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A Circular Conical Antenna Simulator

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Abstract

A possible way to simulate the nuclear electromagnetic pulse on a system in flight is to radiate a large amplitude pulse from an antenna to the system. This note considers some of the characteristics of a circular conical antenna, symmetrically located on a ground plane, for radiating a pulse from a fast capacitive energy source.

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I. Introduction

In simulating the nuclear electromagnetic pulse, one case of interest concerns systems in flight. In some cases it may be desirable to actually have the system in operation in flight during the simulated electromagnetic pulse in order to achieve a more complete simulation. This type of a simulation test may require that very large amplitude field strengths cover very large volumes since the system under test may be moving rather fast during the test, and thus may have to be separated some significant distance from a simulator structure. One approach to such a simulator is to discharge a fast, high-voltage, capacitive generator into a large antenna which in turn radiates a narrow, large-amplitude pulse away from the antenna to the system under test. We consider the antenna to be located on the ground surface so as to allow the use of the largest appropriate generator the state of the art will allow.

For this note we choose the antenna to be a circular cone over a perfectly conducting ground plane (taken infinite in extent for the calculations). This is illustrated in figure 1 together with a generator. For simplicity the generator is taken as a charged transmission line of the same pulse impedance as the circular cone. Thus, when the switch between the generator and antenna is closed (in a time assumed short compared to other times of interest) a rectangular pulse propagates outward on the antenna and some fraction of the energy is radiated away from the antenna. We choose a rectangular pulse from the generator to simplify some of the calculations. Other generator configurations give different pulse shapes and one may desire a different pulse shape.

There are limitations on this type of simulator. Reflections are introduced at the top of the cone. Perhaps the adverse effects of such reflections can be reduced by an appropriately designed cap on the cone, but this is not considered in this note. Also, pulses with widths small compared to the transit time on the cone can propagate away from the antenna with a 1/r dependence for the amplitude, but pulses with widths comparable to or greater than this transit time are severely distorted in propagating away from the antenna. The cone may then have to be quite tall for a good pulse radiator.

In this note we consider some time-domain concepts in order to obtain some bounds on the effectiveness of the circular cone as a pulse radiator. Perhaps cones other than circular can be used for pulse radiators, but we only consider circular cones because of the simplicity introduced into the calculations by the azimuthal (ϕ) independence of the fields. Some other useful calculations for conical antennas (with spherical caps) have also been performed.[1,2,3]

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1. C. H. Papas and R.W.P. King, Input Impedance of Wide-Angle Conical Antennas Fed by a Coaxial Line, Proc. IRE, pp 1269-1271, Nov. 1949.
2. C. H. Papas and R.W.P. King, Radiation from Wide-Angle Conical Antennas Fed by a Coaxial Line, Proc. IRE, pp. 49-51, Jan. 1951.
3. C.W. Harrison, Jr. and C.S. Williams, Jr., Transients in Wide-Angle Conical Antennas, Sandia Corp. SCR-663, June 1963.

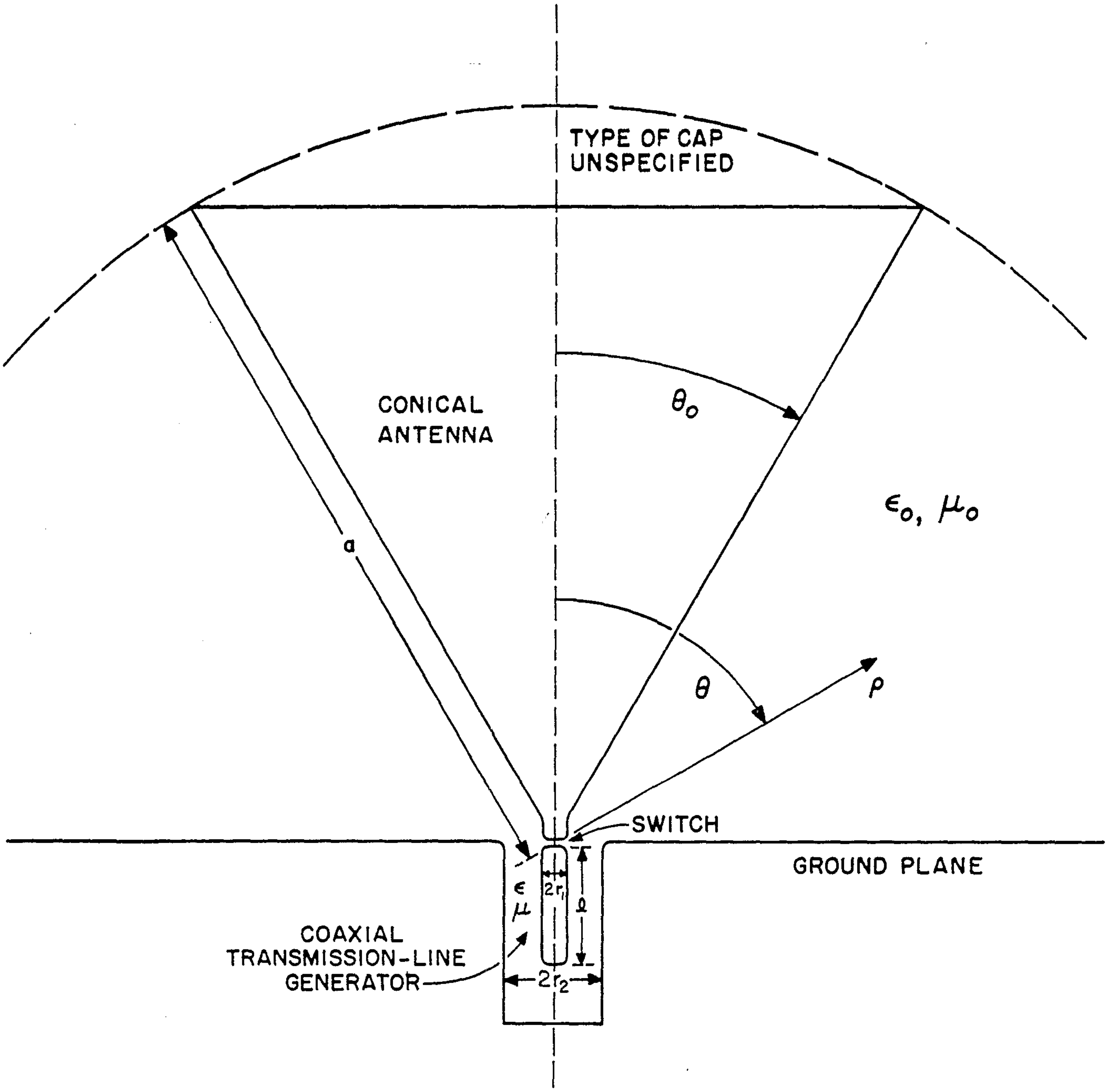

Figure 1. CIRCULAR CONICAL ANTENNA SIMULATOR
WITH MATCHED TRANSMISSION-LINE SOURCE

II. Pulse Impedance and Field Distribution

Considering the TEM wave on the conical antenna, the cone and ground plane may be treated as a conical transmission line. This applies for the pulse from the generator for times before the reflection from the top of the cone reaches an observer situated at $0<r<a$ and $\theta_o < \theta < \frac{\pi}{2}$. There is an equivalent cylindrical transmission line (with coordinates (r,ϕ,z')) given by the transformations[4,5]

$$r = 2z_o \tan\left(\frac{\theta}{2}\right) \quad (1)$$

$$\phi = \phi \quad (2)$$

and

$$\rho = z' \quad (3)$$

where z_o is a constant which can be chosen. Since the antenna has azimuthal (ϕ) symmetry, the potential function for the electric field is only a function of r or θ, and is of the form $C_1 \ln(r)+C_2$ or $C_1 \ln[2z_o \tan\left(\frac{\theta}{2}\right)]+C_2$ where the C's are constants.

