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THE FEASIBILITY OF A PASSIVE ELECTROSTATIC FUZE FOR ANTIMISSILE MISSILES (S)

TN3-9109
DA506-01-010
DOFL Proj 22421

28 February 1958

TR-579
38 pages
Copy No. 33

by

Philip Krupen

FOR THE COMMANDER:

P. E. Landis
Acting Chief, Laboratory 20

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DIAMOND ORDNANCE FUZE LABORATORIES
ORDNANCE CORPS • • • DEPARTMENT OF THE ARMY

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ORDNANCE CORPS **WASHINGTON 25, D. C.**

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ABSTRACT

The small permissible error in the instant of detonation of an antimissile missile imposes a stringent accuracy requirement on any proximity fuze proposed for this application. A study was made that indicates a passive electrostatic fuze would be feasible for the purpose. Proper operation of such a fuze depends on the target's being electrically charged and is independent of the angle or speed of closing between the two missiles. Computations were made which show that functioning would occur at about the point of closest approach even for miss distances greater than 1000 ft. Although available evidence indicates that ballistic missiles are highly charged, it is recommended that a substantiating investigation be undertaken prior to any electrostatic fuze program. Subsequent design and construction of an electrostatic fuze is expected to be relatively simple. (S)

1. INTRODUCTION

The destruction of an ICBM or IRBM by means of an antimissile missile(AMM) involves the problems of early detection of the enemy missile, rapid calculation of its trajectory, associated selection of an intercept trajectory for the antimissile missile, reliable launching and guidance of its flight, and finally precise detonation of its warhead to defeat the enemy mission. The feasibility of a passive electrostatic fuze (PEF) for initiating the detonation at the proper time was studied.

Proper operation of the proposed electrostatic fuze would be independent of the approach aspect and closing velocity between the attacking and target missiles. Since it would not be necessary to gather and store information over an extended period of time prior to operation, this fuze could be simple, small, and light. It need not be integrated with the guidance and control systems of the antimissile missile, which should further reduce the complexity of the over-all systems; however, the arming signal could be supplied by the ground AMM control system.

It is expected that missile encounters will occur at altitudes above 100,000 ft so that free-space conditions will prevail. The AMM will probably contain a nuclear warhead with an omnidirectional blast pattern and a large effective range, on the order of 1000 ft. Since the flight control system will have to bring the AMM within this effective range before the PEF operates, the optimum location for operation will be near the point of closest approach (PCA). It will be shown that the electrostatic fuze will not only indicate the PCA but will also anticipate its occurrence.

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2. DESCRIPTION OF SYSTEM

2.1 General Principles

The signal for a passive electrostatic fuze is the potential difference developed between two probes on the destroying round when it enters the electrostatic field of its target. Consider, for example, the case of an antimissile missile 10 ft long and 1 1/2 ft in diameter constructed so as to create two probes, one 3 1/2 ft long and the other 6 1/2 ft long (Figure 1). As such a missile approaches a charged ICBM, a large voltage is developed between the probes. Figure 2 shows qualitatively how this signal will vary with time for six different conditions of encounter. Detailed characteristics of the signal depend on the actual velocities and the separation distances and will be calculated below for the first two cases.

In Figure 2, it can be seen that the signal increases when the AMM starts approaching the ICBM. In cases A, C, and E, where impact occurs, the slope of the signal is always positive. In the three passing cases (B, D, and F,) the signal changes from positive during the approach phase to negative during the receding phase. The signal has a negative slope during that period when the two missiles are in closest proximity. The duration of the negative slope corresponds to a small change in the distance between the missiles. The optimum time for operation is therefore at or shortly after the instant of maximum signal. For those rare cases of impact, when no maximum occurs, the fuze would be set to function when the signal level or its rate-of-change reaches a large preset value. The tactical situation usually expected (Case B) is that wherein the antimissile missile encounters the missile on a course which is essentially head-on but not colliding. In this case, the warhead should detonate so that its blast and fragments would stream into the nose of the oncoming missile. If the approach aspect is essentially perpendicular (Case D, another rare case), detonation of the warhead should occur at the point of closest approach. In the case of an antimissile missile overtaking the target missile (Case F, which will probably never arise), the warhead would detonate as the antimissile missile approaches close to the target so that the blast would overtake the missile. Practically all tactical situations are expected to fall between those illustrated by Cases B and D, so the optimum time for operation of the fuze coincides with the short negative slope of the signal.

2.2 Charge Considerations

The polarity, magnitude, and rate-of change of the electrostatic fuze signal depend on several factors, which include the charge on the ICBM, the size and shape of the fuze probes, and the closing velocity, angle, and range between the missiles. The major unknown factor is the magnitude of the electric charge on a target missile. Polarity is not critical because a fuze may be designed to respond to both positive and negative charge.

Evidence exists which indicates that missiles are charged considerably, although further investigation should be made before an electrostatic fuze program is undertaken. Walter Dornberger, formerly commanding Officer of the Peenemunde Rocket Research Institute, reported that electrostatic charging was suspected to occur on the missiles flown there.[1] T. R. Burnight and J. F. Clark of the Naval Research Laboratory said (in private discussion) that a field strength of 10,000 v/m has been measured at the midpoint of an Aerobee rocket, which corresponded to a rocket potential of about 25,000 volts. C. G. Stergis and his co-workers reported that their stratosphere ballon may have carried an electrostatic charge which affected their instruments even though the instruments were suspended several hundred feet below the balloon.[2] Tests recently completed by DOFL also indicate that aircraft and rockets are normally charged to high potentials. Preliminary results indicate that the following charges and potentials exist:

B-26 Bomber (Propeller): 0.5 microcoulombs, 1050 volts
F-86 Fighter (Jet): 186 microcoulombs, 744,000 volts
Rocket (HVAR): 0.46 microcoulombs, 9000 volts.

Such data indicate not only that these airborne bodies should make excellent electrostatic targets but also that high-altitude missiles may be similarly carrying a charge during their 30-minute life.

