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A STUDY OF LF TOP-LOADED MONOPOLE ANTENNAS USING NUMERICAL MODELING TECHNIQUES. COMPARISON TO SCALED TEST MODEL MEASUREMENTS.

by

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A Study of LF Top-Loaded Monopole Antennas using Numerical Modeling Techniques. Comparison to Scaled Test Model Measurements.

by

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ABSTRACT

This thesis studies the electrical properties of a low frequency top-loaded monopole antenna. Several configurations of the antenna are developed using numerical modeling techniques. The electrical properties are calculated and compared with a set of measurements of a scaled test model. The results are presented in the form of design curves and comparison tables.

It is important for the U.S. Navy to have a reliable VLF and LF communication systems for world wide coverage. A need exists to increase the power handling capacity and the bandwidth of the existing VLF-LF antenna systems. This study provides the validation of numerical modeling techniques for future simulation of VLF antennas with corona rings. This will permit the design of improvements in the power handling capability by extending the onset of corona.

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I. INTRODUCTION

A. BACKGROUND

The low frequency, LF, portion of the radio frequency spectrum is characterized by relatively low ground wave attenuation and by reflection of the skywave components back to earth with very little penetration and absorption at the ionosphere. The relatively stable and reliable propagation characteristics are of particular importance and interest to communication system design engineers. Hence, maritime navigational aids and some communication systems operate within the frequency range of 10-to-500 kHz. Low frequency is also of special utility in the polar regions. This is due to relatively the low noise levels and severe ionospheric disturbances in these areas.

Low frequency transmission systems are expensive, and there are practical difficulties associated with the construction of antennas having dimensions appreciable with respect to a wavelength. These constraints have resulted in antennas being in the electrically 'small' category. An antenna is defined to be small if its largest dimension does not exceed one-eight wavelength [Ref. 1: p. 19-2]. Small antennas have problems associated with efficiency, power handling capacity and bandwidth. Most existing LF antennas in use are monopole antennas; top-loaded monopole antennas and flat tops.

A typical low frequency antenna is a top-loaded monopole supported by guy wires with an insulated base. The purpose of the capacitive top loading is to increase the system efficiency and the bandwidth or power handling capability of the transmission system [Refs. 2,3: pp. 1026-1038, 864-871].

Antenna engineers often use scale models of antennas as tools in antenna analysis and design. These test models, have the distinctive advantage of being less expensive to build than full size antennas, requiring only a small test area to make measurements and usually their prediction of the response of a full size antenna is satisfactory. Scaled test models are effective because of the linear property of Maxwell's equations. An antenna with certain properties at a given frequency, f, will have identically the same properties at another frequency, xf, provided all linear dimensions are scaled by the ratio 1/x. Thus an antenna design which works in one range of frequencies can be made to work at any other range of frequencies without any additional redesign, provided an exact scaling of dimensions can be accomplished. All the parameters such as length, frequency, dielectric constant, conductivity and permeability can be satisfactorily scaled except for the conductivity. If the full size antenna is constructed of copper or aluminum then it is very difficult to obtain any other material which have conductivities that are proportionally higher by the scaling factor. For VLF-LF antennas, conductivity and ground losses of an antenna play an important part in the radiating properties of the antenna. Slight discrepancies in scaling usually affect the impedance properties, therefore scale model impedance is considered qualitative. [Ref. 1: p. 2-51]

The U.S. Navy had been using VLF-LF regions of the frequency spectrum for many decades. A requirement for comprehensive documentation on the design aspect of VLF-LF antennas was needed. The Navy, in 1964, formed a team to determine the electrical properties of top-loaded LF monopole antennas with various top-hat configurations. This report was released in 1966.

A research and development report on top-loaded low frequency antennas [Ref. 4], also known as the Devaney report, covers the design aspects of the antennas within the frequency range of.50 to 150 kHz. It provides basic monopole information such as, static capacitance, resonant frequency, effective height and radiation resistance plus additional electrical properties, including power-bandwidth characteristics in groups of design curves. These design curves were made from a 100:1 scaled model of an LF top-loaded antenna with 6, 12 and 24 top-hat radials. The monopole, without top-hat, was studied at four frequencies, i.e., 50, 70.7, 100 and 150 kHz, while the top-loaded monopole antenna was investigated at 50 kHz. The reference monopole and top-loaded monopole antennas are as shown in Figure 1.1 and Figure 1.2 respectively.

The model was made with a 76-inch length of 0.375-inch OD brass tubing sitting on a half inch long insulator of slightly greater diameter. Nylon strings were used for structural guying. The top-loading wires were 10 mil. soft drawn copper. The model was constructed without sag in the top-hat radials.

The electrical properties measured for the test models, using test equipment, without top-hat and with top-hat radials, are the shunt capacitance, resonant frequency and effective height. For the top-loaded test model, studies are made with four values for the radial distance of the anchor point from base of the monopole, i.e., ρ = 0.5H, H, 1.5H and 2.0H. Each set of measurements was obtained by varying the projection of the active portion of the top-hat radials on the monopole antenna from 0.1H to

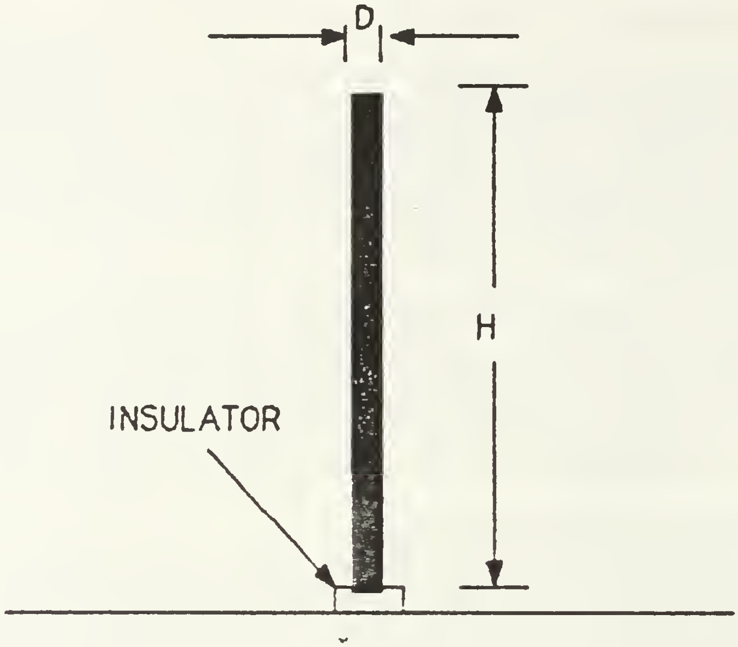


Figure 1.1 Reference Monopole Antenna.

0.9H in steps of 0.1H. The data was obtained for the reference monopole without top-hats by varying its scale height from 300 feet to 1000 feet and was labeled as reference data. This was later used in the computation of data for the design curves of the top-loaded antenna. These curves were presented in terms of ratios rather than absolute values. This study also presented the approximate effects of different monopole height to diameter ratios on the measured data.

The LF top-loaded monopole antenna is in the small antenna category at its frequencies of operation; i.e., the electrical distance from the base of the antenna to the end of the top-hat radials is less than one-eighth wavelength. The effective height of the reference monopole can be considered to be equal to one-half its physical height, and the effective capacitance of each antenna is equal to its static capacitance

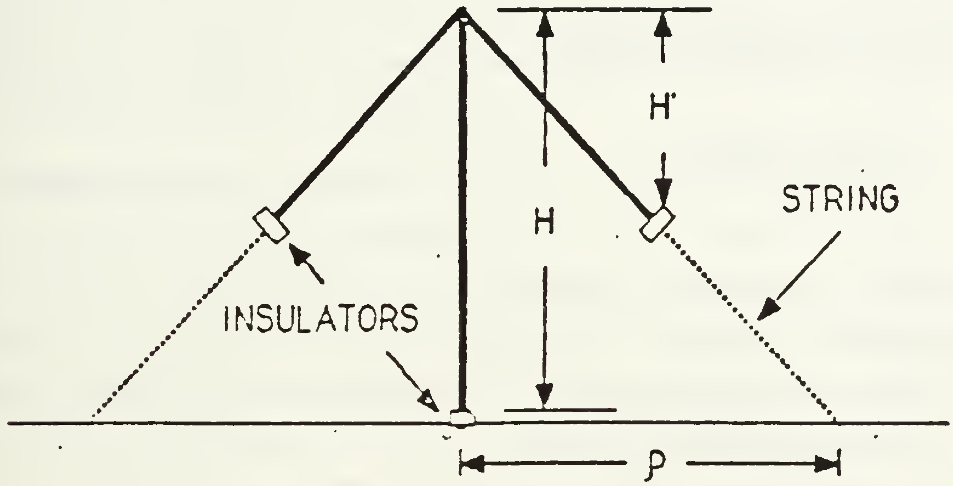


Figure 1.2 Top-Loaded Monopole Antenna.

[Ref. 1: p. 19-3]. The four other electrical properties computed were radiation resistance, antenna system bandwidth-efficiency product, maximum radiated power capability and the power-bandwidth product. These characteristics cannot be directly determined and simple formulas were used for their calculation. The formulas are:

$$RR = \frac{160\pi^2 HE^2}{\lambda^2} \quad \text{ohms} \qquad \text{(eqn 1.1)}$$

where RR is the radiation resistance.

$$\text{BW-}\eta = \frac{320\pi^3 HE^2 f^4 C_e}{c^2} \quad \text{cycles} \qquad \text{(eqn 1.2)}$$

where BW-η is the bandwidth efficiency product.

$$PW = \frac{0.64\pi^4 V^2 f^4 HE^2 C_e^{\ 2}}{c^2} \quad \text{kilowatts} \qquad \text{(eqn 1.3)}$$

where PW is the power handling capability.

$$\text{PW-BW} = \frac{204.8\pi^7 V^2 f^8 HE^4 C_e^{\ 3}}{c^4} \quad \text{kilowatt-cycles} \qquad \text{(eqn 1.4)}$$

where PW-BW is the power bandwidth product.

In the above Equations 1.1 to 1.4,

HE = effective height in meters

a = free space wavelength in meters

f = frequency in kHz

C_e = effective antenna capacitance in farads

V = maximum allowable base voltage

c = 3×10^8 meters per second.

In the actual computation of data for plotting of design curves, the 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 capacity by multiplying the relative radiation resistance by the square of relative capacitance; and the power bandwidth product by multiplying the square of the relative resistance by the cube of the relative capacitance. The design curves for top-loaded monopole antennas were presented in terms of relative values.

The report presented a family of design curves arranged in four groups. The characteristics of reference monopole and top-loaded monopole antennas were presented in the first two groups respectively. The third group contained the design curves for top-loaded antennas with emphasis on variation in characteristics due to the number of top-hat radials. The fourth group provided correction factors for other height-to-diameter ratios.

The report concluded with the study of design curves and a belief that it contained all relevant information needed to determine the electrical properties of top-loaded monopole antennas. The important results in the report were that the projected length of top-hat radials was seven-tenths of the antenna height for optimum bandwidth-efficiency product and it was eight-tenths of the antenna height for optimum power-bandwidth product. In most cases the number of top-hat radials should be 24 and anchored at a distance from base equal to the antenna height. Extending the anchor points outward improves the electrical properties when a height limitation exists [Ref. 4]. The report has been used as a reference by LF antenna design engineers for the past twenty years.

B. NEED FOR THE STUDY

The U.S. Navy is the prime user of the VLF-LF band for its general broadcast over long ranges. The full potential of VLF and LF transmitting stations can only be achieved if the radiating system is designed for maximum radiation efficiency. The degree to which this can be attained is a function of many factors such as, for a new system, land availability, permissible antenna height, bandwidth required, transmitter power and capital outlay. Systems with high reliability, redundant subsystems and high power output (0.25 to 2.0 MW) required by the U.S. Navy are very expensive. In today's age of economy, the Navy cannot afford to build new high power antennas. Alternatives must be explored for increasing the power-handling capacity and bandwidth of existing antennas, via modifications. The limiting factor in high power operation are base terminal voltage and corona. The voltage limit is associated with all insulators in the antenna system, i.e., base insulator assembly and guy wire insulators. The antenna structure is itself limited by the voltage above which the charge distribution caused by very large electric fields near the structure is strong enough to cause corona breakdown in air. When the antenna structure is exposed to wet weather, the voltage limit is reduced considerably below the dry value.

The phenomena of corona reduces the radiation efficiency of the antenna. Possible means to reduce its effects are by using corona rings at the ends of top-hat radials where charge concentrates and at the base of the antenna where high voltages are present due to large base currents flowing through highly reactive tuning elements.

This study provides a validation of numerical modeling techniques for future simulation of VLF antennas with corona rings. This will permit design improvements in power handling capacity by extending the onset of corona.

