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NEL/REPORT 1381

LOW-FREQUENCY TOP-LOADED ANTENNAS

Electrical properties are presented in a series of curves suitable for use in design; criteria for selection of antenna types are given

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PROBLEM

Determine, using model studies, the electrical properties of top-loaded monopole antennas and the changes in these properties with top-hat configuration. Analyze and interpret the results. Present the results in the form of design curves and illustrate their use.

RESULTS

1. Electrical properties of top-loaded monopole antennas are presented in a series of curves suitable for use by a design engineer.

2. Projected length of the top-hat radials should be 0.7 tower height for optimum bandwidth-efficiency product and 0.8 tower height for optimum power-bandwidth product.

3. In most cases there should be 24 radials in the top-hat anchored at a distance from the base equal to the tower height. Extending the anchor points outward will improve electrical properties when a height limitation exists.

4. Comparison of the top-loaded monopole with other antennas of similar size indicates that only the three-tower triatic antenna has superior characteristics.

RECOMMENDATIONS

1. Accept the top-loaded monopole as the Navy standard for low-frequency use.

2. Prepare structural drawings of a set of standard top-loaded antennas meeting various operational requirements.

3. When height limitations make it difficult to meet bandwidth-efficiency requirements with standard top-loaded antennas, first consider extension of the top-hat radius beyond the mechanical optimum, then consider triatic design; if sufficient bandwidth cannot be obtained by these methods, consider resistive loading, but only after careful review of frequency requirements.

ADMINISTRATIVE INFORMATION

Work was done under SF 006 03 05, Task 7916 (NEL B14561) by members of the Antennas Division from November 1964 through May 1965. The report was approved for publication 22 June 1966.

The authors wish to acknowledge the work of L. L. Whittemore and J. H. Thornton on model construction, measurements, and data analysis and compilation.

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INTRODUCTION

The typical low-frequency antenna consists of a guyed tower supported on an insulated base. Capacitive top-loading is normally used to increase bandwidth or power-handling capability.[1-3] Although numerous model studies have been made on the effects of top-loading, they have usually been limited in scope and directed toward a specific design problem. No generalized study has been available for antenna design with specific bandwidth and/or power-handling characteristics for the 50-to-150-kc/s frequency range. This design study was undertaken to provide this basic information plus additional electrical properties, including the power-bandwidth characteristics. The data are presented in groups of design curves.*

MODEL DESCRIPTION

The test antenna (fig. 1) can be considered an idealized 100-to-1 scale model of a 630-foot top-loaded antenna with tower height/diameter (h/d) ratio of 200/1. The model test frequency of 5 Mc/s corresponds to a full-scale frequency of 50 kc/s. The test results are applicable by use of scaling techniques to towers of any height having the same h/d ratio, provided the physical distance from the tower base to the outer edge of top-hat radials is less than $\lambda/8$.

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*Sets of these curves in larger scale, suitable for field use, are available. Address requests to Commanding Officer and Director, U.S. Navy Electronics Laboratory, San Diego, California 92152, attention Code 3250E.

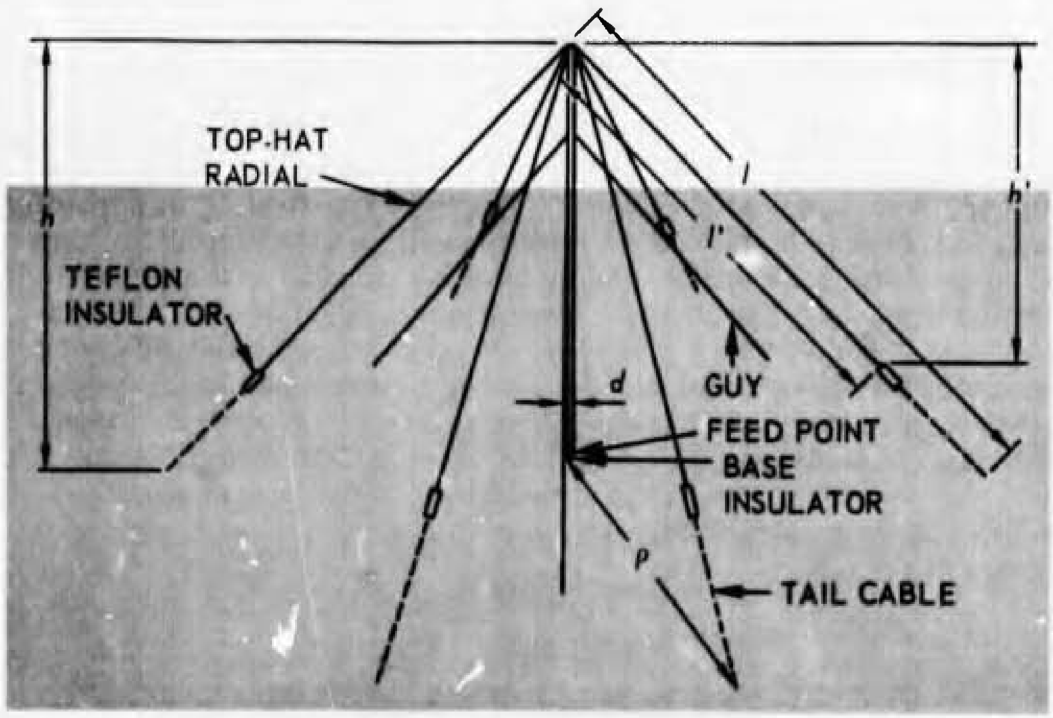

Figure 1. Top-loaded antenna, overall view.

The model was made with a 76-inch length of 3/8-inch OD brass tubing on a ½-inch-long Teflon insulator of slightly greater diameter. Nylon string was used for structural guying. The top-loading wires were 10-mil, number 30, soft drawn copper, and simulated 1-inch radials for the 100-to-1 scale. The model was constructed without sag in the top-hat radials; consequently, in applying results to a full-scale design, a correction has to be introduced. The amount of correction depends on the type of insulators used at the ends of the top-hat radials. For conventional design the effective height is usually lowered by about 4 percent. With the newer fiberglass insulators reduction is about 2 percent. For test purposes the model was placed on a 100-by-160-foot mesh ground plane.

ELECTRICAL PROPERTIES MEASURED

The primary electrical properties measured were the shunt capacitance, resonant frequency, and effective height. Studies were made with 6, 12, and 24 top-hat radials. Each study consisted of four sets of measurements. For each set of measurements ρ the radial distance from the tower base to the radial anchor point was held constant. So that the data could be universally applied, the values of distance ρ were expressed as multiples of tower height h. Four values of ρ — $h/2$, h, $3/2h$, and $2h$ — were selected. For each value of ρ, a set of measurements was obtained by varying the projection of the active portion of the top-hat radials upon the antenna tower. The projection was varied in one-tenth steps from $0.1h$ to $0.9h$. If ℓ is the total length of the top-hat radials, ℓ' the active length, and h' the projection of the active portion on the tower of height h, then, as can be seen from figure 1

$$\ell = (h^2 + \rho^2)^{1/2} \tag{1}$$

$$\ell' = \ell\,(h'/h) \tag{2}$$

The configuration $\rho = h$, and $h'/h = 0.707$ was chosen as typical to determine the approximate effect of tower diameter on the measurements. With 6, 12, and finally 24 radials in the top-hat, the antenna parameters were determined for three different values of tower diameter. For these diameters, h/d was equal to 50, 100, and 200.

MEASUREMENT TECHNIQUES

The primary properties of the top-loaded model antennas were found in terms of the equivalent properties of the center tower of the model. In the case of the static capacitance, the absolute value was measured with a Boontoon model 260-A Q-meter, and the ratio of the capacitance of the top-loaded model antennas to the reference tower was obtained. The ratio of the resonant frequencies was found with a grid dip meter. Each frequency reading was monitored on an electronic counter. The method of coupling the grid dip meter to the antenna being measured introduced an error of constant percentage into the results.

The error was of no concern in determining the relative values, since it canceled out. However, it was also necessary to know the true resonant frequency of the reference tower antenna. This frequency was carefully measured by inducing a voltage into the antenna and determining the frequency for maximum base current. It was found that resonance occurred at $0.956 f_r$, where f_r was the resonant frequency of an infinitely thin antenna of the same height.

The relative effective height was determined by finding the ratio of the field intensity of the top-loaded model antenna to that of the reference tower. A block diagram of the test setup is shown in figure 2. Measurements were made with a constant current at a frequency of 5 Mc/s. The model being measured was always placed at the same point on the ground plane and the field-intensity meter at another fixed point. The effective capacitance of the model antennas being studied varied from about 22 picofarads for the reference tower to over 300 picofarads for some of the top-loaded configurations. The shunt capacitance of the antenna-current meter and its connecting lead was several picofarads. Since a part of the current indicated by the meter was shunted to ground through this capacitance, an error was introduced in the current reading varying from about 1 percent to as much as 12 percent. A small glass capacitor was placed in the antenna-current lead as shown in figure 2 to hold this error constant. The value of the capacitor was varied with each test condition in such a way that the antenna-current meter always looked into 22 picofarads. Under these conditions the shunting error canceled out when ratios were taken.

Daily variations in field intensity were noted, and each data set was completed within a 4-hour period on the same day to avoid these variations. The absolute effective height of the reference antenna was considered to be one-half its physical height.

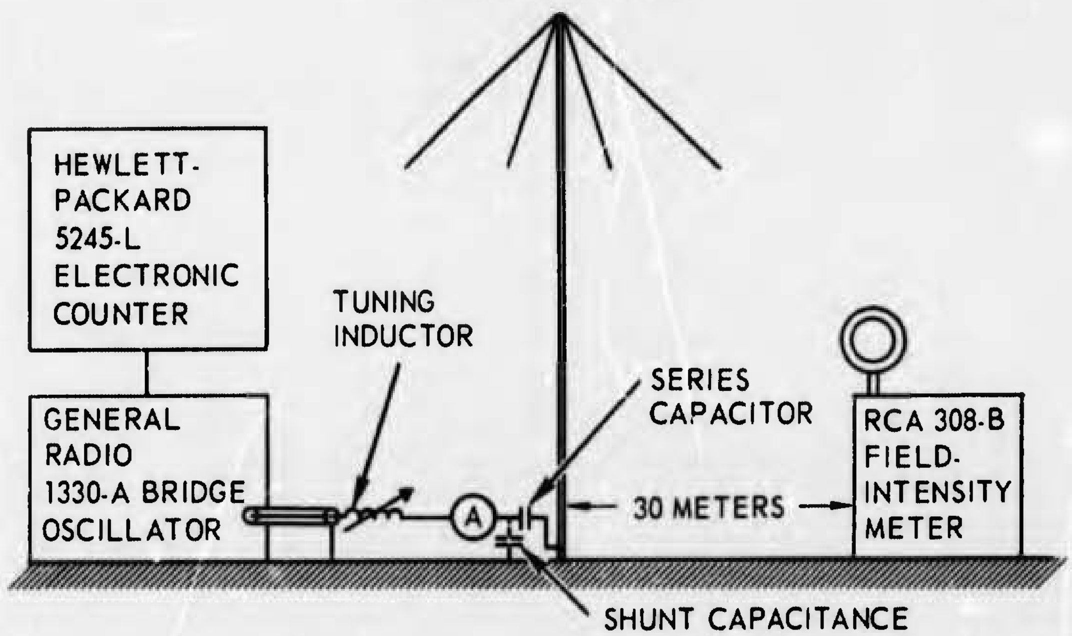

Figure 2. Test equipment for determining antenna characteristics.

DATA ANALYSIS

It is assumed that any antenna designed with the help of this study will be electrically short at its lowest frequency; that is, the electrical distance from the base of the antenna to the end of the top-hat radials will be less than $\lambda/8$. Because of this restriction the effective height of the reference antenna can be considered equal to one-half its physical height, and the effective capacitance of each of the antennas equal to its static capacitance.[4-6] In addition, simple formulas can be used to compute important electrical characteristics not directly determined. The four of particular interest are radiation resistance, antenna system bandwidth-efficiency product, maximum radiated-power capability, and power-bandwidth product. The radiation resistance is important in determining the allowable losses in the ground system and tuning system for a given efficiency. The bandwidth-efficiency product indicates the capability of the transmitting system to handle the multichannel broadcasts which are being increasingly employed because of growing density of traffic.

This bandwidth-efficiency product is sometimes expressed in terms of the transmitting system, in which case it is assumed to be twice that of the antenna system. Because this two-to-one relationship is only approximate, and depends on the nature of the transmitter used, bandwidth is expressed in this report in terms of the antenna system alone. To obtain the "loaded" bandwidth-efficiency product, the reader should multiply the values presented here by two. The radiated-power capability must be sufficient to meet coverage requirements. It is limited by the allowable base voltage, which for this study is assumed to be 100 kV. Finally, the power-bandwidth product — that is, the product of the maximum radiated-power capability and the bandwidth-efficiency product — is a commonly used figure of merit for antennas.

The expressions used in calculating properties of the reference antenna are:

Radiation resistance $(R_r) = 160\pi^2(h_e/\lambda)^2$ ohms (3)

Bandwidth-efficiency product $(\overline{BW}\eta) = \dfrac{320\pi^3 h_e^2 f^4 C_e}{c^2}$ cycles (4)

Power-handling capability $(P_m) = \dfrac{0.64\pi^4 V_b^2 f^4 h_e^2 C_e^2}{c^2}$ kilowatts (5)

Power-bandwidth product $(P_m \overline{BW}) = \dfrac{204.8\pi^7 V_b^2 f^8 h_e^4 C_e^3}{c^4}$ kilowatt-cycles (6)

where

h_e = Effective height in meters

λ = Free-space wavelength in meters

f = Frequency in cycles per second

C_e = Effective antenna capacitance in farads

V_b = Maximum allowable base voltage

c = Velocity of light = 10^8 meters per second

Since only relative values of computed properties are needed for the top-loaded structures. simpler expressions can be used. If we use primes to indicate the relative values and add a zero to the sub-script to designate the reference antenna

$$R_r' = (h_e/h_{e0})^2 \tag{7}$$

$$(\overline{BW}n)' = R_r'(C_e/C_{e0}) = R_r'C_e' \tag{8}$$

$$P_m' = R_r'(C_e')^2 \tag{9}$$

$$(P_m\overline{BW})' = (R_r')^2(C_e')^3 \tag{10}$$

In actual computation. the relative radiation resistance was found by squaring the relative field intensity; the relative bandwidth-efficiency product by multiplying the relative radiation resistance by the relative capacitance; the relative power-handling capability by multiplying the relative radiation resistance by the square of the relative capacitance; and the power-bandwidth product by multiplying the square of the relative radiation resistance by the cube of the relative capacitance.

RESULTS: DESIGN CURVES

The results of the study are presented as a family of design curves arranged in four groups. The first two groups contain data on seven important antenna characteristics. The third group plots some of the same information in a different form to emphasize the dependence of antenna properties on the number of radials. The fourth group supplies correction factors for estimates of antenna properties for tower h/d ratios other than the 200/1 considered in the model studies.

Electrical Properties of Reference Tower Antenna (Group I)

Figures 3 to 9 contain data on static capacitance. resonant frequency. effective height. radiation resistance, bandwidth-efficiency product. radiated-power capability. and power-bandwidth product. The absolute values of the quantities are plotted as functions of tower height for heights from 300 to 1000 feet. In figures 6 through 9 frequency is a parameter. and there are curves for 50. 70.7. 100. and 150 kc/s. The curves were plotted by standard scaling techniques from measurements made on the model reference antenna. For example. the measured static capacitance of the 6.3-foot reference antenna was 22 picofarads. The capacity of a 630-foot tower will therefore be 2200 picofarads. since for a constant h/d ratio the static capacitance is proportional to antenna height.

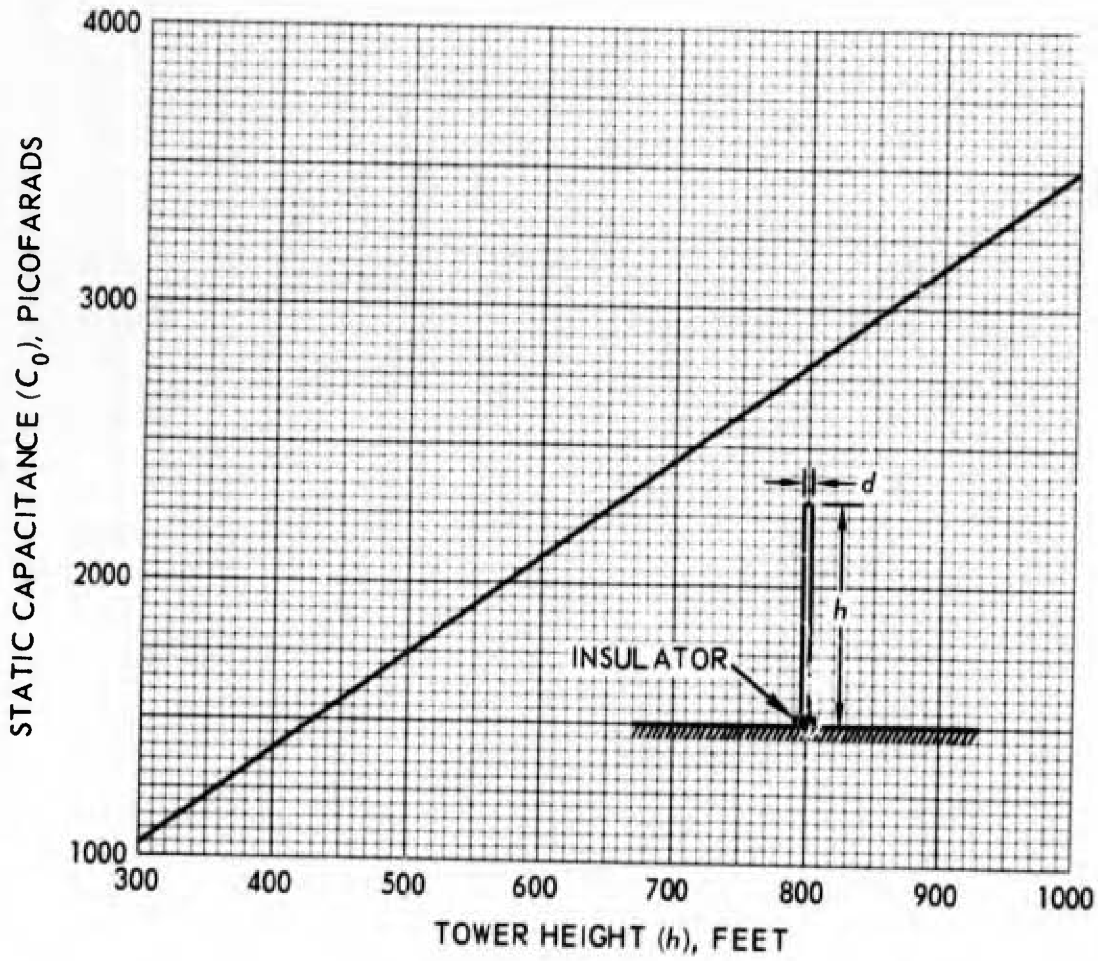

Figure 3. Variation of static capacitance of reference antenna with tower height ($h/d = 200$).