2.3 Signal Characteristics

Calculations were made to determine the characteristics of the PEF signal for the two encounters corresponding to A and B of Figure 2.

---

1. All References listed on page 13.

Consider first the tactical situation illustrated in Figure 1 with $\theta = 0$, for which the missiles are going to collide head-on. The equation for the PEF signal is

$$V = -\frac{QG}{2\beta^2 \gamma C}\left(\frac{1}{p^2} - \frac{1}{p} - e^{p} P\right) \tag{1}$$

where
V = PEF signal, volts
Q = electric charge on the target ICBM, coulombs
G = geometric factor determined by the length and diameter of the AMM and the length of its probe, ft^2
γ = another geometric factor determined by the length and diameter of the AMM, dimensionless
C = Capacitance between the probes, farads
p = h/β
h = distance between the missiles, ft
β = vRC, ft
v = closing velocity between the missiles, ft/sec
R = resistance between the probes, ohms
P = $\int_{\infty}^{p} \frac{e^{-u}}{u}\, du$ (exponential integral, tabulated in Reference 3)
u = variable of integration.

The basis for Equation 1 was derived for an active electrostatic fuze in Reference 4 and experimental verification was given in Reference 5. A derivation of the equation for the passive electrostatic fuze is given in Appendix A, page 27. The equation shows that the signal V increases as the length-to-diameter ratio a/b increases. The signal also varies with the probe size ratio c/a and is a maximum at c=a.

In order to compute the signal V as a function of the separation distance h, the following assumptions were made:

Q = - 30 microcoulombs
R = 10,000 megohms
C = 30 μμf
v = 25,000 ft/sec.

The values of R and C were selected on the basis of previous experience with electrostatic fuzes. The values of Q and v were selected as being reasonable. (The Q value represents a potential of about 175,000 volts on a 10-ft sphere.) With other factors constant, V is directly proportional to Q and is not affected appreciably by v as long as the product vRC is appreciably larger than the effective range of the warhead. In this example, vRC = 7500 ft.

The geometric factors G and γ were computed for and ellipsoid from the AMM dimensions given in Figure 1, so that

$$a = 5.0 \text{ ft (semimajor axis)}$$
$$b = 0.75 \text{ ft (semiminor axis)}$$
$$c = 3.5 \text{ ft (probe length)}$$
$$f = \sqrt{a^2 - b^2} = 4.94 \text{ ft}$$

$$m = f/a = 0.989$$
$$G = m^3 c\,(2a-c) = 21.99 \text{ ft}^2$$
$$\gamma = \ln \frac{1+m}{1-m} - 2m = 3.19$$

The PEF signals computed from Equation 1 for different values of h are given in Table 1 and shown graphically in Figure 3 (collision trajectory). It can be seen that the signal increases more rapidly than $1/h^2$ as the separation between the missiles decreases. The magnitude of the signal is 1 volt at a separation of about 1700 ft and approaches 100,000 volts on impact. The rate of rise of the signal, shown in Figure 4, follows approximately a $1/h^3$ law in the range indicated.

The size and shape of the ICBM are immaterial since it may be considered as a point source of charge for the distances under consideration. The centroid of the electric charge on the ICBM is the origin of the electrostatic field that influences the fuze. The larger the ICBM, the larger is its capacitance and the larger is the quantity of electric charge it can maintain for a given potential.

Let us now consider the case in which the AMM misses the ICBM by 1000 ft (Figure 2, Case B). Equation 1 must be modified to introduce the effect of the angle θ between the trajectory of the AMM and a line drawn from the AMM to the ICBM (Figure 1). β is replaced by $\beta \cos\theta$, since the effective closing velocity is now $v \cos\theta$. In addition, the signal V is reduced by a factor of $\cos\theta$ because the effective component of the electrostatic field is that which is parallel to the axis of the AMM. The substitutions yield

$$V = -\frac{QG}{2\beta^2 rC\cos\theta}\left(\frac{1}{p_1^2} - \frac{1}{p_1} - e^{p_1 P}\right) \qquad (2)$$

where $p_1 = h/\beta\cos\theta$.

The PEF signal was computed from Equation 2 for a trajectory with a miss-distance of 1000 ft and with all the other factors unchanged from the collision trajectory. The results are shown in Table 2 and in Figure 3. The PEF signal reaches a maximum value of 1090 mv at a separation distance of 1240 ft. (The look-forward angle θ is 54° at this range, for which vRC cosθ = 4400 ft.) The signal then drops very rapidly toward zero at the PCA, after which the polarity reverses. Thus, the distance between the two missiles varies from 1240 ft to 1000 ft while the signal changes from its peak value to zero. The rate of change of the signal is given in Table 2 and in Figure 4. The AMM warhead can be detonated at the peak value of the PEF signal or shortly thereafter so that the resulting blast envelops the oncoming ICBM.

3. INTERFERENCE CONSIDERATIONS

It has been shown that the PEF signal should be large, over 80 mv, for ranges up to a mile from the target and for the assumed value of charge on the target. The signal, which should not be altered significantly by other reasonable choices of the attack parameters, size of the antimissile missile, or magnitude of the fuze parameters, will now be compared with possible unwanted signals from various sources.

One source of interference is microphonic noise. This includes the thermal and vibration noise from the tube elements, electronic components, and power supply. Considerable past experience with proximity fuzes indicates that it should be possible to maintain such microphonic noise amplitudes below 10 mv, which is far below that of the expected PEF signal.

The excellent CCM capability of electrostatic fuzes has been demonstrated repeatedly. Three organizations, Airborne Instruments Laboratory, Norden-Ketay Corporation, and Melpar, Inc have had contracts with the Signal Corps for the development of suitable countermeasures against electrostatic fuzes. Each company suggested a v variant of the same basic technique - create a false target far enough ahead of the real target to cause the electrostatic fuze to operate prematurely. [6,7,8] The tactical difficulty of such a procedure in connection with missiles presents an enormous problem.

