}	0.28
3×10^{-9}	1.3×10^{-1}	0.26
10×10^{-9}	3.8×10^{-1}	0.22
100×10^{-9}	0.99	0.06
1×10^{-6}	1.0	0.006
10×10^{-6}	1.0	0.0006
$M = 1.2 \times 10^{-8}$ H	$L_S = 0.23 \times 10^{-6}$ H	
$R_{RL} = 50\Omega$	$R_R = 2550\Omega$	$R_S = 11\Omega$

Table 4. P78-2 Design (Preliminary)

t_r	(e factor)	V_p
1×10^{-9}	4.7×10^{-2}	13.9
3×10^{-9}	1.3×10^{-1}	13.3
10×10^{-9}	3.8×10^{-1}	11.3
100×10^{-9}	0.99	3.0
1×10^{-6}	1.0	0.3
10×10^{-6}	1.0	0.03
100×10^{-6}	1.0	0.003
$M = 1.2 \times 10^{-8}$ H	$L_S = 0.23 \times 10^{-9}$ H	
$R_{RL} = 4,700\Omega$	$R_R = 4,750\Omega$	$R_S = 1$[illegible]Ω

These data show that the inductive coupling in the Viking design is unimportant. This is because the loop resistance in the receptor circuit (2550 ohms) is 51 times the resistance across the digital receiving circuit (50 ohms). Conversely, the P78-2 design has practically all the resistance (24,000 ohms) across the digital input, when the transistor is conducting.

2.4 P78-2 Design Modification

The P78-2 preliminary design shows that voltages greater than the noise rejection capability of normal digital circuitry (1 volt) can occur when there is an arc discharge to the circuit shield. The design must, therefore, be modified to reduce the voltage to below 1 volt, which is the digital noise rejection capability. Adding a second braided shield was considered, but since it would only reduce the coupled voltage slightly, it was rejected. The reduction is only slight, since the shield voltage increases from 256 V to a measured 730 V, because of the increase of Z_o between the two configurations and the second shield only provides a shielding increase of 20 dB. The configuration included having the overshield 0.37-in. above the ground plane.

A solid overshield will reduce the coupled voltage better than a braided shield and, therefore, will be used in the final space vehicle design. The aluminum foil overwrap was tested on the typical circuits with the following results as shown in Table 5.

Table 5. Viking and P78-2 Design

Viking Design	
Electric coupling	0.45 V peak
Total coupling	0.35 V peak
P78-2 Final Design	
Electric coupling	3.5 V peak
Total coupling	4.0 V peak

3. SPACE VEHICLE VERIFICATION TESTING

3.1 Viking Testing

The Viking Lander was tested in an environment which simulated corona interference. The vehicle operated properly without degradation during this test. A capacitor discharge test was performed to simulate arcing that could occur during parachute deployment by charging a 0.05 μF capacitor to 2000 V and discharging it through the vehicle structure to the parachute attach point and the foot pads, respectively. This test at first caused the ground equipment to malfunction. After the ground equipment was reconfigured to be less suspectible, the vehicle passed the test.

3.2 P78-2 Planned Testing

The P78-2 vehicle will be tested by arcing directly to the vehicle at several selected points where arcing can possibly be expected. The arc source will be a 10 kV, 2.5-mJ source and the vehicle must operate without degradation of performance.

Appendix A

Calculation of the Voltage on a Shield Due to an Arc Discharge to the Shield

Consider the following configuration, Figure A1:

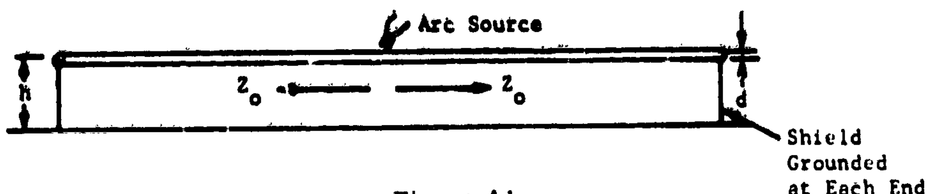


Figure A1

$$Z_o = 138 \log_{10} \frac{4h}{d} = 138 \log_{10} 4 \frac{10 \text{ in.}}{0.096 \text{ in.}} = 361.53 \text{ ohms} \quad . \tag{A1}$$

Impedance at arc point is then

$$\frac{361.53}{2} = 180.77 \text{ ohms} \quad . \tag{A2}$$

Voltage on shield = arc current × 180.77. If shield wire is in a bundle of shielded wires (see Figure A2 and equations A3-A4)