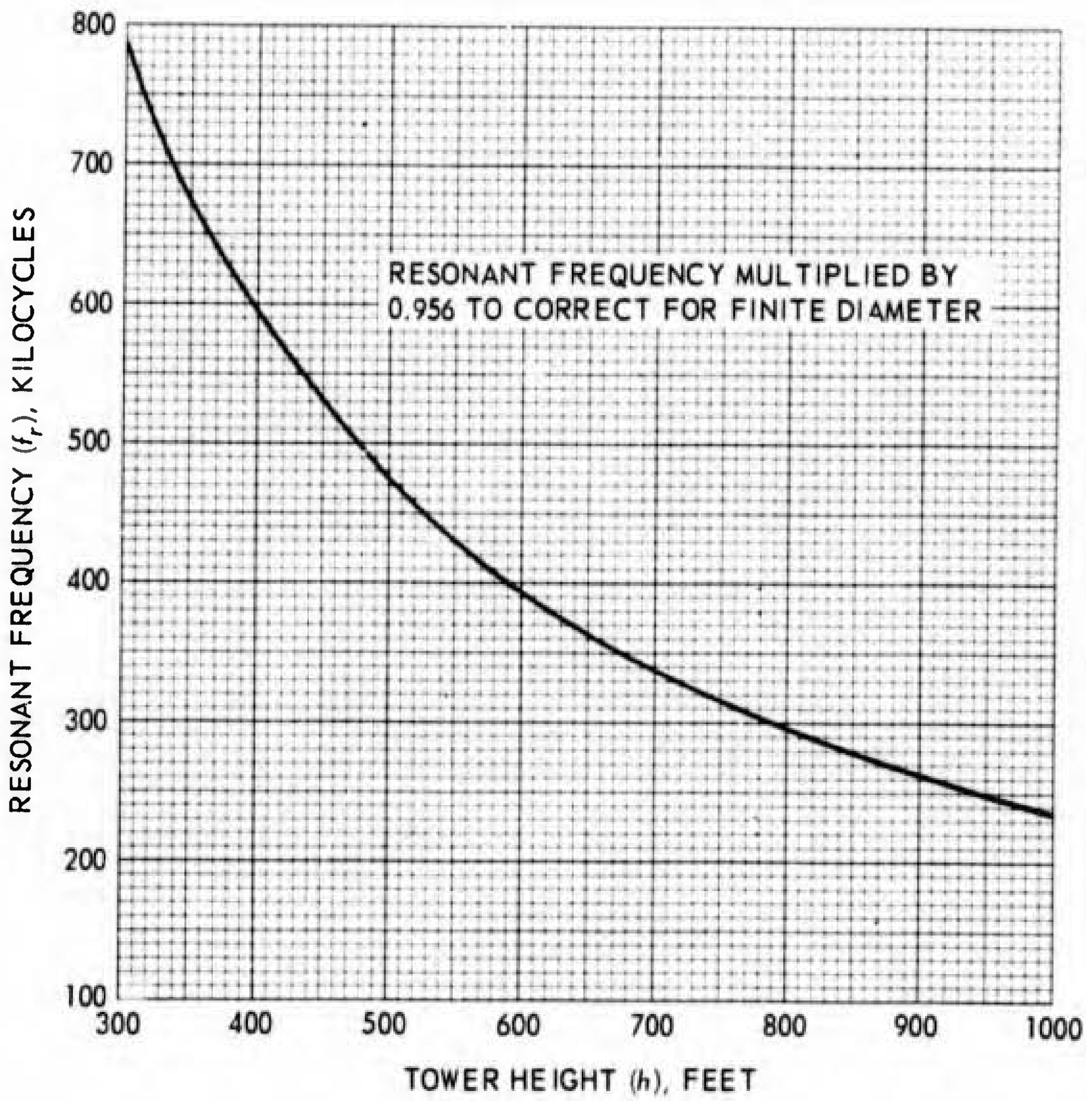

Figure 4. Computed resonant frequency of reference antenna as a function of tower height ($h/d = 200$).

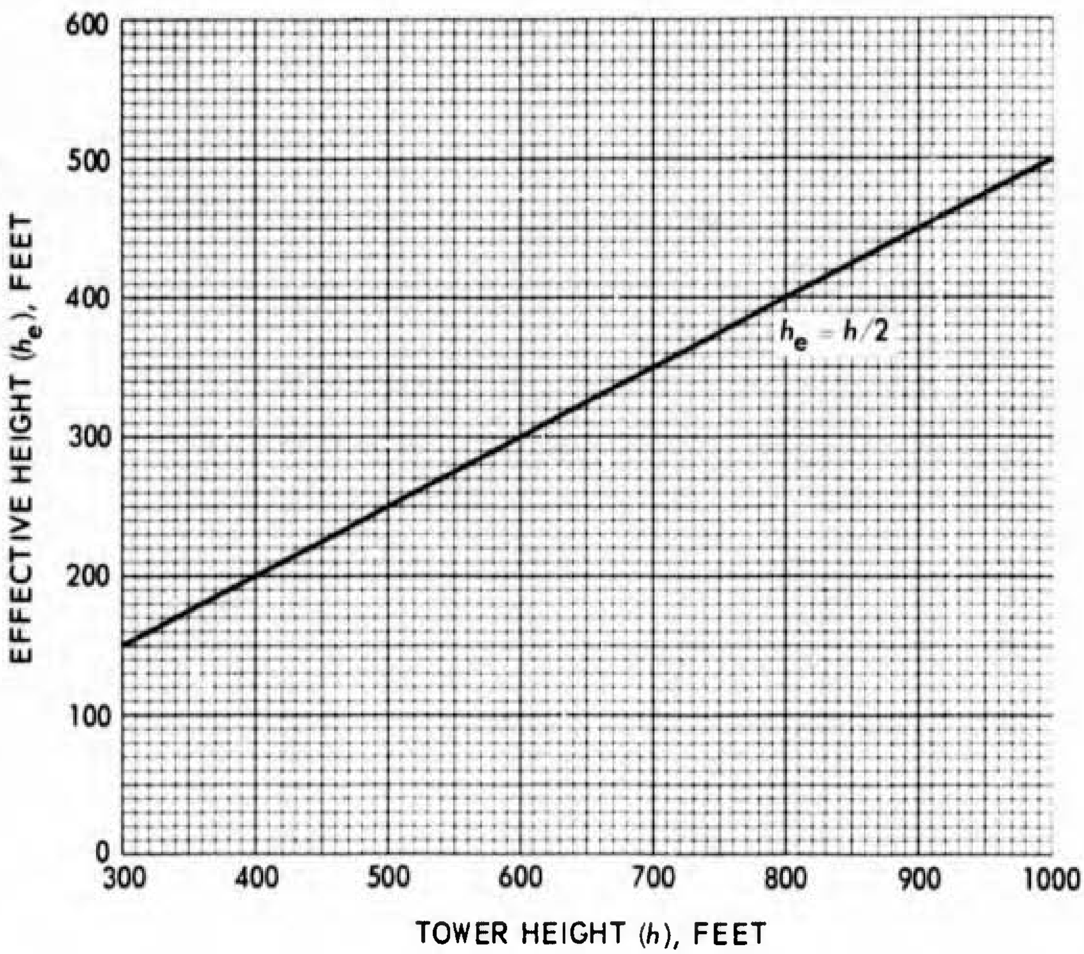

Figure 5. Variation of effective height of reference antenna with tower height ($h/d = 200$).

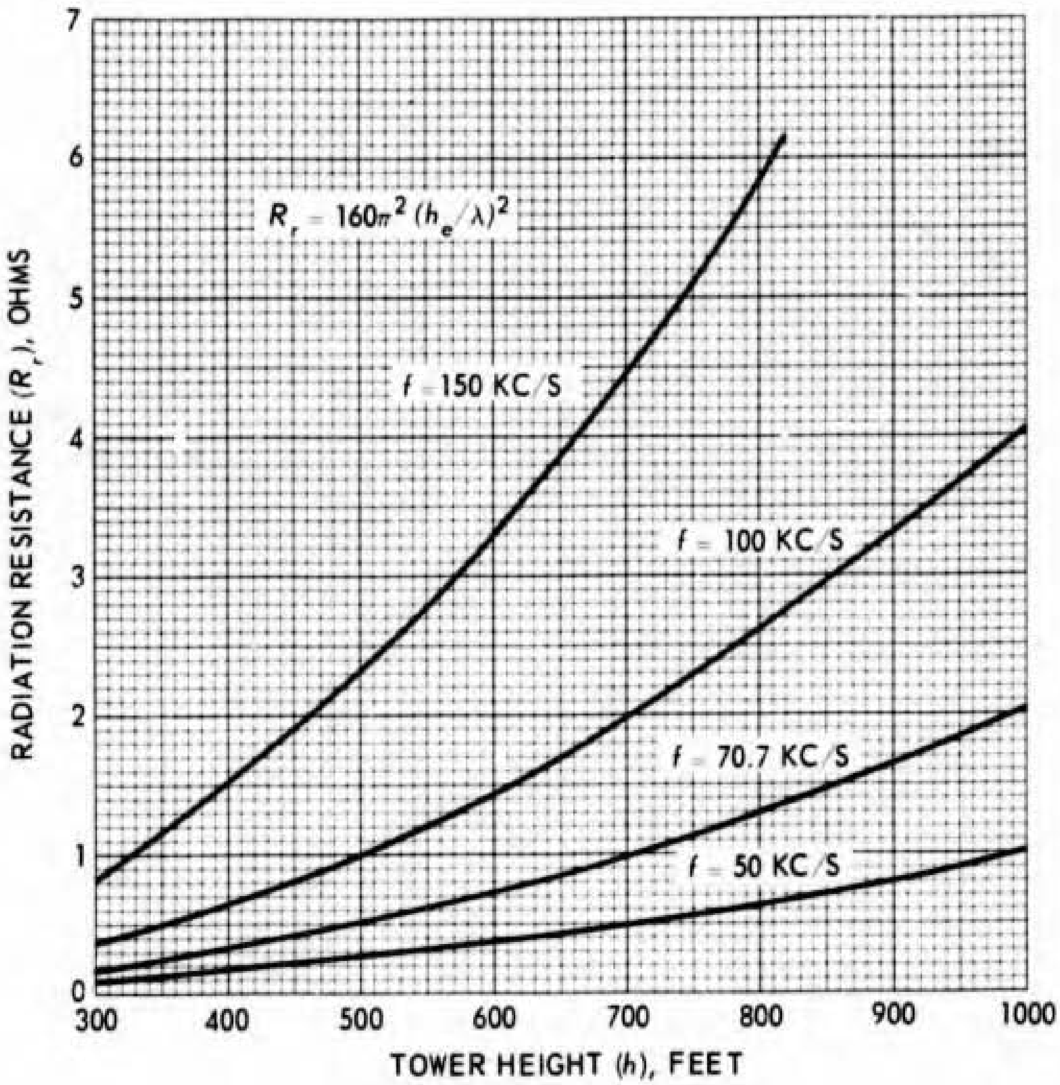

Figure 6. Variation of radiation resistance of reference antenna with tower height ($h/d = 200$).

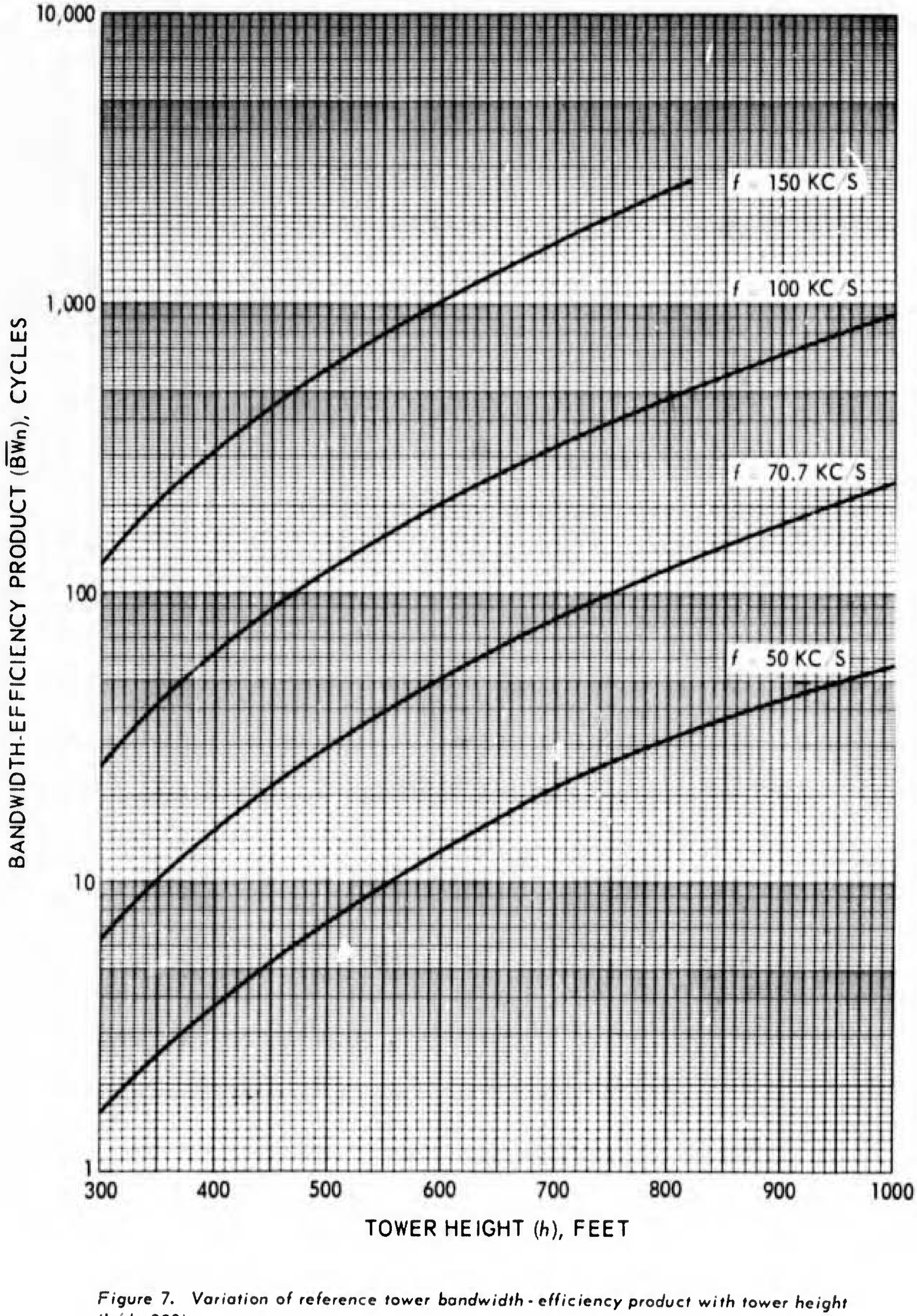

Figure 7. Variation of reference tower bandwidth - efficiency product with tower height (h/d = 200).

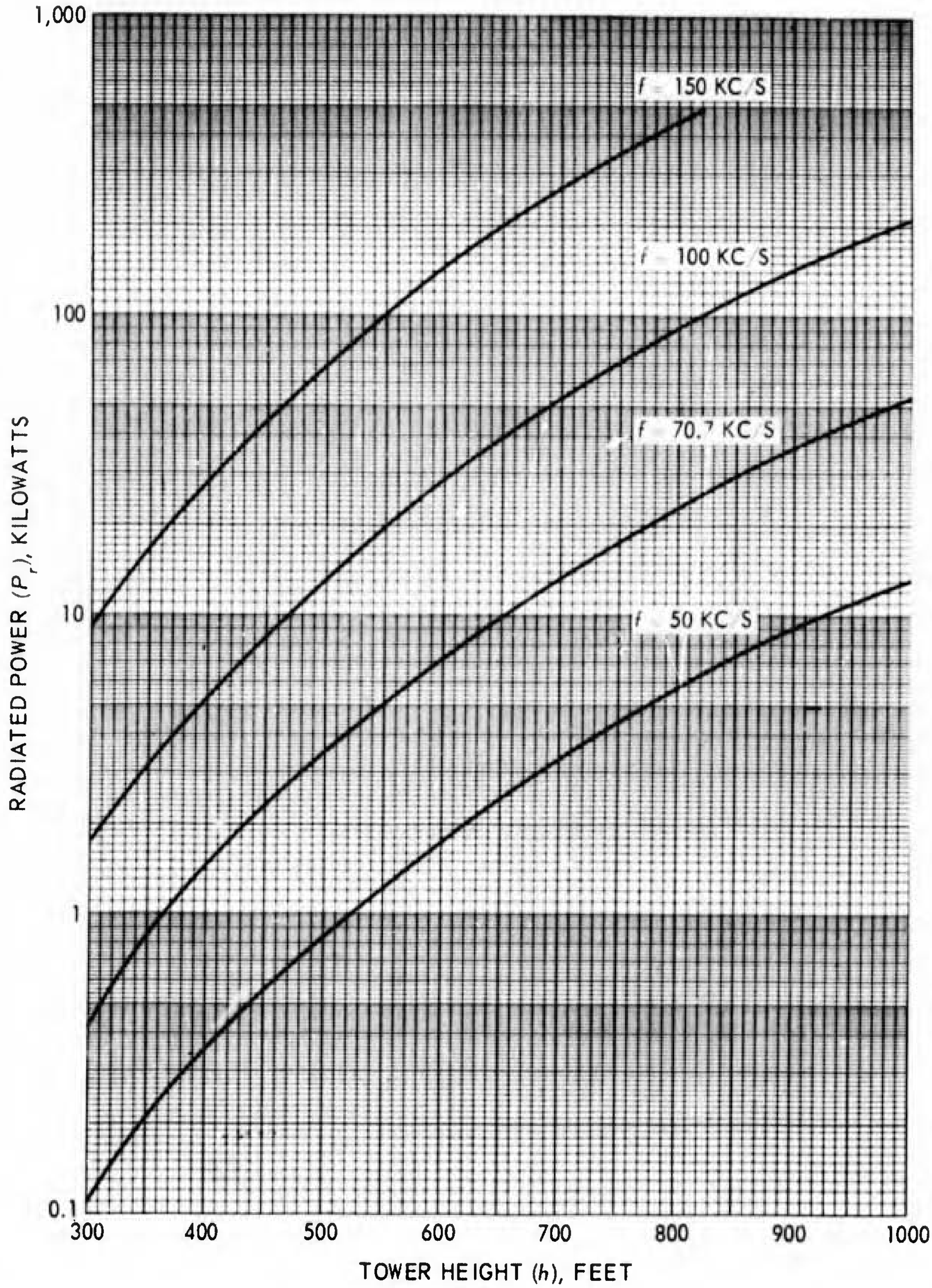

Figure 8. Variation of reference tower maximum radiated-power capability with tower height (h/d = 200).