The pulse impedance of the coaxial, transmission-line generator of inner radius, r_1, and outer radius, r_2, is

$$Z_c = \sqrt{\frac{\mu}{\varepsilon}}\ \frac{1}{2\pi} \ln\left(\frac{r_2}{r_1}\right) \quad (4)$$

where ε and μ are the permittivity and permeability, respectively, of the insulating medium in the generator. Taking ε and μ as equal to ε_o and μ_o, respectively, (free space parameters) gives

$$Z_c = \sqrt{\frac{\mu_o}{\varepsilon_o}}\ \frac{1}{2\pi} \ln\left(\frac{r_2}{r_1}\right) \simeq 60 \ln\left(\frac{r_2}{r_1}\right) \quad (5)$$

Likewise using the transformation from equation 1, the pulse impedance of the circular conical antenna is

4. W.R. Smythe, Static and Dynamic Electricity, 2nd ed. 1950, p. 479.
5. Capt Carl E. Baum, Sensor and Simulation Note XXXI, The Conical Transmission Line as a Wave Launcher and Terminator for a Cylindrical Transmission Line, Jan. 1967

$$Z_a = \sqrt{\frac{\mu_o}{\varepsilon_o}}\ \frac{1}{2\pi}\ \ln\ \left[\frac{2z_o \tan\left(\frac{\pi}{4}\right)}{2z_o \tan\left(\frac{\theta_o}{2}\right)}\right] = \sqrt{\frac{\mu_o}{\varepsilon_o}}\ \frac{1}{2\pi}\ \ln\ \left[\cot\left(\frac{\theta_o}{2}\right)\right]$$

$$\approx 60\ \ln\ \left[\cot\left(\frac{\theta_o}{2}\right)\right] \tag{6}$$

Equating Z_c and Z_a from equations (5) and (6) gives the relation

$$\frac{r_2}{r_1} = \cot\left(\frac{\theta_o}{2}\right) \tag{7}$$

which matches the pulse from the generator onto the antenna. Choosing convenient values of Z_a, the following table is obtained using the above relations.

Z_a (ohms)	θ_o (radians)	θ_o (degrees)	tan (θ_o)	r_2/r_1
25	1.165	66.8	2.330	1.516
50	.820	47.0	1.070	2.313
75	.558	31.9	.624	3.49
100	.373	21.36	.391	5.31
125	.2474	14.17	.2525	8.02
200	.0712	4.07	.0712	27.77

Table I. Pulse Impedance for Antenna and Generator

The pulse impedance of the cone is plotted in figure 2 versus θ_o.

The TEM waves on the cone (in the time domain) have a potential function for the electric field of the form

$$V = V_o f_V(\theta)\ f_1(t \pm r/c) \tag{8}$$

where V_o is a constant, f_1 is an arbitrary function of $t \pm r/c$, and f_V is a distribution function of θ. For convenience f_V is normalized by setting it to zero for $\theta = \frac{\pi}{2}$ and +1 for $\theta = \theta_o$ giving

$$f_V = \frac{\ln[\tan\left(\frac{\theta}{2}\right)]}{\ln[\tan\left(\frac{\theta_o}{2}\right)]} = \frac{\ln[\cot\left(\frac{\theta}{2}\right)]}{\ln[\cot\left(\frac{\theta_o}{2}\right)]} \tag{9}$$

This is plotted in figure 3 versus θ for various values of θ_o, corresponding to various values of Z_a.