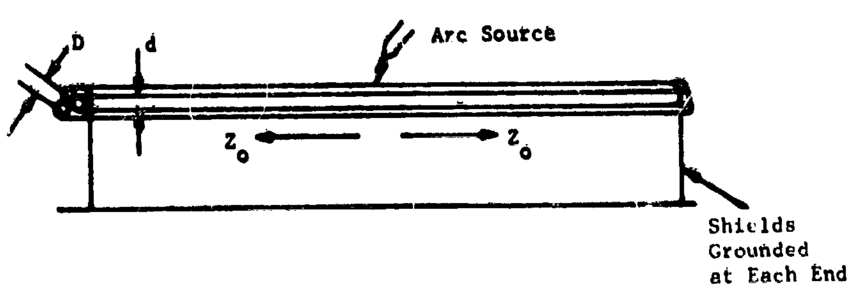


Figure A2

then

$$Z_0 = \frac{120}{2\sqrt{\varepsilon_r}} \cosh^{-1} \frac{D}{d} = \frac{120}{2\sqrt{3.5}} \cosh^{-1} \frac{0.10}{0.094} \tag{A3}$$

$$Z_0 = 32.07 \times 0.345 - 11.06 \text{ ohms} \quad . \tag{A4}$$

Appendix B

Method for Calculating Electromagnetic Interference Coupled into a Circuit From an Adjacent Circuit (Time Domain Method)

1. ELECTRIC FIELD COUPLING

The electric field interference is capacitively coupled from an interference source wire into the receptor circuit. The model circuit (see Figure B1) to be used for this coupling is as follows:

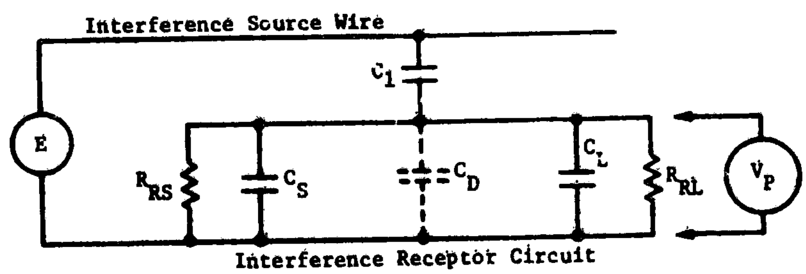


Figure B1

where:

- E = interference source voltage, in volts.
- C_1 = maximum coupling capacity between source and receptor circuit, in farads.
- R_{RS} = maximum source resistance of signal in receptor circuit, in ohms.
- C_s = maximum capacity of signal source circuit in the receptor circuit, in farads.
- C_D = maximum distributed capacity in the receptor circuit, in farads.
- C_L = maximum capacity of load circuit in receptor circuit, in farads.
- R_{RL} = maximum load resistance in receptor circuit, in ohms.
- V_P = peak noise voltage induced in the receptor circuit, in volts.

$$R_T = \frac{R_{RS} \times R_{RL}}{R_{RS}\, R_{RL}} \tag{B1}$$

$$C_2 = C_s + C_D + C_L \quad . \tag{B2}$$

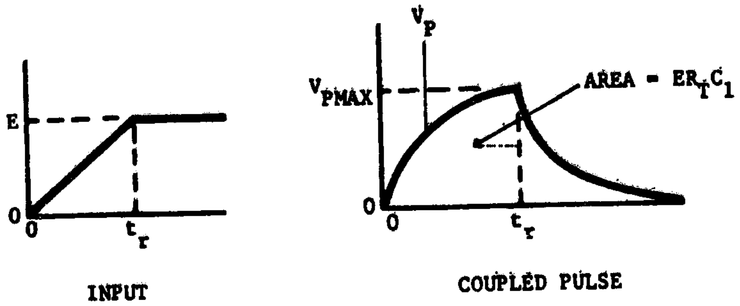
Assuming that t_r is the minimum rise time or fall time of the interference source voltage E, in seconds, the solution to the model circuit equations is as follows (see Equation B2):

$$V_P = \frac{E}{t_r} R_T C_1 \left[1 - \exp\left(- \frac{t_r}{R_T(C_1 + C_2)} \right) \right] \tag{B3}$$

$$V_{PMAX} = E \frac{C_1}{C_1 + C_2} \tag{B4}$$

where rise-time of E is very short.