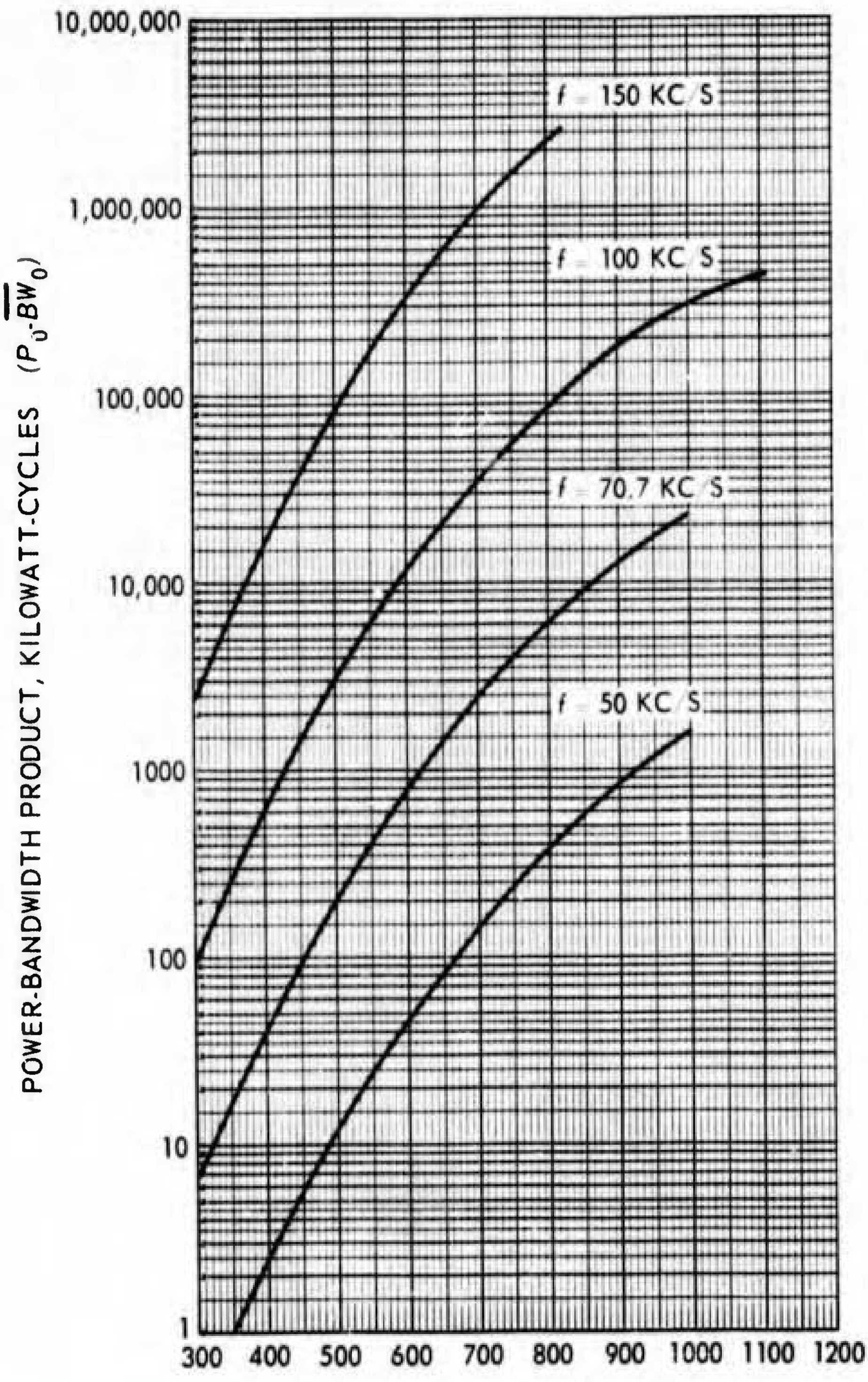

Figure 9. Variation of reference antenna power-bandwidth product with tower height ($h/d = 200$).

Electrical Properties of Top-Loaded Antennas (Group II)

Figures 10 to 30 show the properties of the top-loaded configurations studied in terms of the properties of reference antennas of the same height. The data are plotted against the fractional projected lengths of the active portion of the top-hat radials for lengths between one-tenth and nine-tenths the center-tower height. Figures are arranged according to the number of top-hat radials — 6, 12 or 24. The four curves in each figure correspond to the four values of the parameter ρ (refer to Electrical Properties Measured).

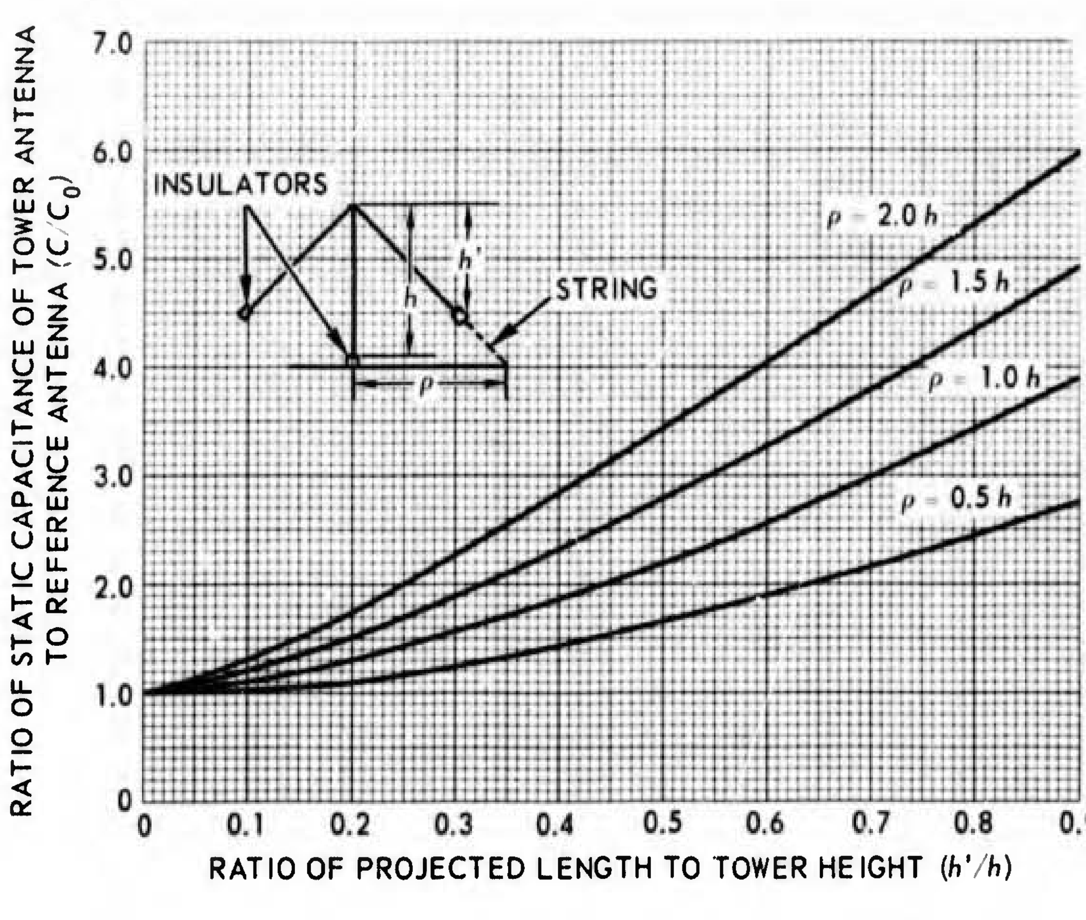

Figure 10. Normalized static capacitance of top-loaded antenna, N = 6.

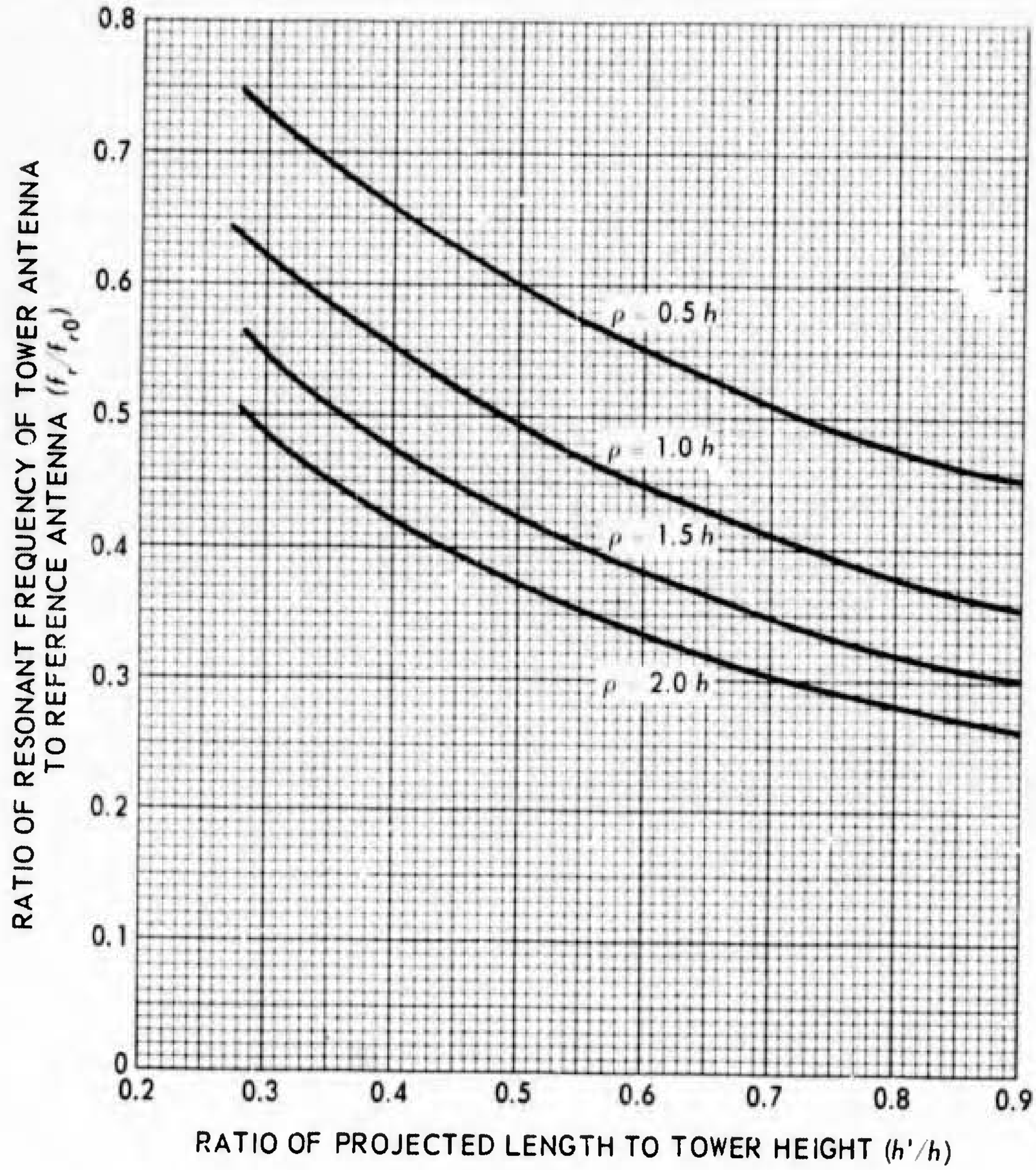

Figure 11. Normalized resonant frequency of top-loaded antenna, $N=6$.

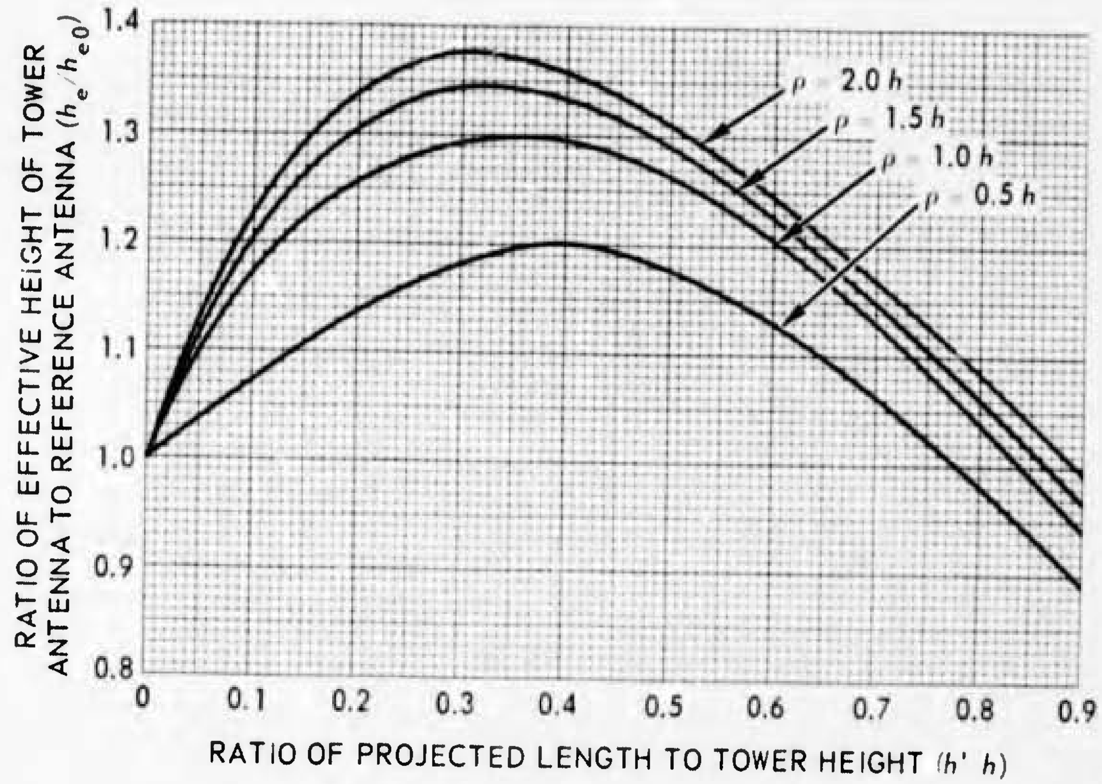

Figure 12. Normalized effective height of top-loaded antenna, N = 6.

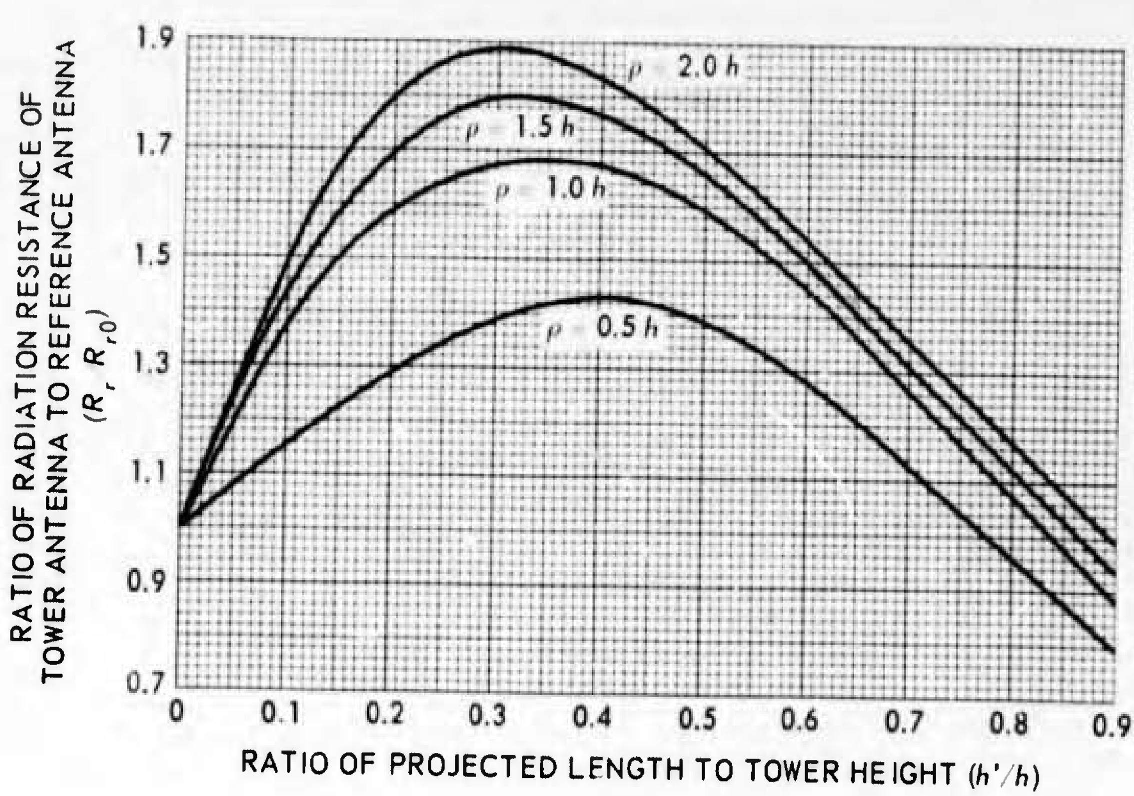

Figure 13. Normalized radiation resistance of top-loaded antenna, N = 6.