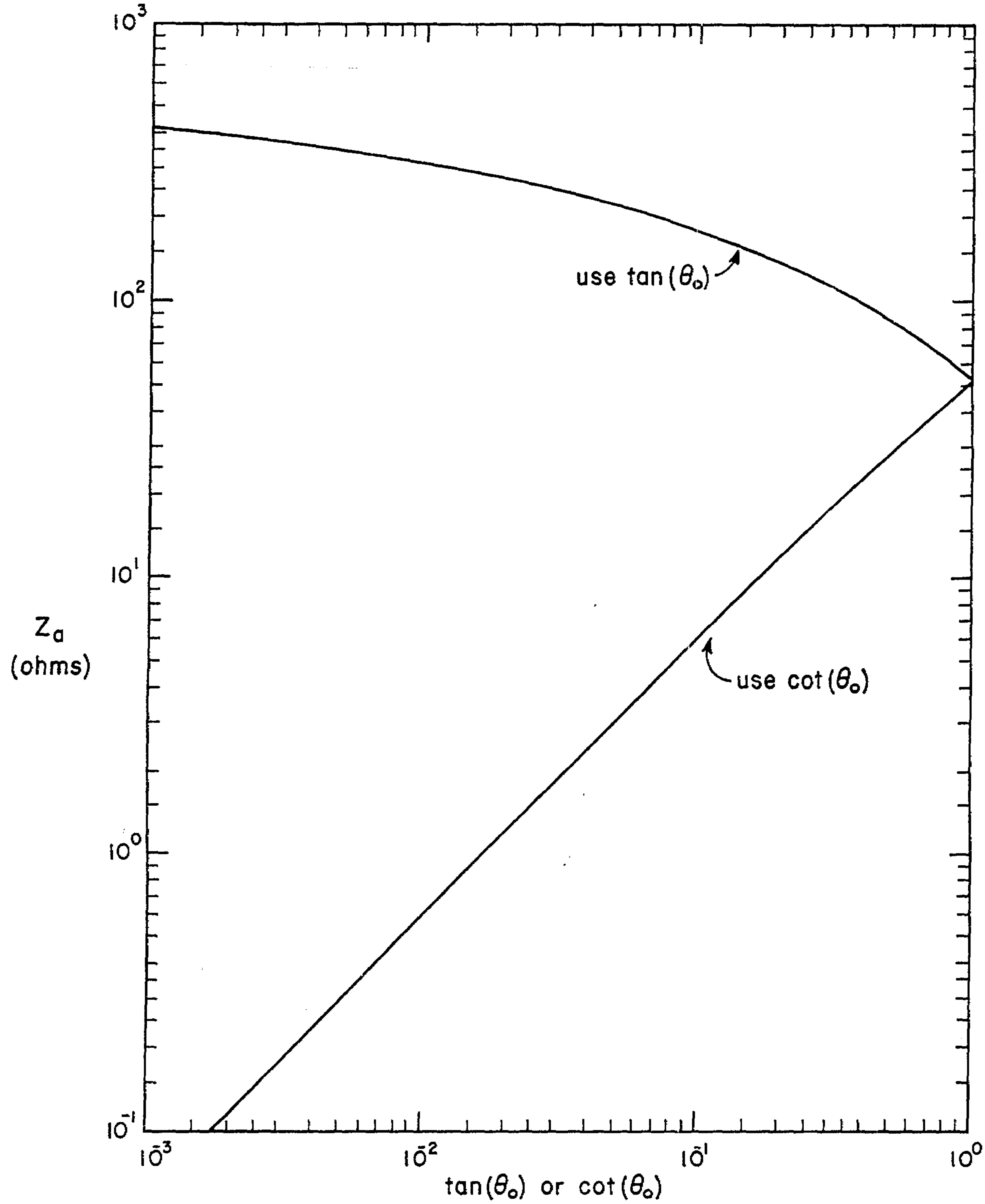

Figure 2. PULSE IMPEDANCE OF CIRCULAR CONICAL ANTENNA SIMULATOR

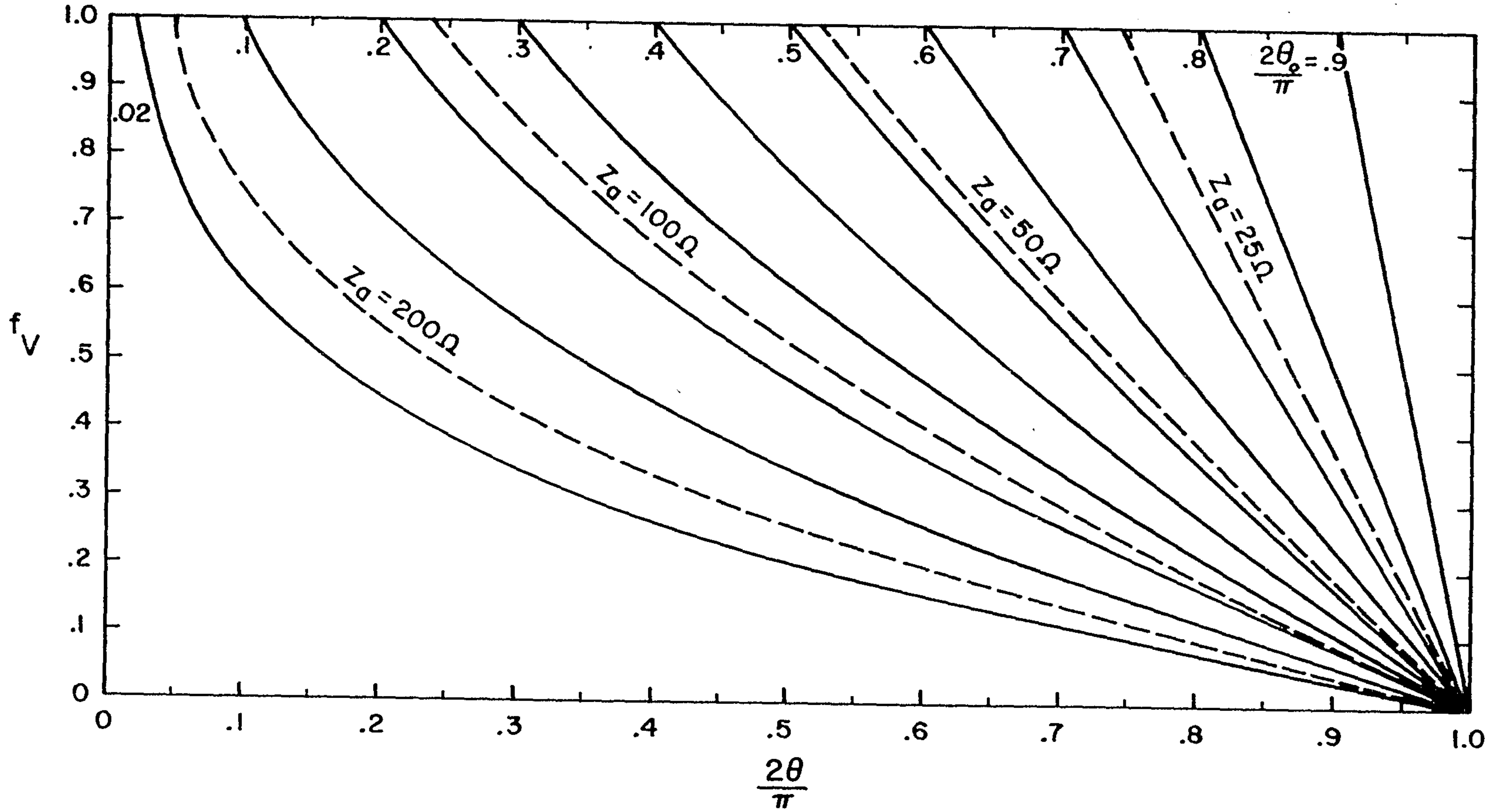

Figure 3. NORMALIZED POTENTIAL DISTRIBUTION ON CIRCULAR CONICAL ANTENNA SIMULATOR

The electric field associated with such TEM waves is of the form

$$E_\theta = - V_o \frac{1}{r} \frac{\partial f_V(\theta)}{\partial \theta} f_I(t \pm r/c) = \frac{V_o}{r} f_E(\theta) f_I(t \pm r/c) \tag{10}$$

where the electric field distribution function is

$$f_E = - \frac{\partial f_V}{\partial \theta} \tag{11}$$

or

$$f_E = - \frac{1}{\ln[\tan\left(\frac{\theta_o}{2}\right)]} \frac{1}{\tan\left(\frac{\theta}{2}\right)} \frac{\sec^2\left(\frac{\theta}{2}\right)}{2} = \frac{1}{\ln[\cot\left(\frac{\theta_o}{2}\right)] 2\sin\left(\frac{\theta}{2}\right) \cos\left(\frac{\theta}{2}\right)}$$

$$= \frac{1}{\sin(\theta) \ln[\cot\left(\frac{\theta_o}{2}\right)]} \tag{12}$$

For given r and t the electric field is maximum on the cone, $\theta = \theta_o$, at which the electric field distribution function is

$$f_E(\theta_o) = \frac{1}{\sin(\theta_o) \ln[\cot\left(\frac{\theta_o}{2}\right)]} \tag{13}$$

The normalized electric field distribution is plotted in figure 4 versus θ for various values of θ_o, corresponding to various values of Z_a. The maximum value (equation (13)) for $\theta = \theta_o$ is also included in this graph.

