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Electromagnetic Pulse Phenomena

Sandia National Laboratories

Michele Caldwell
Mike Dinallo

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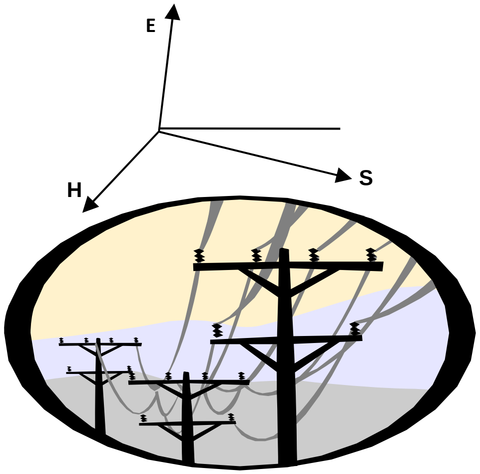
Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Overview of Topics

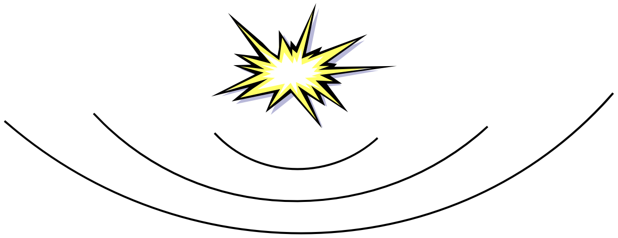
- Basic Phenomenology and Concern
- Origin of Electromagnetic Pulse
  - Gamma Rays, Compton Electrons, Lorentz Force
- Electric Field Interaction
  - Current Induction, Wire Coupling, Calculation Methods
- Simulations
  - Polarized Simulators, Pulsed Power, Field Sensors
- Field Penetration
  - Mechanisms, Equivalent Sources, Transmission Lines
- Electronics Effects
  - Damage, Upsets, Modeling
- Some Research Topics

Electromagnetic Pulse Interference To Electrical Systems



Current Will Be Induced On Power Lines And Propagate Into Buildings

Accurate Models Are Used To Estimate Induced Current



Ambient And Electrical Line Penetration Into Buildings Can Be Modeled

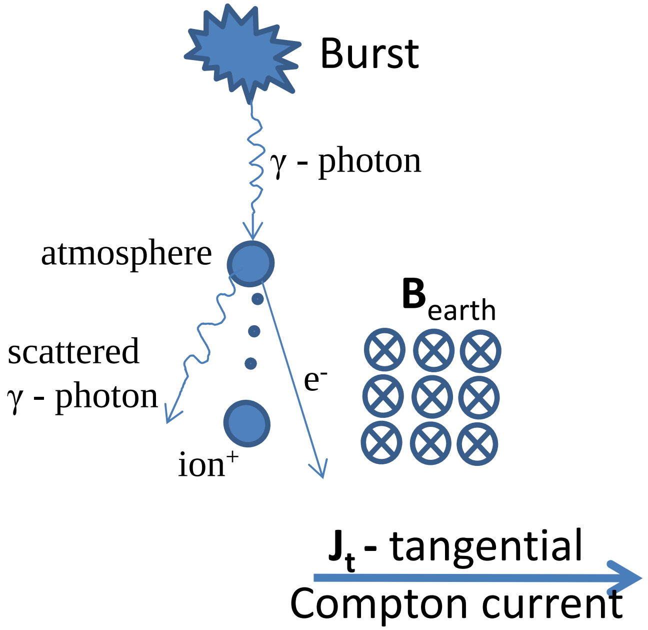
Electrical Stress At Outlet Is Uncertain Due To Variation Of Ingress Element Characteristics (Transformers, Switches, Wire Installation, Loads)

Monitoring And Control Electronics Are Expected To Be More Vulnerable To Power And Signal Line Current

Strain Levels Of Electronics Can Be Modeled Or Measured

HEMP Generation[*][†][‡]

- Expanding spherical gamma ray source impinges upon the atmosphere creating Compton current of electrons
- Earth magnetic field creates a (evB) tangential Compton current component J_t, and to a lesser extent asymmetrical gamma distribution



$$2\partial(rE_t)/\partial r+Z_0\sigma(rE_t)=-Z_0(rJ_t)$$

[*] Karzas, W.J. and Latter, R.; Physical Review, vol. 137, No. 5B March 1965

[†] C.L. Longmire; IEEE Transactions AP, vol. AP-26, No. 1, January 1978

[‡] R.A. Roussel-Dupre; IEEE Transactions EMC, vol. 47, No.3, August 2005

HEMP Generation II

- $F_\gamma \sim e^{-r/\lambda_a}/4\pi r^2$ (gamma flux)
- $F_e = F_\gamma R_{mf}/\lambda_s$ (recoil electron flux)
- J_r= radial Compton current (determine from F_γ)
- $J_t \approx J_r R_{mf}/2R_L$ ($R_L = m_e v/eB$)
- $2\partial(rE_t)/\partial r + Z_0\sigma(rE_t) = -Z_0(rJ_t)$ (HEMP E_t-field)
- $\sigma = eN_e\mu_e$ ($N_e$electron density, $\mu_e$electron mobility)

Atmospheric Conductivity Considerations

Free electron removal

$e + O_2^+ \rightarrow O + O$

$e + N_2^+ \rightarrow N + N$

Ion removal

$O_2^- + O_2^+ + (O_2 \text{ or } N_2) \rightarrow O_2 + O_2 + (O_2 \text{ or } N_2)$

$O_2^- + N_2^+ \rightarrow O_2 + N_2$

S-rate of production electron-ion pairs

$dN_e/dt = S-k_1N_e-k_2N_eN_+$

$dN_+/dt = S-k_2N_eN_+- k_3N_+N_-$ N_e, N_+, N_-

$dN_-/dt = k_1N_e- k_3N_+N_-$

N_i - densities

k_i – rates

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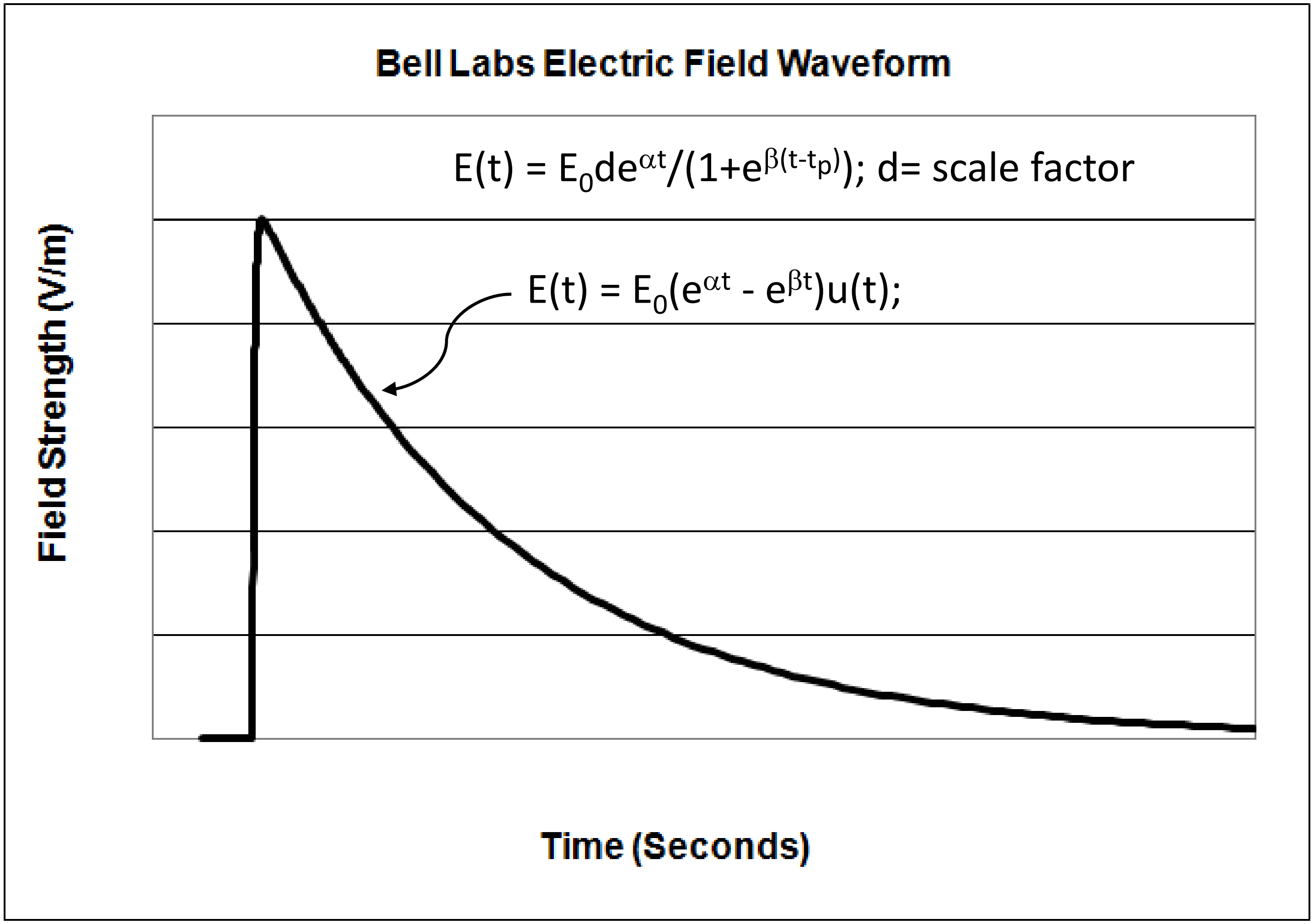
Hypothetical HEMP Waveform