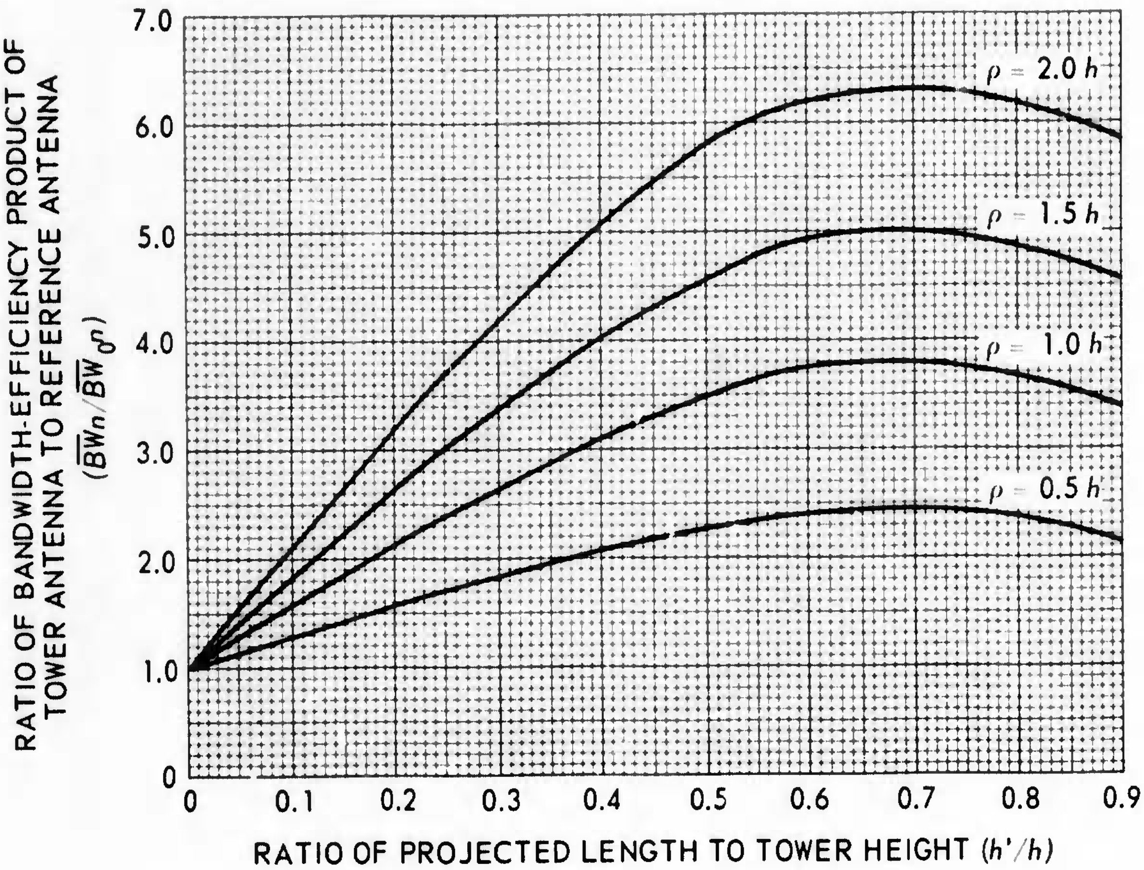

Figure 14. Normalized bandwidth-efficiency product of top-loaded antenna, $N=6$.

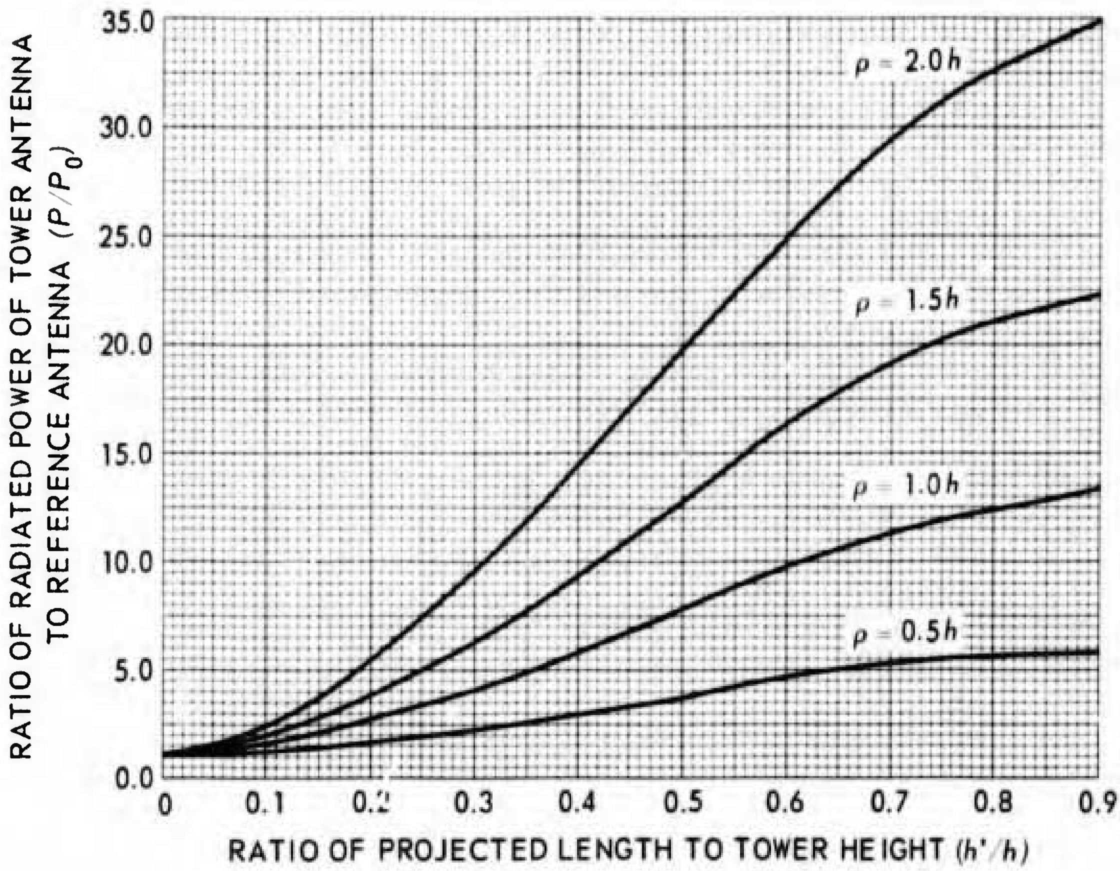

Figure 15. Normalized radiated power of top-loaded antenna, N = 6.

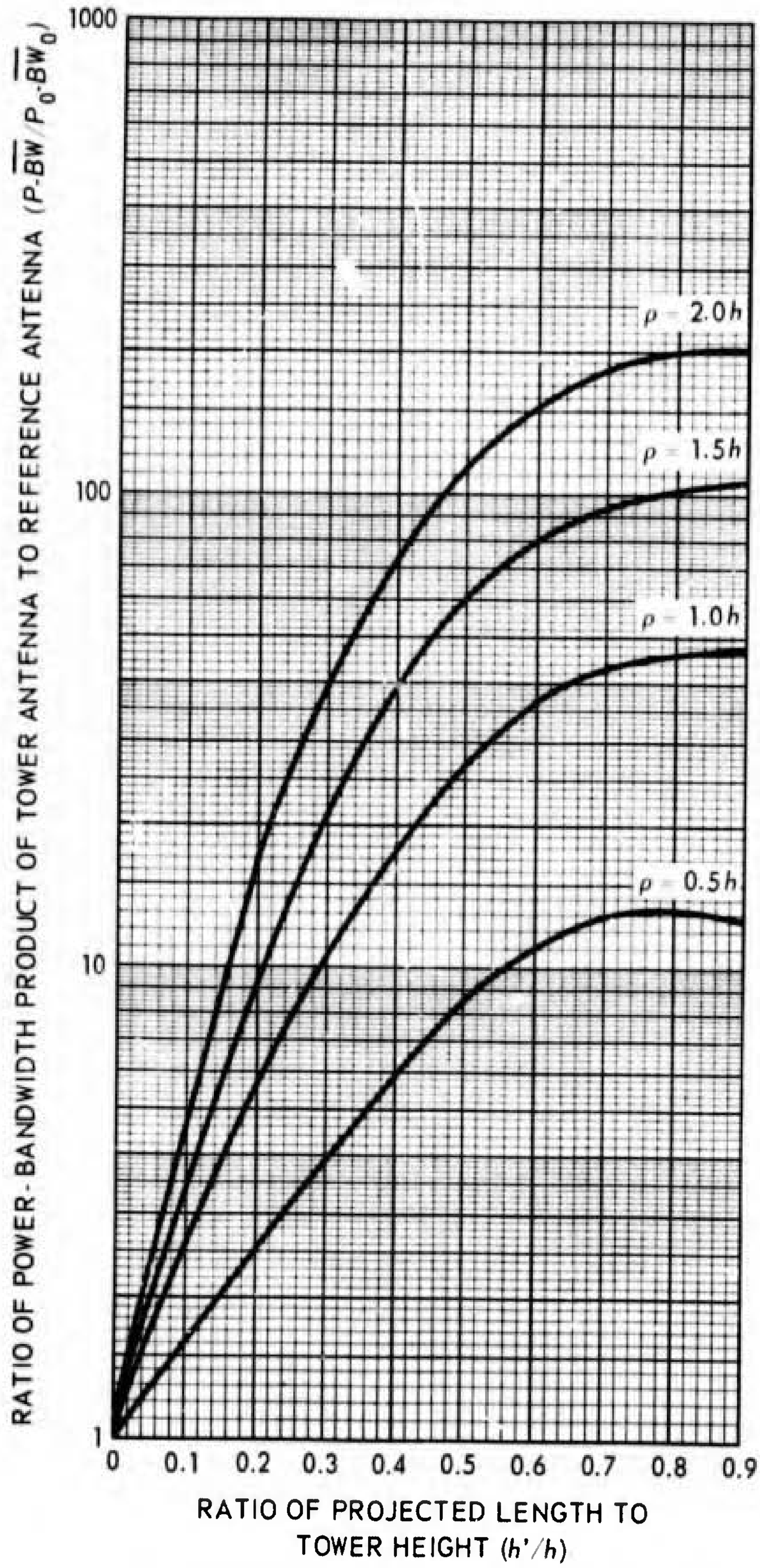

Figure 16. Normalized power-bandwidth product of top-loaded antenna, $N = 6$.

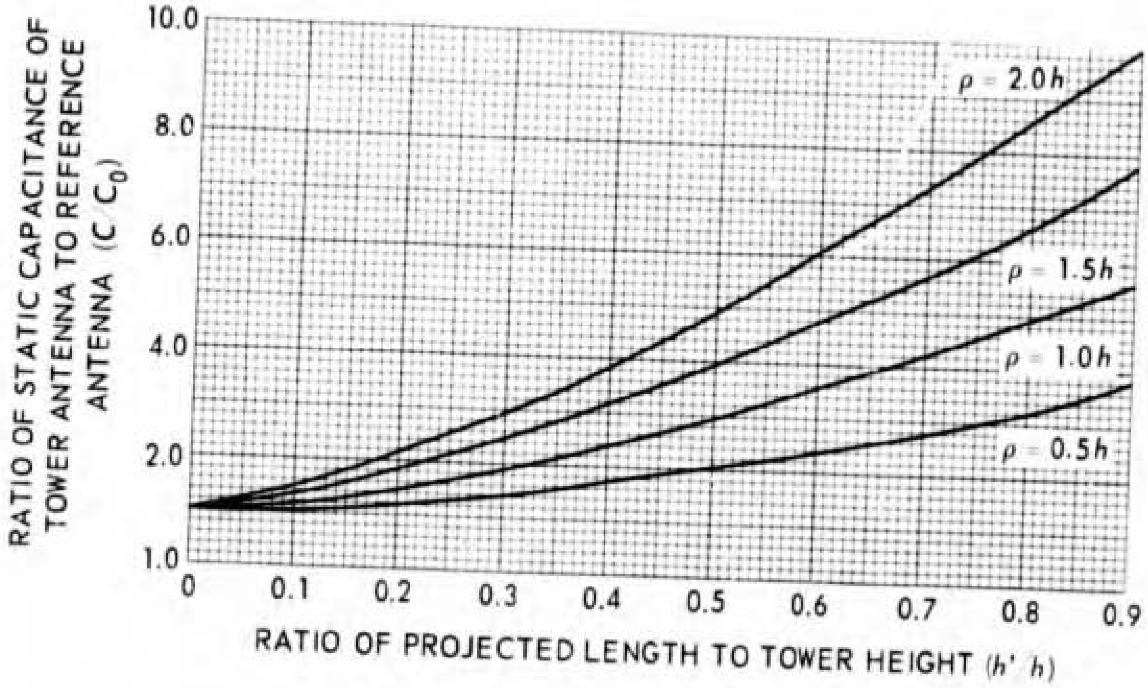

Figure 17. Normalized static capacitance of top-loaded antenna, N = 12

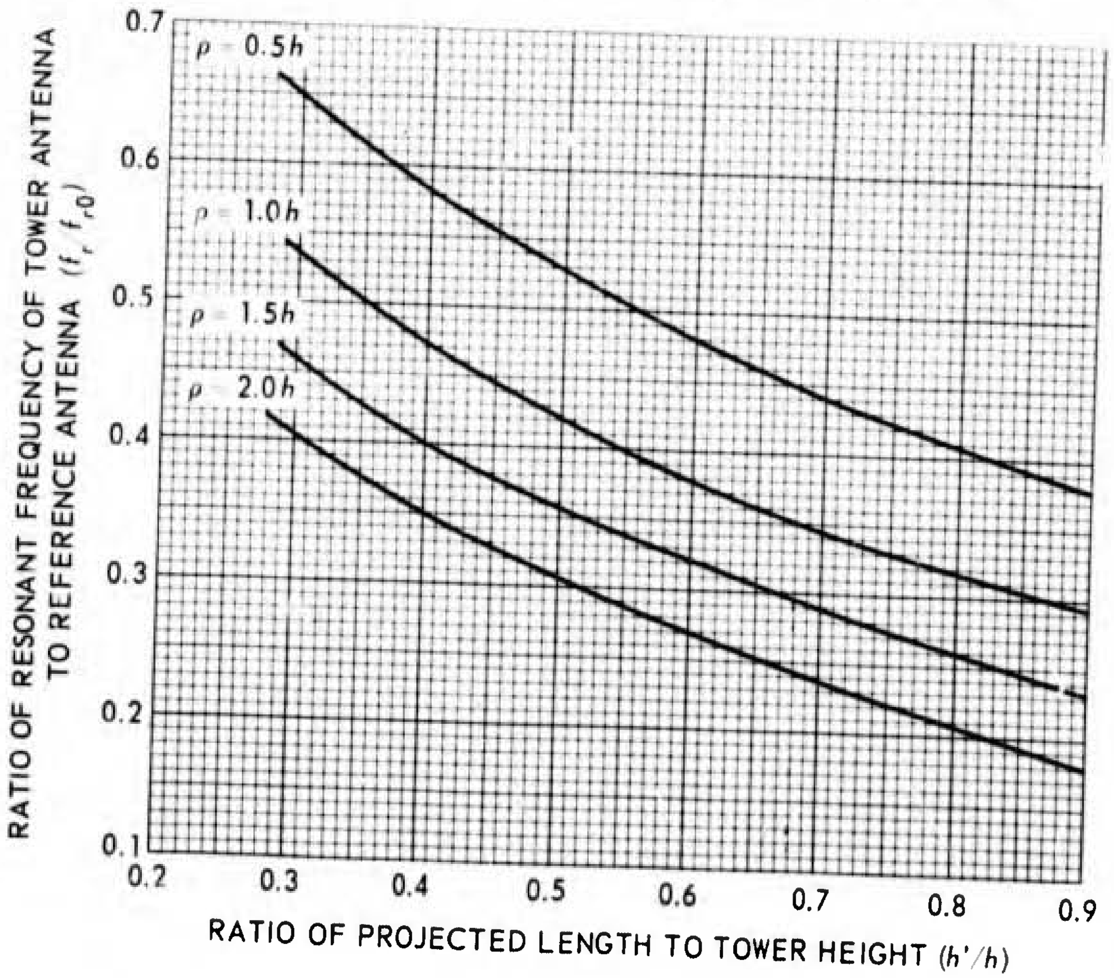

Figure 18. Normalized resonant frequency of top-loaded antenna, N = 12.

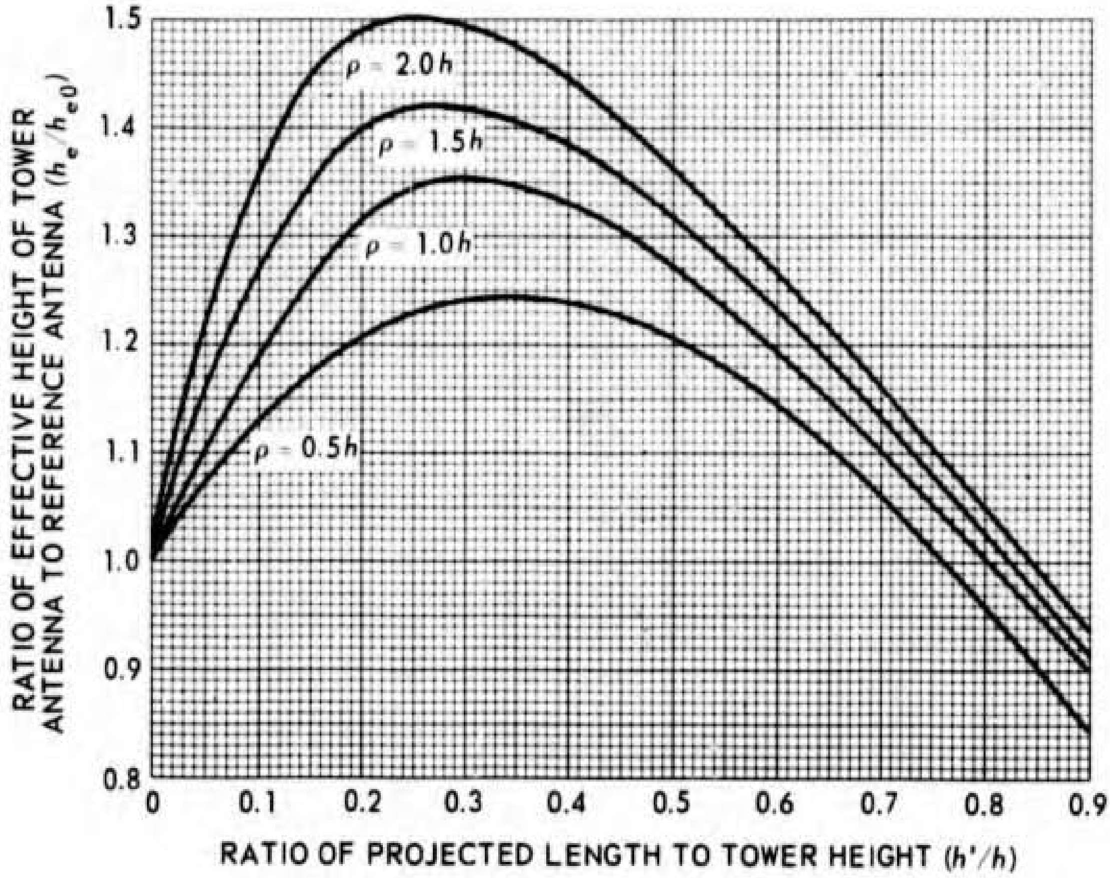

Figure 19. Normalized effective height of top-loaded antenna, $N = 12$.