For a given voltage on the antenna there is a particular θ_o for which the maximum electric field is minimized as can be seen in figure 4. Call this particular θ_o as θ_2. Instead of minimizing $f_E(\theta_o)$ maximize $f_E^{-1}(\theta_o)$ (from equation (13))as

$$\frac{\partial}{\partial \theta_o} [f_E^{-1}(\theta_o)] \Big|_{\theta_o = \theta_2} = 0 \tag{14}$$

Then

$$\cos(\theta_2) \ln[\cot\left(\frac{\theta_2}{2}\right)] + \frac{\sin(\theta_2)}{\cot\left(\frac{\theta_2}{2}\right)} \left[- \frac{\csc^2\left(\frac{\theta_2}{2}\right)}{2} \right] = 0 \tag{15}$$

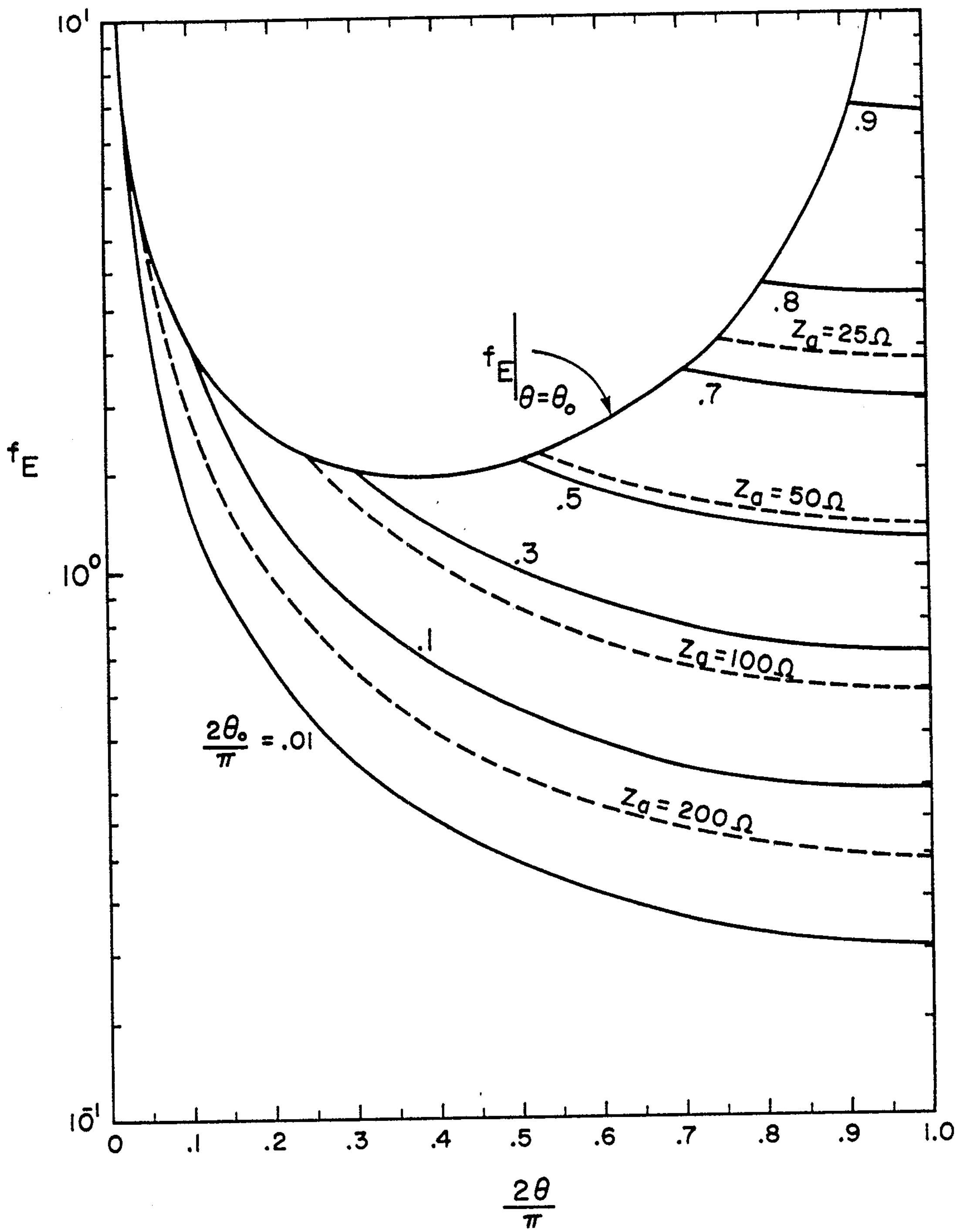

Figure 4. NORMALIZED FIELD DISTRIBUTION ON CIRCULAR CONICAL ANTENNA SIMULATOR

or

$$1 = 2\sin\left(\frac{\theta_2}{2}\right)\cos\left(\frac{\theta_2}{2}\right)\cot(\theta_2)\ln[\cot\left(\frac{\theta_2}{2}\right)]$$

$$= \cos(\theta_2)\ln[\cot\left(\frac{\theta_2}{2}\right)]$$

$$= \frac{\cos(\theta_2)}{2}\ln\left[\frac{1+\cos(\theta_2)}{1-\cos(\theta_2)}\right]$$

$$= \cos(\theta_2)\operatorname{arctanh}[\cos(\theta_2)] \qquad (16)$$

This transcendental equation can be solved for $\cos(\theta_2)$ giving

$$\cos(\theta_2) = .834 \qquad (17)$$

or

$$\theta_2 = .585 \qquad (18)$$

and thereby from equation (6)

$$Z_a \Big|_{\theta_o = \theta_2} \simeq 72 \text{ ohms} \qquad (19)$$

There are other conditions under which one might wish to minimize the maximum electric field. Instead of holding the antenna voltage constant one might hold the power, V^2/Z_a, constant. In each case some intermediate θ_o is optimum.

III. Clear Time

Now consider a time domain concept concerning the fields radiated from such a conical antenna. As illustrated in figure 5 send a pulse from the generator out onto the cone. Up until the time that the leading edge of the pulse reaches the top of the cone (of slant height, a) there are no reflections and the pulse maintains its shape with the fields decreasing in amplitude as 1/r (for a constant retarded time, t-r/c). Consider an observation point specified by $\theta_o<\theta<\frac{\pi}{2}$ and r>>a. The first fields to arrive at the observation point have propagated along a path of constant θ. This initial signal is a spherical TEM wave as in equation (10). Subsequently a signal arrives at the observation point from the disturbance at $(r,\theta) = (a,\theta_o)$. The time delay between these two signals we call the clear time, t_b. Considering the pulse to start at the base of the cone at t = 0, then for $0\le t-r/c<t_b$ the signal is a TEM wave and a faithful reproduction of the initial pulse shape while for larger retarded times the pulse shape may be distorted. The corresponding clear distance, b, or difference between the two propagation paths, in the limit of large r, is