The area of the interference pulse in the receptor circuit is ER_TC_1:



(B5)

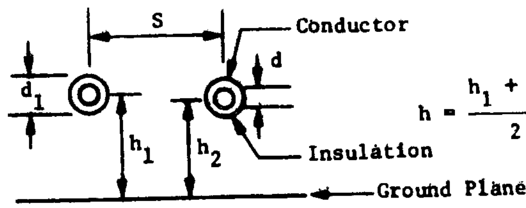
Figure B2

The coupling capacity and the distributed capacity for unshielded wires can be calculated with the following formulas (see Figure B3):

$$C = \frac{12.05\, \ell \times 10^{-12}}{\log_{10}\left[\frac{2\,S}{d} \cdot \frac{1}{\sqrt{1 + \left(\frac{S}{2h}\right)^2}} \right]} \text{ farads} \tag{B6}$$

where:

- C = capacity between wires of a "go and return" circuit, in farads.
- ℓ maximum length of wire, in meters.
- S = separation between wires (in same units as d and h).
- d_1 = minimum diameter of the wire including insulation (in same units as S, d, and h). If unshielded wires are in the same bundle, then $S = d_1$.
- d = maximum diameter of the wire conductor (in the same units as S and h).
- h = minimum average height above the ground plane (in the same units as d, and S).



$$h = \frac{h_1 + h_2}{2} \qquad \text{(B7)}$$

Figure B3

The capacity from a wire to the ground plane is as follows (see Figure B4):

$$C = \frac{24.12\,\ell \times 10^{-12}}{\log_{10}\left(\frac{4h}{d}\right)} \text{ farads} \qquad \text{(B8)}$$

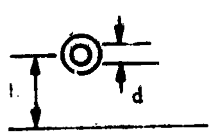


Figure B4

Capacities for shielded wires can be calculated as follows:

$$C = \frac{24.1\,\varepsilon_r\,\ell}{\log_{10}\frac{D}{d}} \text{ picofarads} \qquad \text{(B9)}$$

where:

C = capacity between inner conductor and inside of shield, in picofarads.

ϵ_r = relative dielectric constant of the inner wire jacket (relative to air = 1.0).

ℓ = length of the coax, in meters.

D = maximum inside diameter of the shield (in the same units as d).

d = minimum outside diameter of the inner conductor (in the same units as D).

Capacity between the inner conductor and the outside of the shield is the capacity calculated above times the lack of shielding coverage (that is, C $\times$ 0.05 for a shield coverage of 95 percent).

The capacity between two wires, with a shield between the wires, is the capacity between the wires without the shield times the lack of shielding coverage for the shield. If there are two shields between the wires, the capacity is reduced by the product of the lack of shield coverage (that is, 0.05 $\times$ 0.05 $\times$ C).

Note that twisted shielded pair wire should be measured. The formulas do not provide accurate answers where insulation is very thin. Viking wire measured 415 pF for 5 ft (capacity between one wire and the shield with other wire terminated in 5k ohm to ground).

2. MAGNETIC FIELD COUPLING

The magnetic field interference is magnetically coupled from an interference source circuit into a receptor circuit. The model to be used for this coupling is as follows (see Figure B5):

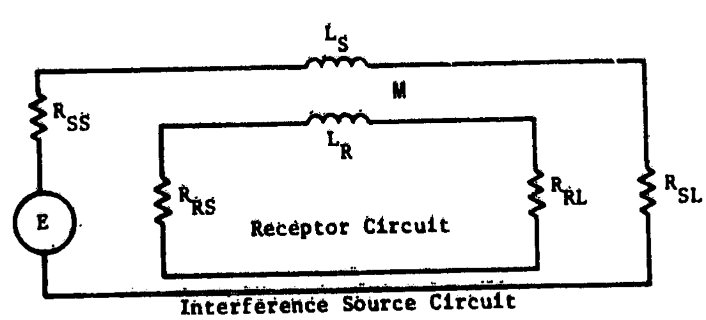


Figure B5

where:

E voltage versus time is as follows (see Figure B6):

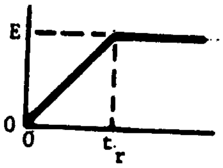
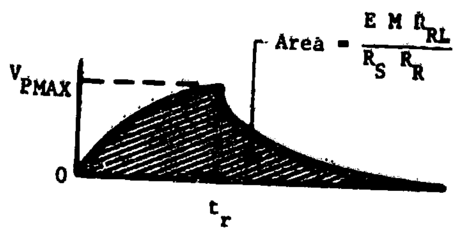


Figure B6

and V_p is as follows (see Figure B7):



(B10)

Figure B7

Assuming that t_r is the minimum rise-time or falltime of the interference source voltage E, in seconds, the solution to the model circuit (see Figure B8) is shown in Eqs. (B12)-(B17), and with simplification is as follows:

$$V_P = \frac{E\ M\ R_{RL}}{t_r\ R_S\ R_R}\left[1 - \exp\left(-\frac{t_r\ R_R\ R_S}{L_S(R_R + R_S)}\right)\right] \qquad \text{(B11)}$$