C. STATEMENT OF THE PROBLEM

This thesis determines using computer model studies, the electrical properties of top-loaded monopole antennas, operating in the low frequency range of 50-to-150 kHz, and the changes in these properties with variation in top-hat configuration and compares the computer model design curves with those from the Devaney report on low frequency top-loaded antennas.

Devaney's report was prepared by using a test model which was considered an idealized 100-1 scaled model of a 630 ft. top-loaded monopole with an antenna height-to-diameter, H/D, ratio of 200/1. The number of top-hat radials used were 6, 12 and 24. The antenna was operated at a scale frequency of 50 kHz and assumed to be base voltage limited at 100 KV(rms).

The computer models of the monopole and top-loaded antennas are developed by using a numerical modeling technique and with the same antenna parameters as the test model operating at a frequency of 50 kHz, and with 100 KV(rms) limit on the base voltage. The diameter of the top-hat radials was not scaled exactly due to code limitations on radius ratios for connecting wires. Comparison is made between the design curves of the scaled test model in the report and those obtained using the computer model.

D. SCOPE AND LIMITATIONS

This study presents a series of design curves for the LF top-loaded antennas using a computer model of the antennas. These curves are compared with those in the Devaney report, to validate numerical modeling techniques and provide a comparison for use by antenna design engineers. The study of a monopole antenna without a top-hat is limited to three frequencies; ie. 50 kHz, 100 kHz and 150 kHz. For the top-loaded antenna the frequency is 50 kHz and the number of top-hat radials are restricted to 6, 12 and 24. This limitation is because of the large volume of data required for the presentation of the design curves. Validation of numerical modeling techniques will allow further studies on top-loaded monopole antennas to be undertaken in the VLF-LF ranges for investigation of problems associated with limitations on power handling capacity of these antennas.

Additionally, this study determines the electrical properties of low frequency top-loaded antennas and the variation of properties with changes in the number of top-hat radials and their projected height (H′). Design curves are produced for use by antenna design engineers in choosing the dimensions of an antenna, given constraints on radiated power and system bandwidth.

II. COMPUTER MODELING

A. COMPUTER MODELS

This section presents the study of the models of low frequency monopole antennas. These models include monopole antennas with and without top-hat loading. All antenna structures are developed over perfect ground.

1. Reference Monopole Antenna (without top-hat)

The model is named the "reference monopole antenna" because all data computed is used to normalize data obtained for the top-loaded monopole antennas for convenience in design usage. This data is presented as design curves of top-loaded monopole antennas in term of ratios rather than absolute values. Height is varied from 300 feet to 1000 feet in steps of 100 feet. Height-to-diameter, H/D, ratio is 200/1 for all cases at 50 kHz, 100 kHz, and 150 kHz. The base is excited with a one volt E-gap voltage source. For effective height calculations, excitation is by an incident electric field of one volt/meter.

2. Top-Loaded Monopole Antenna

The low frequency top-loaded monopole antenna is modeled at an antenna height of 630 feet. Antenna parameters are the same as for the reference monopole except the number of top-hat radials are 6, 12 and 24. The diameter of the top-hat radials is the same as the center monopole. The frequency is 50 kHz. For each case study, the antenna is modeled with a fix number of top hat radials and for four values of radial distance of anchor point from the base of the antenna.

B. ELECTRICAL PROPERTIES OF MONOPOLE ANTENNAS

The electrical properties studied and computed for both monopole antennas are static capacitance, resonant frequency, effective height, radiation resistance, bandwidth-efficiency product, power handling capability and power-bandwidth product.

Variations in top-hat configuration, in the radial distance of the anchor point from the base of the antenna and in the active height are exactly the same as for the scaled test model. Design curves are normalized and all the values for height and distances are expressed in terms of monopole height, H, for universal application.

C. DATA ANALYSIS

1. Small Antenna Characteristics

In the low frequency region of the radio frequency spectrum the wavelength is very long, and even though antennas operating in this range are physically large radiating structures, they are still small with respect to a wavelength. These antennas have low radiation resistance and high input reactance. The low value of radiation resistance results in large currents for a given amount of radiated power. This combined with circuit, conductor and ground losses, results in reduced radiation efficiency. The large reactance results in large voltages on the antenna structure and the need for a tuning device. The ratio of large reactance to small resistance produces a high circuit Q for the antenna, resulting in small antenna system bandwidth. The equivalent circuit for an electrically short top-loaded monopole is shown in Figure 2.1.

The equivalent circuit is a single tuned circuit, tuned to resonance with an inductor. The antenna consists of components to the right of the antenna base terminal. The antenna system includes both the antenna and the tuning reactance.

The antenna input base impedance, Z_b, and the base voltage, V, are given by the following equations:

$$Z_b = R_b + jX_b \quad \text{ohms} \qquad \text{(eqn 2.1)}$$

$$V = I_b X_b \quad \text{volts} \qquad \text{(eqn 2.2)}$$

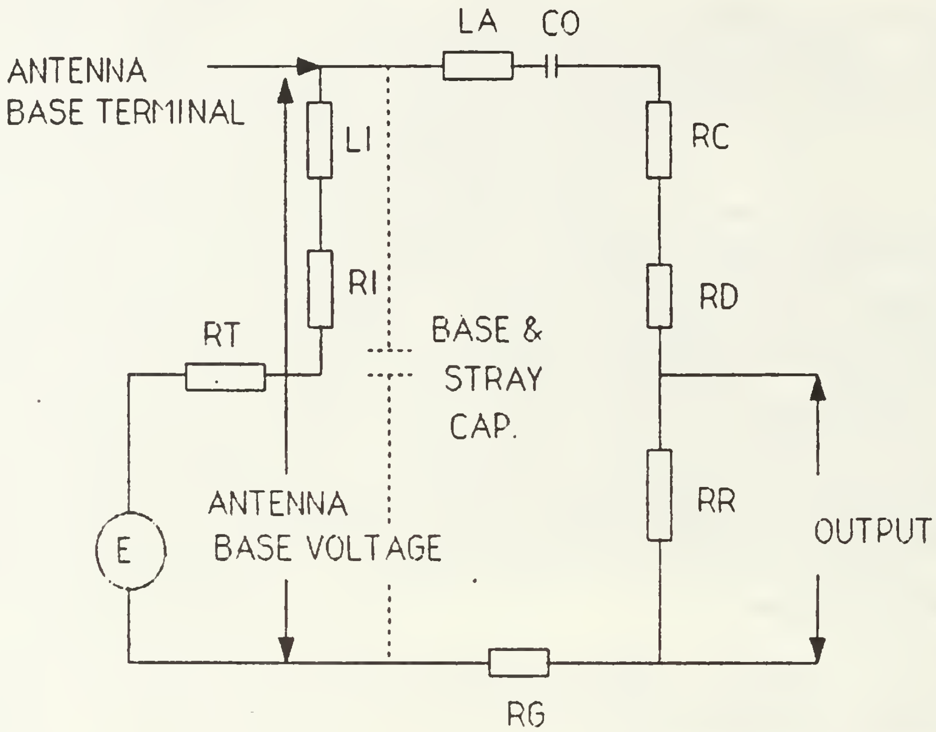
Since for electrically small antennas $X_b >> R_b$, $|Z_b|$ is approximately equal to X_b. The radiated power, PW, for the antenna is:

$$PW = I_b^2 RR \quad \text{watts} \qquad \text{(eqn 2.3)}$$

where RR is the radiation resistance.

The current required for a given radiated power depends upon the radiation resistance only and is:

$$I_b = \frac{\sqrt{(PR)}}{\sqrt{(RR)}} \quad \text{amperes} \qquad \text{(eqn 2.4)}$$



CO : ANTENNA STATIC CAPACITANCE
RC : COPPER LOSS RESISTANCE
RD : EQUIVALENT SERIES DIELECTRIC RESISTANCE
RR : RADIATION RESISTANCE
RG : GROUND LOSS RESISTANCE
RT : EQUIVALENT TRANSMITTER RESISTANCE

Figure 2.1 Antenna Equivalent Circuit.

Thus for a given radiated power, the antenna system voltage and current are independent of efficiency. As efficiency is reduced below one, more input power is required to maintain the same radiated power. The antenna current and voltage will remain the same. Another mathematical expression for determining radiated power is:

$$\frac{X_b^{\,2}}{RR} = \frac{V^2_{max}}{PW} \qquad \text{(eqn 2.5)}$$

where, V_{max} is the maximum base voltage. This relationship is very useful if given only the base voltage limit and the radiated power requirement.

The radiation efficiency of an antenna can be defined by:

$$\eta = \frac{RR}{R_b} \quad \text{ohms} \qquad \text{(eqn 2.6)}$$

where

$R_b = RR + RC + RD + RG.$

The antenna system loss resistance, R_{as}, is greater than the antenna loss resistance, R_b, because the resistance of the tuning reactances is included. The antenna system radiation efficiency, η_{as}, is less than the antenna efficiency and is given by:

$$\eta_{as} = \frac{RR}{R_{as}} \qquad \text{(eqn 2.7)}$$

where

$R_{as} = R_b + RI.$

The antenna bandwidth-efficiency product is the 3dB bandwidth of the antenna, in the absence of losses, i.e., for a radiation efficiency of 1. It is expressed as:

$$BW = \frac{f}{Q_r} \qquad \text{(eqn 2.8)}$$

where

f = the operating frequency

Q_r = ratio of capacitive reactance to radiation resistance.

The antenna system consists of the antenna and the tuning reactive element. The unloaded antenna system bandwidth is greater than antenna bandwidth because the antenna system radiation efficiency is less than antenna efficiency. The loaded antenna bandwidth includes the effects of the transmitter resistance, RT.

The power handling capability of an antenna is limited by either high voltage causing insulator breakdown or high current resulting in excessive heating. Voltage is usually the limiting factor in the case of low frequency antennas. All insulators used in the antenna system have associated voltage limits; even the radiating structure itself is voltage limited by fields near the structure which can become strong enough to cause breakdown of air resulting in corona effects.

2. Computer Model Data Calculation Methods

Models developed for the reference monopole and the top-loaded monopole antennas are electrically 'small'. The monopole can be considered as a center driven dipole in free space whose lower half is imaged in the ground. Currents on the vertical part of the monopole and its image flow in the same direction, i.e., the currents are in phase. In the case of top-loaded monopole antenna the current in the top- hat radials and its image are partially out of phase. Hence, radiation due to these almost cancels. The base resistance of the model antennas is sum of the radiation resistance and ground resistance. Ground resistance, copper loss resistance and equivalent series dielectric resistance, are zero for this study as the antennas are modeled over a perfect ground and with perfect conductors. Thus, base resistance is equal to radiation resistance.

Numerical Electromagnetic Code, NEC, produces output which includes impedance, voltage at the input terminals of the antenna and current distribution along the length of the radiator. All electrical properties for the antennas are computed by utilizing the output obtained from the NEC runs. Static capacitance is determined by lowering the operating frequency; as it approaches zero and the value of capacitance becomes constant. This constant value is termed static capacitance. The self resonant frequency of the antenna is determined by observing the operating frequency at which the antenna terminal reactance is zero, at which point the terminal current and voltage are in phase. These LF antennas are operated below their self resonant frequency. Effective height, a very useful parameter in antenna analysis, is derived from the ratio of the open circuit voltage at the terminals of an antenna to the incident electric field exciting it [Ref. 5: p. 4-23], and is:

$$HE = \frac{V_{op}}{E_i} \qquad \text{(eqn 2.9)}$$

where

HE = effective height

V_{op} = open circuit terminal voltage

E_i = incident electric field.

The open circuit voltage using NEC is found by determining the short circuit current and the base impedance. The incident electric field, E_i, used to excite the antenna is one volt/meter. NEC produces twice the effective height because with one volt/meter incident free-space excitation, two volts/meter exists over a perfect ground, due to reflections.

Radiation resistance is important in determining the allowable losses in the ground and tuning system for a given efficiency. Radiation resistance in this investigation is equal to the base resistance. Therefore, the efficiency of the antenna models is 100 percent. The bandwidth efficiency product indicates the capability of a transmitting system to handle wideband information. In this study, antenna bandwidth is a calculated quantity. It is determined by operating the antenna at its operating frequency, 50 kHz. All the reactance is tuned out by placing a reactive tuning element in the antenna circuit. The frequency is then varied above 50 kHz while observing the reactance until the reactive component of input impedance is equal to the resistive component. This is the upper 3dB frequency limit; the lower 3dB value is calculated in the same way by lowering the frequency. The difference between the upper and lower 3dB frequencies is the bandwidth of the antenna. Maximum radiated-power is limited, in this study, to 100 KV(rms) at base. This is determined from the radiation resistance across the input terminals and the current required to produce 100 KV. The power bandwidth product is computed by multiplying maximum radiated-power and the bandwidth-efficiency product. It is a commonly used figure of merit for these antennas.