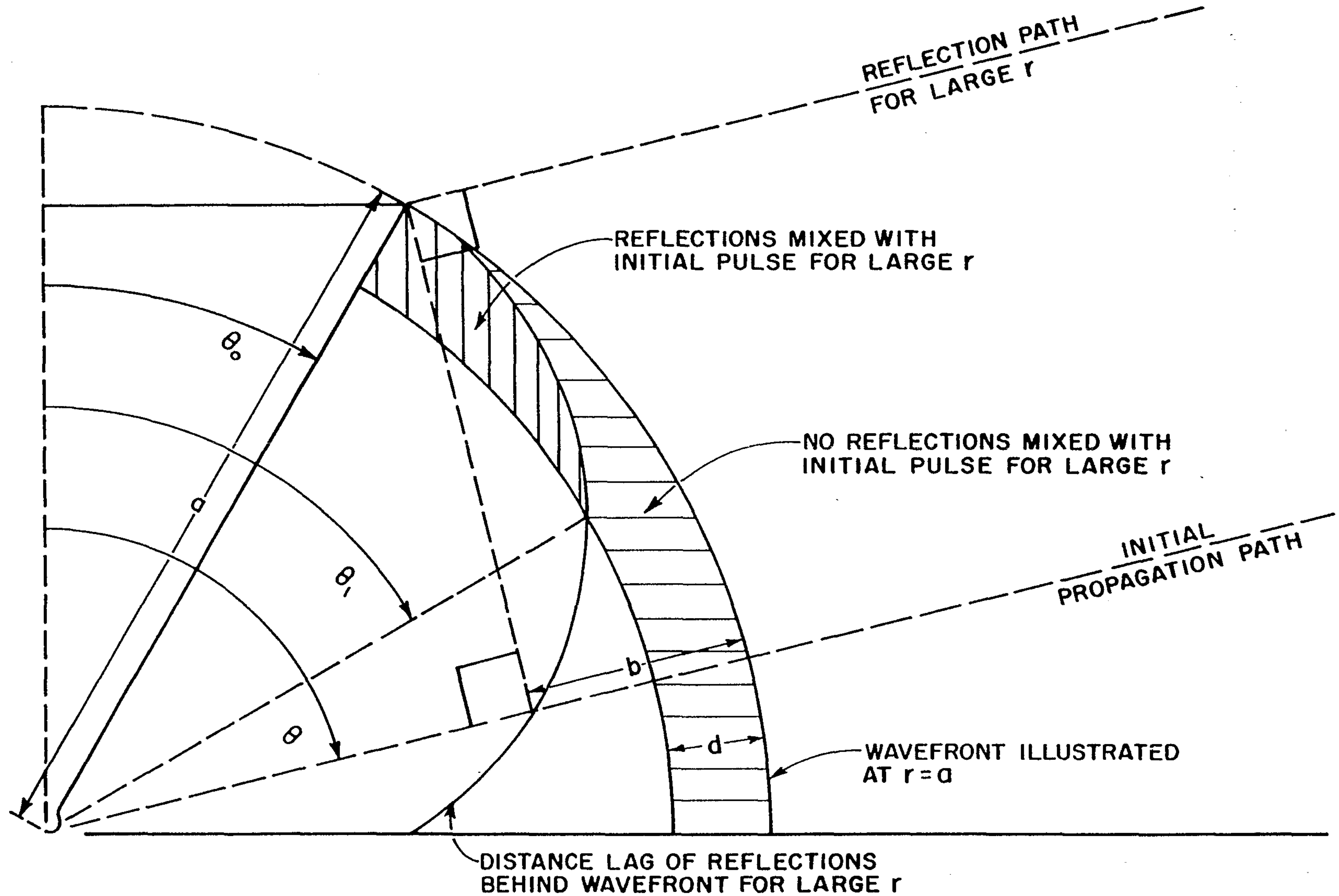

Figure 5. RECTANGULAR PULSE ON CIRCULAR CONICAL ANTENNA SIMULATOR

$$b = a\,[1-\cos(\theta-\theta_o)] \qquad (20)$$

The clear time, t_b, is just b/c.

The transit time on the cone, t_a, is just a/c. A convenient parameter is

$$B = \frac{t_b}{t_a} = \frac{b}{a} = 1-\cos(\theta-\theta_o) \qquad (21)$$

which normalizes the clear time to t_a. Defining t_ℓ as the transit time on the assumed transmission-line generator, the rectangular pulse from the generator has a width

$$t_d = 2t_\ell = 2\,\frac{\ell}{c} = \frac{d}{c} \qquad (22)$$

where now d is the spatial width of the pulse. Again it is convenient to normalize the pulse width and define

$$D = \frac{t_d}{t_a} = \frac{2t_\ell}{t_a} = \frac{2\ell}{a} = \frac{d}{a} \qquad (23)$$

Then for D<B the observer at large r sees the entire pulse before any reflections arrive; for D>B the observer at large r sees reflections mixed in with part of the pulse. The dividing angle, θ_1, between these two cases, defined by setting D=B, is given by

$$\cos(\theta_1 - \theta_o) = 1-D \qquad (24)$$

providing, of course, that D is small enough to give a θ_1 less than $\frac{\pi}{2}$. The extent in space, d, of the initial undistorted pulse is shown in figure 5 with the leading edge of the pulse at r = a. In addition, there is illustrated a contour for the distance lag of reflections behind the initial pulse (for large r). This contour also defines that part of the initial pulse (when extended to large r) which has reflections mixed with it, thus graphically illustrating the part of the initial pulse which is distorted versus θ. From this we can observe that to decrease the distortion of the initial pulse for a given θ and decrease θ_1 we can decrease D and/or decrease θ_o.

After the reflections arrive at the observer the description of the waveform becomes much more complex and is not treated here. One thing can be said, however, about the radiated pulse based on frequency domain concepts. For high frequencies ($\omega t_a \gg 1$) the fields propagate away from the antenna with an amplitude dependence of r^{-1}; for low frequencies ($\omega t_a \ll 1$) the amplitude of the fields falls off much faster than r^{-1}, a well-known result for a dipole antenna. In the limit of large r and zero frequency the fields are negligible compared to the high-frequency fields. In the time domain this means that for a finite pulse amplitude on the antenna, r times the full time integral of the waveform is zero in the limit of large r, while r times the wave amplitude is independent of r in the limit of large r. Assuming that a single polarity pulse is put on the cone, the waveform then has both polarities for large r; the reflections combine to give a net time integral which compensates for the time integral of the initial pulse. However, the reflections are delayed in time relative to the initial pulse. Perhaps by appropriate design of the cone, including the cap on the cone, the reflections can be spread out in time to give a much lower absolute amplitude than the initial pulse.

There are then a few relatively simple things which can be said about the radiated pulse. For retarded times less than the clear time the radiated waveform is the same as the waveform applied to the antenna; for large r the time integral over the complete waveform is practically zero with both polarities present in the waveform. There are perhaps some things which can be done to improve the waveform for late retarded times, but these are not considered here.

IV. Efficiencies

As an indication of the manner in which various parameters effect the performance of this type of simulator, consider the efficiency of this simulator for radiating electromagnetic energy. First, consider a maximum efficiency, η_1, based on the stored capacitive energy before and after firing the generator. Initially there is stored in the charged coaxial generator an energy

$$U_1 = \frac{1}{2} C_c V_1^2 \tag{25}$$

where V_1 is the voltage on the generator and where the generator capacitance is given by

$$C_c = \frac{t_\ell}{Z_c} \tag{26}$$

After the generator has fired and the generator-antenna combination has settled down to a voltage, V_2, there is left an energy (neglecting leakage of charge from the antenna and generator)

$$U_2 = \frac{1}{2} (C_c+C_a) V_2^2 \tag{27}$$

where the antenna capacitance is given by

$$C_a \simeq \frac{t_a}{Z_a} \tag{28}$$

Due to fringing fields at the top of the cone and to additional structures on top of the cone for waveform shaping, C_a is actually larger than the value from equation (28) which is used for these calculations.