Little can be said about the possible effects of atmospheric noise sources because of the lack of sufficient data on high-altitude conditions. No interference is expected from rain or clouds because they are practically nonexistent at altitudes over 50,000 ft. Concentrations of electric charge that might act as false targets would have to be comparable with that assumed to be on the ICBM and are highly improbable. For example, if the enemy missile is assumed to be a sphere 10 ft in diameter, a charge of 30 microcoulombs t... uniformly distributed throughout the volume of the sphere corresponds to a uniform charge density of 0.8×10^{-9} coul/cc. (Of course, the charge is actually distributed on the surface of the body.) The maximum free charge densities for the ionosphere layers are as follows: [9]

Ionosphere Layer	Altitude (Km)	Maximum Electron Density electrons/cc	coul/cc
E	100	1.5×10^{5}	2.4×10^{-14}
F_1	200	2.5×10^{5}	4.0×10^{-14}
F_2	300	1.5×10^{6}	2.4×10^{-13}

The largest of these densities is some 30,000 times less than the assumed charge concentration on the ICBM. It will still be necessary to determine whether the ionosphere could interfere with the operation of the fuze, despite this much lower charge density.

Nothing significant is expected to happen to the PEF signal when the antimissile missile is itself charged, even to the same potential as the ICBM. The passive fuze would then be subjected to an additional signal equivalent to that caused by an active electrostatic fuze, which may be additive or subtractive, depending on the relative polarities of the charges on each missile. In any case, since the electrostatic image of the AMM in the ICBM is very weak, and the image is located at twice the distance to the target (reducing its intensity by a factor of 4), the active signal would be orders of magnitude smaller than the passive signal and so would be insignificant.

A passive electrostatic fuze may conceivably be affected by the earth's electrostatic potential gradient. This gradient, obtained from various sources, is as follows:

Altitude (ft)	Potential Gradient (v/cm)
Sea Level	1.30
5,000	0.50
10,000	0.25
15,000	0.13
20,000	0.10
30,000	0.07
50,000	0.06

Data for altitudes over 50,000 ft could not be found. The gradient due to the ICBM at a range of 700 ft is 0.06 v/cm; thus the earth's electric field may be the largest interfering signal. However, it should be recognized that the earth gradient is probably smaller at the altitudes of interest. Since the effect of the earth's field is known and can be easily attenuated, (because it is a steady state or, at most, a slowly varying condition), it should not affect the operation of the fuze.

The possibility has recently been raised that high-altitude missiles create an ionized trail which might affect the electric charge on an ICBM.[10] Furthermore, the AMM may be surrounded by an ion sheath which may conceivably attenuate any electric signals. These factors would have to be investigated. The effects of meteors, cosmic rays, and other extraterrestrial phenomena would also have to be investigated, as with any other fuze system. The associated concentrations of charge are expected to be significantly lower than that of the ICBM. The probability of occurrence must also be considered.

4. FUZE DESIGN

The design and assembly procedures for a passive electrostatic fuze are not materially different from those of other types of proximity fuzes. Details will depend on the limitations imposed by the size, shape, temperature, and other requirements of a particular application. No unusual difficulties are anticipated. Satisfactory electrostatic fuzes have been designed, built, and tested successfully in large quantities on bombs and mortar shells. (11,12) Practically all this work has been done in connection with active proximity fuzes, for which the requirements are far more severe than they are for passive fuzes.

Two basic circuits have been developed for electrostatic fuzes. One requires a single, cold-cathode, gas-discharge tube specially developed to serve as both the detecting and triggering element. Another, more sensitive circuit uses two standard fuze tubes, a pentode and a thyratron, to perform the same functions. Both systems require some care in handling in order to maintain a high input impedance (>1000 megohms). These circuits were developed to meet the difficult requirements associated with the performance of mortar shells: simplicity, low cost, ruggedness, small volume. These requirements should be ameliorated in the antimissile missile application which would permit the development of entirely new and improved circuits.

Two problems associated with previous electrostatic fuzing developments are eliminated entirely in the AMM application. The first is that of charging the round; this feature becomes unnecessary for a passive fuze. The second is that of including precautions so that the round will not malfunction in rain. This feature would no longer be necessary because the missile encounters take place in the upper atmosphere where rain does not occur and also because the AMM does not have to be electrostatically charged.

The power-supply requirements for electrostatic fuzes have always been simple. The power consumed is so low that it may be supplied by a charged capacitor for the one-tube circuit. The two-tube circuit would require the addition of a low-drain A supply, and perhaps a C battery. The total power does not exceed 0.1 watt.

The design of the safety and arming system would be determined by the AMM requirements. The PEF might require that the detonator be kept out-of-line until the AMM altitude exceeds 50,000 ft in order to obviate any malfunctions due to clouds. The fuze circuit could be warming up during this period so that the PEF will be ready to operate any time afterward.

Work may be required in order to design the probes to be compatible with the airframe of the antimissile missile. The construction of the "Explorer" with a Fiberglas insulator at its midsection would be entirely satisfactory. If necessary, the forward probe could be a dummy nose overlapping the rearward probe; there is no need for the insulator to be visible. Any deleterious effect of temperature on the insulating material will also have to be considered. However, this should not be significant inasmuch as atmospheric density decreases with altitude as the speed of the AMM increases, and there is no re-entry problem.

5. CONCLUSION

It appears possible to build a passive electrostatic fuze for an anti-missile missile. Such a fuze would initiate detonation of the warhead at or shortly before the point of closest approach to the enemy missile so that the blast or fireball destroys the target. The fuze would be simple, would perform its function without requiring auxiliary information, and would be immune to any foreseeable sources of malfunction or counter-measures.

Operation of the PEF depends on the target's carrying an electric charge. Although evidence exists which indicates that an ICBM is probably highly charged during its flight, there is no certainty that this is the case. The existence of ionized sheaths about both attacking and defending missiles in another possibility. Accordingly, it is recommended that a measurements program be undertaken immediately to determine the electric charges to be expected on and around long-range missiles.