The expressions in Equation 2.10 to Equation 2.12, are used to compute bandwidth-efficiency product, BW-η, maximum radiated-power PW, and power-bandwidth product, PW-BW, respectively. Maximum radiated-power is also referred to as power handling capability in this study.

$$BW\text{-}\eta = RR'C' \qquad \text{(eqn 2.10)}$$

$$PW' = RR'(C')^2 \qquad \text{(eqn 2.11)}$$

$$PW\text{-}BW = (RR')^2(C')^3 \qquad \text{(eqn 2.12)}$$

where

$$C' = \frac{C}{CO} \qquad \text{(eqn 2.13)}$$

Data for the top-loaded monopole antenna is in "relative values", i.e., top-loaded monopole values are divided by reference monopole values, and are indicated by the use of primes with the terms. Oh's are added to designate terms for the reference antenna.

III. COMPUTER MODEL RESULTS

The results of this computer model study of low frequency top-loaded monopoles, using numerical modeling techniques, are presented as a family of design curves. These are arranged in three sections. The first two sections present the electrical properties of a reference monopole and a top-loaded monopole with 6, 12, and 24 top-hat radials. In the third section emphasis is on the dependence of antenna performance on the number of top-hat radials. All curves are plotted along with those from the Devaney report, for comparison purposes.

A. ELECTRICAL PROPERTIES OF A REFERENCE MONOPOLE ANTENNA

The design curves in this section, from Figure 3.1 to Figure 3.7, present the electrical properties of reference monopole antenna. These are static capacitance, resonant frequency, effective height, radiation resistance, bandwidth-efficiency product, maximum radiated power, and power-bandwidth product and are plotted as a function of monopole heights of 300 to 1000 feet in steps of 100 feet. Data for radiation resistance, bandwidth-efficiency product, maximum radiated-power, and power-bandwidth product is also plotted with frequency as a parameter, for 50 kHz, 100 kHz, and 150 kHz. Height-to-diameter, H/D, ratio is maintained constant at 200/1.

The design curves show that as the height of the antenna increases, the static capacitance increases. This reduces the capacitive reactance of the antenna resulting in a more uniform distribution of current and increases radiation resistance, hence, improves efficiency and bandwidth of the antenna. Effective height and other electrical properties increase with increase in physical height of the antenna except the resonant frequency which decreases. A comparison between NEC design curves and scaled test model curves is made in terms of percent difference and is presented in Table 1.

The absolute value of static capacitance for the reference monopole test model was measured with a Boonton Model-260A Q-meter. Errors up to 12 percent were expected. The difference between the static capacitance curves, in Figure 3.1, is 4 percent, well within the test model error limits. The true resonant frequency was carefully measured by inducing a voltage into the test 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 same height. The

TABLE 1

COMPARISON OF DESIGN CURVES-REFERENCE MONOPOLE ANTENNA

Antenna Properties	Percentage Difference
Static Cap.	3.4% to 4.4%
Resonant Freq.	less than 1.5%
Effective Ht.	96% to 99.5%
Radiation Res.	less than 6%
BW-η Product	65% to 75%
Rad. Power	less than 16%
PW-BW Product	less than 35%

resonant frequency of the computer model of the reference monopole antenna is where the terminal reactance becomes zero. The difference between the curves, in Figure 3.3, for the test model and the computer model is less than 1.5 percent.

The calculated effective height is almost twice that of the scaled test model because of the difference in incident field. For the test model it was specified equal to one-half of the physical height while for the computer model it is calculated for the incident electric field, as shown in equation 2.9. When the antenna is excited by an incident electric field of one volt/meter, two volts/meter exists over perfect ground due to ground wave reflection. NEC thus gives twice the effective height as it does not account for the reflected energy from ground when incident fields are specified.

The bandwidth-efficiency product, in Figure 3.5, is 65% to 75% higher than that of the scaled test model. This may be because of the difference in the method of calculations used in the two studies. The bandwidth of the computer model is determined from radiation properties of the antenna. The bandwidth of the test model is calculated by using the formula given in Equation 1.2 and is a function of effective height, frequency and static capacitance.

It is evident from the curves for effective height, Figure 3.3, and bandwidth-efficiency product, Figure 3.5, that increasing effective height results in greater bandwidth-efficiency product. There is a practical cost effective monopole height limit beyond which an increase in antenna static capacitance is obtained by using top-loading with the monopole to increase bandwidth efficiency product. Power-bandwidth product, a figure of merit, is the product of radiated-power and bandwidth-efficiency product and can be improved by increasing breakdown voltage limits.

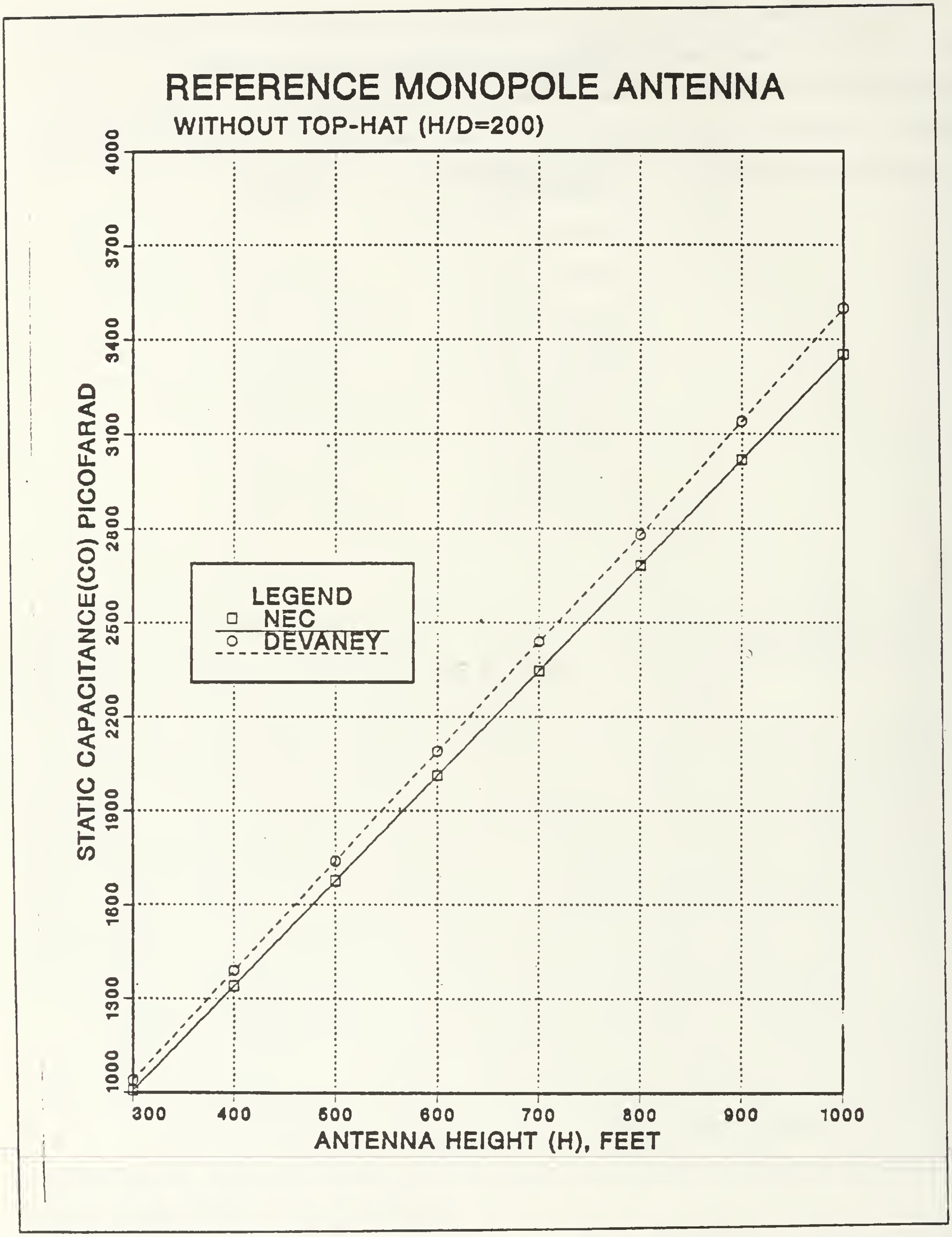


Figure 3.1 Variation of Static Capacitance of Reference Antenna as a Function of Antenna Height.

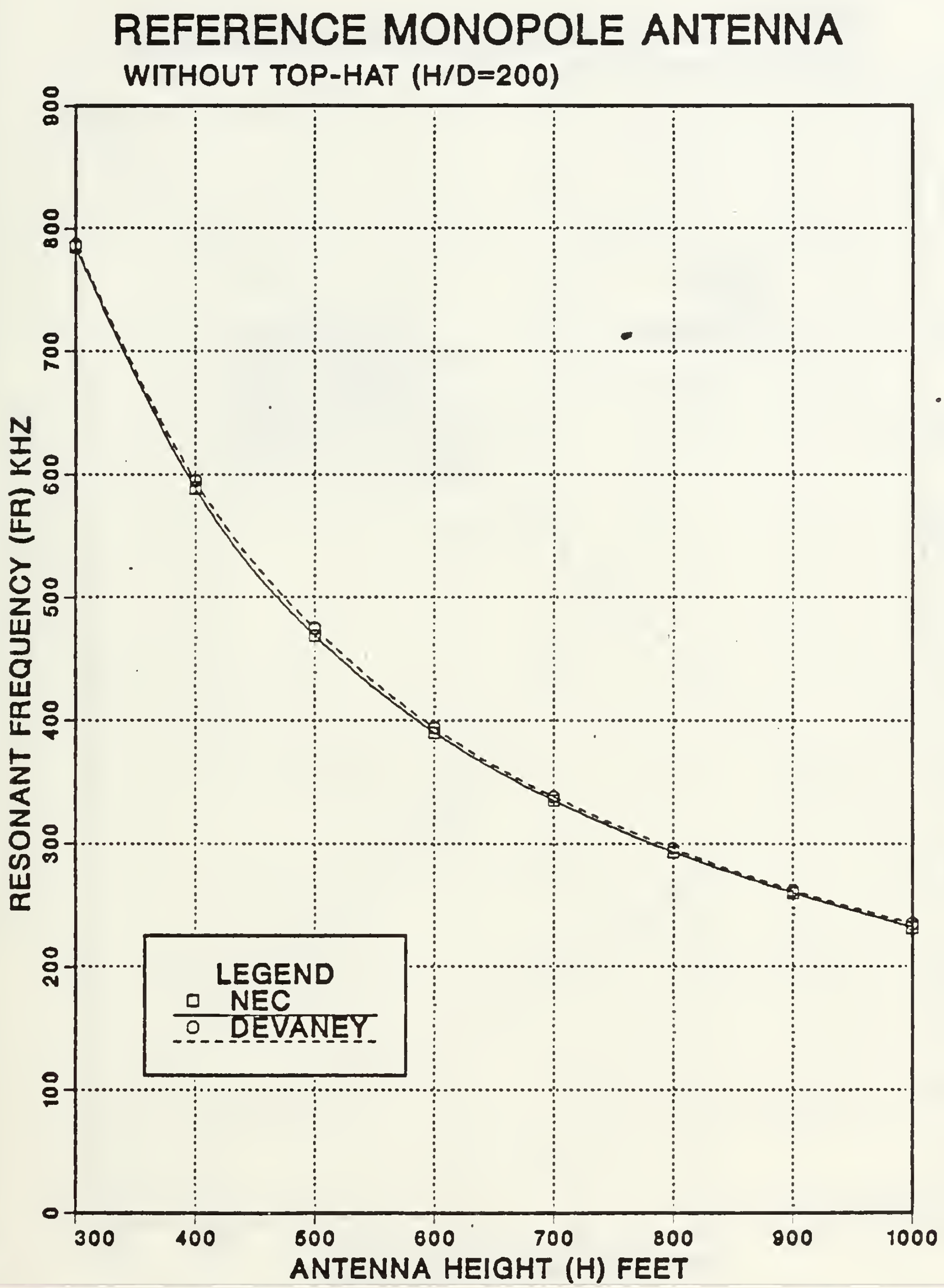


Figure 3.2 Variation of Resonant Frequency of Reference Antenna as a Function of Antenna Height.