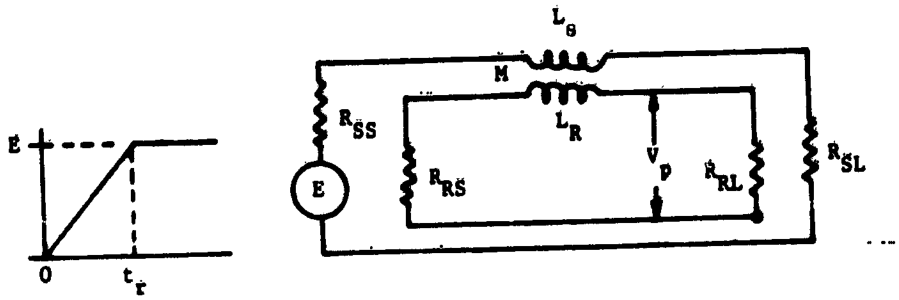


Figure B8. Magnetic Field Coupling Circuit

$$V_p = \frac{E\,M\,R_{RL}}{t_r\,R_s\,R_R}\left[1 + \frac{e^{-\frac{2\,R_S\,R_R\,t}{Q}}}{\frac{4\,R_S\,R_R(L_s^2 - M^2)}{Q^2} - 1} + \frac{e^{-\frac{Qt}{2(L_s^2 - M^2)}}}{\frac{Q^2}{4\,R_S\,R_R(L_s^2 - M^2)} - 1}\right] \quad \text{(B12)}$$

where

$$Q = L_S(R_S + R_R) \pm \sqrt{L_S^2(R_S + R_R)^2 - 4(L_s^2 - M^2)\,R_S\,R_R} \quad \text{(B13)}$$

$$R_{SS} + R_{SL} = R_S \quad \text{(B14)}$$

$$R_{RS} + R_{RL} = R_R \quad \text{(B15)}$$

$$V_p = V_{MAX} \text{ when } t = t_r \quad \text{(B16)}$$

$$V_{PMAX} = \frac{E\,M\,R_{RL}}{L_S(R_R + R_S)} \text{ if rise-time of E is very short.} \quad \text{B(17)}$$

Retardation is not considered.

where:

- E = interference source voltage, in volts.
- R_{SS} = minimum interference source circuit resistance, in ohms.
- R_{SL} = minimum interference source circuit load resistance, in ohms.

R_S = $R_{SS} + R_{SL}$.

R_{RS} = maximum source resistance of signal in receptor circuit, in ohms.

R_{RL} = maximum load resistance in receptor circuit, in ohms.

R_R = $R_{RS} + R_{RL}$.

L_S = maximum inductance of the interference source circuit, in henries.

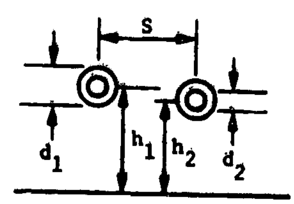
L_R = maximum inductance of the interference receptor circuit, in henries.

M = maximum possible mutual inductance between the interference source circuit, in henries.

V_{PMAX} = maximum peak noise voltage induced in the receptor circuit load due to E, volts, with a very rapid rise in E.

L in a go and return circuit (see Figure B9) can be computed as follows:

$$L = 0.921 \times 10^{-6} \times \ell \times \log_{10} \left[\frac{2S}{d_2} \cdot \frac{1.}{\sqrt{1 + \left(\frac{S}{2h}\right)^2}} \right] \text{henries} \qquad \text{(B18)}$$



$$h = \frac{h_1 + h_2}{2} \qquad \text{(B19)}$$

Figure B9

where:

L = inductance of a go and return circuit above a ground plane, in henries.

ℓ = maximum length of cable, in meters.

S = maximum average separation between wire centers in the cable bundle (in the same units as d_2 and h). s = d_1 if twisted.

d_2 = minimum diameter of the wire conductor (in the same units as S and h).

h = minimum average height above the ground plane (in the same units as S and d_2).

The inductance of a single ended circuit (see Figure B10) (ground plane return) is as follows:

$$L = 0.460 \times l \times 10^{-6} \times \log_{10} \frac{4h}{d_2} \text{ henries} \quad \text{(B20)}$$

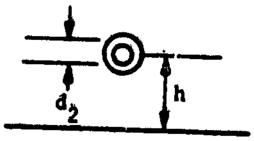


Figure B10.

M in a normal digital cable bundle, where all circuits use a common return wire, is as follows:

$$M = L_S - L_L \quad \text{(B21)}$$

where L_L = leakage inductance between the source circuit and the receptor circuit.
Then:

$$M = L_S - \frac{l \times 10^{-6}}{2} \ln \frac{2d_1}{d_2} \quad \text{(B22)}$$

where d_1 = minimum diameter of the wire including insulation (in the same units as d_2) and d_2 = minimum diameter of wire conductor (in same units as d).

$$\ln = \log_e \quad \text{(B23)}$$