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TABLE 1. PEF Signal vs Separation Distance for a Collision Trajectory

Separation (ft)	Signal (mv)	Rate-of-Rise (v/sec)
75	607,000	
150	150,000	
225	66,200	9120
300	36,900	5380
375	23,400	3010
450	16,100	1810
525	11,800	1150
600	8,900	790
675	7,000	590
750	5,600	435
900	3,850	241
1050	2,790	121
1200	2,110	92
1350	1,550	60
1500	1,320	34
2250	550	
3000	290	
3750	180	
4500	120	
5250	83	
6000	61	
6750	47	
7500	37	

TABLE 2. PEF Signal vs Separation Distance for a Trajectory with Miss Distance of 1000 ft

Separation (ft)	Signal (mv)	Rate-of-Rise (v/sec)
1000	0	-759
1009	274	
1011	311	-93.3
1015	363	
1019	425	
1023	473	
1027	523	
1033	578	
1041	645	
1053	723	-51.2
1070	821	
1102	942	-25.18
1172	1060	-17.44
1240	1090	0.00
1315	1070	6.17
1540	908	7.44
1919	645	5.50
2384	435	4.03
2803	314	2.46
3202	238	1.72
3606	186	1.22
3994	149	0.88
4379	123	
4771	101	
5148	85	
5935	62	
6687	47	
7561	37	