Since charge is conserved on the generator-antenna combination in this configuration, then

$$C_c V_1 = (C_c+C_a) V_2 \tag{29}$$

The ratio of the two energies is now

$$\frac{U_2}{U_1} = \frac{C_c+C_a}{C_c} \frac{V_2^2}{V_1^2} = \frac{V_2}{V_1} = \frac{C_c}{C_c+C_a} \tag{30}$$

Assuming the difference of the two energies is all radiated from the antenna, this gives a maximum efficiency

$$\eta_1 = 1 - \frac{U_2}{U_1} = \frac{C_a}{C_c + C_a} \tag{31}$$

With matched generator and antenna pulse impedances, permittivities, and permeabilities we have

$$\eta_1 = \frac{t_a}{t_\ell + t_a} = [1 + \frac{\ell}{a}]^{-1} = [1 + \frac{D}{2}]^{-1} \tag{32}$$

In this last form the maximum efficiency is related to the normalized pulse width, D, showing that one can increase η_1 by decreasing D.

Second, consider a minimum efficiency, η_o, based on the fraction of the energy stored in the generator which is radiated in the initial pulse before any reflections are mixed in, as observed at $r \gg a$. This is illustrated in figure 5 which shows part of the initial pulse with no reflections mixed in it (at large r). Consider then a square pulse of voltage, V_o, current, I_o, and pulse width, t_d. The power in this pulse is

$$P_o = V_o I_o = \frac{V_o^2}{Z_a} \tag{33}$$

and the total energy is

$$U_o = P_o t_d = \frac{V_o^2}{Z_a} t_d \tag{34}$$

Using the distribution function of equation (9), a voltage, V, as a function of θ can be considered as

$$V = V_o f_V(\theta) \tag{35}$$

Then for this TEM wave the power between angles θ and $\frac{\pi}{2}$ is

$$P_3 = V_o f_V I_o = \frac{V_o^2}{Z_a} f_V \tag{36}$$

This last point can be seen by constructing another cone at angle, θ, and considering the power on each of the two conical transmission lines separately. The power per unit angle is then

$$p_3 = -\frac{\partial P_3}{\partial \theta} = -\frac{V_o^2}{Z_a}\frac{\partial f_V}{\partial \theta} = \frac{V_o^2}{Z_a} f_E \tag{37}$$

Finally, we have an energy per unit angle, θ, and per unit radius, r, in the initial pulse as

$$u_o = \frac{p_3}{c} = \frac{1}{c}\frac{V_o^2}{Z_a} f_E \tag{38}$$

The minimum efficiency, η_o, as we have defined it, is the ratio of the energy in the initial pulse before reflections are mixed in it, at large r, to the total energy, or equivalently one minus the ratio of the energy in that part of the initial pulse which has reflections mixed in it, at large r, to the total energy. Taking the latter approach gives

$$\eta_o = 1 - \frac{1}{U_o}\int_{\theta_o}^{\theta_1} (d-b)u_o d\theta \tag{39}$$

The factor, d-b, is the radial extent of the initial pulse for which reflections are mixed in for large r; θ_1 is the largest θ for which this factor applies. Substituting for u_o and U_o gives

$$\eta_o = 1 - \int_{\theta_o}^{\theta_1} (1-\frac{B}{D})f_E d\theta \tag{40}$$

Expand B as

$$\begin{aligned} B &= 1 - \cos(\theta-\theta_o) \\ &= 1 - \cos(\theta)\cos(\theta_o)-\sin(\theta)\sin(\theta_o) \end{aligned} \tag{41}$$

Substituting into equation (40) then gives

$$\begin{aligned} \eta_o = 1 + \frac{1-D}{D}\int_{\theta_o}^{\theta_1} f_E d\theta - \frac{\sin(\theta_o)}{D}\int_{\theta_o}^{\theta_1} \sin(\theta)f_E d\theta \\ - \frac{\cos(\theta_o)}{D}\int_{\theta_o}^{\theta_1} \cos(\theta)f_E d\theta \end{aligned} \tag{42}$$

Substituting for f_E from equations (11) and (12) the three integrals are

$$\int_{\theta_o}^{\theta_1} f_E d\theta = - f_V\Big|_{\theta_o}^{\theta_1} = 1-f_V(\theta_1) = 1 - \frac{\ln[\cot\left(\frac{\theta_1}{2}\right)]}{\ln[\cot\left(\frac{\theta_o}{2}\right)]} \tag{43}$$

$$\int_{\theta_o}^{\theta_1} \sin(\theta)f_E d\theta = \frac{\theta_1 - \theta_o}{\ln[\cot\left(\frac{\theta_o}{2}\right)]} \tag{44}$$

and

$$\int_{\theta_o}^{\theta_1} \cos(\theta)f_E d\theta = \frac{1}{\ln[\cot\left(\frac{\theta_o}{2}\right)]}\int_{\theta_o}^{\theta_1} \cot(\theta)d\theta = \frac{\ln\left[\frac{\sin(\theta_1)}{\sin(\theta_o)}\right]}{\ln\left[\cot\left(\frac{\theta_o}{2}\right)\right]} \tag{45}$$

Thus the minimum efficiency is

$$\eta_o = 1 + \frac{1-D}{D}\left\{1 - \frac{\ln[\cot\left(\frac{\theta_1}{2}\right)]}{\ln[\cot\left(\frac{\theta_o}{2}\right)]}\right\} - \frac{\sin(\theta_o)}{D}\frac{\theta_1 - \theta_o}{\ln[\cot\left(\frac{\theta_o}{2}\right)]}$$

$$- \frac{\cos(\theta_o)}{D}\frac{\ln\left[\frac{\sin(\theta_1)}{\sin(\theta_o)}\right]}{\ln[\cot\left(\frac{\theta_o}{2}\right)]}$$

$$= 1 - \left\{D\ln[\cot\left(\frac{\theta_o}{2}\right)]\right\}^{-1}\left\{(D-1)\ln\left[\frac{\cot\left(\frac{\theta_o}{2}\right)}{\cot\left(\frac{\theta_1}{2}\right)}\right] + \sin(\theta_o)[\theta_1 - \theta_o] + \cos(\theta_o)\ln\left[\frac{\sin(\theta_1)}{\sin(\theta_o)}\right]\right\} \tag{46}$$

where θ_1 can be replaced in terms of θ_o and D from equation (24).

This minimum efficiency, η_o, is plotted in figure 6 versus D for various values of θ_o. Note that η_o is increased by decreasing D. For comparison η_1 from equation (32) is also included on this graph. In figure 7, η_o is plotted versus θ_o for various values of D. Note that η_o has a maximum value for a fixed D at some intermediate θ_o. This maximum value, $\eta_{o_{max}}$, and the corresponding value of θ_o are plotted versus the normalized pulse width, D, in figure 8. To achieve a large value of $\eta_{o_{max}}$ one can see that it is necessary to make the slant height, a, of the cone rather large compared to the spatial pulse width, d.