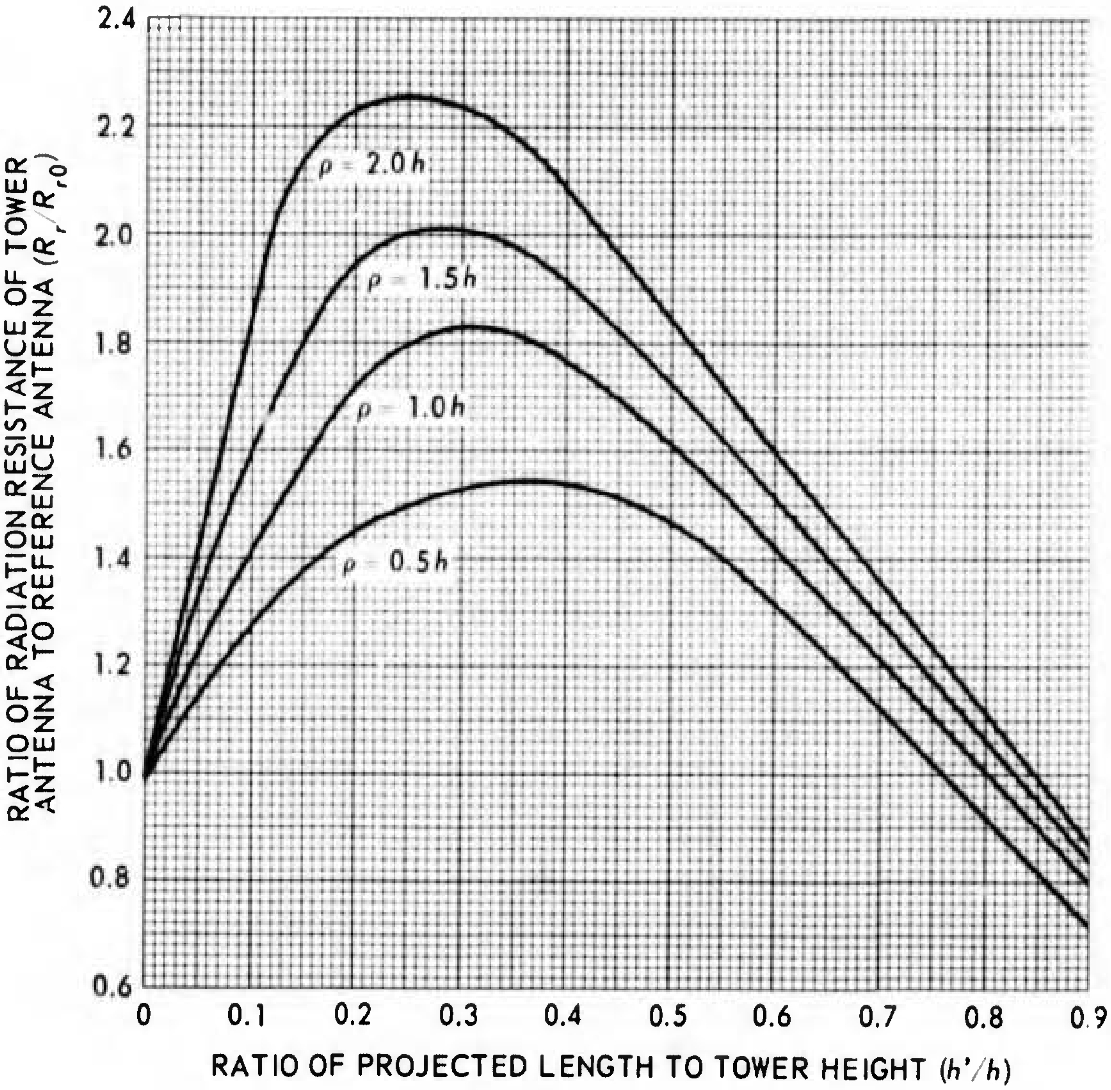

Figure 20. Normalized radiation resistance of top-loaded antenna, $N = 12$.

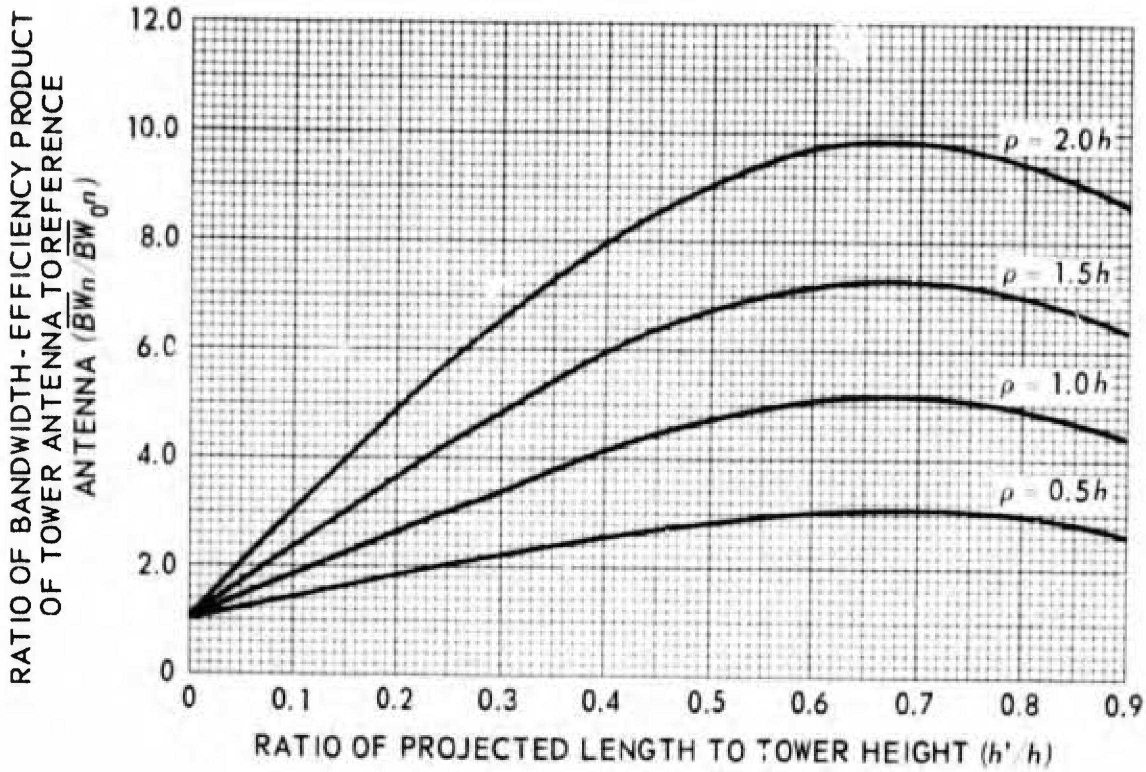

Figure 21. Normalized bandwidth-efficiency product of top-loaded antenna, $N = 12$.

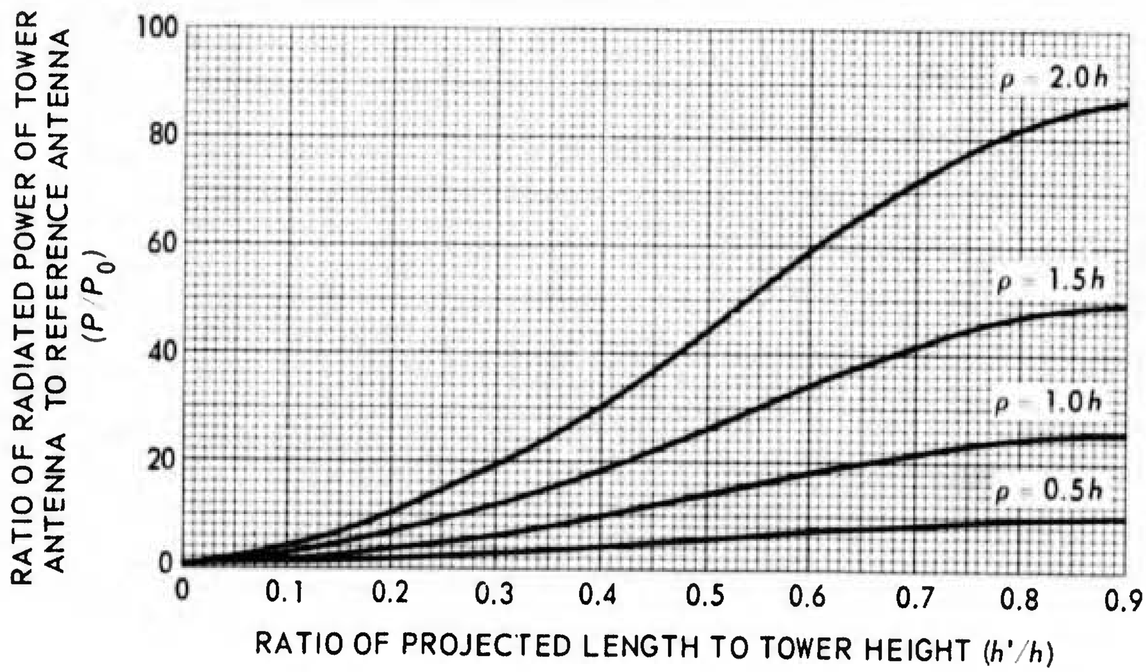

Figure 22. Normalized radiated power of top-loaded antenna, $N = 12$.

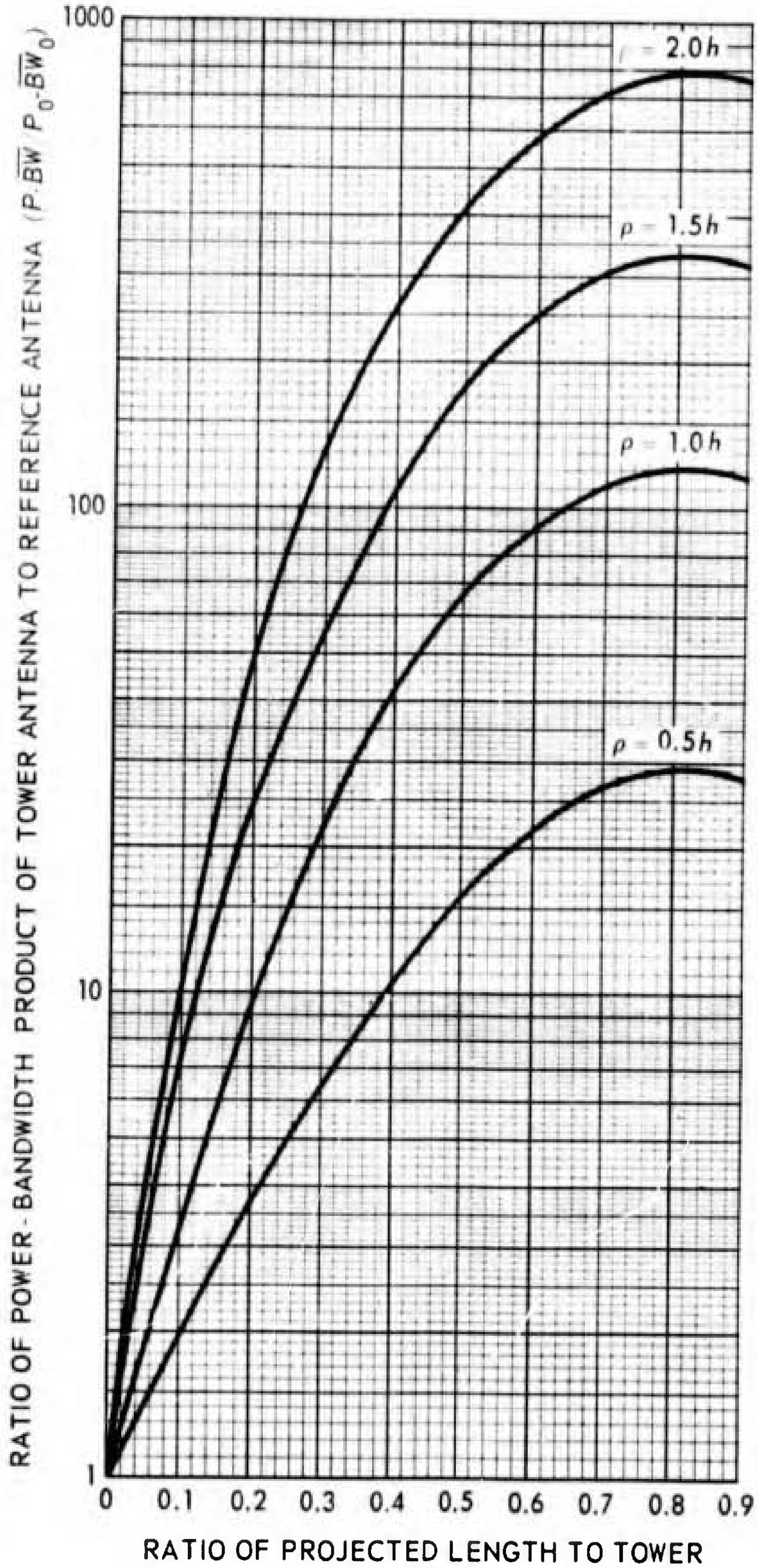

Figure 23. Normalized power-bandwidth product of top-loaded antenna, $N = 12$.

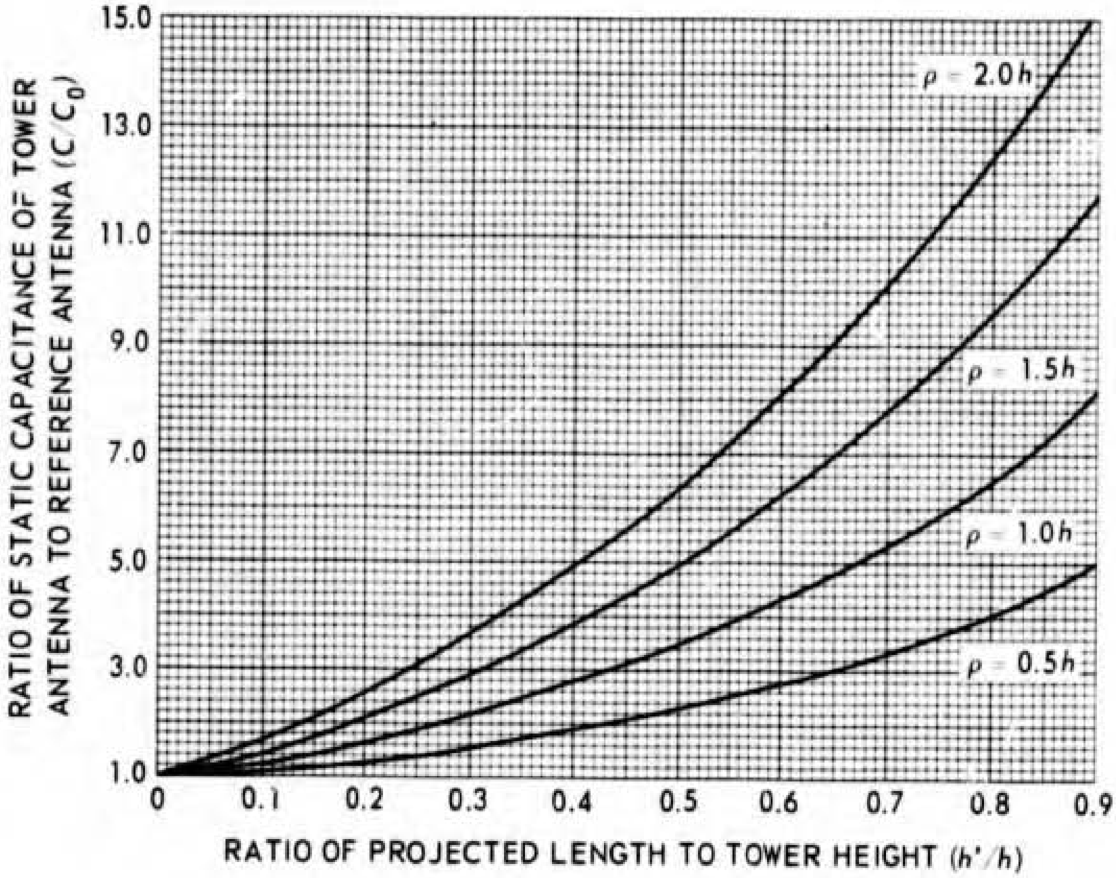

Figure 24. Normalized static capacitance of top-loaded antenna, $N = 24$.