Bell Labs Electric Field Waveform

$E(t) = E_0 d e^{\alpha t}/(1+e^{\beta(t-t_p)})$; d= scale factor

$E(t) = E_0(e^{\alpha t} - e^{\beta t})u(t)$;

$E(\omega) = E_0(\beta-\alpha)/[(\alpha-i\omega)(\beta-i\omega)]$ – Fourier Transform

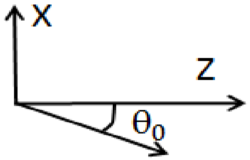
$E(\omega) = (E_0 d\pi/\beta)e^{(\alpha+i\omega)t_p}/\sin[(\alpha+i\omega)\pi/\beta]$ – Fourier Transform

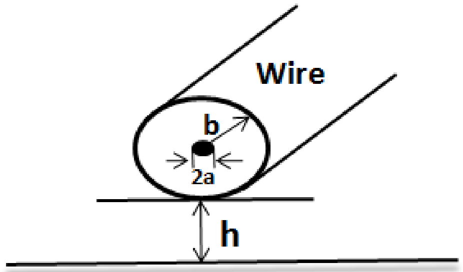
Incident Field – Wire Above Ground Coupling*

Transmission Line: $(d^2/dz^2 + k_L^2)I = -YE_z^{inc}$, $k_L^2 = ZY$, $Z = Z_0 + Z_2 + Z_4$, $1/Y = 1/Y_e + 1/Y_4$

- $E_z^{inc} = E(\omega)\sin\theta_0[e^{-ihk_0\sin\theta_0} - R_H e^{+ihk_0\sin\theta_0}]e^{izk_0\cos\theta_0} = A_0 e^{izk_0\cos\theta_0}$

$k_0^2 = \omega^2\mu_0\varepsilon_0$





- $R_H = [(k_4/k_0)^2\sin\theta_0 - \{(k_4/k_0)^2 - \cos^2\theta_0\}^{1/2}]/[(k_4/k_0)^2\sin\theta_0 + \{(k_4/k_0)^2 - \cos^2\theta_0\}^{1/2}]$
- $Z_0 = [\omega\mu_0/2\pi i]\text{Arccosh}(h/b)$, $h \geq b$, $Z_2 = [\omega\mu_0/2\pi i]\ln(b/a)$
- $Z_4 \approx -i\,\omega\mu_0 H_0^{(1)}(k_4h)/[2\pi\, k_4hH_1^{(1)}(k_4h)]$, $h \geq b$

- $Y_e = -i\,\omega\, C_e$, $1/C_e \approx \{((h/h_e)/C_0 + 1/C_2)^2 - ((b/h_e)/C_0 + A_2/C_2)^2\}^{1/2}$, $h \geq b$
- $C_0 = 2\pi\varepsilon_0/\text{Arccosh}(h/b)$, $h \geq b$, $C_2 = 2\pi\varepsilon_0/\ln(h/a)$, $h_e=\{h^2 - b^2\}^{1/2}$
- $A_2 = 0.7(1-a/b)[(\varepsilon_2 - \varepsilon_0)/(\varepsilon_2 + \varepsilon_0)](1-h_e/h)$,
- $Y_4 \approx -i\pi(\omega\varepsilon_4 + i\sigma_4)k_4hH_1^{(1)}(k_4h)/H_0^{(1)}(k_4h)$, $h>b$
- $k_4^2 = \omega^2\mu_0(\varepsilon_4 + i\sigma_4/\omega)$ – soil parameters

$I(\omega) = YA_0e^{izk_0\cos\theta_0}/(k_L^2 - k_0^2\cos\theta_0^2)$ Infinite Wire

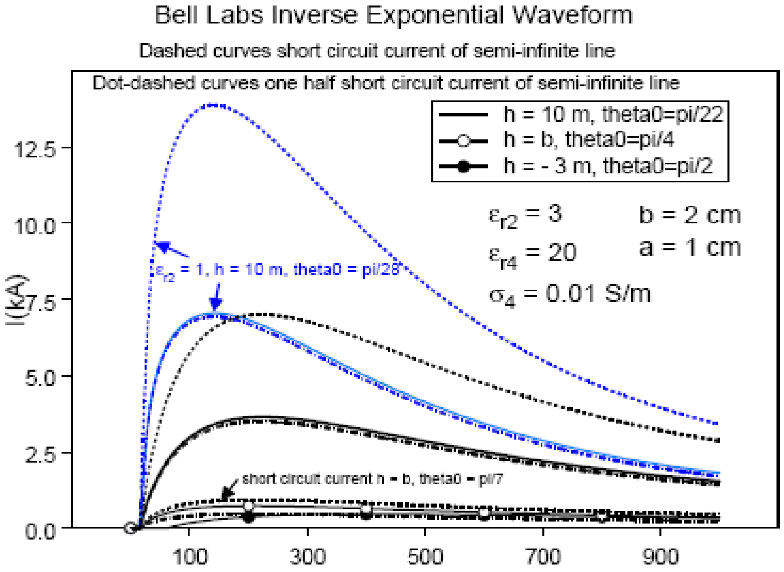
*L.K. Warne and K. C. Chen, *Long Line Coupling Models*, SAND2004-0872, Unlimited Release.

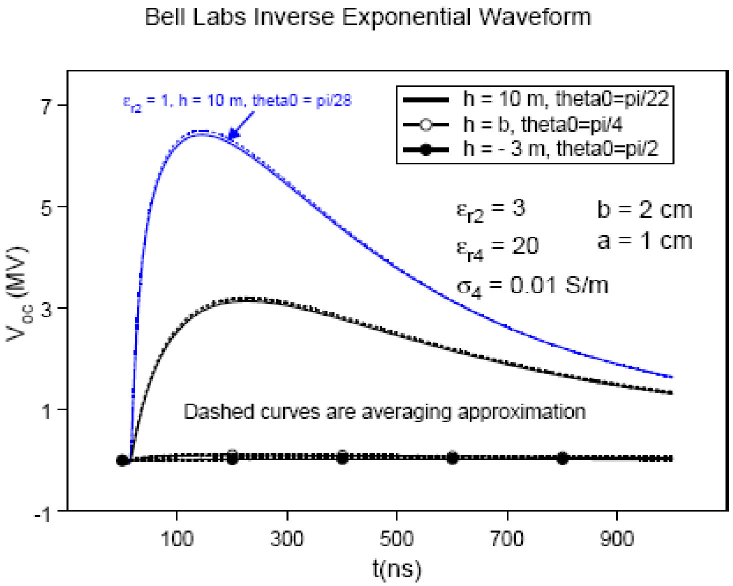
Wire Coupling Results*

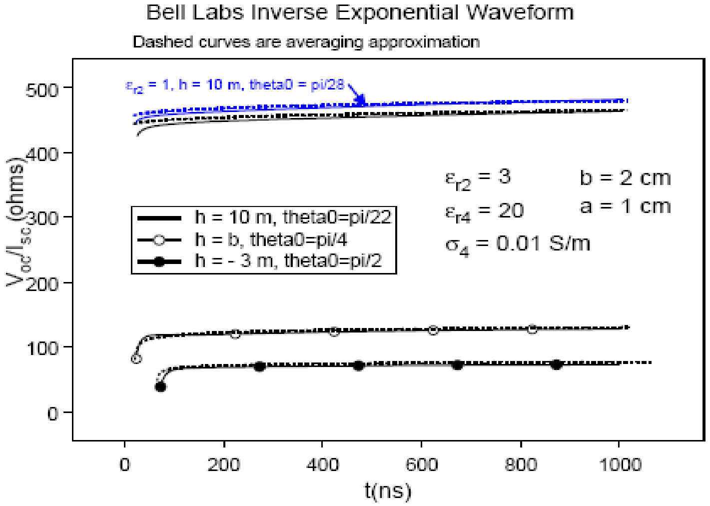
$$I(t) = 1/\pi\int_0^\infty \cos(\omega t)\mathrm{Re}\{I(\omega)\}d\omega + 1/\pi\int_0^\infty \sin(\omega t)\ \mathrm{Im}\{I(\omega)\}d\omega$$