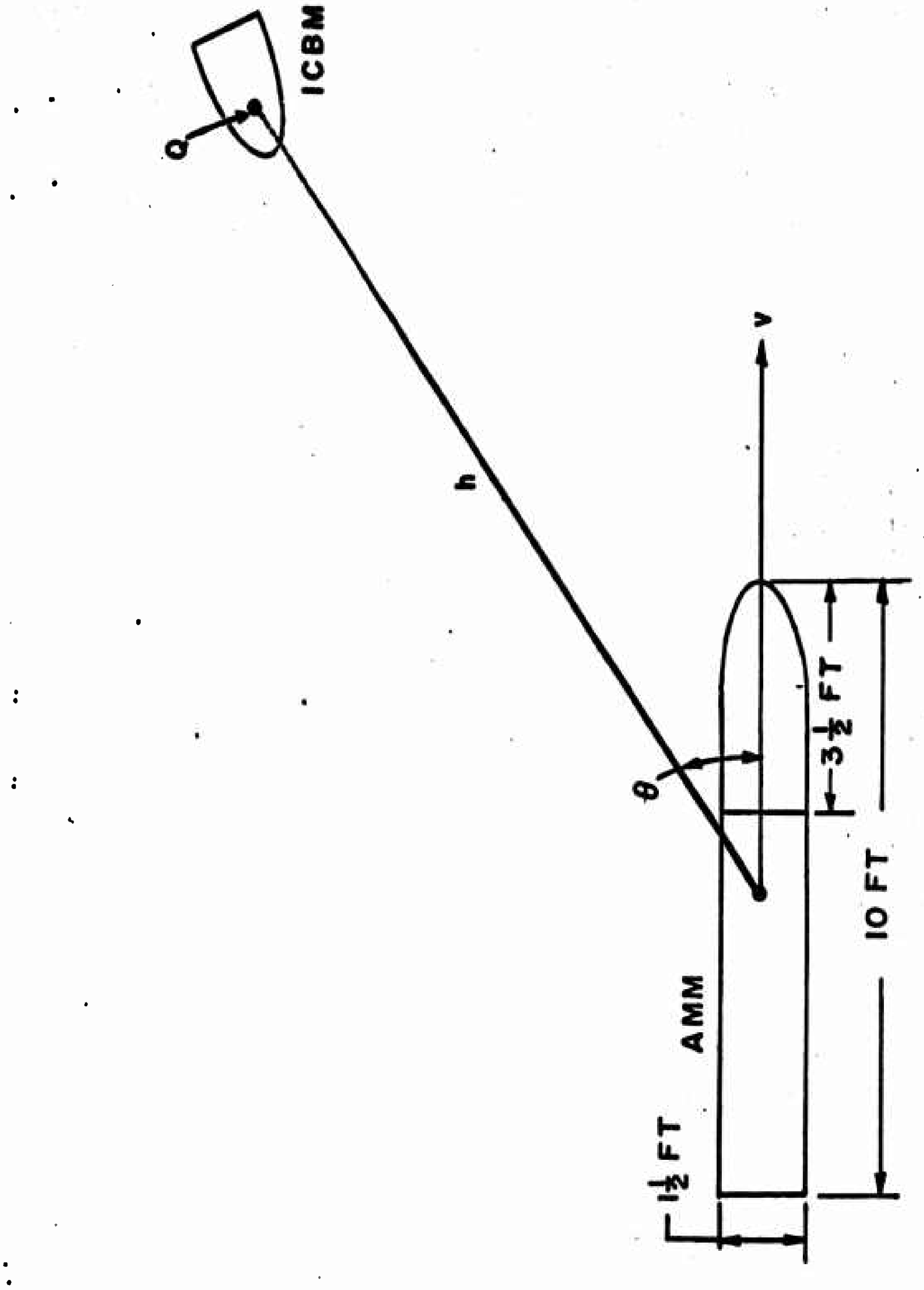


FIGURE 1 — GEOMETRY OF AN ENCOUNTER

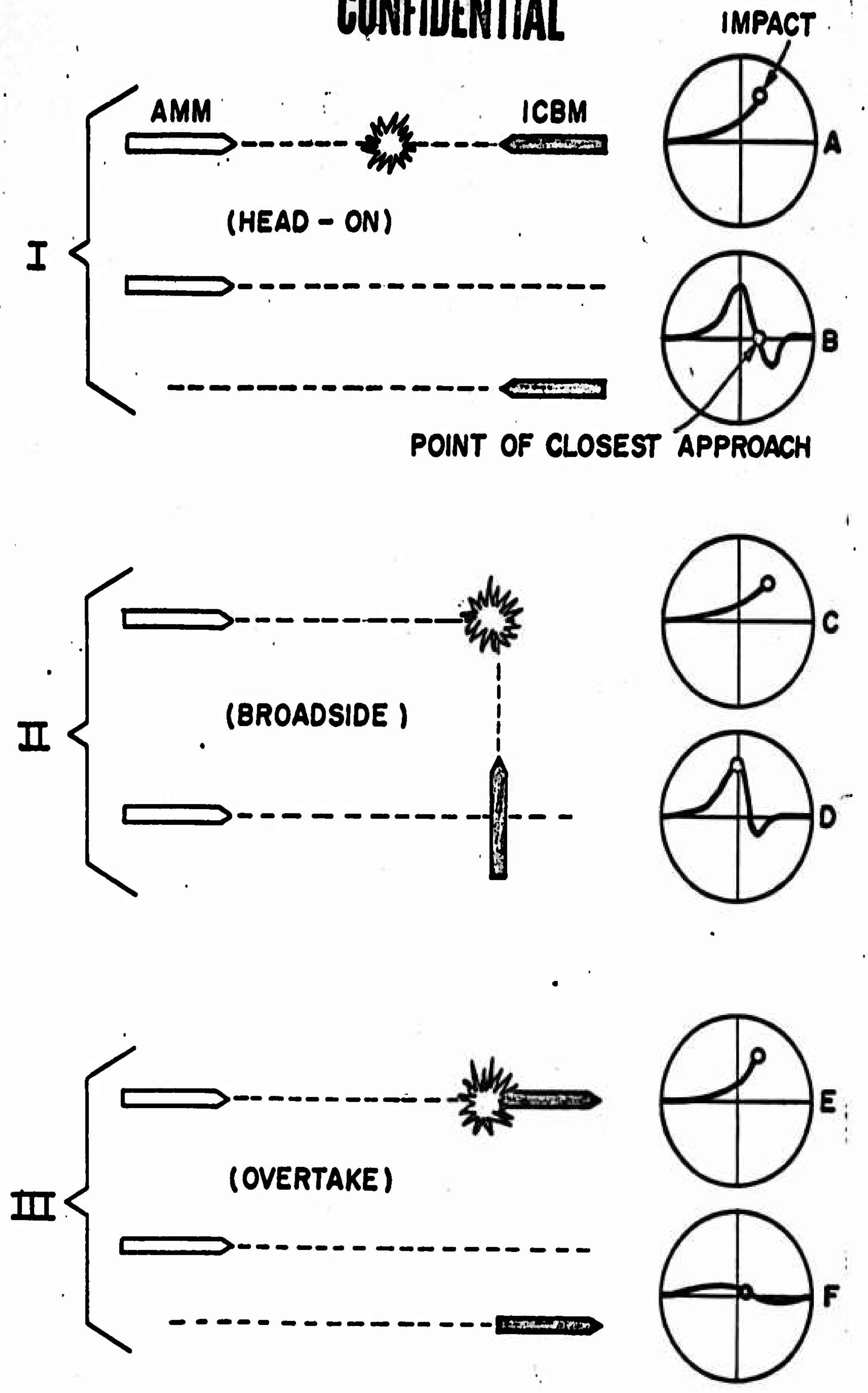


FIGURE 2 - CHARACTERISTICS OF PEF SIGNALS FOR DIFFERENT CONDITIONS OF ENCOUNTER