V. Summary

A circular conical antenna can then radiate, at least initially, a pulse which is a faithful reproduction of the pulse applied to the antenna. For better results the pulse width in space should be small compared to the slant height of the cone. Perhaps the performance of such a simulator can be improved by adding an appropriate cap to the antenna to increase the antenna capacitance and to minimize the adverse effects of the reflection of the pulse at the top of the cone. There are limitations on the simulator performance in that r times the complete time integral of the radiated waveform must go to zero in the limit of large r. For convenience in the calculations we have taken a cone which is symmetric about the vertical axis. Actually, other types of conical structures might be used in an attempt to optimize various aspects of the radiated waveform. One might desire a different orientation for the radiated fields; one might try to optimize the waveform radiated in a particular direction at the expense of the waveforms in other directions.

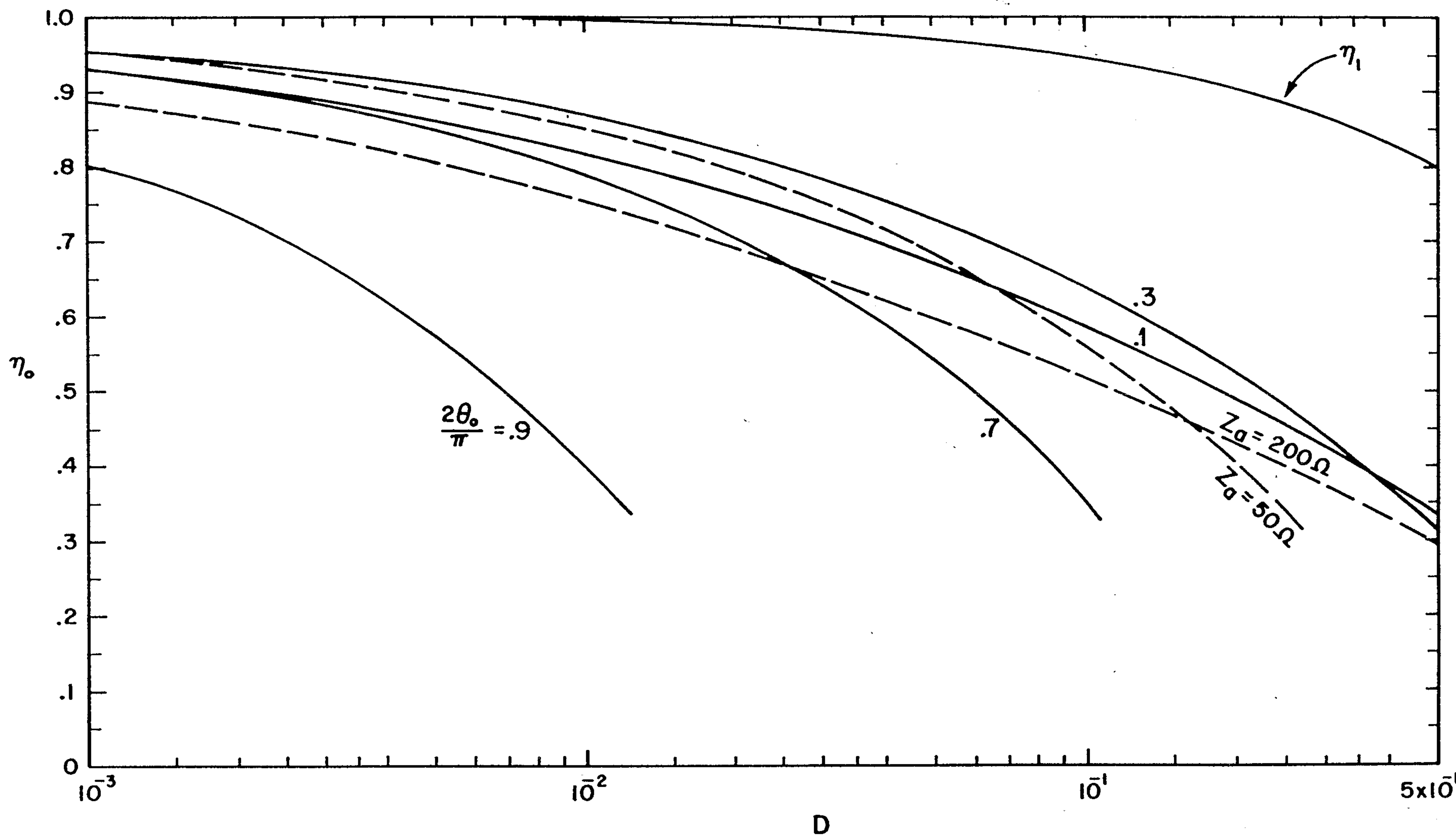

Figure 6. EFFICIENCIES FOR CIRCULAR CONICAL ANTENNA SIMULATOR

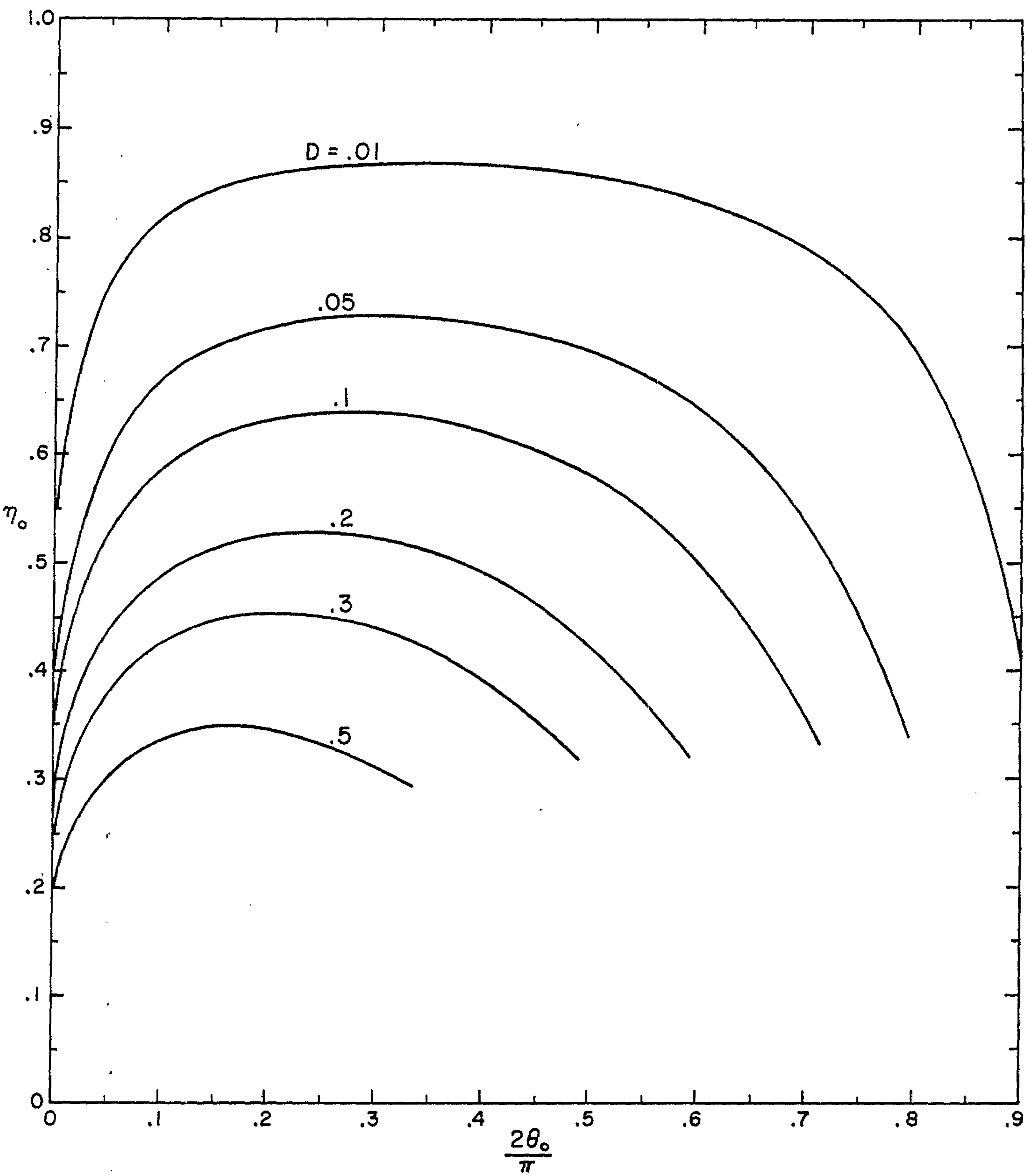

Figure 7. MINIMUM EFFICIENCY FOR CIRCULAR CONICAL ANTENNA SIMULATOR

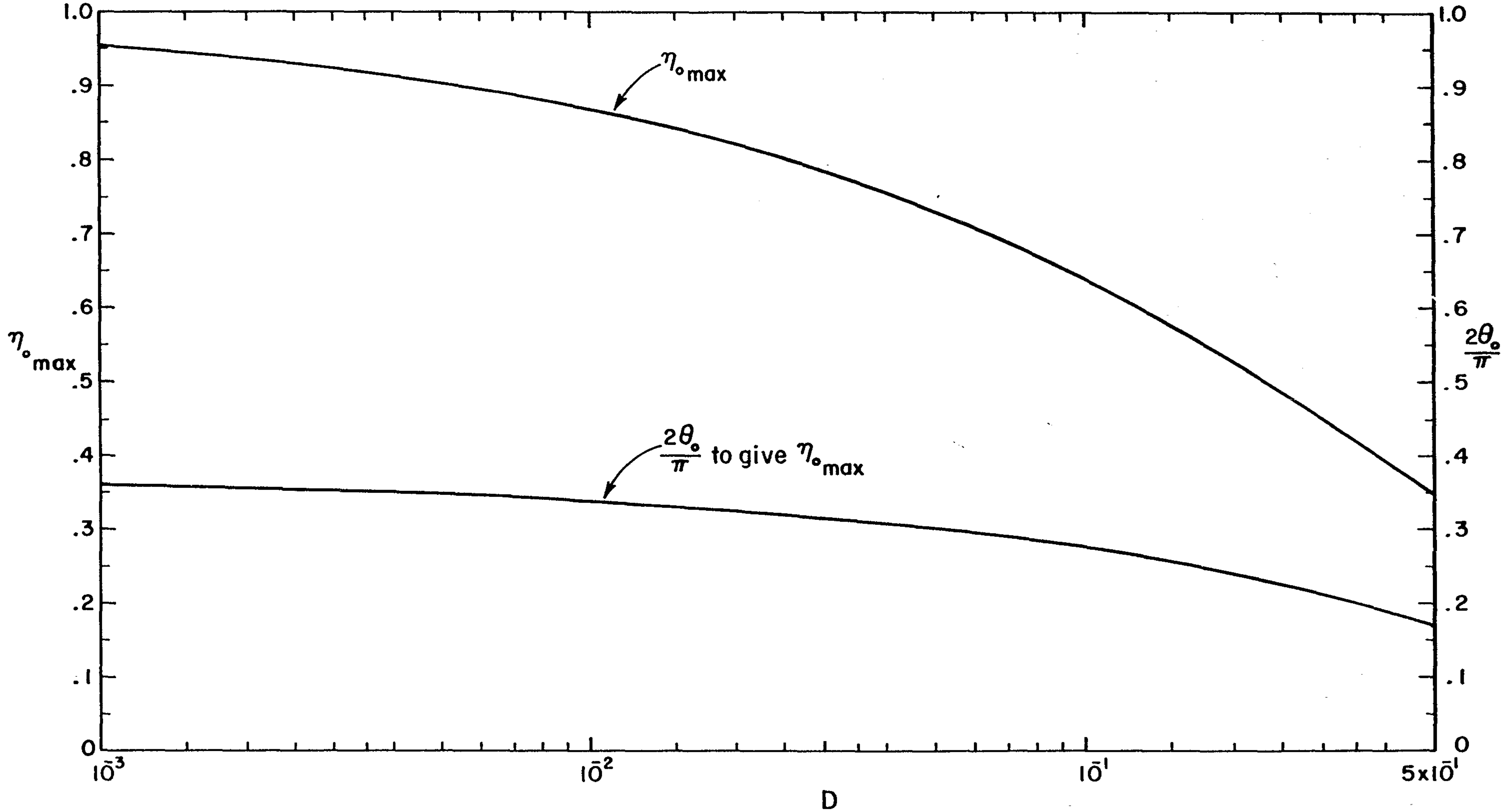

Figure 8. OPTIMUM PARAMETERS FOR CIRCULAR CONICAL ANTENNA SIMULATOR BASED ON MINIMUM EFFICIENCY