$I_{sc} = -A_0(Y/k_L)/(k_L - k_0\cos\theta_0)$

$V_{oc} = iA_0/(k_L - k_0\cos\theta_0) = Z_c I_{sc}$







$Z_c = (Z/Y)^{1/2} \approx \{(L_e + Z_4/s)/C_e\}^{1/2}$

$Z = Z_e + Z_4,\ Z_e = i\omega L_e = sL_e$

$L_e = L_2 + L_0$

$Y_4 \rightarrow \infty$

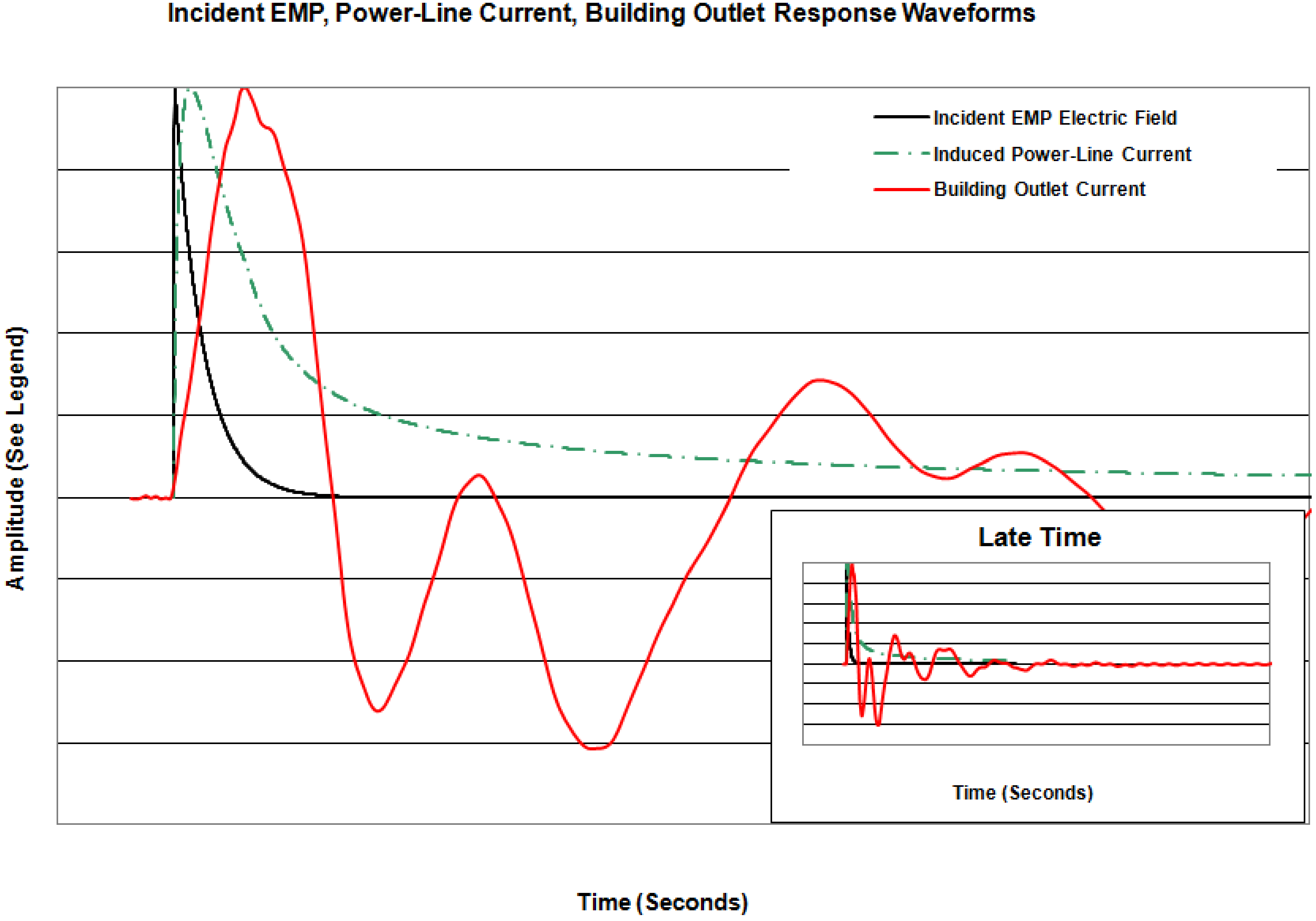
$Z_4/s \approx (\mu_0/2\pi)\ln(1+\langle 1/s\rangle)/[h(\mu_0\sigma_4\langle 1/s\rangle+\mu_0\varepsilon_4)^{1/2}]$

$\langle 1/s\rangle=1/\alpha[(\alpha t)^{1/2}/F((\alpha t)^{1/2}) - 1],$

F = Dawson's Integral

*Warne and Chen, loc. primo. cit.

Coupling into a Building Outlet



Baum's Singularity Expansion Method (SEM)

Response of a scatterer requires ***evaluation for each incidence field***

$$R(\bar{r},t) = 1/2\pi \int_{C^*} \overset{\text{Incident Source}}{\downarrow} V_0(\omega)\underset{\substack{\uparrow \\ \text{Scatterer Contribution}}}{G_0}(\bar{r},\omega)e^{-i\omega t}d\omega$$

SEM decomposes the source and scatterer contributions into natural resonance frequencies ω_n , coupling coefficients, and natural modes Res. $G_0(r,\omega_n)$[‡]

ω_n and Res. $G_0(r,\omega_n)$ provide insight, only coupling coefficients are calculated

$$R(\bar{r},t) = -i\sum_{n} \underset{\substack{\nearrow \\ \text{coupling coefficient}}}{V_0(\omega_n)}\ [\text{Res. } \underset{\substack{\uparrow \\ \text{natural modes}}}{G_0(\bar{r},\omega_n)}]\ \ e^{-i\omega_n t}$$

$$\uparrow$$

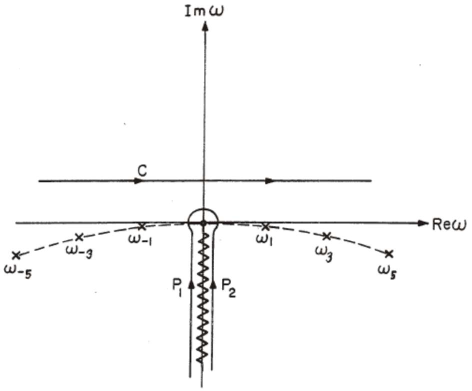
$$\omega_n = \underset{\substack{\nearrow \\ \text{(oscillation period)}}}{\text{Re}\ \omega_n} + i\underset{\substack{\uparrow \\ \text{(attenuation)}}}{\text{Im}\ \omega_n}$$

Computational Version → $\underline{{}^{††}I(t) = \sum_{\alpha} V_0(s_\alpha)[c_\alpha][c_\alpha]^T e^{s_\alpha t}}$

$[c_\alpha]$ - coupling vector, $[Z(s_\alpha)]^T[c_\alpha]=0$, $[Z(s)]$ – impedance matrix

$[Z(s)][\mathbf{I}(s)]=[V(s)]$ ($\mathbf{I}$ and V are response and source vectors)

$[Z(s_\alpha)][\mathbf{I}(s_\alpha)]=0$ determines natural frequencies



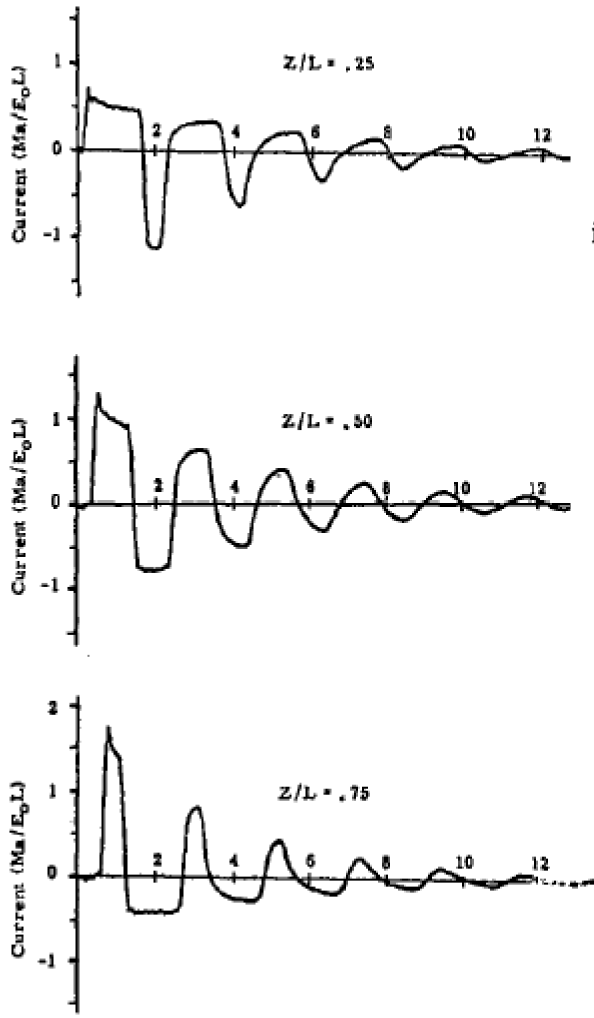
C* - $G_0(r,\omega)$ and $V_0(\omega)$ is regular in the upper half complex ω-plane.