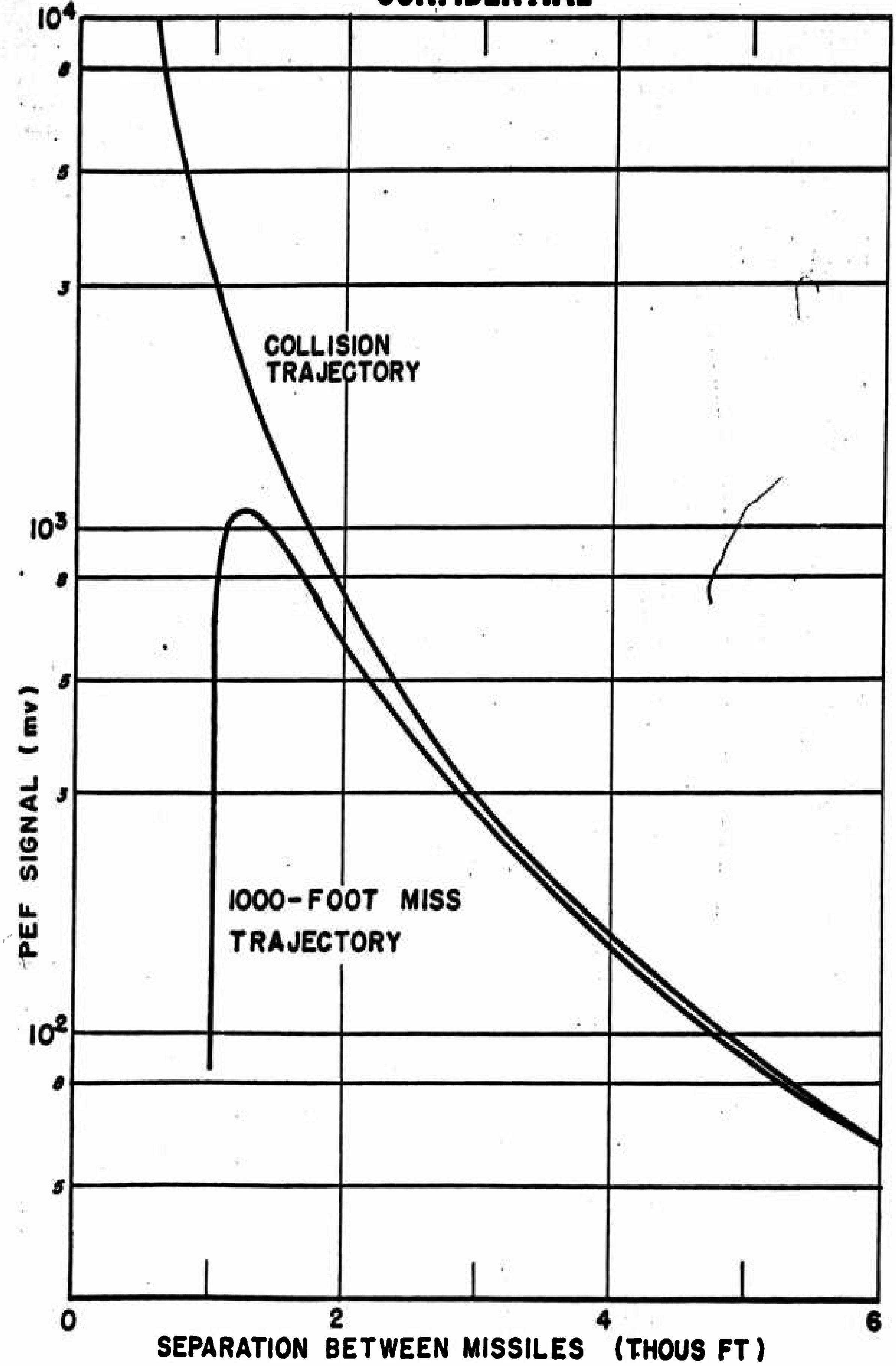


FIGURE 3 - PEF SIGNAL VS DISTANCE

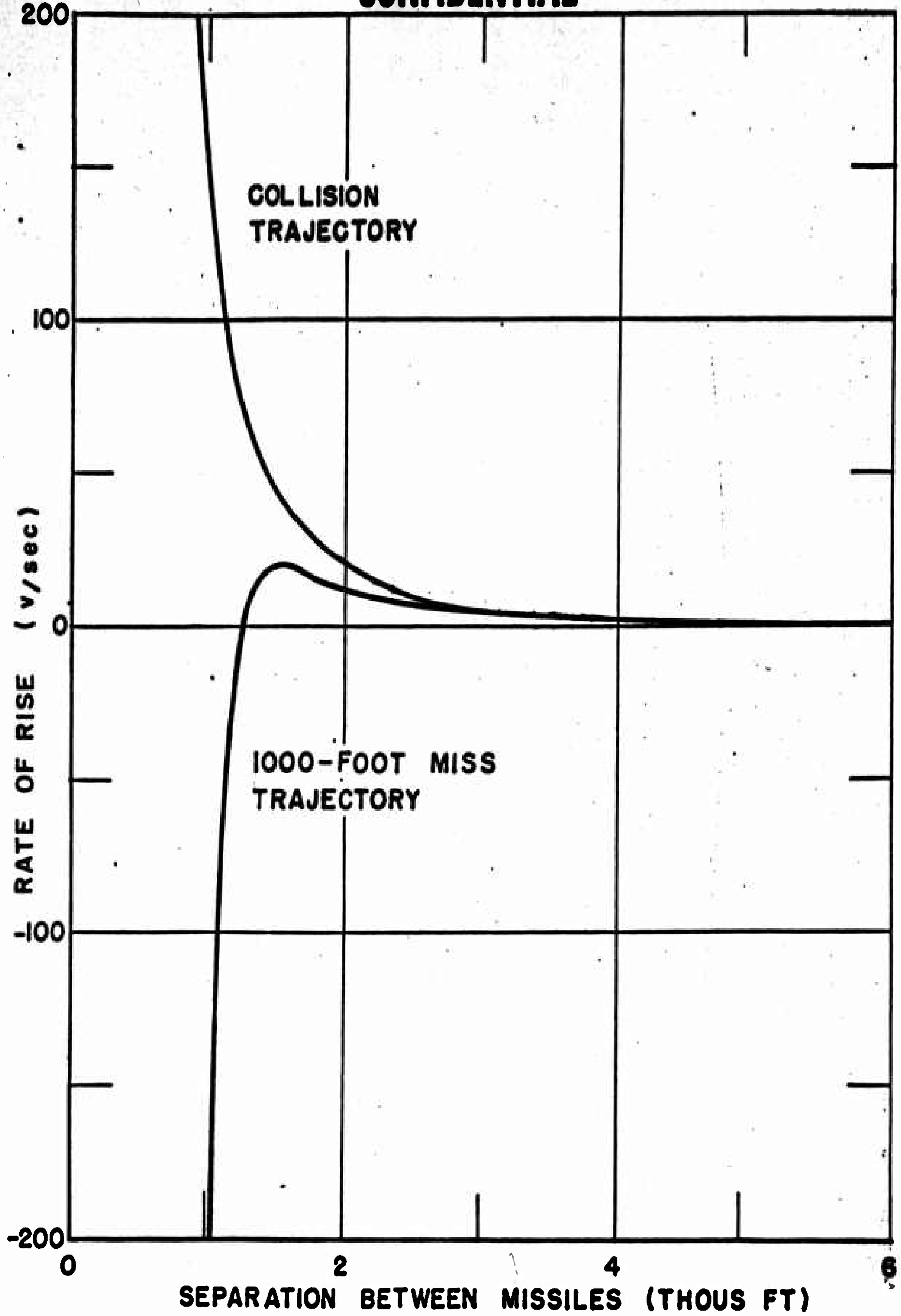


FIGURE 4 - RATE OF CHANGE OF PEF SIGNAL VS DISTANCE.