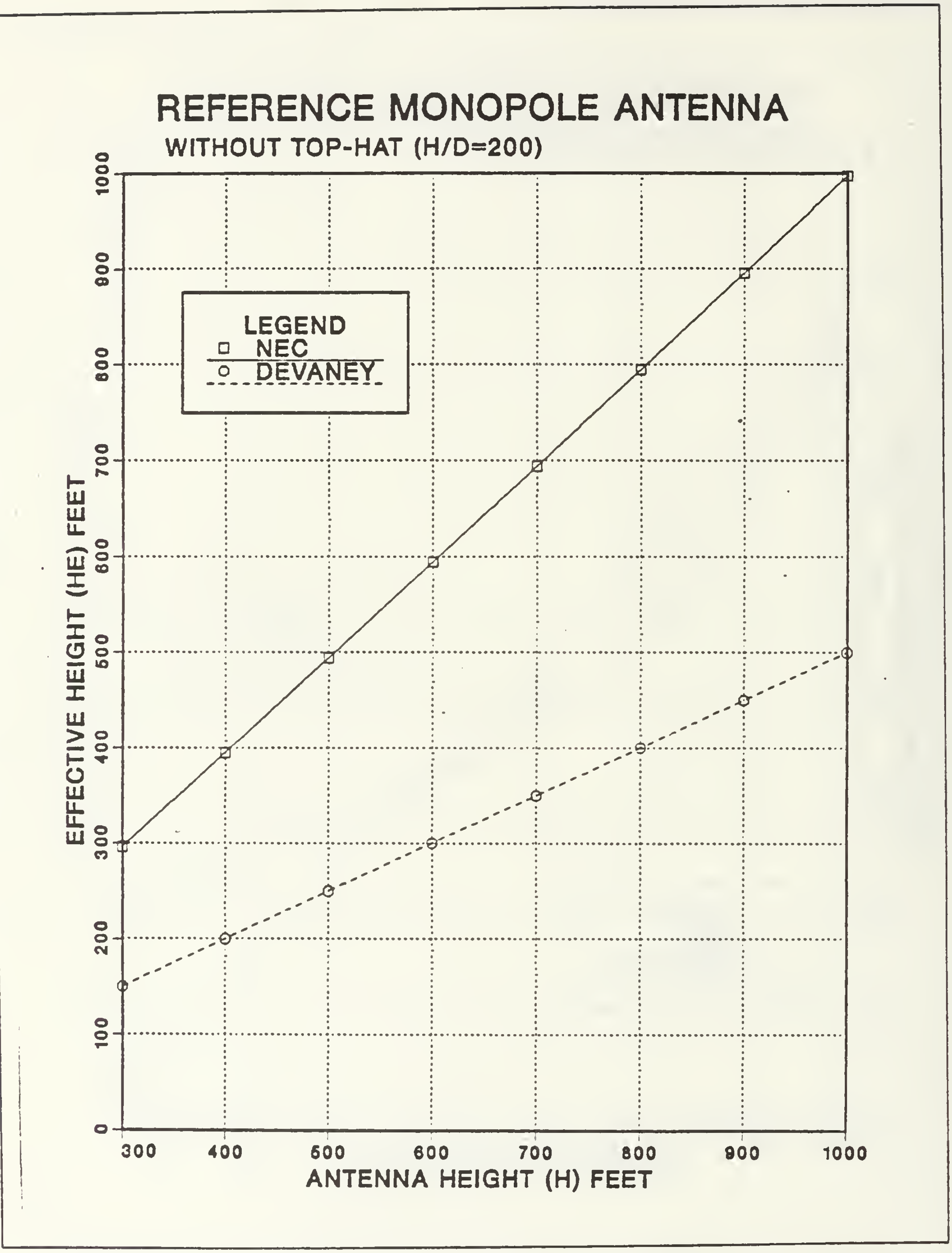


Figure 3.3 Variation of Effective Height of Reference Antenna as a Function of Antenna Height.

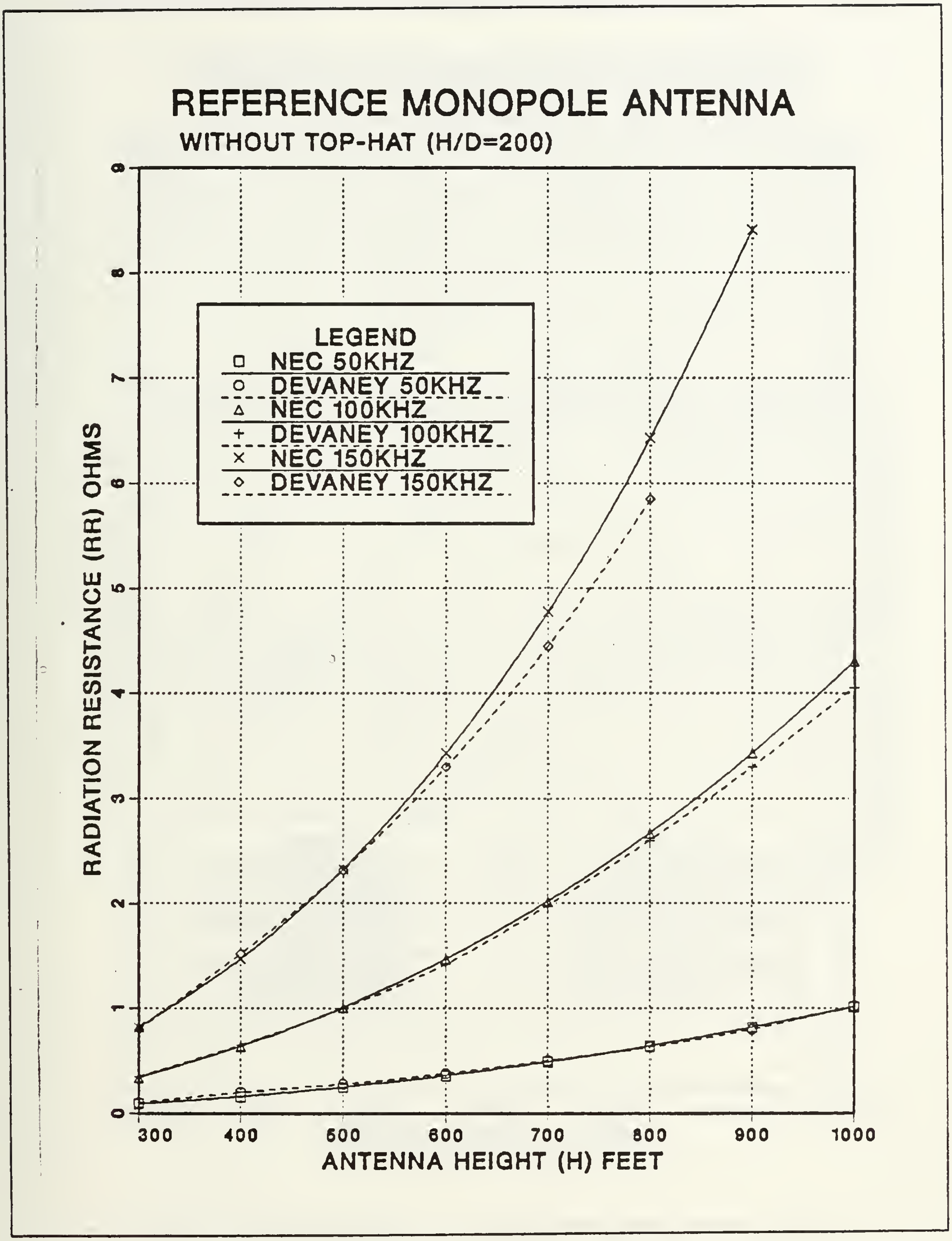


Figure 3.4 Variation of Radiation Resistance of Reference Antenna as a Function of Antenna Height.

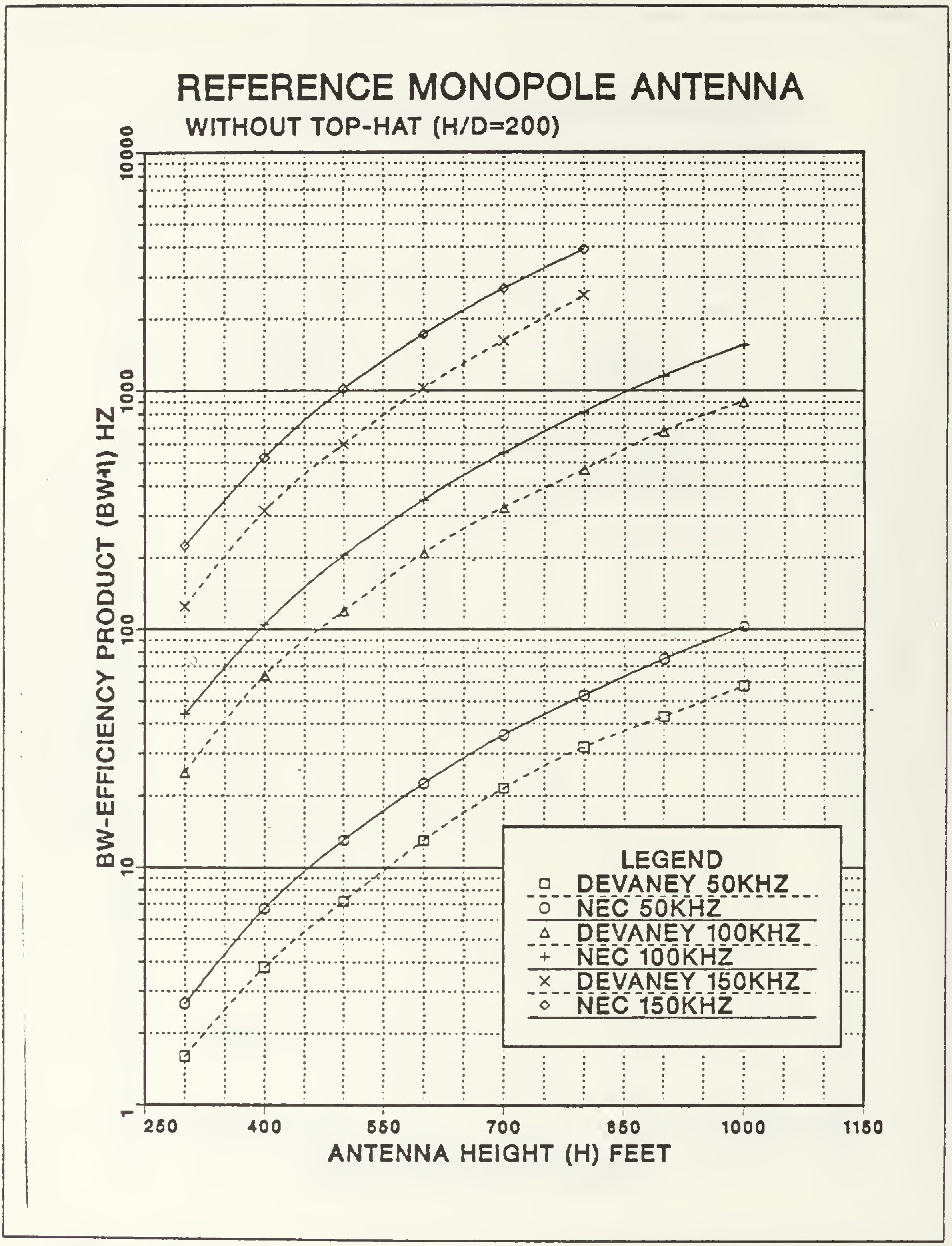


Figure 3.5 Variation of Reference Antenna Bandwidth-Efficiency Product as a Function of Antenna Height.

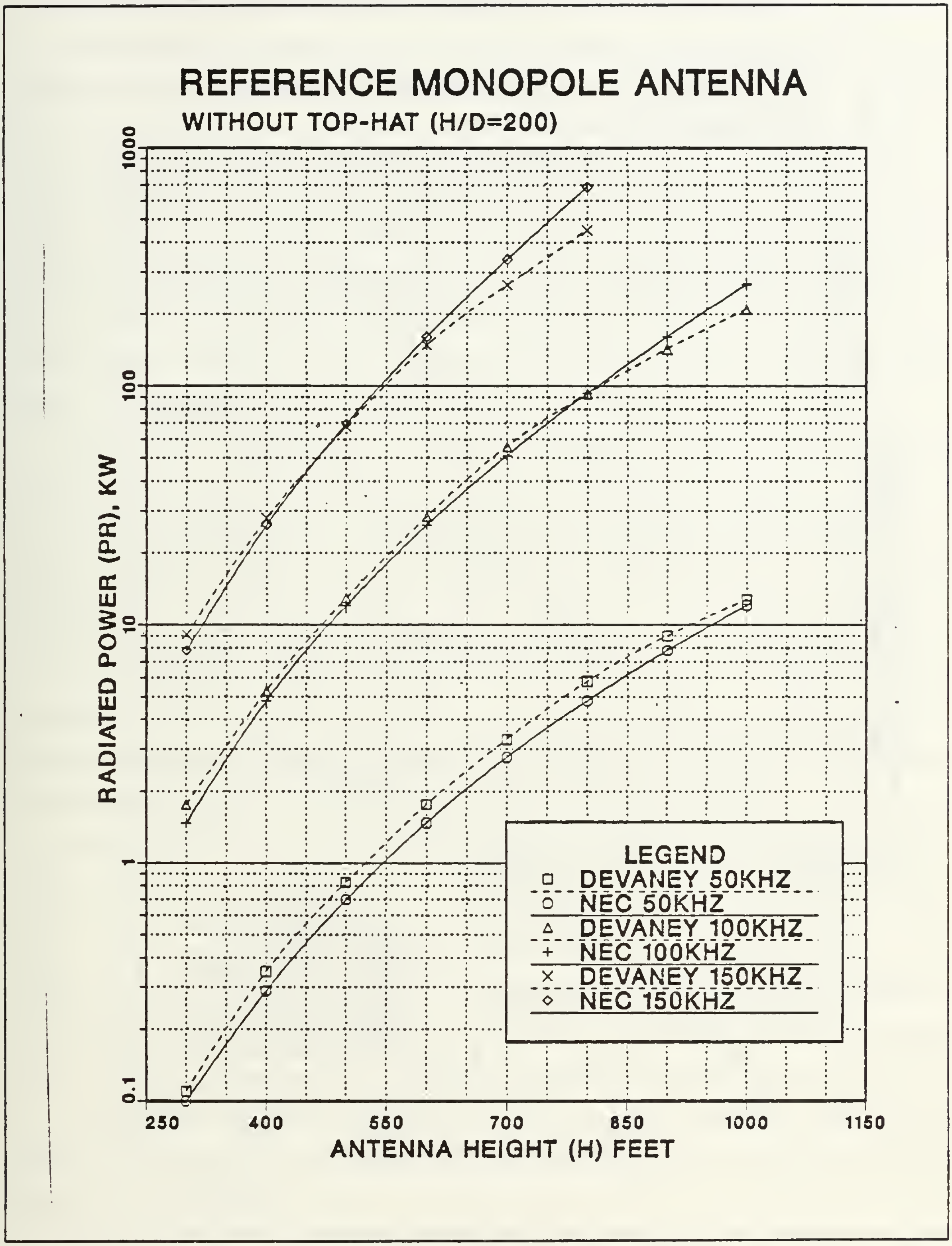


Figure 3.6 Variation of Reference Antenna Maximum Radiated-Power Capability as a Function of Antenna Height.