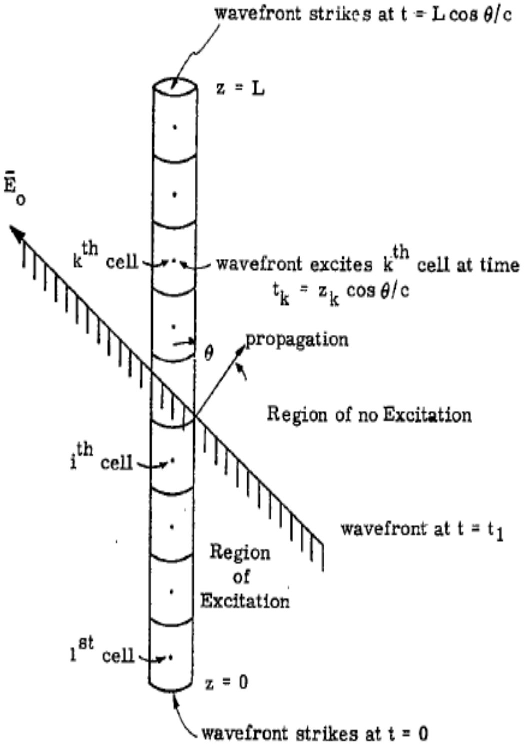
[‡] $G_0(r,\omega_n)$ pole locations in the lower complex ω-plane, the contour C (see inset), used in the Fourier transform, is modified to include poles and branch cuts[†].

[†] S.W. Lee and B. Leung, Interaction Notes, IN 96, February 1972. [††] F.M. Tesche, Interaction Notes, IN 102, April 1972.

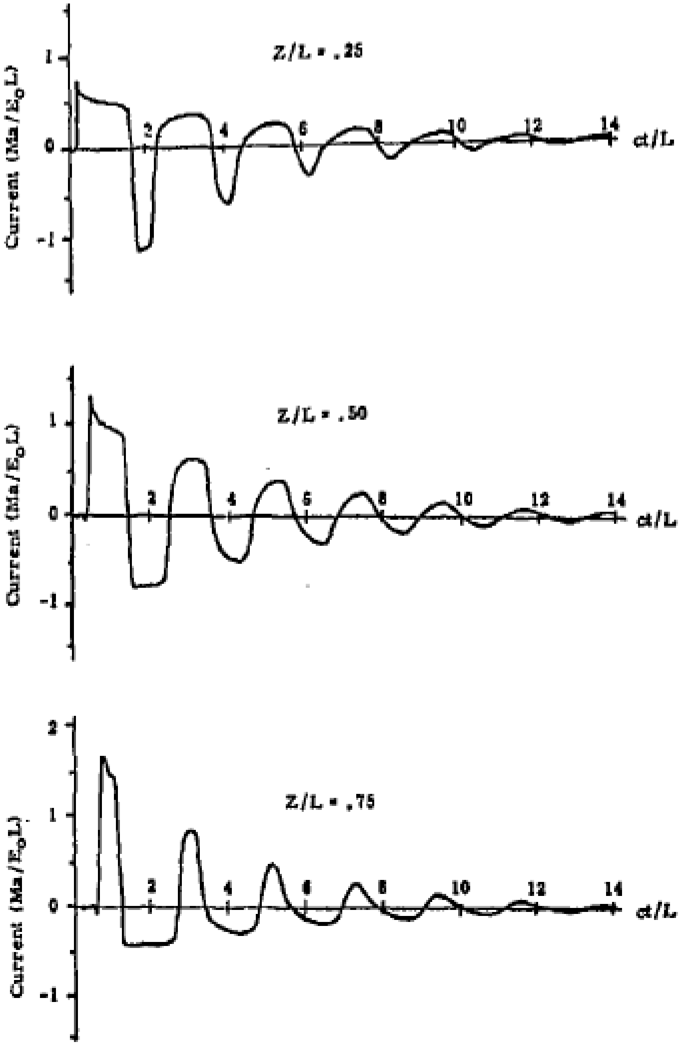
Comparison of SEM and Integral Equation Methods

SEM Method





Integral Equation



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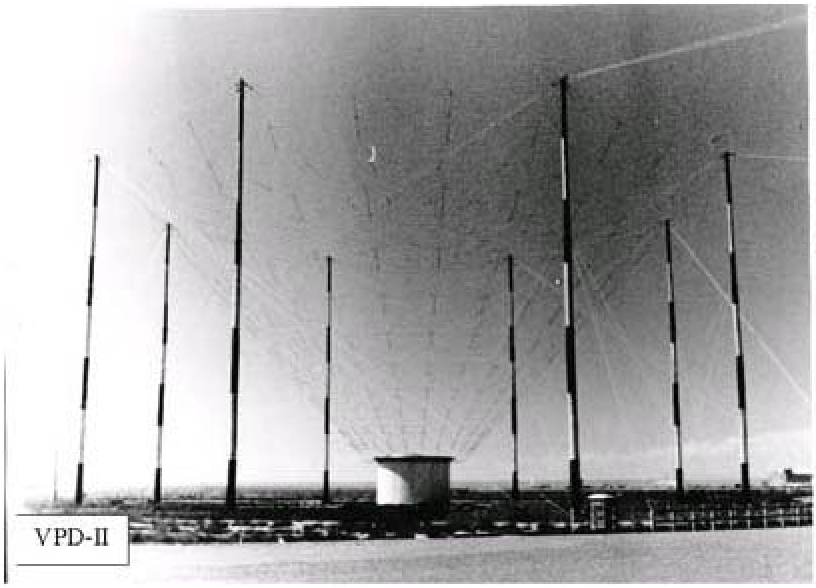
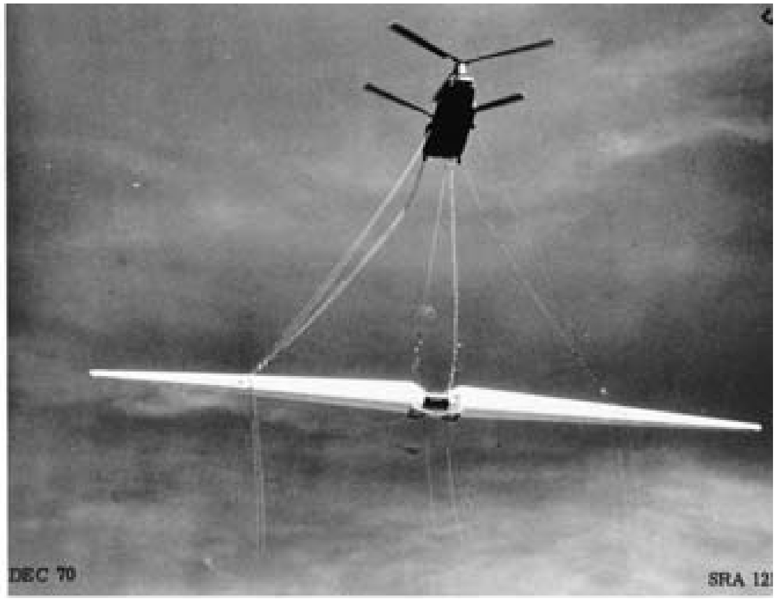
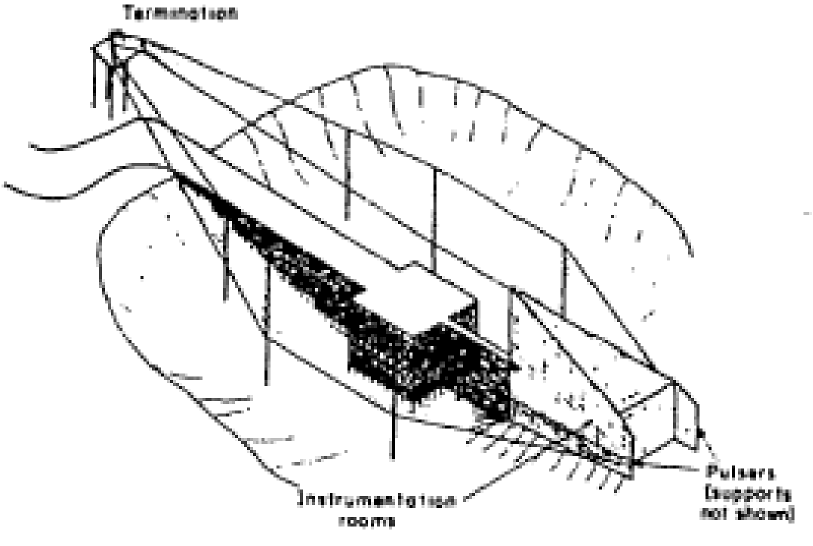
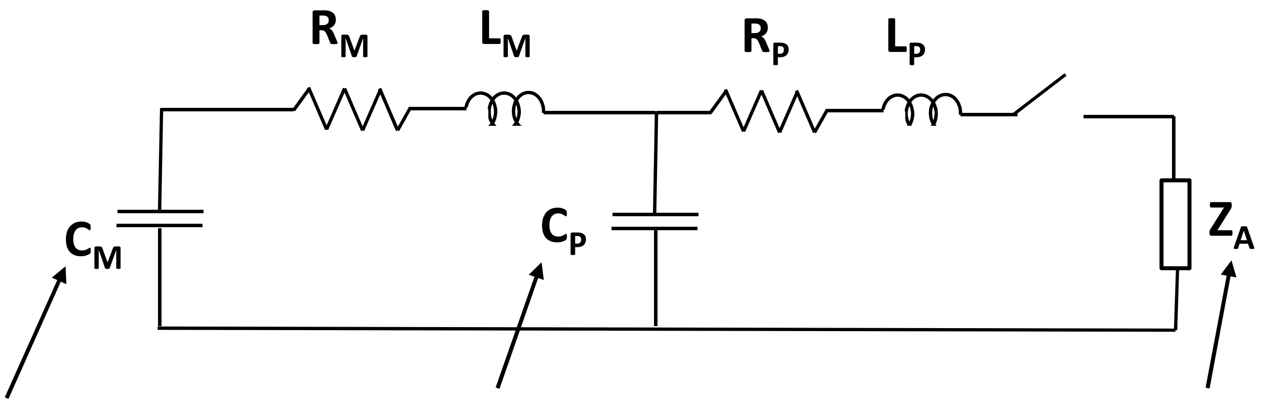
HEMP Simulators