APPENDIX A

DERIVATION OF EQUATION 1

The equipotential surfaces around a charged conducting ellipsoid of revolution (I, Figure I) in free space are confocal ellipsoids (II, Figure I).[13] The electrostatic field is identical with that which exists around a line charge uniformly distributed between the foci, + f and - f. If the line charge density is

$$\lambda = \frac{Q}{2f} , \qquad \text{(A1)}$$

then the potential of an equipotential surface is

$$\phi_s = \frac{1}{4\pi\epsilon_0} \frac{Q}{2f} \ln \frac{a+f}{a-f} , \qquad \text{(A2)}$$

where Q is the total charge on the body and a is the semimajor axis of the surface. The electrostatic field intensity parallel to the major axis is

$$E_{s_x} = -\frac{\partial \phi_s}{\partial x} = -\frac{Q}{4\pi\epsilon_0} \frac{ax}{a^4 - f^2 x^2} \qquad \text{(A3)}$$

At the tip of the surface, for example, x = a so that

$$E_{s_a} = -\frac{1}{4\pi\epsilon_0} \frac{Q}{a^2 - f^2} . \qquad \text{(A4)}$$

The field configuration surrounding an uncharged ellipsoid subjected to a constant electrostatic field parallel to its major axis can be computed in an analagous manner. The field resulting from the redistribution of charge on the ellipsoid will be assumed to be identical with that of a line charge having a density

$$\lambda = \alpha w \tag{A5}$$

where $-f \leq w \leq +f$ and α is a constant to be determined later. The associated potential field is given by

$$\phi_L = \frac{\alpha x}{4\pi\epsilon_0}\left(\ln\frac{a+f}{a-f} - 2\frac{f}{a}\right) \tag{A6}$$

and the associated field intensity in the x-direction is

$$E_{L_x} = -\frac{\partial \phi_L}{\partial x} = -\frac{\alpha}{4\pi\epsilon_0}\left[\ln\frac{a+f}{a-f} - 2\frac{f}{a}\left(1+\frac{a^2x^2}{a^4-f^2x^2}\right)\right]. \tag{A7}$$

Specifically, when $x = a$,

$$E_{L_a} = -\frac{\alpha}{4\pi\epsilon_0}\left[\ln\frac{a+f}{a-f} - 2\frac{f}{a}\left(1+\frac{a^2}{a^2-f^2}\right)\right]. \tag{A8}$$

The factor α may now be evaluated. The potential ϕ in the vicinity of ellipsoid I is obtained by superposition of three potentials; that due to the free ellipsoid (ϕ_0), that due to the inducing field E, and that due to the induced line charge (ϕ_L). The field E is essentially constant and parallel to the x-axis over the short distance involved so its field is Ex. Therefore,

$$\begin{aligned}\phi &= \phi_0 + Ex - \phi_L \\ &= \phi_0 + \left[E - \frac{\alpha}{4\pi\epsilon_0}\left(\ln\frac{a+f}{a-f} - 2\frac{f}{a}\right)\right] x .\end{aligned} \tag{A9}$$

At the surface of the ellipsoidal object, $a = a_0$ and $\phi = \phi_0$, so the expression within the brackets must vanish, giving

$$\alpha = \frac{4\pi\epsilon_0 E}{\ln\frac{a_0+f}{a_0-f} - 2\frac{f}{a_0}}$$

$$= \frac{4\pi\epsilon_0 E}{\ln\frac{1+m}{1-m} - 2m} = \frac{4\pi\epsilon_0 E}{\gamma} \qquad \text{(A10)}$$

where $m = f/a_0$, the eccentricity of the object

and $\gamma = \ln \frac{1+m}{1-m} - 2m$.

Thus, α is directly proportional to E and the constant of proportionality is $4\pi\epsilon_0/\gamma$, which depends on the eccentricity of the object.

Substituting Equation A10 into Equation A9 gives

$$\phi - \phi_0 = \left(1 - \frac{\ln\frac{a+f}{a-f} - 2\frac{f}{a}}{\gamma}\right) E x \ . \qquad \text{(A11)}$$

The density of the induced charge on the surface of the ellipsoid is

$$\sigma = -\epsilon_0 \frac{\partial(\phi-\phi_0)}{\partial n}\Big|_{a=a_0}$$

$$= -\frac{2\epsilon_0 E f^3 x}{\gamma a_0 b_0 \sqrt{a_0^4 - f^2 x^2}} \ . \qquad \text{(A12)}$$

The charge on an annular ring of width ds and radius y is

$$dq = \sigma \, 2\pi y \, ds$$

$$= \frac{4\pi\epsilon_0 E f^3 x y}{\gamma a_0 b_0 \sqrt{a_0^4 - f^2 x^2}} ds \ . \qquad \text{(A13)}$$

Since
$$ds = dx\sqrt{\frac{a^4 - f^2x^2}{a^4 - a^2x^2}}$$

and
$$\frac{y}{b_0} = \sqrt{1 - \frac{x^2}{a_0^2}},$$

$$dq = -\frac{4\pi\epsilon_0 E f^3 x}{\gamma a_0^3}dx \quad . \qquad \text{(A14)}$$

The charge accumulated on one side of an imaginary plane perpendicular to the major axis and at a distance c from the positive end is

$$Q_1 = \int_{a_0-c}^{a_0} dq = -\frac{4\pi\epsilon_0 E f^3}{\gamma a_0^3}\int_{a_0-c}^{a_0} x\,dx$$

$$= -\frac{2\pi\epsilon_0 E f^3}{\gamma a_0^3}\,c\,(2a_0 - c)$$

$$= -\frac{2\pi\epsilon_0 G E}{\gamma} \qquad \text{(A15)}$$

where G = $m^3\,c\,(2a_o - c)$.

The field due to the charge on the target is

$$E = \frac{Q}{4\pi\epsilon_0 h^2} \qquad \text{(A16)}$$

and h = distance between the missiles.

where Q = charge on the ICBM

and h = distance between the missiles.

Hence,

$$Q_1 = -\frac{QG}{2\gamma h^2} \tag{A17}$$

The signal voltage V which builds up between the probes of the anti-missile missile must satisfy the differential equation

$$\frac{dQ_1}{dt} = \frac{V}{R} + C\frac{dV}{dt} \tag{A18}$$

where R = resistance across the gap
C = capacitance across the gap
t = time.

Substituting Equation (A17) into Equation (A18) and re-arranging terms gives

$$\frac{dV}{dt} + \frac{V}{RC} = -\frac{QG}{2\gamma C}\frac{d}{dt}\left(\frac{1}{h^2}\right)$$

$$= \frac{QG}{\gamma C h^3}\frac{dh}{dt} \tag{A19}$$

After multiplying through by the integrating factor e $^{t/RC}$, Equation A19 can be integrated formally.

$$\int_0^\tau \left(\frac{dV}{dt} + \frac{V}{RC}\right)e^{\frac{t}{RC}}dt = \frac{QG}{\gamma C}\int_0^\tau \frac{e^{\frac{t}{RC}}}{h^3}\frac{dh}{dt}dt \tag{A20}$$

where τ = a selected time.
The left side is equal to

$$V_\tau e^{\frac{\tau}{RC}} - V_0 = V_\tau e^{\frac{\tau}{RC}} \quad \text{(A21)}$$

if $V_0 = 0$.