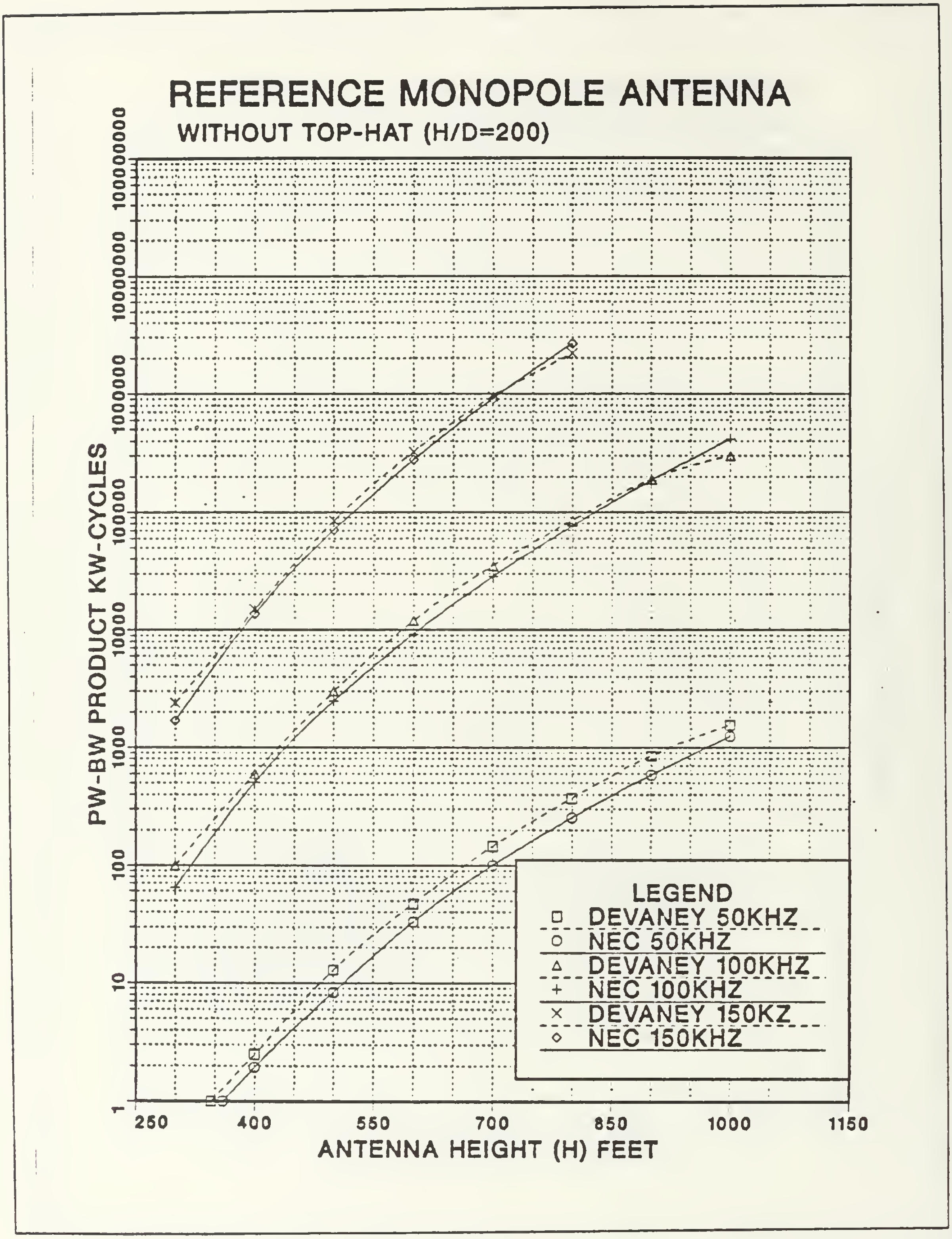


Figure 3.7 Variation of Reference Antenna Power-Bandwidth Product as a Function of Antenna Height.

B. ELECTRICAL PROPERTIES OF TOP-LOADED ANTENNAS

The electrical properties of a top-loaded monopole antenna, height 630 feet, are studied for three different top-hat configurations. Design curves are presented in terms of properties of a reference monopole antenna of the same height. Curves in Figure 3.8 to Figure 3.14 are plotted for 6 top-hat radials. Figures A.1 to A.7 for 12 top-hat radials and Figures A.8 to A.14 for 24 top-hat radials are placed in Appendix A. Four curves are plotted in each figure for four values of ρ, the radial distance from the base of center monopole to the anchor point, i.e., 0.5H, H, 1.5H, and 2.0H. For each curve data is plotted versus the fractional projected lengths of the active height, H', of the top-hat radials, which vary from one-tenth to nine-tenth of the center monopole height in steps of one-tenth.

These design curves indicate the manner in which the electrical properties of the antennas change with variation in active height, H', the distance of anchor point from the guys, ρ, and the number of top-hat radials, N. As H'/H, ρ and N increases, the relative capacitance also increases and resonant frequency decreases. The effective height and the radiation resistance increase only to a point, beyond which they decrease even with an increase in antenna top-loading. For a given value of ρ, the maximum value for effective height and radiation resistance are for H'/H approximately equal to 0.2. If an antenna is designed at this ratio of H'/H, it will have maximum radiation resistance and maximum effective height but will have a small top-hat resulting in narrow bandwidth and low power-handling capability.

Bandwidth-efficiency product, power-handling capability and power-bandwidth product are three important electrical properties. Curves for bandwidth-efficiency product show that it increases with ρ. The maximum value is in a broad region near H'/H = 0.55. Power-handling capability also increases very rapidly with ρ. It is maximum in the region where H'/H = 0.7 to 0.8 and beyond this, starts to decrease. The power-bandwidth product curves are similar to bandwidth-efficiency product curves and have a broad region of slow variation near the maximum value of H'/H = 0.7. This means, if H'/H is selected as 0.7 both power-handling capability and bandwidth-efficiency product will be close to the optimum and will result in maximum power-bandwidth product.

Bandwidth-efficiency product, power-handling capability and power-bandwidth product are also a function of ρ. To determine the manner in which these change with variation in ρ, consider the number of top-hat radials, N = 6, and ρ = H. The bandwidth-efficiency product, in Figure 3.12, has an optimum value at 0.55, and when ρ is changed to 2H the corresponding increase is 34 percent. Power-handling capability, in Figure 3.13, varies slowly between H'/H = 0.6 to 0.9 and power increase within this region is 10 percent at 0.8. If ρ is changed from H to 2H the power improvement at its optimum value, increases by 150 percent. Power-bandwidth curve, in Figure 3.14, also varies very slowly in the neighborhood of its optimum value. If ρ is increased from H to 2H the improvement in power-bandwidth product is rapid, increasing by 313 percent. Similar improvements shall also be observed if the set of curves for N = 12 and N = 24 are considered.

In brief, the increase in top loading of the antenna results in an increase in capacitance, reducing the capacitive reactance at the base of the antenna and increasing the current moment, thus increasing the radiation resistance. This results in improvements in radiation efficiency and bandwidth. It also reduces base terminal voltage because the tuning reactance required to cancel capacitive reactance of the antenna is reduced. A comparison between these design curves and scaled test model curves is made in terms of percent difference and is presented in Table 2. Table 3 shows the comparison between optimum values for the computer model and the scaled test model.

There are differences between the design curves of the computer model and the scaled test model. The principle reason for differences may be that the diameter of top-hat radials for the computer model is equal to the diameter of the center monopole, while the diameter of top-hat radials of the test model was the scaled value of 10 mil. or a full scale value of 1 inch. Another reason could be that the curves for all the electrical properties of computer model are calculated from the data obtained from a radiating antenna, such as input impedance and current, as discussed in Section C of Chapter II. For the test model, the static capacitance was measured with a Boonton Model 260A Q-meter, and the ratios of capacitance of a top-loaded monopole antenna to reference monopole were obtained. The ratio of resonant frequencies was found with a grid dip meter. Each frequency reading was monitored on an electronic counter. The relative effective height of the test model was determined by finding the ratio of field intensity of the top-loaded monopole to that of the reference antenna, which was considered one-half of the physical height.

TABLE 2

MAXIMUM DIFFERENCES FOR NEC VS DEVANEY TOP-LOADED MONOPOLE ANTENNA

Antenna Properties	H'/H Region	N = 6	N = 12	N = 24
Static Capacitance	0.1 to 0.9	27%	30%	30%
Resonant frequency	0.1 to 0.9	15%	12%	12%
Effective Height	0.1 to 0.5	15%	15%	16%
Radiation Resistance	0.1 to 0.5	12%	13%	15%
BW-η Product	0.4 to 0.8	23%	26%	25%
Radiated Power	0.5 to 0.9	40%	34%	25%
PW-BW product	0.6 to 0.8	35%	32%	28%

TABLE 3

COMPARISON OF OPTIMUM VALUES OF TOP-LOADED MONOPOLE ANTENNAS

Antenna properties	Optimum for NEC Model	Optimum for Test model
Radiation Res.	0.2-to-0.3	0.3
Effective Ht.	0.2-to-0.3	0.3
BW-η Product	0.5-to-0.6	0.7
Rad. Power	0.7-to-0.8	0.9
PW-BW Product	0.6-to-0.7	0.8