As mentioned in the beginning, one motivation for this type of a simulator for the nuclear electromagnetic pulse is to be able to radiate a fast, large-amplitude pulse at a system which is in operation in flight. An interesting question might be how large a pulse one might be able to achieve. Take around 10 MV (into the antenna) for the rough capabilities for the energy sources for the upcoming super flash X-ray machines. Choose a θ_o of about $.15\pi$ and a D of about .1 for an assumed pulse width from the generator of about 70 ns. The slant height of the cone is then about 210 meters. (This could present significant mechanical problems.) Letting f_E be roughly one for some θ of interest, we can estimate the magnitude of the electric field versus r. At 100 meters we have about 10^5 volts/meter, at 1 kilometer about 10^4 volts/meter, and at 10 kilometers about 10^3 volts/meter. These numbers can, of course, be scaled to other generator voltages.

Various practical problems, such as voltage breakdown on the antenna, will have to be considered for a real simulator. Before one builds such a large structure (as indicated by the above numbers) it may be advisable to measure the electrical response on an electrical scale model. This would also permit an empirical evaluation of the full characteristics of the radiated waveform, including the effects of adding various cap configurations to the top of the cone.

We would like to thank Mr. John N. Wood and A1C Anthony Regal for the numerical calculations and the resulting graphs.