Generic Pulsed Power Circuit for Simulators

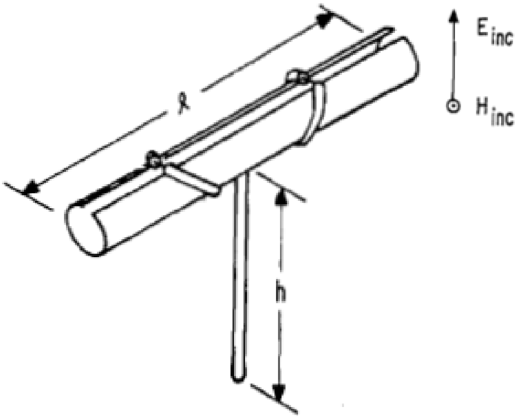


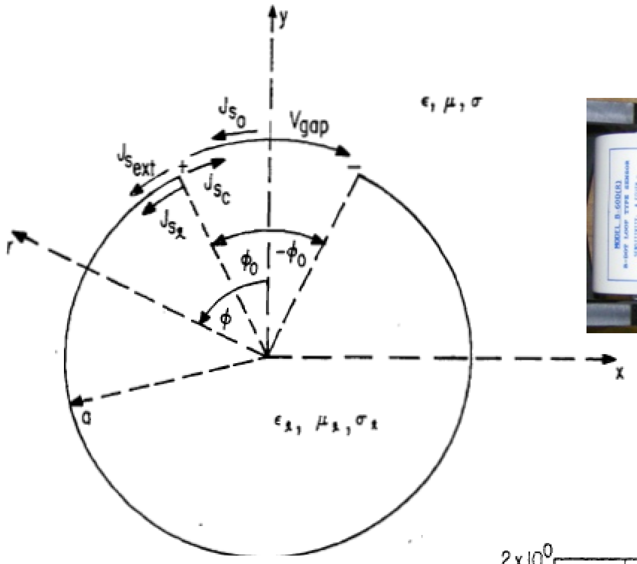
Main Marx Bank
Capacitive Storage
(power supply charge)

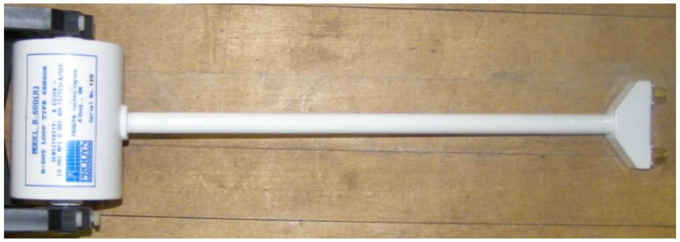
Peaking Capacitor

Simulator Load

Measurement Sensor B-Dot*



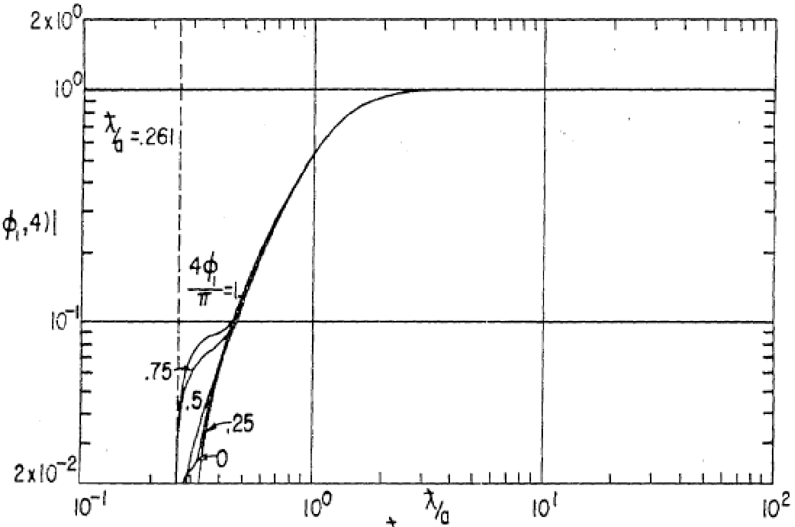




$$H_z(r,\phi) = H_{z_o}\left[a_o H_o^{(2)}(kr)+2\sum_{n=N}^{\infty,N} a_n H_n^{(2)}(kr)\cos(n\phi)\right]$$

$$E_\phi(r,\phi) = jZH_{z_o}\left[a_o H_o^{(2)'}(kr)+2\sum_{n=N}^{\infty,N} a_n H_n^{(2)'}(kr)\cos(n\phi)\right]$$

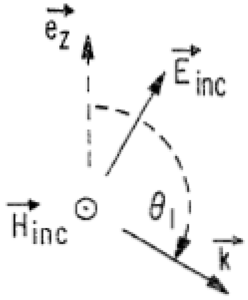
$$a_n = \frac{jV_{gap}J_o(n\phi_o)}{2\pi aZH_{z_o}H_n^{(2)'}(ka)}$$

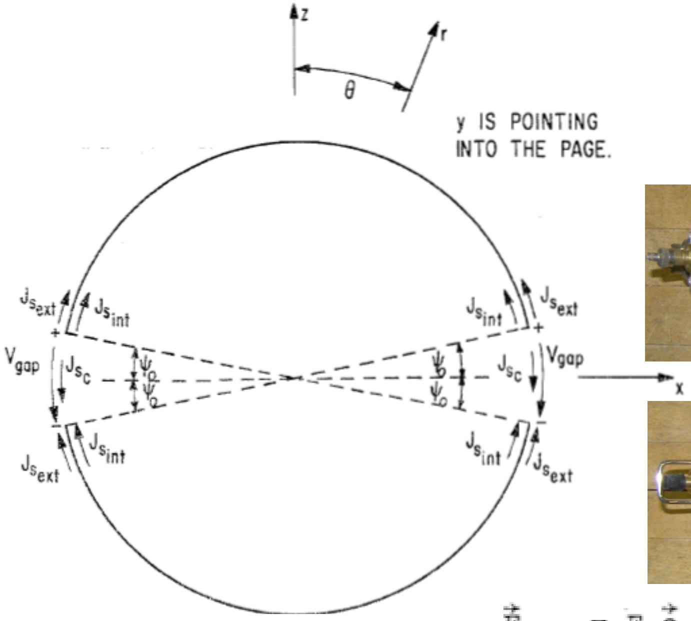


A. MAGNITUDE OF R(ϕ_1,4) vs. λ/a WITH ϕ_1 AS A PARAMETER

*C.E. Baum, Sensor and Simulation Note 41, May 1967.