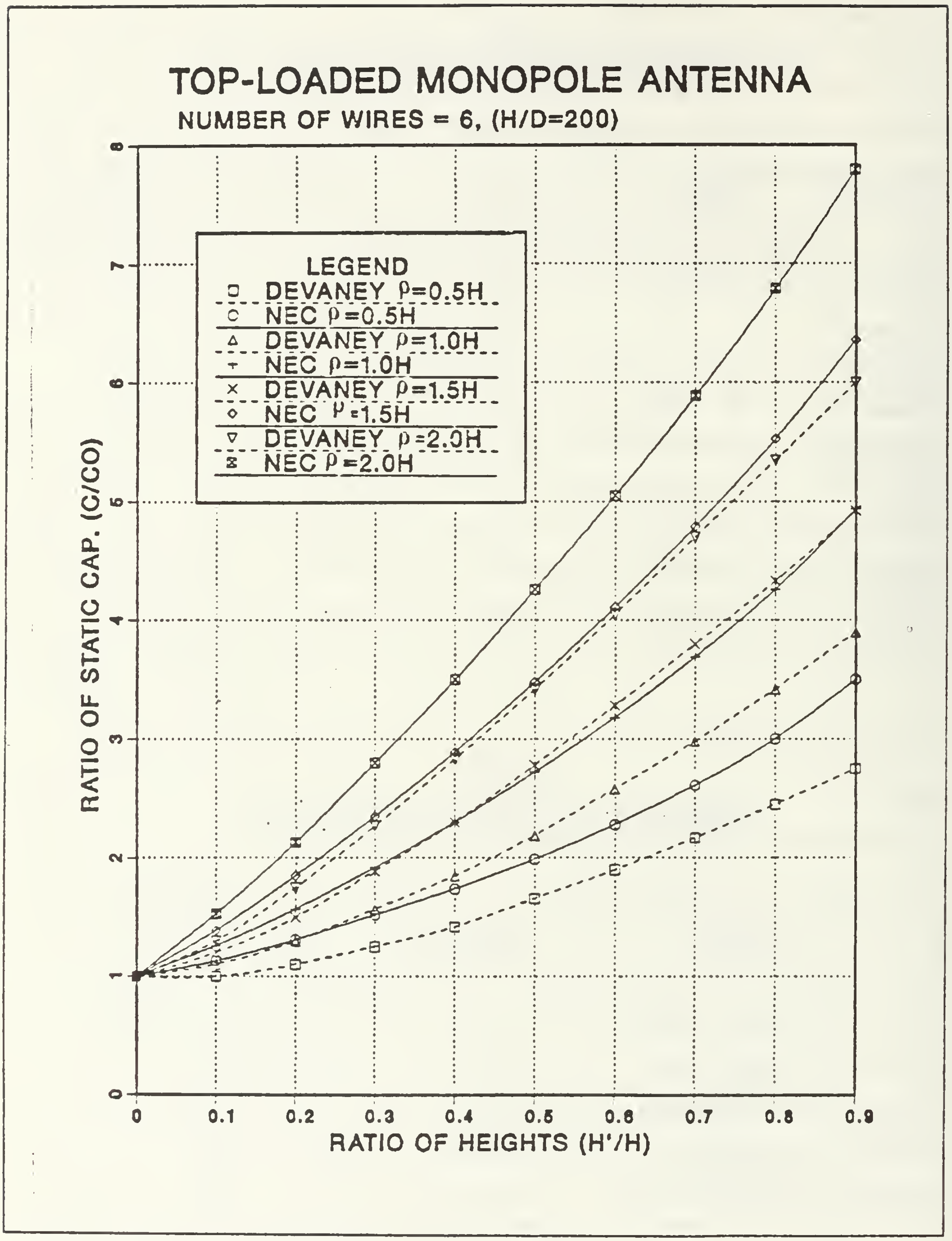


Figure 3.8 Normalized Static Capacitance of Top-Loaded Antenna, the Number of Top-Hat Radials N = 6.

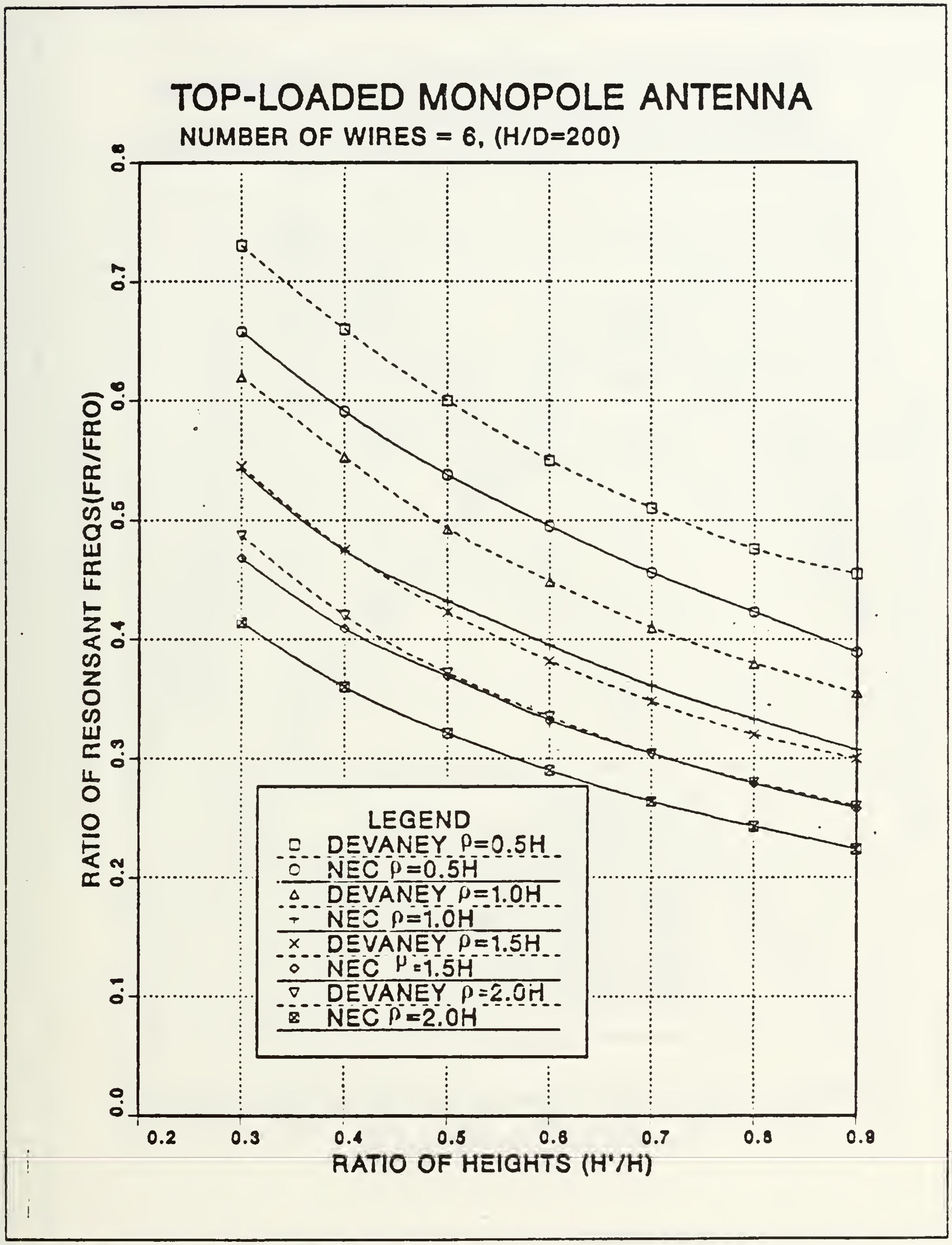


Figure 3.9 Normalized Resonant Frequency of Top-Loaded Antenna, the Number of Top-Hat Radials N = 6.

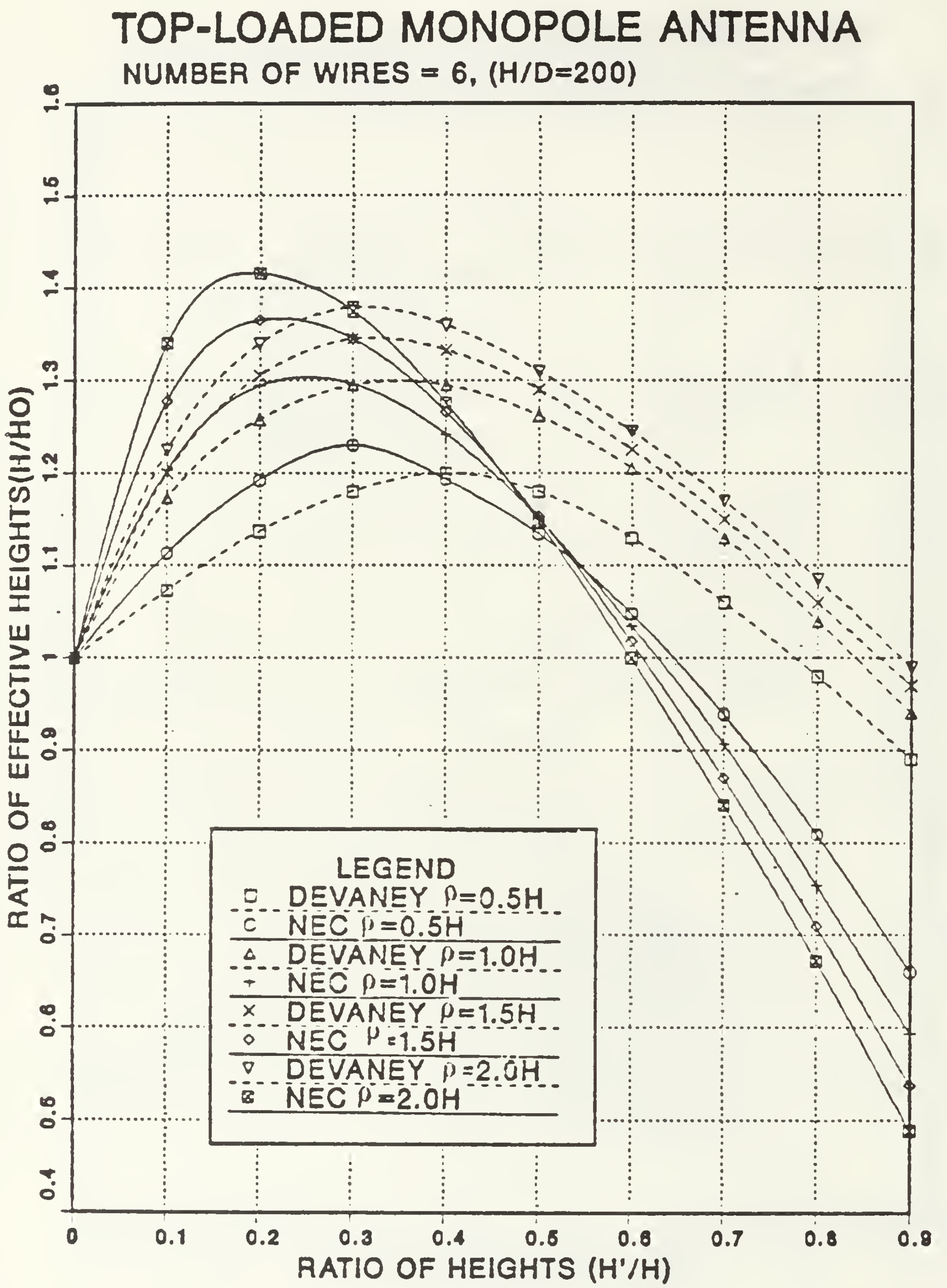


Figure 3.10 Normalized Effective Height of Top-Loaded Antenna, the Number of Top-Hat Radials N = 6.

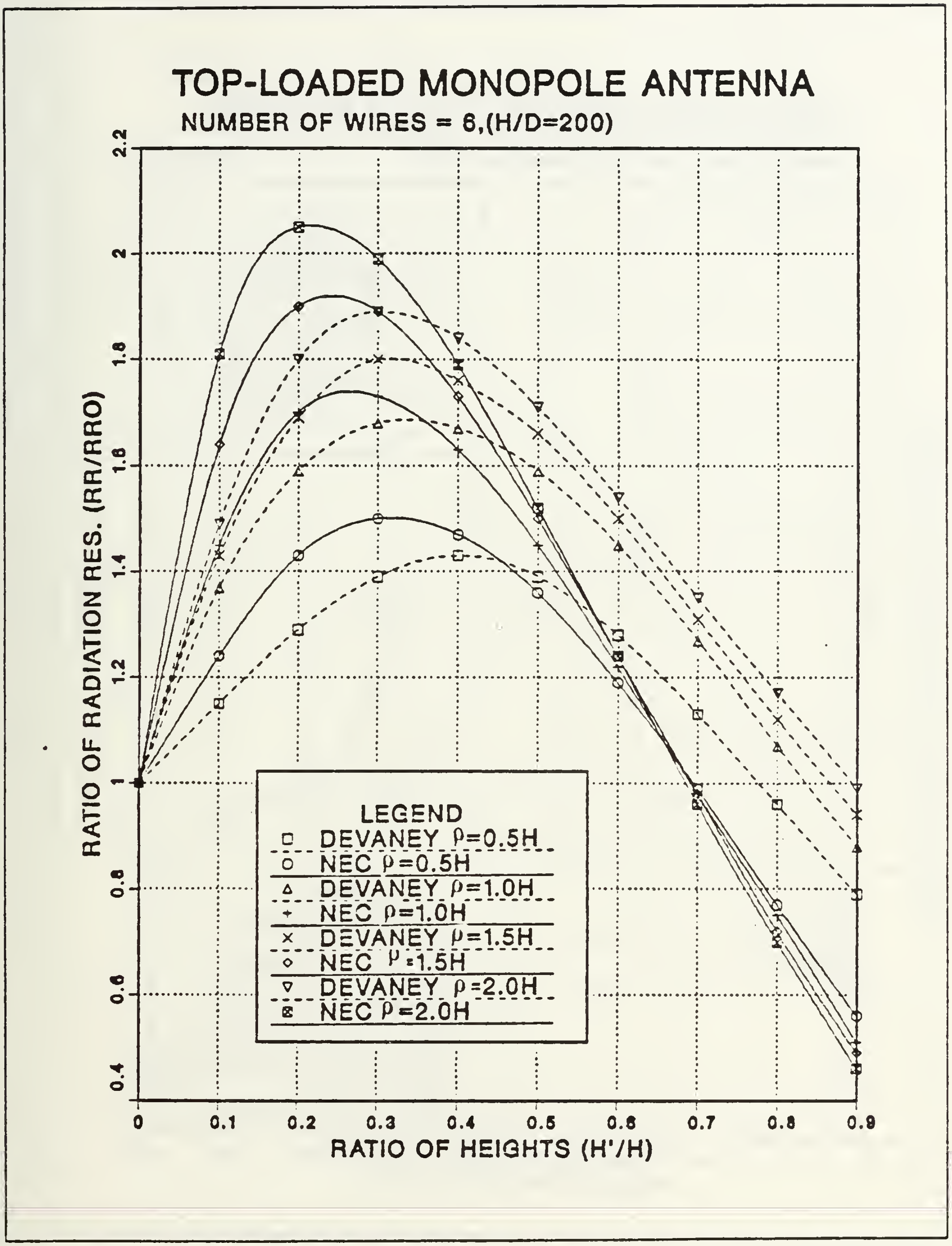


Figure 3.11 Normalized Radiation Resistance of Top-Loaded Antenna, the Number of Top-Hat Radials N = 6.