To solve the right side of equation A 20, let

$$h_t = h_0 - vt \quad \text{(A22)}$$

where h_0 = some initially large distance for which $V_0 = 0$
v = velocity of approach, assumed constant.
t = time of flight from position h_0.

Substituting Equations A22 and A21 into Equation A20 gives

$$V_\tau e^{\frac{h_0 - h_\tau}{vRC}} = \frac{QG}{\gamma C} \int_{h_0}^{h_\tau} e^{\frac{h_0 - h}{vRC}} \frac{dh}{h^3} . \quad \text{(A23)}$$

On setting $\beta = vRC$ and $p = h/\beta$,

Equation 23 becomes

$$V_\tau e^{-p_\tau} = \frac{QG}{\beta^2 \gamma C} \int_{p_0}^{p_\tau} e^{-p} \frac{dp}{p^3} . \quad \text{(A24)}$$

Solving for V_τ and allowing $p_0 \to \infty$,

$$V_\tau = \frac{QG}{2\beta^2 \gamma C} \left(-\frac{1}{p_\tau^2} + \frac{1}{p_\tau} + e^{p_\tau} P_\tau \right). \quad \text{(A25)}$$

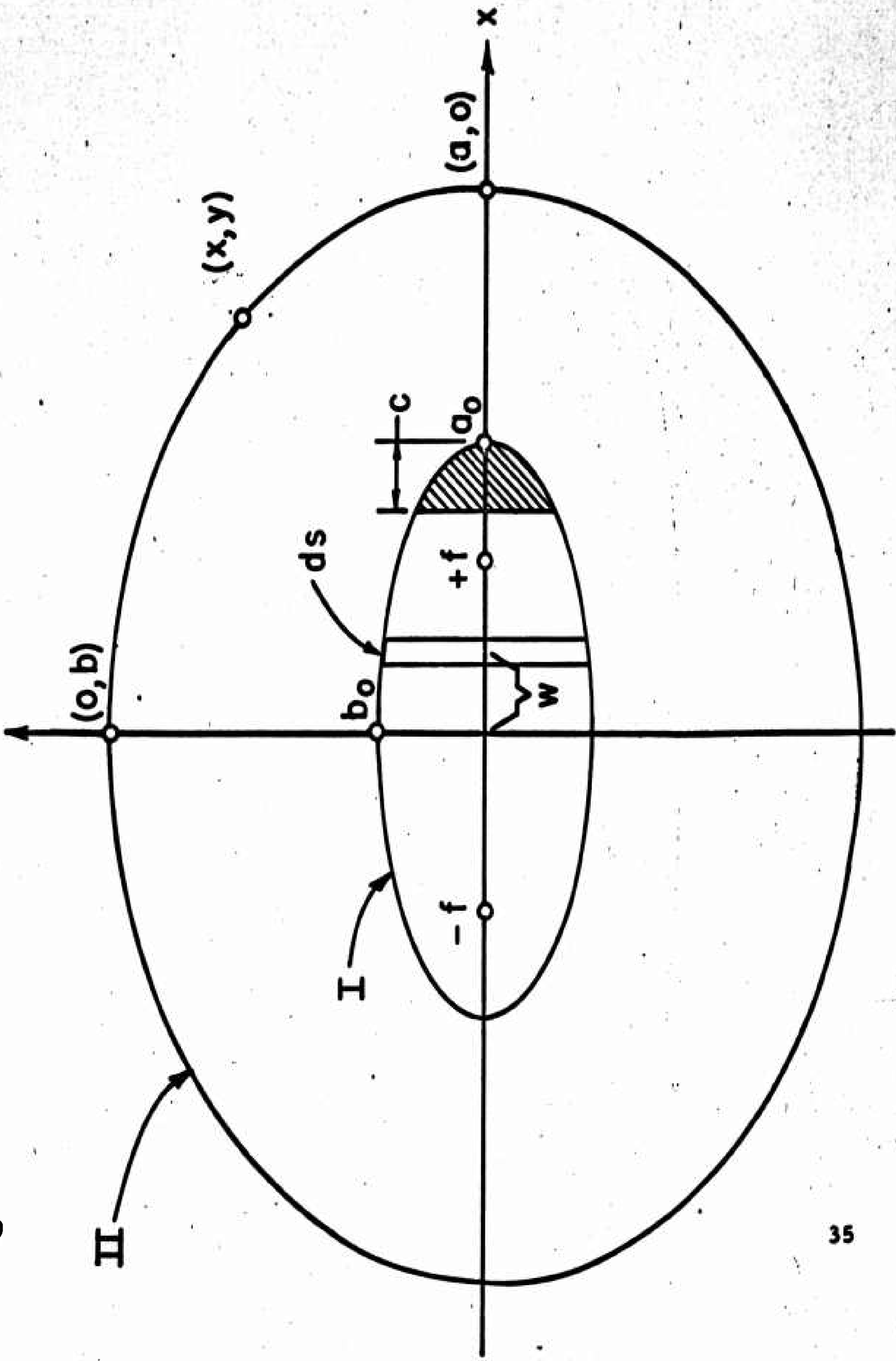
P_τ is an exponential integral defined by

$$P_\tau = \int_\infty^{p_\tau} \frac{e^{-p}}{p}\, dp \quad . \tag{A26}$$

A table of P_τ values may be found in Reference 3.

Dropping the subscript τ yields the equation given in the text of the report:

$$V = -\frac{QG}{2\beta^2 \gamma C}\left(\frac{1}{p^2} - \frac{1}{p} - e^{p} P\right). \tag{1}$$



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