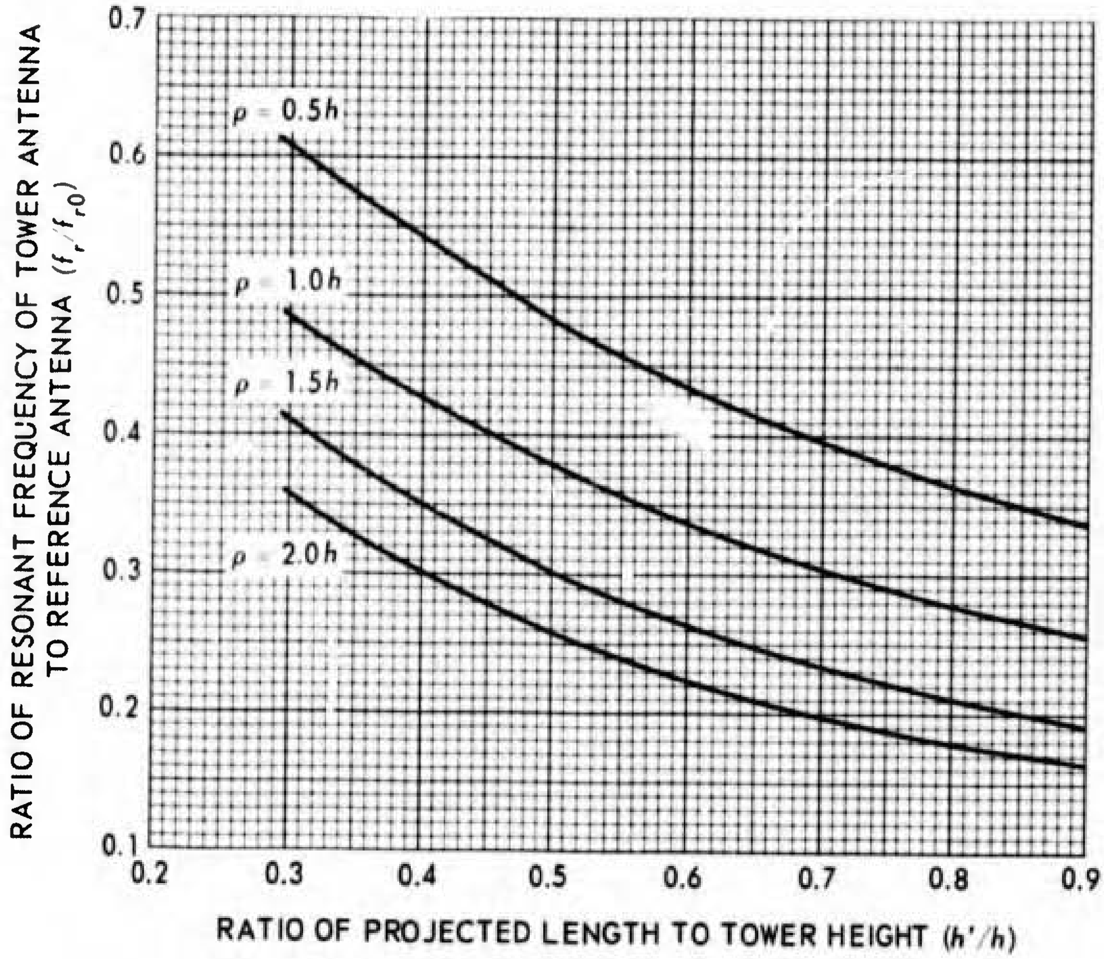

Figure 25. Normalized resonant frequency of top-loaded antenna, $N = 24$.

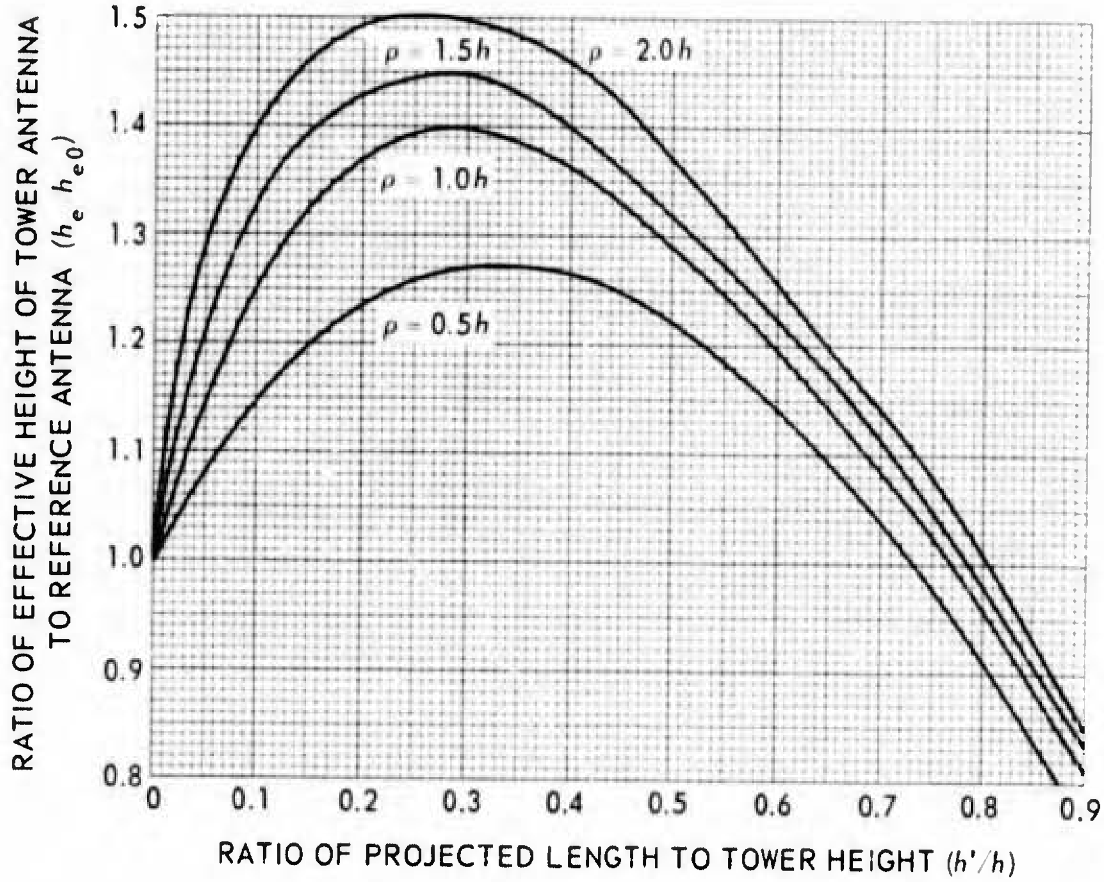

Figure 26. Normalized effective height of top-loaded antenna, N = 24.

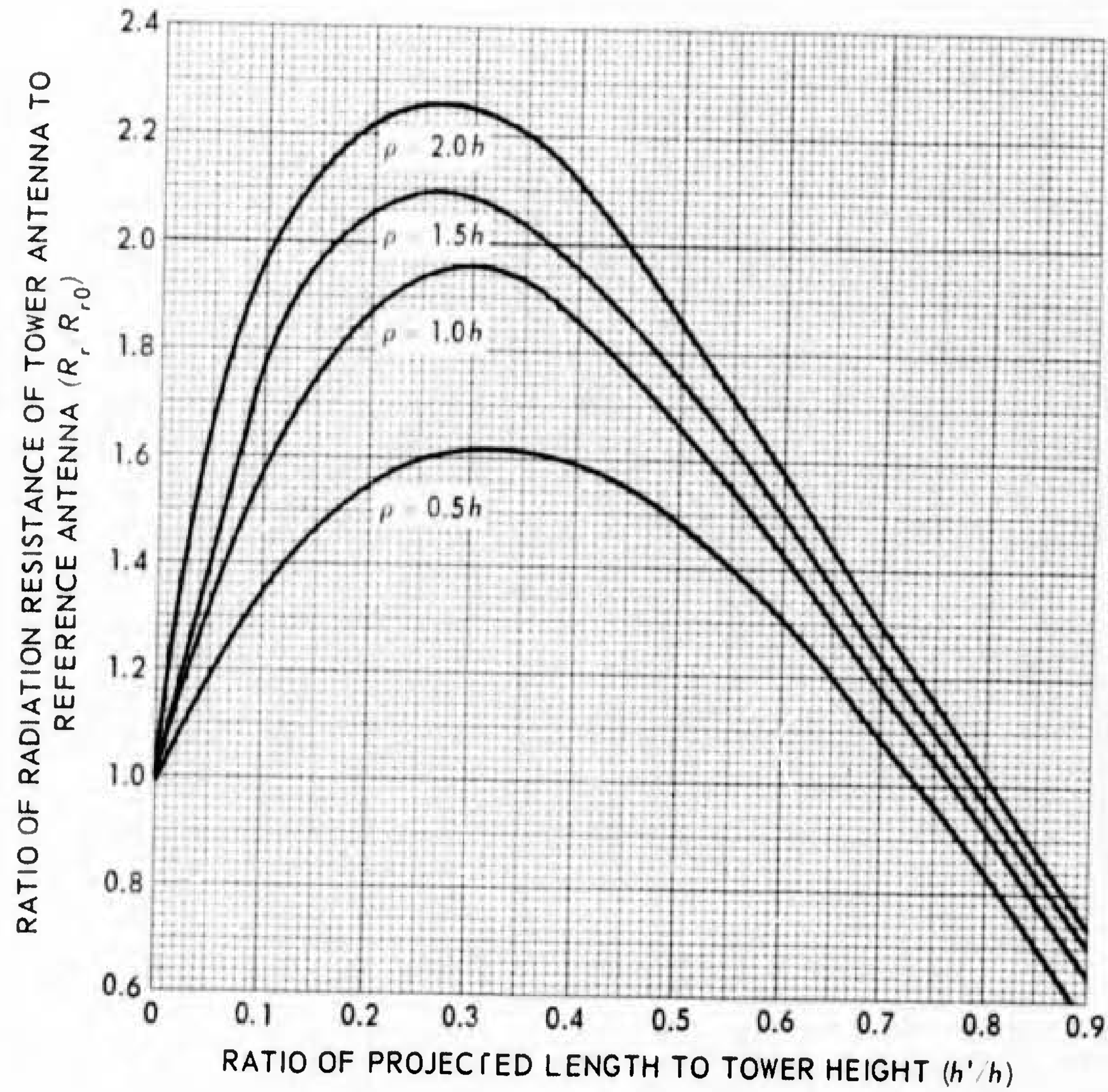

Figure 27. Normalized radiation resistance of top-loaded antenna, $N = 24$.

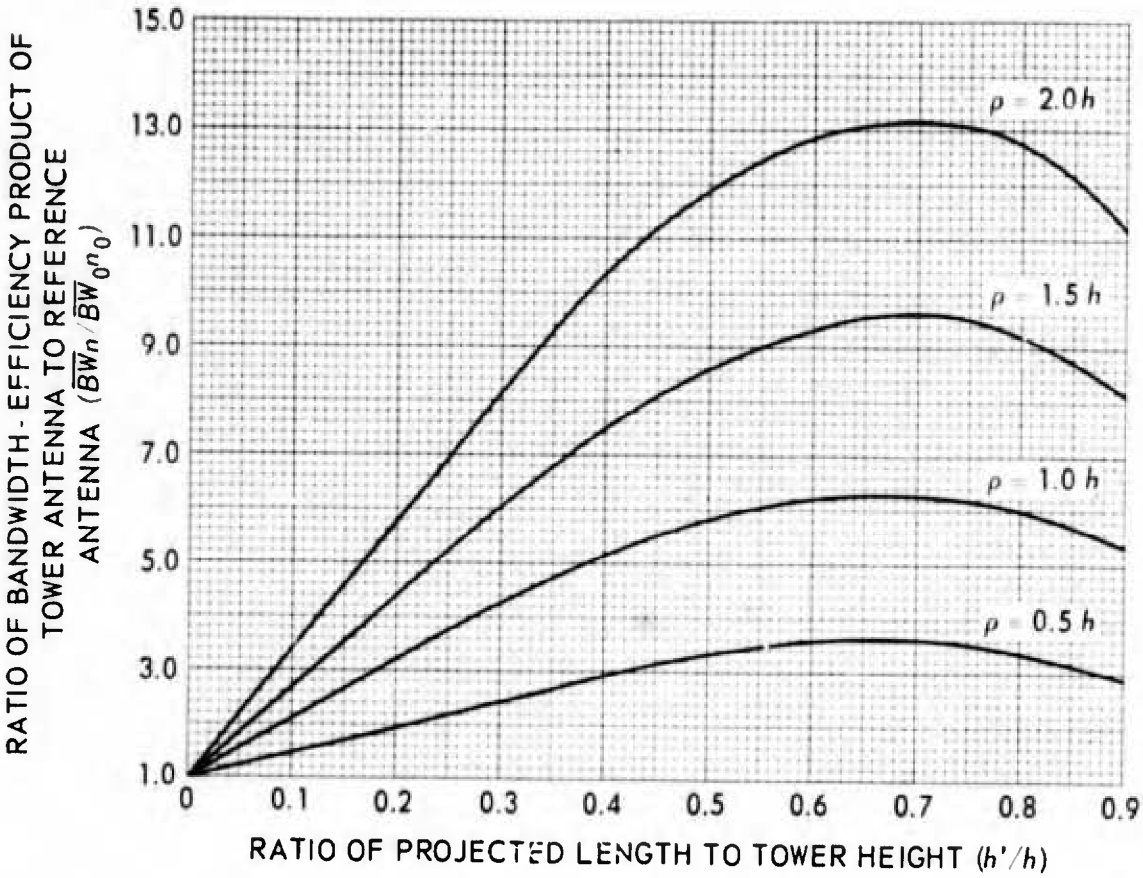

Figure 28. Normalized bandwidth - efficiency product of top - loaded antenna, $N = 24$.

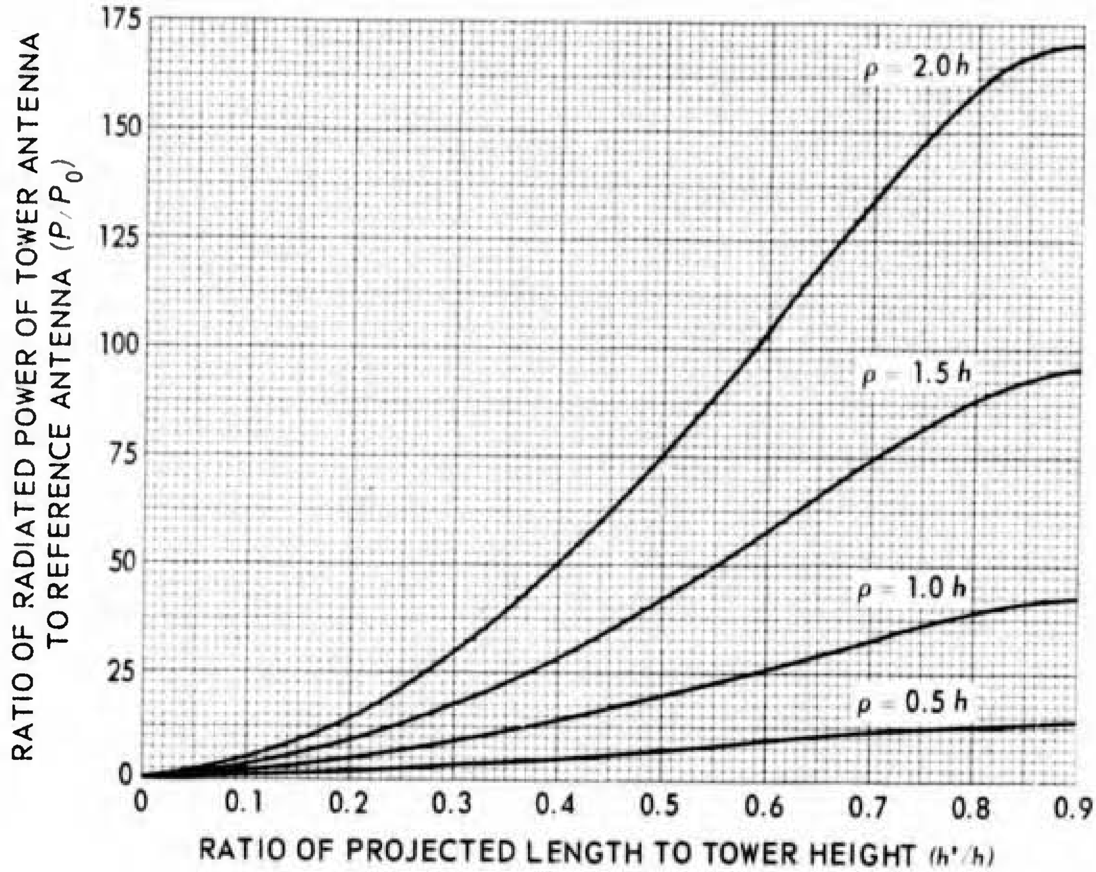

Figure 29. Normalized radiated power of top-loaded antenna, $N = 24$.

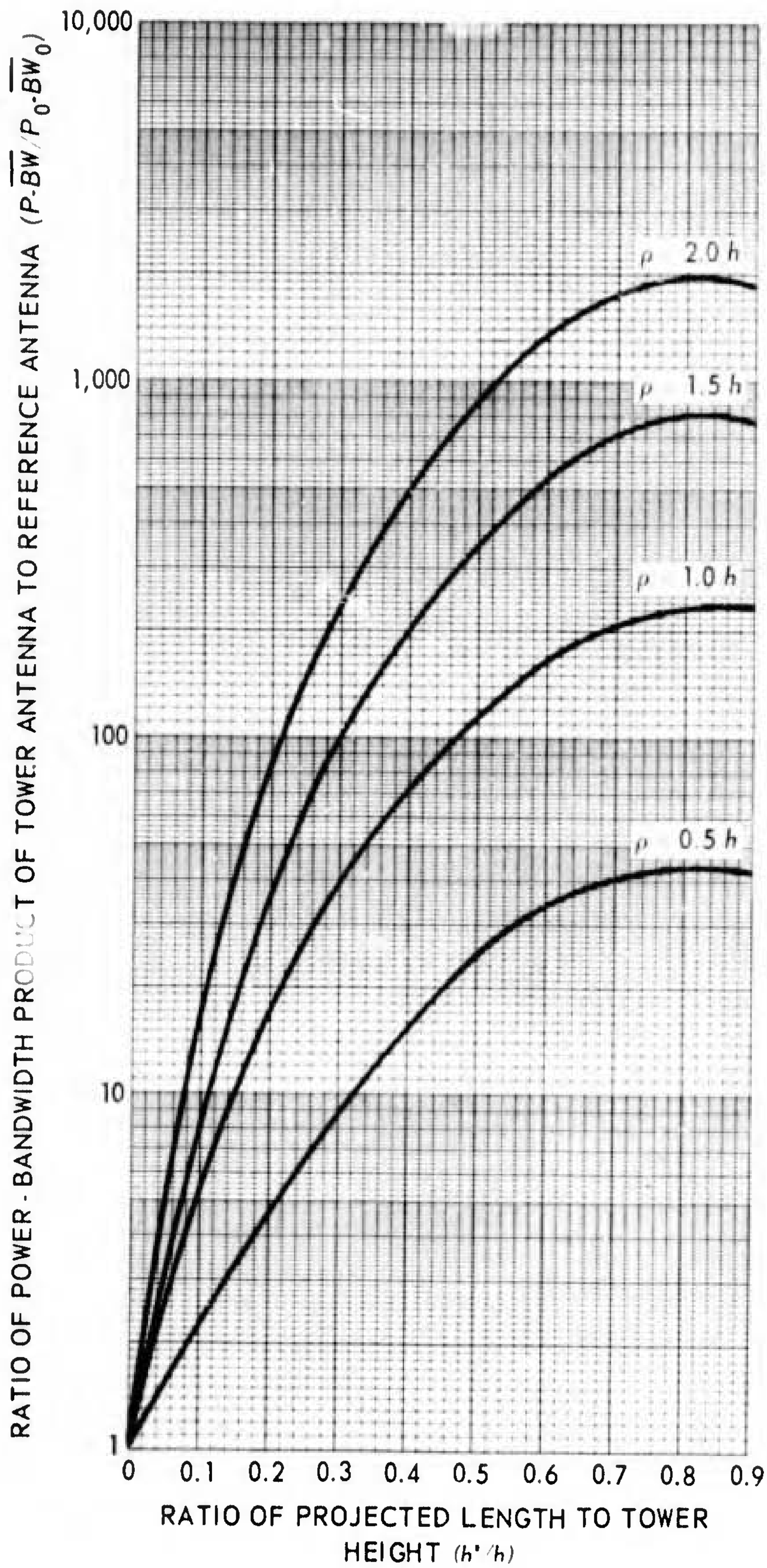

Figure 30. Normalized power-bandwidth product of top-loaded antenna, N = 24.