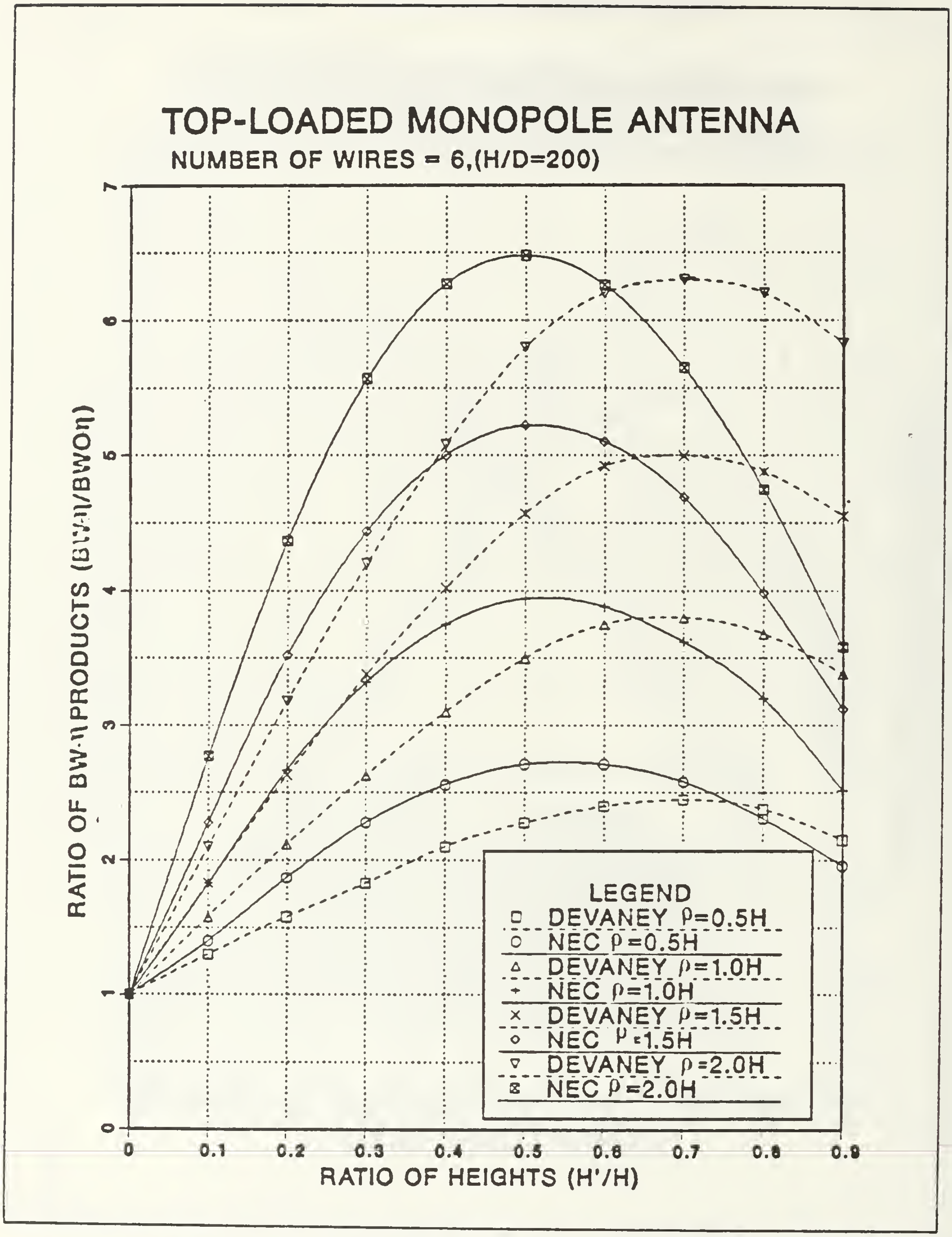


Figure 3.12 Normalized Bandwidth-Efficiency Product of Top-Loaded Antenna, the Number of Top-Hat Radials N = 6.

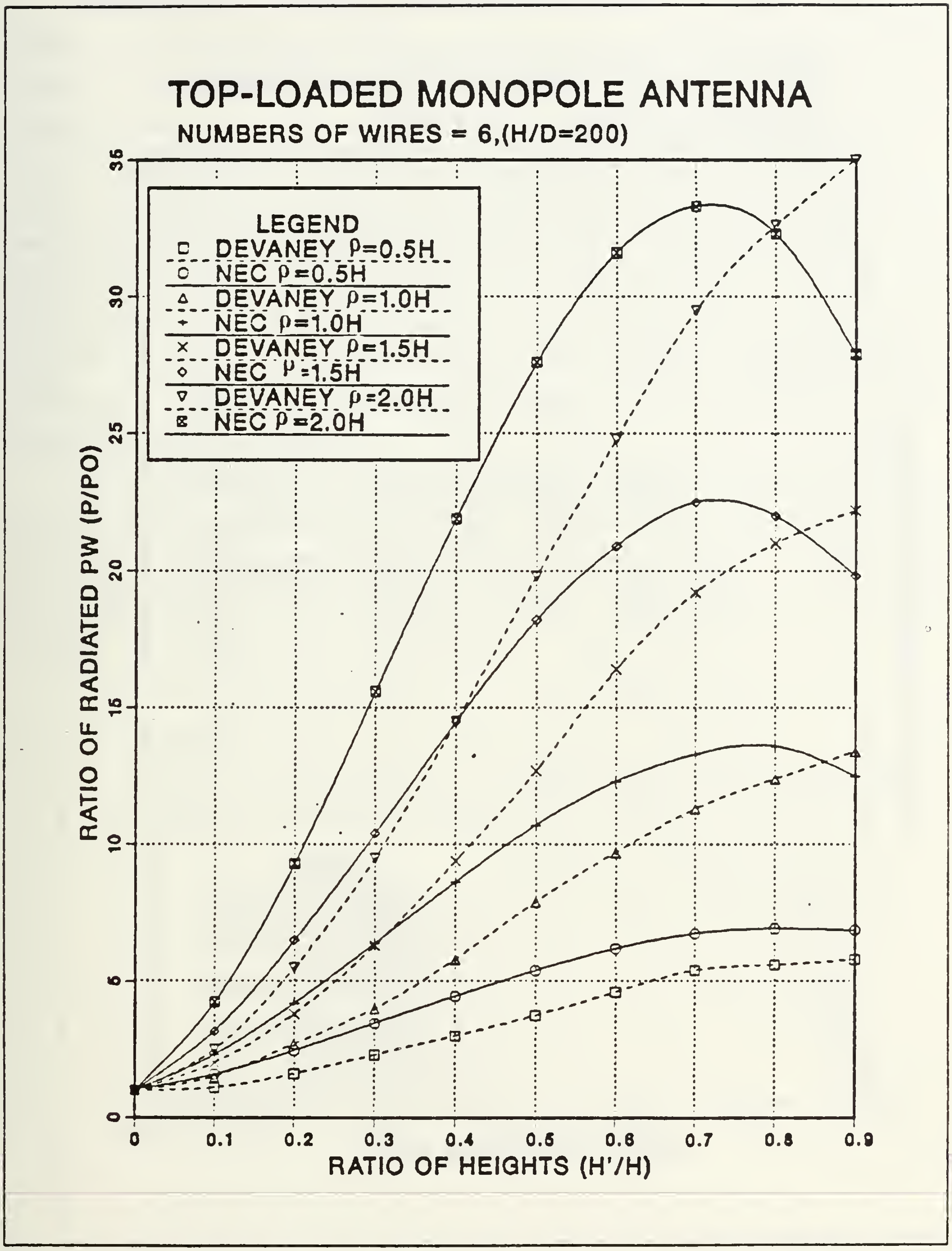


Figure 3.13 Normalized Maximum Radiated-Power of Top-Loaded Antenna, the Number of Top-Hat Radials N = 6.

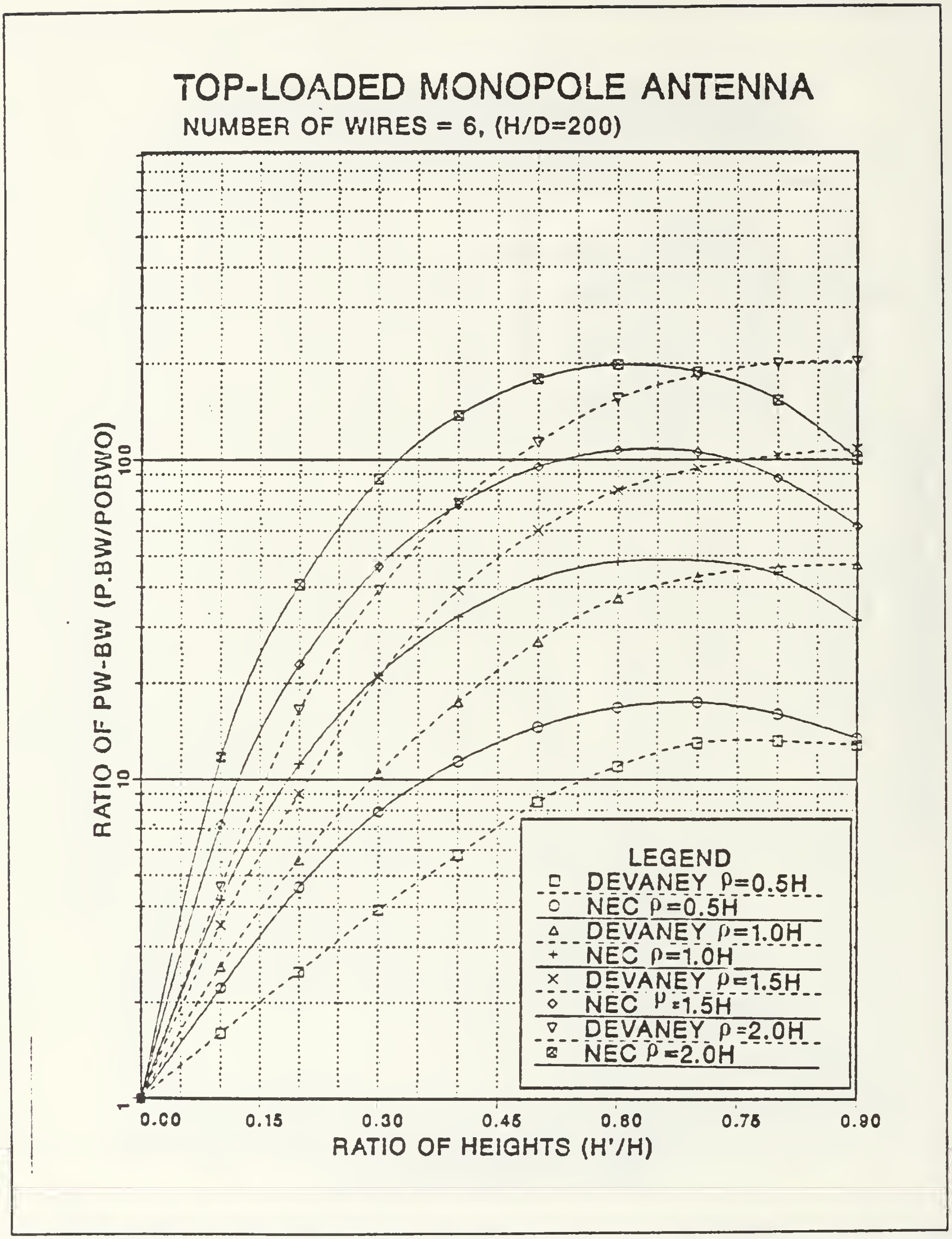


Figure 3.14 Normalized Power-Bandwidth Product of Top-Loaded Antenna, the Number of Top-Hat Radials N = 6.