Measurement Sensor E-Dot*





$$\vec{E}_{inc} = E_o\vec{e}_2 e^{-i\vec{k}\cdot\vec{r}}$$

$$\nabla^2\vec{E} + k^2\vec{E} = \vec{0}\ , \qquad \nabla^2\vec{H} + k^2\vec{H} = \vec{0}$$

$$\Xi^{(\ell)}(n,\ m,\ {e \atop o}) \equiv f_n^{(\ell)}(kr)P_n^m(\cos(\theta))\left|\begin{matrix}\cos(m\phi)\\ \\ \sin(m\phi)\end{matrix}\right\}$$

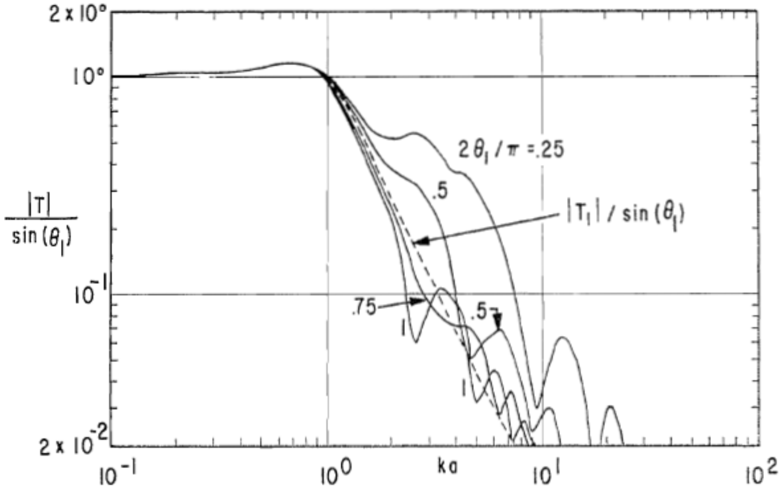
$$\vec{e}_2 e^{-i\vec{k}\cdot\vec{r}} = \sum_{n=1}^{\infty}\sum_{m=o}^{n}\left[a_{n,m}\vec{M}^{(1)}(n,m,o) + b_{n,m}\vec{N}^{(1)}(n,m,e)\right]$$

$$\vec{M}^{(\ell)}(n,\ m,\ {e \atop o}) \equiv \nabla \times \left[r\Xi^{(\ell)}(n,\ m,\ {e \atop o})\vec{e}_r\right]$$

$$\vec{N}^{(\ell)}(n,\ m,\ {e \atop o}) \equiv \frac{1}{k}\nabla \times \vec{M}^{(\ell)}(n,\ m,\ {e \atop o})$$

$$\vec{E} = E_o\sum_{n=o}^{\infty}\sum_{m=o}^{n}\left|\alpha_{n,m}\vec{M}^{(\ell)}(n,\ m,\ {e \atop o}) + \beta_{n,m}\vec{N}^{(\ell)}(n,\ m,\ {e \atop o})\right|$$

$$\vec{H} = i\,\frac{E_o}{Z}\sum_{n=o}^{\infty}\sum_{m=o}^{n}\left|\alpha_{n,m}\vec{N}^{(\ell)}(n,\ m,\ {e \atop o}) +- \beta_{n,m}\vec{M}^{(\ell)}(n,\ m,\ {e \atop o})\right|$$



*C.E. Baum, Sensor and Simulation Note 91, July 1969.

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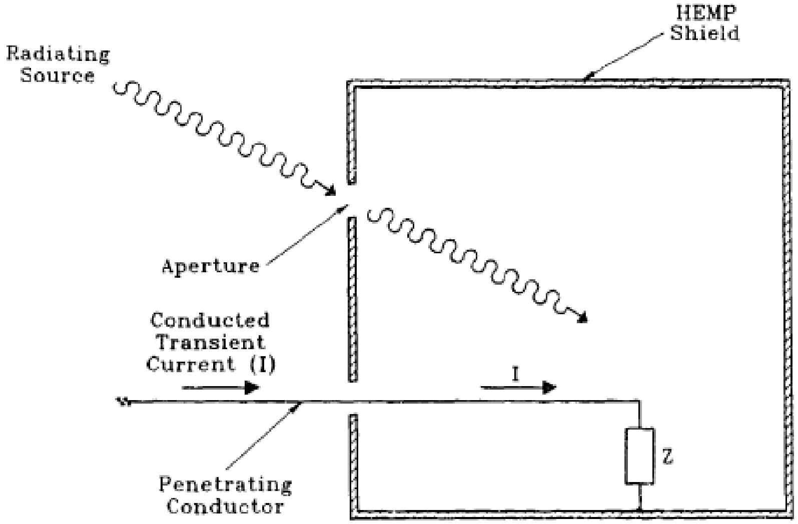
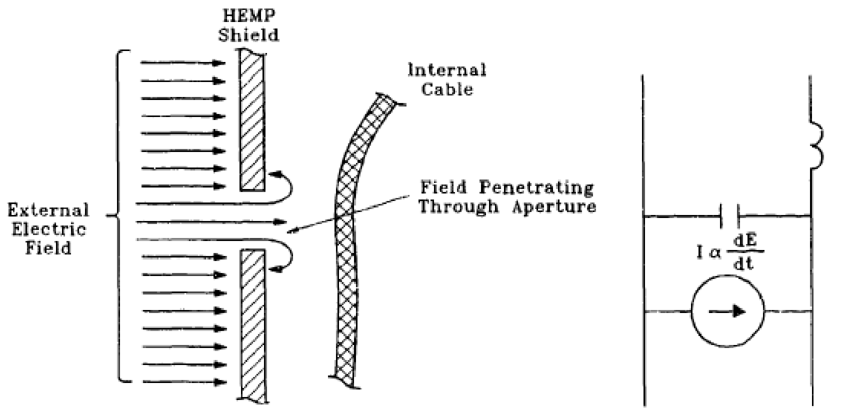
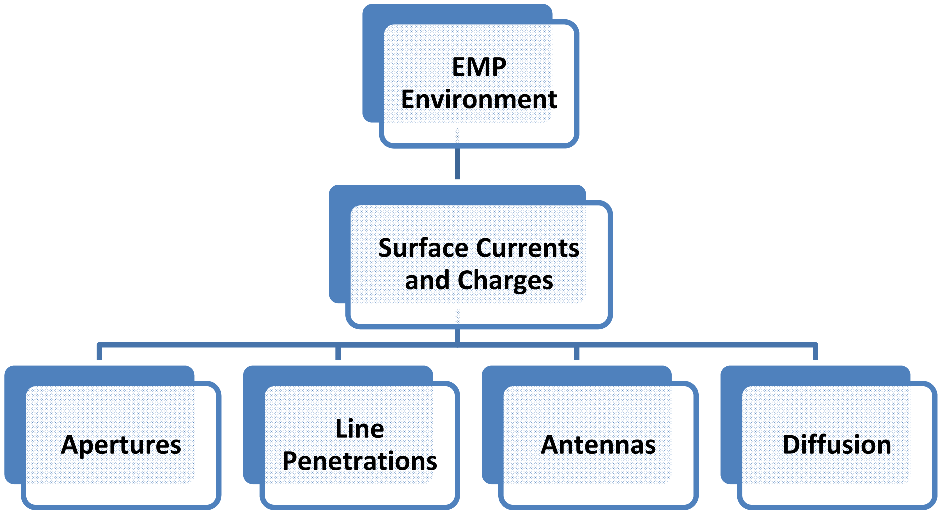
Exterior to Interior Penetration of HEMP





a. Electric field.