Electrical Properties Versus Number of Radials (Group III)

Figures 31 through 33 present bandwidth-efficiency product, radiated-power capability, and power-bandwidth product for the set $\rho = h$. Each figure has curves for 6, 12, and 24 radials, and b''ings out clearly the dependence of the antenna property on the number of radials.

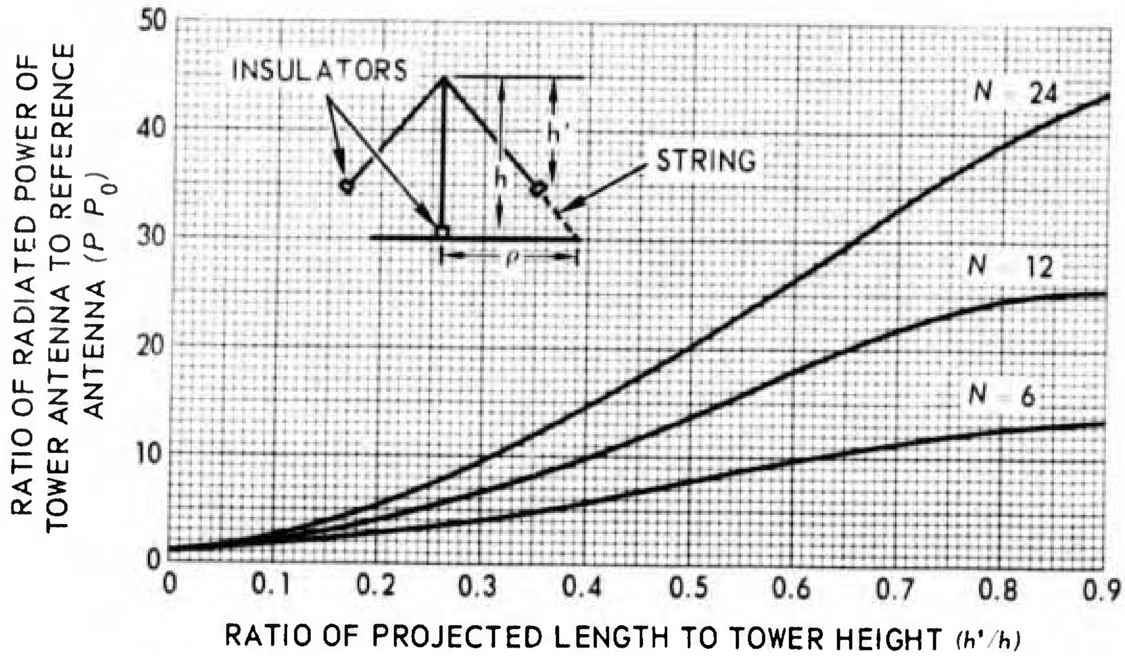

Figure 31. Normalized radiated power of three top-loaded antennas, $\rho = h$.

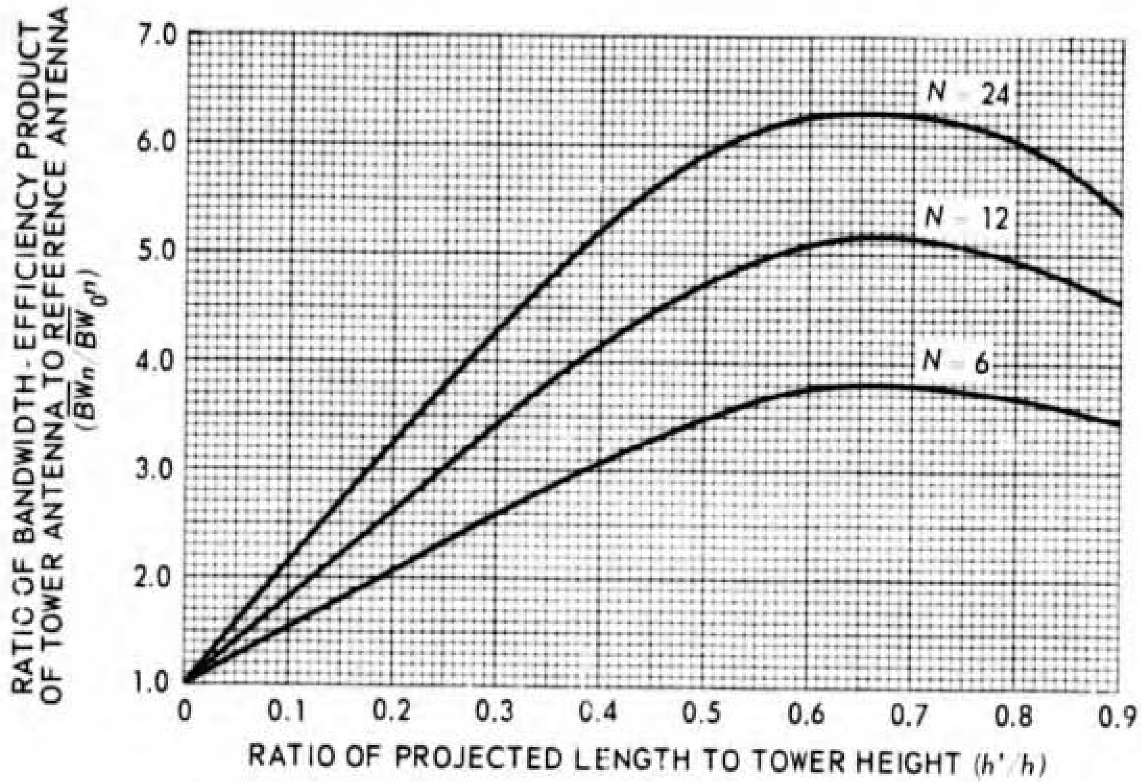

Figure 32. Normalized bandwidth-efficiency product of three top-loaded antennas, $\rho = h$.

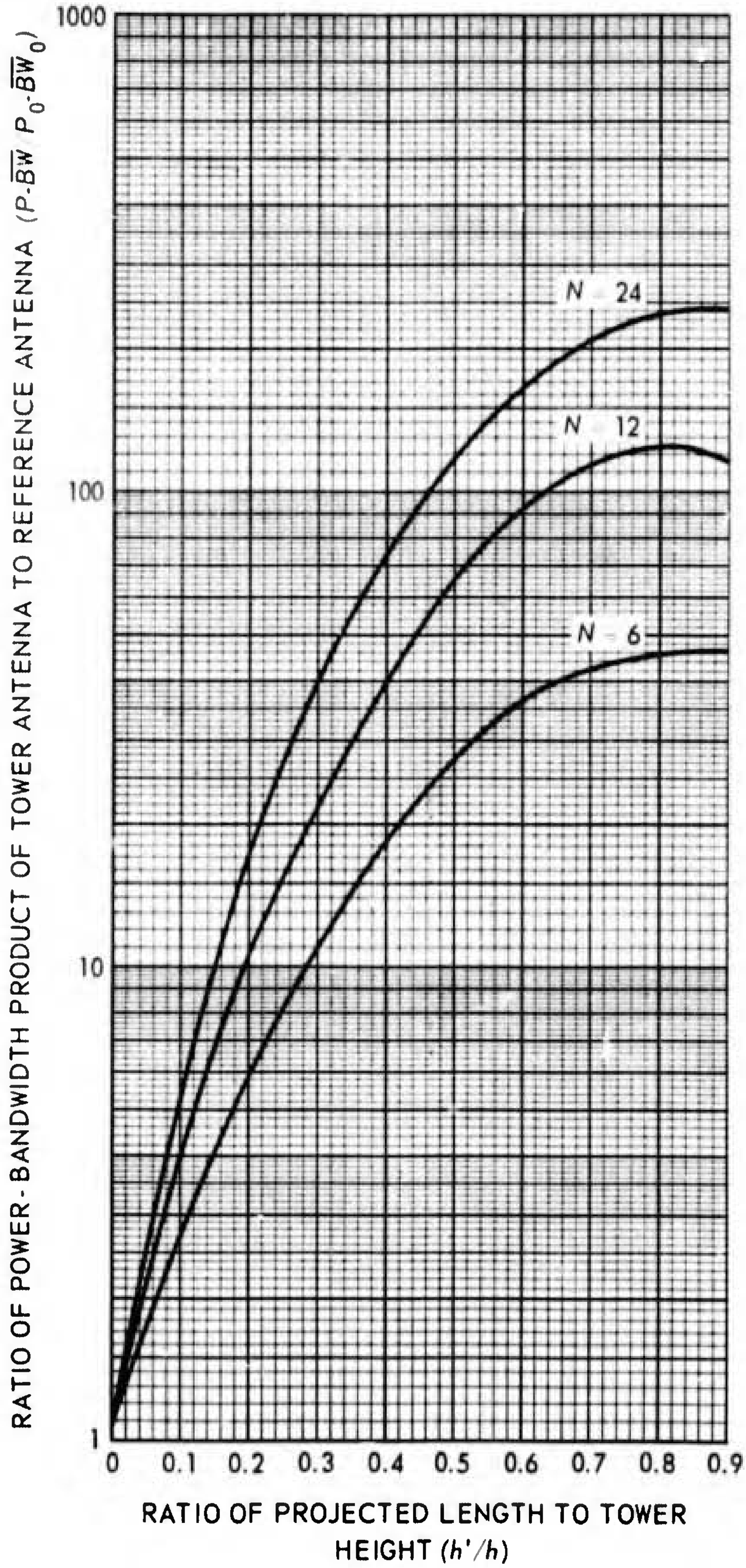

Figure 33. Normalized power-bandwidth product of three top-loaded antennas, $\rho = h$.

Correction Factors for h/d Ratios Other Than 200/1 (Group IV)

Figures 34 through 36 are to be used to correct the estimates of antenna properties for tower h/d ratios other than the 200/1 considered in the model studies. Figure 34 gives a common correction factor for capacitance and bandwidth-efficiency product; figure 35 the correction factor for power-handling capability; and figure 36 the correction factor for resonant frequency. Figures 34 and 35 have curves for 6, 12, and 24 top-hat radials; figure 36 does not, since the resonant frequency correction factor is not a function of the number of radials. The other characteristics studied, effective height and radiation resistance, do not vary significantly with tower diameter.

The correction factors are fully accurate only for the configuration for which $\rho = h$ and radial length = tower height. However, since the corrections are small, and since most practical designs will be close to this configuration, they are adequate for engineering purposes.

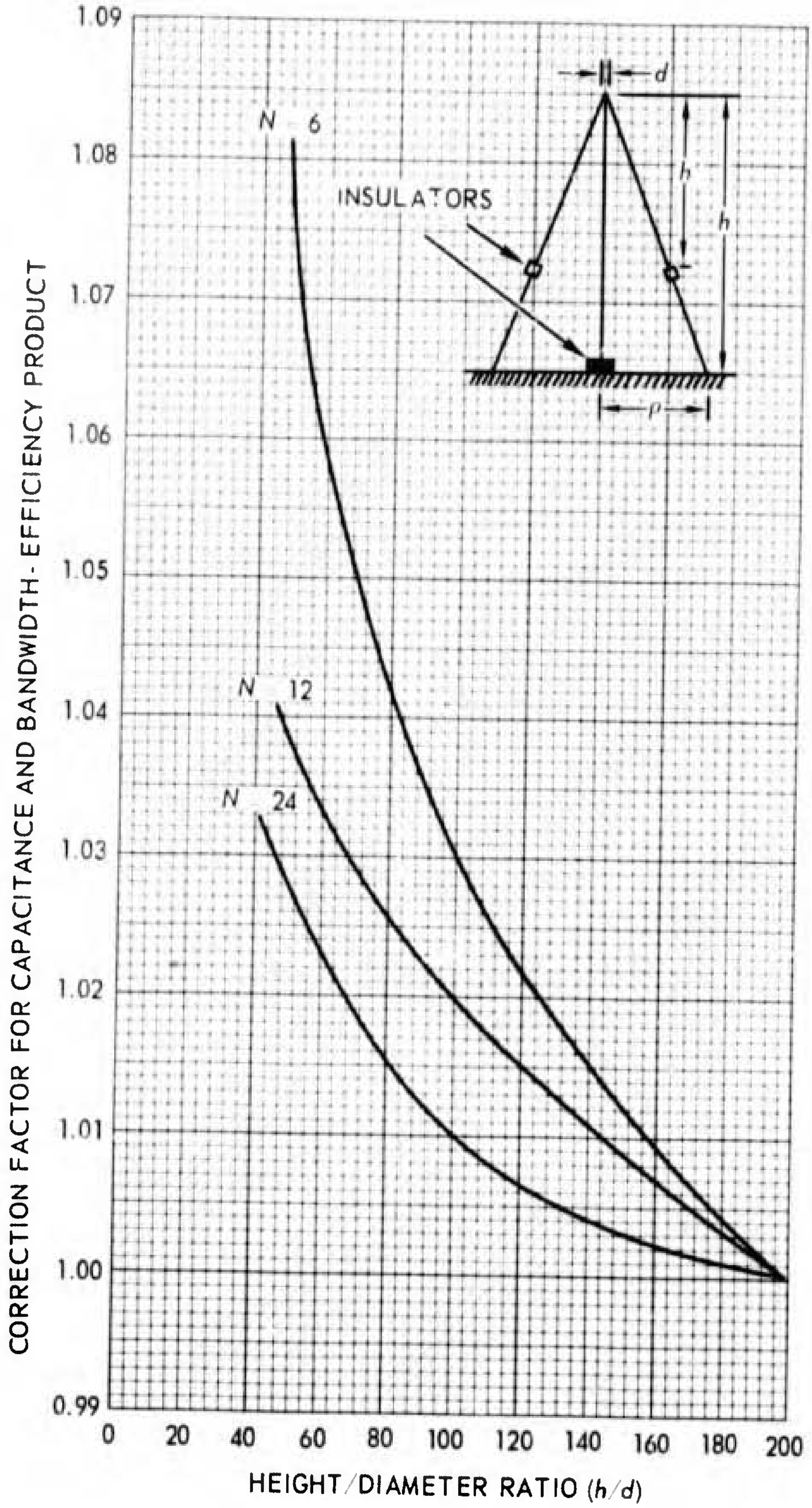

Figure 34. Correction factor for capacitance and bandwidth-efficiency product, $\rho = h$.

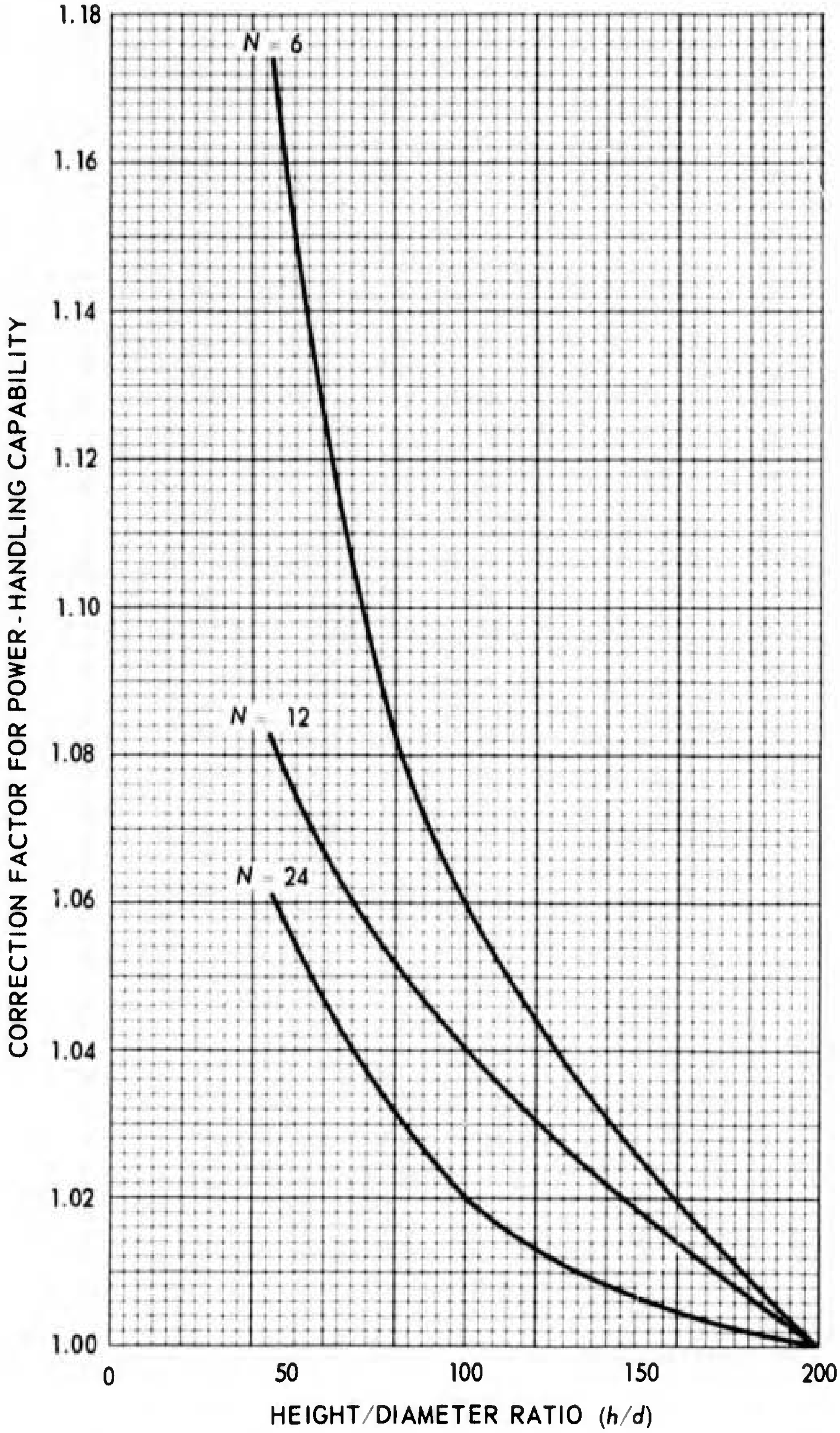

Figure 35. Correction factor for power-handling capability, $\rho = h$.

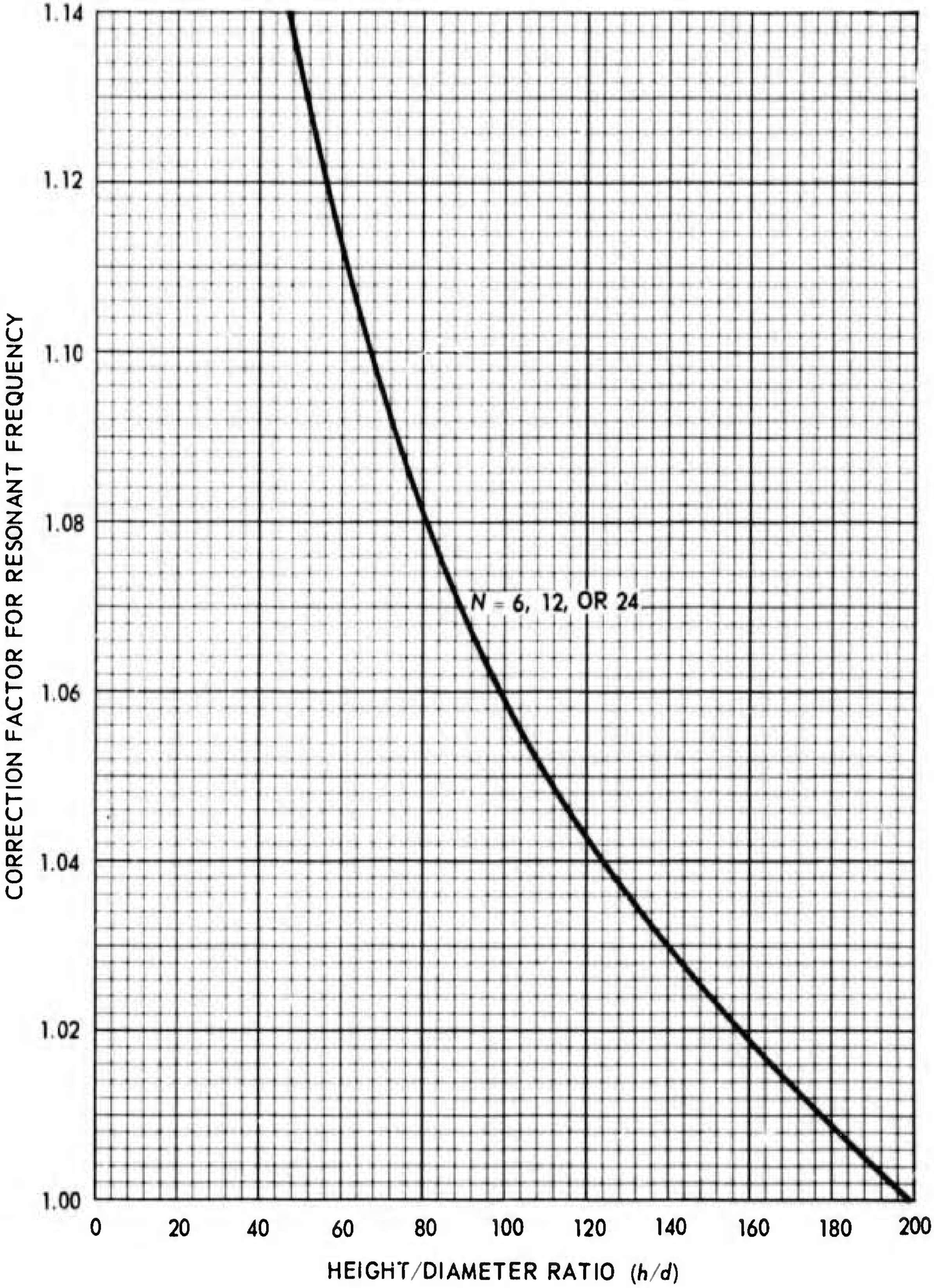

Figure 36. Correction factor for resonant frequency $\rho = h$.

STUDY OF RESULTS

Before we consider the uses of the data in specific applications, it will be helpful to consider the manner in which antenna properties change with top-hat configuration. For this purpose let us study the set $N = 12$ in Group II. The first two figures in the group are relative capacitance and relative resonant frequency. The relative capacitance is roughly proportional to top-hat area, and consequently increases continuously with increasing h'/h and increasing ρ. Since the resonant frequency varies inversely as the square root of the effective capacitance, the resonant frequency decreases with increasing h'/h and increasing ρ.

The third and fourth figures are closely related, since the relative radiation resistance is the square of the relative effective height. Both characteristics increase with ρ and both have a maximum for $h'/h \approx 0.3$. Therefore, an antenna designed for maximum radiation resistance will have a small top-hat. As is seen from the remaining figures, such an antenna will have poor bandwidth and poor power-handling capability. Since these later characteristics are generally of prime importance, no attempt is usually made to optimize the effective height.

The last three figures, which show bandwidth-efficiency product, power-handling capability, and power-bandwidth product, are of principal interest in antenna design. Looking at the figure for bandwidth-efficiency product, we find that for a given value of ρ the curve has a broad maximum in the neighborhood of $h'/h = 0.7$. For all values of h'/h, the bandwidth-efficiency product increases with ρ, being roughly proportional to ρ at the maximum.

The radiated-power capability is seen to increase with increasing h'/h and increasing ρ. The behavior is of particular interest in the neighborhood of $\rho = h$ and $h'/h = 0.7$, because $\rho = h$ is desirable from mechanical considerations, and $h'/h = 0.7$ provides optimum bandwidth-efficiency product. The figure shows that the gain in power-handling capability for $\rho = h$ is relatively slow as h'/h is increased beyond 0.7, the gain being about 18 percent at 0.9. For $h'/h = 0.7$, the gain with increasing ρ is quite rapid, being over 300 percent from $\rho = h$ to $\rho = 2h$.

The curves for power-bandwidth product resemble the curves for bandwidth-efficiency product. However, they reach maximum at $h'/h = 0.8$ instead of 0.7. As previously noted, for the important case, $\rho = h$, the radiated-power capability increases slowly between $h'/h = 0.7$ and $h'/h = 0.9$, and the bandwidth-efficiency product maximum is rather broad. It follows that if h'/h is made equal to 0.8 to maximize power-bandwidth product, both bandwidth-efficiency product and radiated-power capability will be close to maximum. The gain of power-bandwidth product with increasing ρ is very rapid. For example, with h'/h

optimum, a change from $\rho = h$ to $\rho = 2h$ increases the power-bandwidth product by over 600 percent.

It may seem from the sharp gains observed in bandwidth-efficiency product, power-handling capability, and power-bandwidth product with increasing ρ that the design engineer should strive to use maximum ρ. However, if the antenna form factor is kept constant, these properties also change rapidly with antenna height. For example, the power-bandwidth product varies as the seventh power of the height. Consequently, the 600-percent gain in power-bandwidth product which can be obtained by increasing ρ from h to $2h$ can also be obtained by increasing the height and all other dimensions by about 29 percent. In situations where there is no height limitation, mechanical and cost considerations usually favor the latter course.

So far we have considered only the set of figures for $N = 12$, but the same general conclusions would have been reached if we had considered the set $N = 6$ or $N = 24$. What remains is to determine how the antenna properties vary with the number of top-hat radials. The three figures of Group III present relative bandwidth-efficiency product, power-handling capability, and power-bandwidth product for the condition $\rho = h$, with the number of radials as a parameter. All three properties increase materially with increasing N. For example, if the bandwidth-efficiency product for $N = 12$, $h'/h = 0.7$ is taken as the reference, increasing N to 24 will increase the bandwidth-efficiency product by 23 percent and the power-handling capability by 50 percent.

Although the gains in performance with increase in number of top-hat radials are obviously substantial and do not involve any serious mechanical problems, an increase has to be justified on the basis of comparative cost. For a typical top-loaded antenna, it is believed that a 24-radial design will cost about 20 percent more than a 12-radial design. The same gain in performance could be achieved by increasing all dimensions by about 10 percent, which also would increase the cost by about 20 percent. Since there are many reasons other than cost for using the smallest suitable antenna, the 24-radial design is probably to be preferred in most cases.

DESIGN APPLICATIONS

As illustrations of the use of the design curves, two typical design problems will be considered. The first problem assumes that a 50-to-150-kc/s top-loaded antenna is to be designed for a site where the height limitation is 350 feet and the diameter cannot exceed 1000 feet. Cost does not allow the use of auxiliary towers. The antenna is to be used with a 50-kW transmitter. It is to have the maximum bandwidth-efficiency product consistent with other requirements.

The limited-space problem can be readily solved with the design curves. Since the bandwidth-efficiency product increases with the number of radials N and the value of ρ, the maximum practical number of top-hat radials, twenty-four, and the maximum permissible value of ρ, $(500/350)h$, or $1.43h$, are chosen. From the bandwidth-efficiency data for 24 radials and ρ equal $1.43h$, it is found that the bandwidth-efficiency product will be maximum for an h'/h ratio of 0.7, and will have a relative value of approximately 9. Since the bandwidth-efficiency product of the 350-foot reference antenna is 2.5 cycles at 50 kc/s (fig. 7), it follows that bandwidth-efficiency product for the proposed design is (9) (2.5), or 22.5 cycles.

For the conditions $N = 24$, $\rho = 1.43h$, and $h'/h = 0.7$, the radiated-power capability of the antenna at 50 kc/s is (0.206) (66), or 13.6 kW,

and the resonant frequency is (674) (0.245), or 165 kc/s.

The effective height is (175) (1.11), or 194 feet,

the radiation resistance at 50 kc/s is (0.125) (1.22), or 0.1525 ohm,

and the static capacitance is (1225) (7.45), or 9126 picofarads.

The static reactance (X_s) at 50 kc/s will be -347 ohms.

The input reactance of this type of antenna can readily be found for any frequency for which the electrical distance from the antenna base to the edge of the top-hat is not much greater than $\lambda/8$. Subject to this restriction the top-hat may be considered a capacitor with capacitance equal to the static capacitance of the antenna. This capacitance is in series with the inductance of the tower. At the resonant frequency of the antenna the top-hat capacitive reactance is canceled by the inductive reactance of the tower. From this approach

$$X_{in} = X_s \left[1 - (f/f_r)^2\right] \quad \text{ohms}$$

and for the design under consideration we have, at 50 kc/s,

$$X_{in} = -347\left[1 - (50/165)^2\right] = -315 \text{ ohms}$$

Now that the electrical properties of the tentative design have been established, the size of the transmitter needed for maximum radiated power must be determined. For this purpose we turn to the ground system design curves of Wait.[7] We find that for an idealized ground system extending to 500 feet and an average ground conductivity of 10 millimhos per meter, the ground loss resistance will be 0.06 to 0.07 ohm. Most measured data seem to indicate actual ground loss resistance several times these idealized values, perhaps 0.20 ohm for this design. With a tuning system Q of 1500 at 50 kc/s, the tuning loss resistance will be 0.21 ohm. Antenna system efficiency n will then be

$$\frac{0.15}{0.15 + 0.20 + 0.21}, \text{ or 27 percent}$$

The antenna system will require (13.6/0.27), or 50.4 kW, for maximum output. Losses in the matching transformer will be about 2 kW, so that about 52 kW of transmitter power will be needed for maximum output at 50 kc/s. Therefore, the proposed design meets the requirements of maximum bandwidth-efficiency product and suitability for use with a 50-kW transmitter.

The second problem is the design of an antenna for multichannel operation at 50 kc/s. For this method of communication an antenna system bandwidth of 1000 cycles might be required. If an antenna system efficiency of 50 percent is assumed, the required antenna system bandwidth-efficiency product becomes 500 cycles.

The bandwidth-efficiency product of the 360-foot antenna just considered is 22.5 cycles at 50 kc/s. If we remember that the static capacitance for a given design is proportional to antenna height, it is apparent from equation (4) that the bandwidth-efficiency product of the configuration just studied will increase as the cube of the height. A projection made on this basis indicates that an antenna suitable for multichannel operation at 50 kc/s will have to be at least 1000 feet high. A preliminary design is therefore considered which is 1000 feet high and has 24 top-hat radials and a value of ρ equal to h. The value $\rho = h$ is selected for mechanical considerations which are important in structures of this size.

A study of the relative bandwidth-efficiency curve for $N = 24$ and $\rho = h$ shows that at the optimum value of h'/h

$$\overline{BW}n = (58.5)(6.4), \text{ or 374 cycles}$$

To reach a bandwidth-efficiency product of 500 cycles, we must obviously either increase the ratio of ρ to h or increase the size of the antenna. Considering first an increase in ρ, we study figure 28. Since the bandwidth-efficiency product of the reference tower antenna is 58.5 cycles, a value of ρ must be chosen for which the relative bandwidth-efficiency product is 8.54. This value is $1.33h$. A check of the design curves reveals that for this configuration the resonant frequency is 62 kc/s.

Since for a constant form factor, the bandwidth-efficiency product varies as the cube of the height, the height will have to be increased by $(500/374)^{1/3}$, or 1.102 for a bandwidth-efficiency product of 500 cycles. Accordingly an 1100-foot antenna designed like the reference 1000-foot antenna will have the necessary bandwidth-efficiency product. Since the resonant frequency of the 1000-foot antenna was about 74 kc/s, the resonant frequency of the 1100-foot antenna will be 67 kc/s.

The tentative designs will have a radiation capability of many hundreds of kilowatts even at 50 kc/s, so that in this respect they exceed any probable requirement. However, the basic assumption upon which this analysis is based, that the electrical distance from the antenna base to the edge of the top-hat does not exceed $\lambda/8$, is violated over most of the 50-to-150-kc/s range. Above first resonance the input resistance and the input reactance will increase more rapidly than simple theory would predict. Model studies have shown, however, that the impedance characteristics will still be good up to about 2.4 times the frequency of first resonance, and the impedance properties of the 1100-foot design will accordingly be good up to about 160 kc/s. For the extended top-hat design the upper frequency of 150 kc/s is slightly beyond the region of good characteristics. As the 1100-foot design is also better mechanically, it is the better choice.

Other properties of this antenna are:

$$h_e = 616 \text{ feet}$$

$$C_s = 19,250 \text{ picofarads}$$

$$R_r = 1.54 \text{ ohms (at 50 kc/s)}$$

and

$$X_{in} = -73 \text{ ohms (at 50 kc/s)}.$$

CONCLUSIONS

It is believed that the design curves contain all the information needed to determine the electrical properties of top-loaded monopole antennas. Comparisons have been made between the properties predicted from these curves and those of actual full-scale antennas. After an adjustment has been made for the effect of sag upon the effective height, the agreement has been found to be good. For example the predicted static capacitance, effective height, and resonant frequency of the modified 612-foot top-loaded monopole antenna at the Navy Radio Station, Dixon, California, are all within a few percent of the measured values.

The design data have also been used to make comparisons between the electrical properties of various proprietary low-frequency antenna designs and those of top-loaded monopole antennas of comparable size and cost. In every case the properties of the top-loaded antennas have been better than those of the other antennas.

When a similar comparison is made between the 600-foot three-tower triatic antenna at Chollas Heights and top-loaded antennas of comparable height, the properties of the triatic antenna are found to be superior. For example, the Chollas Heights antenna has a bandwidth-efficiency product of about 2750 cycles at 100 kc/s while the 612-foot Dixon top-loaded monopole has a bandwidth-efficiency product of 1261 cycles. A more meaningful comparison can be made by considering the relative merits of a 600-foot triatic antenna and a top-loaded monopole antenna with the same bandwidth-efficiency product. A modern 600-foot triatic antenna, similar to the Chollas Heights antenna but using guyed towers to reduce cost, would occupy a roughly circular area about 800 feet in radius, and would cost more than twice as much as the present Dixon antenna. A top-loaded monopole antenna of the Dixon design but with the same bandwidth-efficiency product as the Chollas Heights antenna would be approximately 800 feet high and would occupy about the same area as the modern triatic antenna. The enlarged Dixon-type antenna would cost about 70 percent more than the present Dixon antenna. It follows that a triatic antenna will have about three-fourths the height of an equivalent top-loaded monopole antenna but will probably cost about 25 percent more. Therefore, the top-loaded monopole antenna should be used when cost is the controlling factor, but the triatic design should be considered when a height limitation makes it difficult to obtain the required bandwidth-efficiency product with the Dixon design.

RECOMMENDATIONS

It is recommended that the top-loaded monopole antenna be accepted as the Navy standard for low-frequency use.

It is also recommended that (1) operational requirements be established for a set of standard top-loaded antennas, (2) the various electrical designs which meet the requirements be determined from the design curves in this report, (3) the best designs from the mechanical and cost standpoints be selected, and (4) structural drawings be prepared for general Navy use.

Standard low-frequency antennas selected in this manner will closely resemble the modified Dixon antenna. They will differ from each other primarily in size. When a height limitation makes it difficult to meet operational requirements, the operational requirements should be compared with the properties of the largest standard antenna that can be built. If the required bandwidth-efficiency product is less than twice that of the standard antenna, it is recommended that it be obtained by modifying the standard design by extending the radius of the top-hat. If an area restriction does not permit an increase in the antenna diameter, then a triatic design should be used.

Finally, if the required bandwidth-efficiency product is more than twice that of the standard antenna, it is recommended that efficiency be reduced by resistor loading so that the bandwidth can be obtained by either of the two approaches mentioned above. However, before this is done, the required operating frequency should be carefully reviewed. It is probable that a higher operating frequency would be the better choice.

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13. ABSTRACT

Electrical properties of top-loaded monopole antennas and changes in these properties with top-hat configuration are analyzed and interpreted. It is recommended that the top-loaded monopole be accepted as the Navy standard for low-frequency use. Curves suitable for use in design are presented.

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