EMP Environment

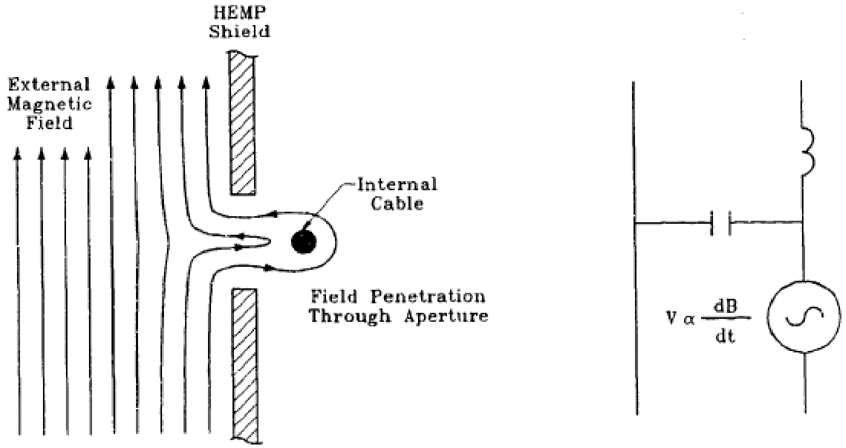
Surface Currents and Charges

Apertures

Line Penetrations

Antennas

Diffusion

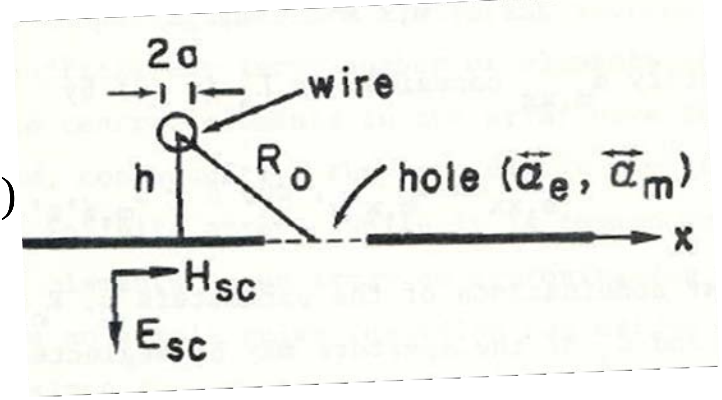


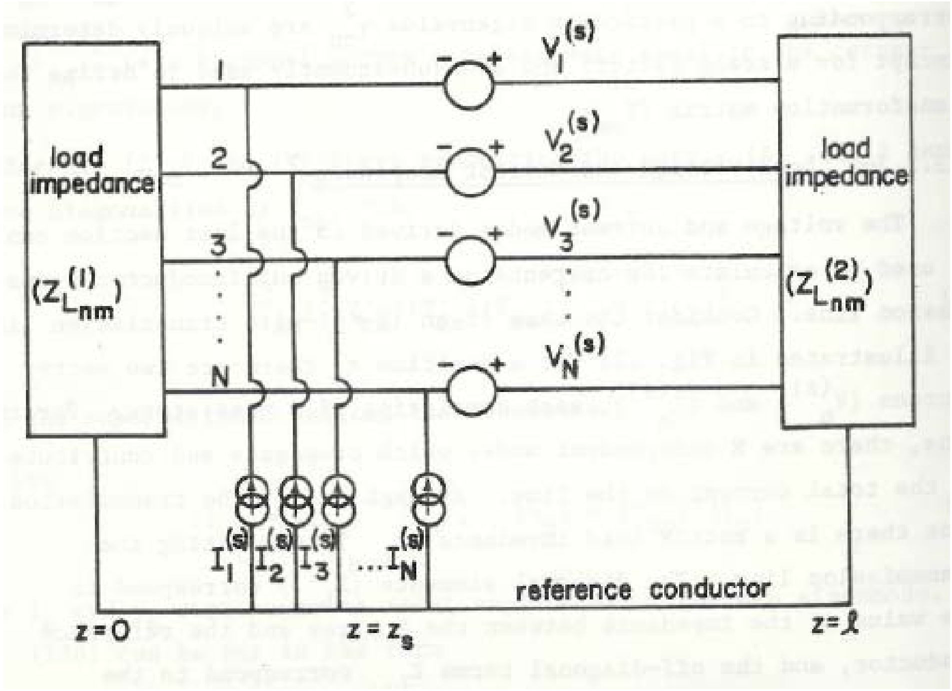
b. Magnetic field.

Transmission Line Equations for Interior Response

$\partial V/\partial z + ZI = V'(z, s) = j\omega\mu_0(h/\pi R_0^2)\alpha_m H_{sc}$

$\partial I/\partial z + YV = I'(z, s) = j\omega\varepsilon_0(h/\pi R_0^2)\alpha_m E_{sc}(Z_0/Z_c)$





$\partial V_n/\partial z + Z_{nm}I_m = V'_n(z, s)$

$\partial I_n/\partial z + Y_{nm}V_m = I'_n(z, s)$

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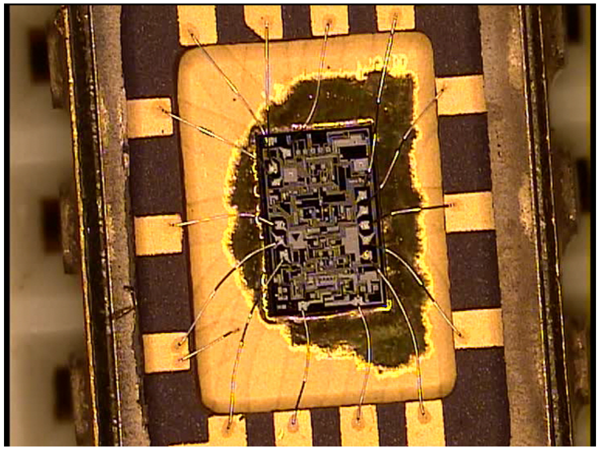
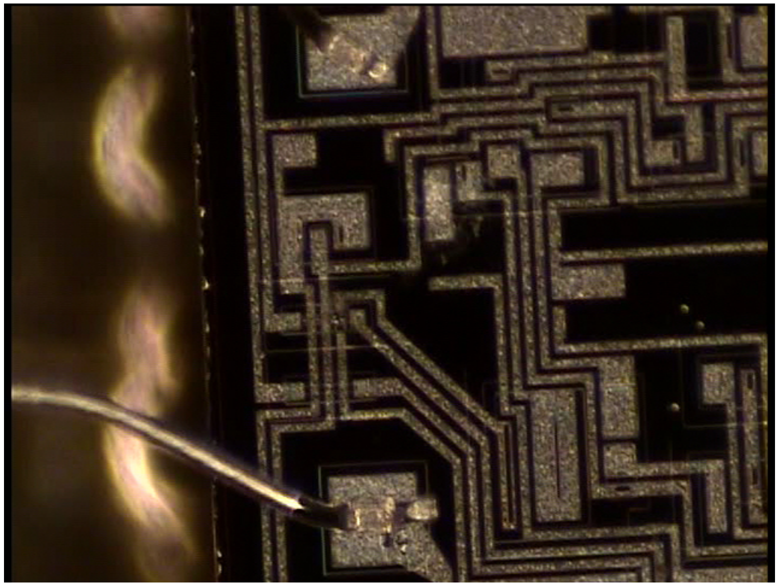
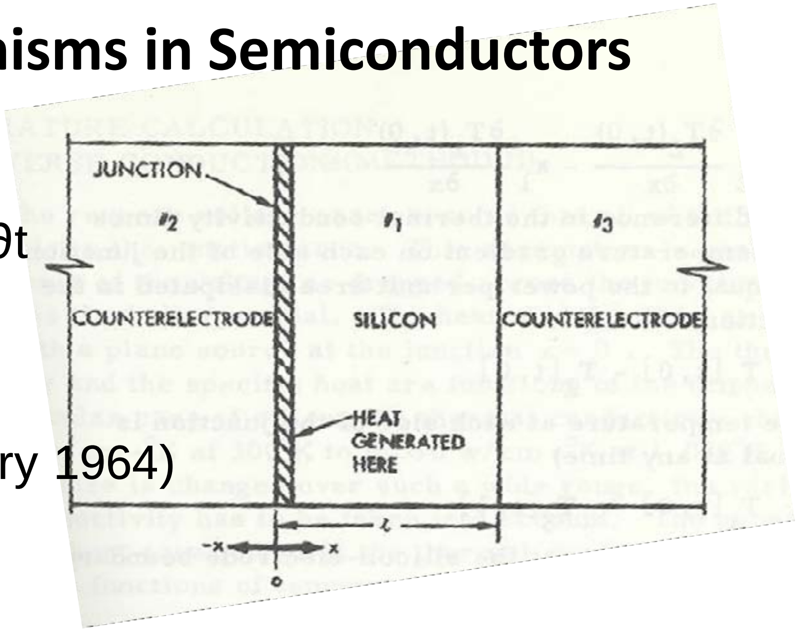
EMP Induced Semiconductor Based Electronics Failure Modes





- Junction Thermal Damaged
  - Heating creates a low impedance shunt due to re-solidified melt
- Interconnection Device Metallization
  - Thermal damage due to melt, splatter, gapping (open circuits)
- Second Breakdown
  - Reversed biased junctions
  - Thermal runaway due to severe current, materials defects high fields

Thermal Modeling Damage Mechanisms in Semiconductors



- Planar Heat Flow $\partial/\partial x(\kappa\partial T/\partial x) – \rho C_p\ \partial T/\partial t$
  - Wunsch-Bell (1968)

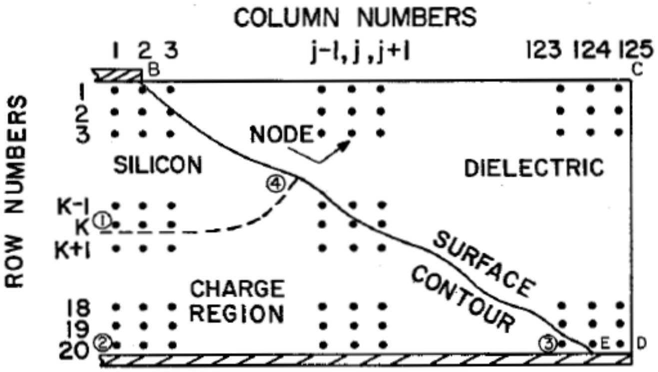
$$T = Q/(4\pi\alpha)^{1/2} \int [e^{-(x-x')^2/4\alpha(t-t')} /(t-t')^{1/2}]dt$$

$$P = A(\pi\kappa\rho C_p)^{1/2}\, t^{-1/2}\, [T_m – T_i]\ \text{(also see Gentry 1964)}$$

- Spherical 3-D Analysis
  - Tasca (1970)

$$P = \left\{4\pi a^3\rho C_p/3 + 4\pi a^2(\pi\kappa\rho C_p)^{1/2}\, t^{-1/2} + 8\pi a\kappa t/3\right\} [T_m – T_i]$$

- Numerical Computation Surface Electric Field
  - Gentry (1964)

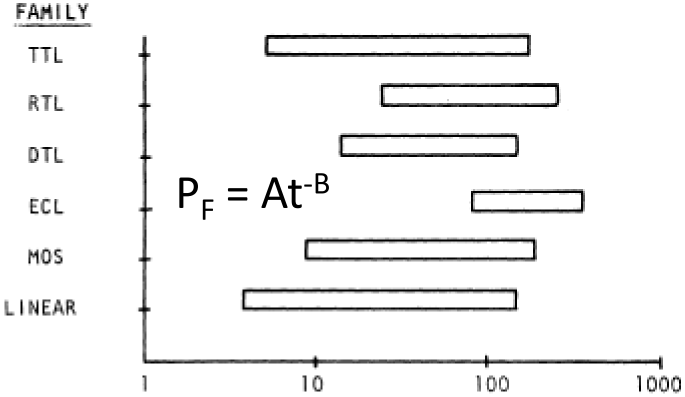


$$\nabla^2 U(x,y) + qN(x,y)/\varepsilon = 0$$

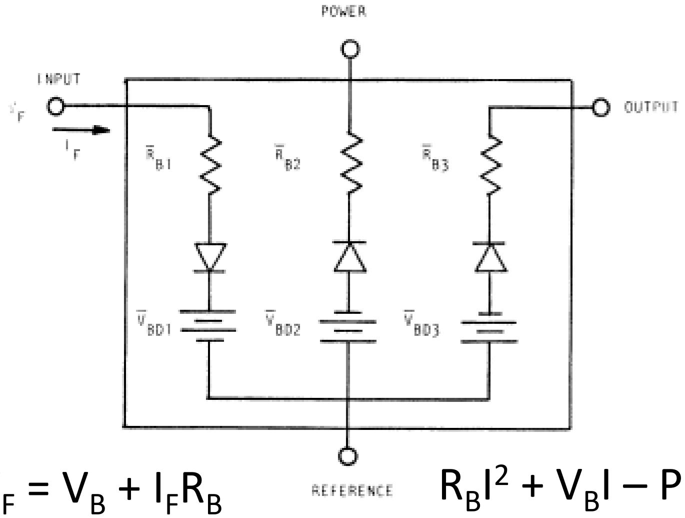
Simplified Model for Device Failure Power and Current Levels*

Diodes, Transistors, Integrated Circuits

Input Terminal Failures for 1µs

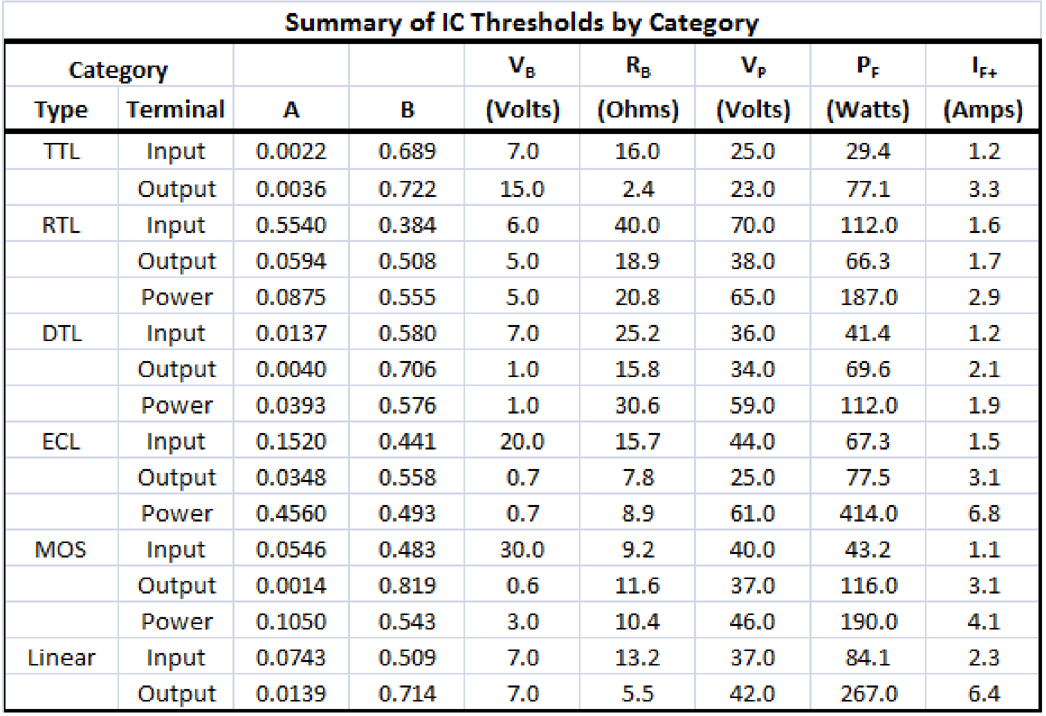


$P_F = At^{-B}$



$V_F = V_B + I_F R_B$

$R_B I^2 + V_B I - P_F = 0$



Summary of IC Thresholds by Category

Category				V_B	R_B	V_P	P_F	I_{F+}
Type	Terminal	A	B	(Volts)	(Ohms)	(Volts)	(Watts)	(Amps)
TTL	Input	0.0022	0.689	7.0	16.0	25.0	29.4	1.2
	Output	0.0036	0.722	15.0	2.4	23.0	77.1	3.3
RTL	Input	0.5540	0.384	6.0	40.0	70.0	112.0	1.6
	Output	0.0594	0.508	5.0	18.9	38.0	66.3	1.7
	Power	0.0875	0.555	5.0	20.8	65.0	187.0	2.9
DTL	Input	0.0137	0.580	7.0	25.2	36.0	41.4	1.2
	Output	0.0040	0.706	1.0	15.8	34.0	69.6	2.1
	Power	0.0393	0.576	1.0	30.6	59.0	112.0	1.9
ECL	Input	0.1520	0.441	20.0	15.7	44.0	67.3	1.5
	Output	0.0348	0.558	0.7	7.8	25.0	77.5	3.1
	Power	0.4560	0.493	0.7	8.9	61.0	414.0	6.8
MOS	Input	0.0546	0.483	30.0	9.2	40.0	43.2	1.1
	Output	0.0014	0.819	0.6	11.6	37.0	116.0	3.1
	Power	0.1050	0.543	3.0	10.4	46.0	190.0	4.1
Linear	Input	0.0743	0.509	7.0	13.2	37.0	84.1	2.3
	Output	0.0139	0.714	7.0	5.5	42.0	267.0	6.4

*C.R. Jenkins and D.L. Durgin, “EMP Susceptibility of Integrated Circuits,” IEEE Transactions on Nuclear Science, Vol NS-22, No. 6, December 1975.

Upset/Interference Considerations

- Switch Activation
  - Relays
  - On/Off Transformers

- Logic State Changes
  - Active
  - Stored

- Operational Real-Time Interference
  - Communications, Control
  - Resets

Some On-Going Areas of Research

- Civilian Response to EMP Event
  - Alternative Communications, Media Information
  - Protection Strategies, Replacement Hardware
- In-the-field shielding measurements
  - Instrumentation Approaches
  - Transfer Function Measurements
- Analyses Studies
  - Data Extrapolation to Differing Environments
  - Statistical Response Trends, Materials Properties
- Laboratory Characterizations
  - Terminal Protection Measurements
  - Box Level Electrical Stress/Strain Response Thresholds