C. ELECTRICAL PROPERTIES VERSUS NUMBER OF TOP-HAT RADIALS

Design curves in this section emphasize the dependence of electrical properties on the number of top-hat radials. In Figures 3.15 to 3.17, curves of bandwidth-efficiency product, power-handling capability and power-bandwidth product are shown for 6, 12 and 24 top-hat radials with ρ equal to H. Analyzing at optimum values, consider the number of top-hat radials, N = 6, as a reference. If N is increased to 12 the optimum bandwidth-efficiency is at $H'/H = 0.55$ and shows a gain of 28 percent. The improvement in power-handling capability at its optimum value is 77 percent higher and in power-bandwidth it is 123 percent. When the number of top-hat radials is increased to 24 from N = 12 as a reference, the increase in bandwidth-efficiency product is 16 percent, in power-handling capacity is 52 percent and in power-bandwidth product is 70 percent.

It can be concluded, by increasing the number of top-hat radials the percentage improvement in bandwidth-efficiency product, power-handling capability and power-bandwidth product are substantial. When height restriction exists, in order to meet bandwidth-efficiency requirements, the number of top-hat radials is an important consideration in design of top-loaded antennas.

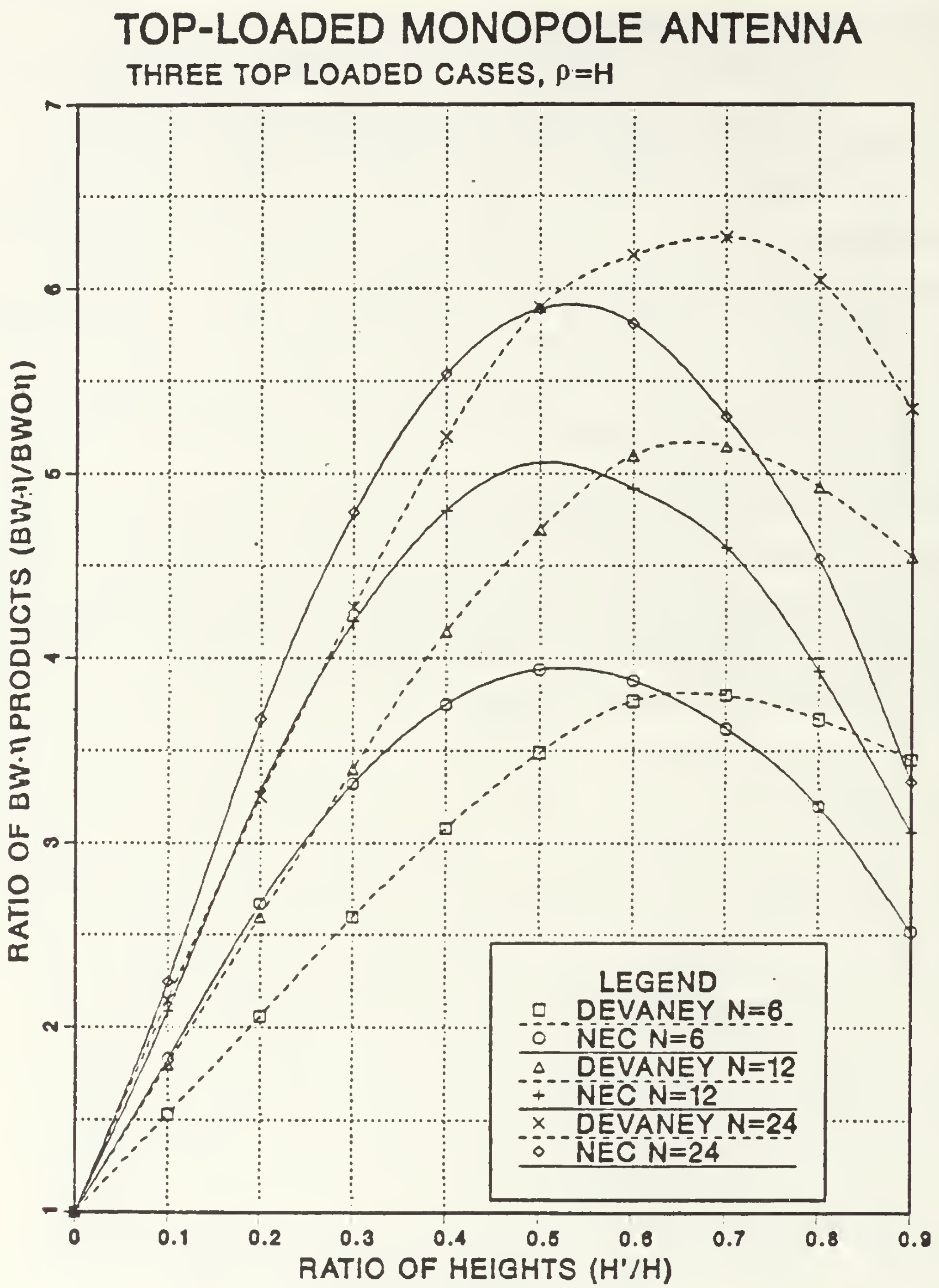


Figure 3.15 Normalized Bandwidth-Efficiency Product of Top-Loaded Antenna, $\rho = H$.

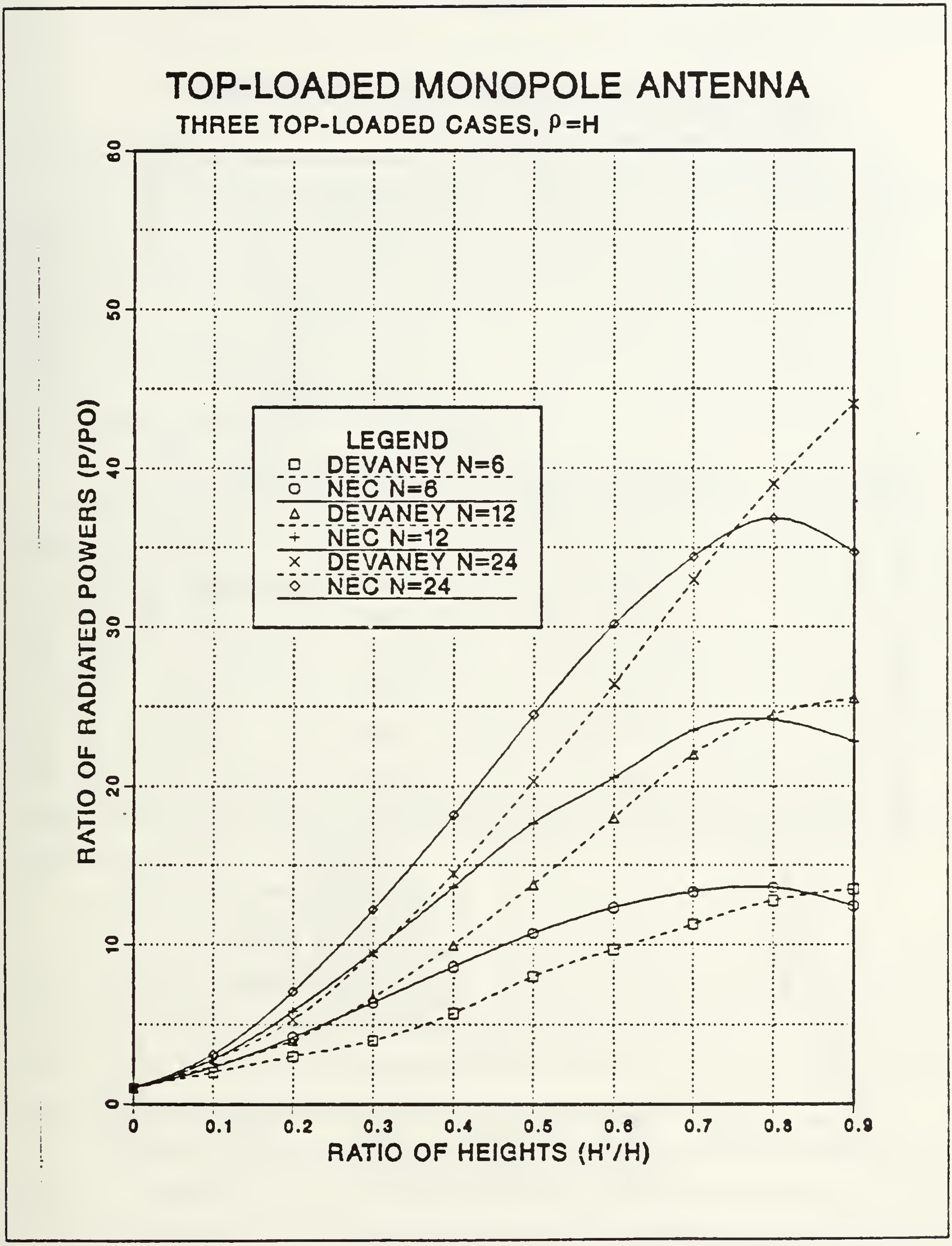


Figure 3.16 Normalized Maximum Radiated-Power of Top-Loaded Antenna, ρ = H.

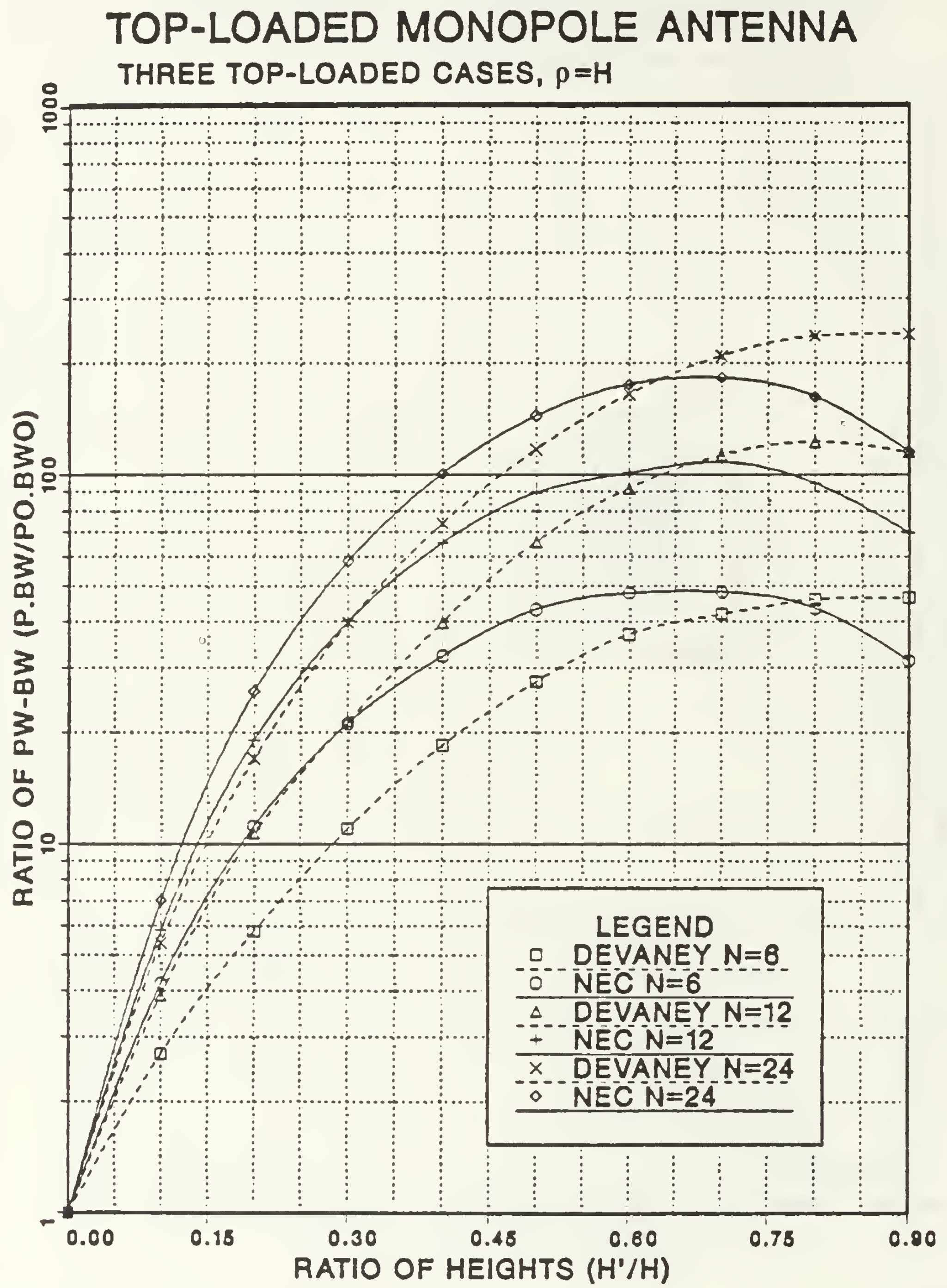


Figure 3.17 Normalized Power-Bandwidth Product of Top-Loaded Antenna, ρ = H.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis presents a study of several configuration of low frequency top-loaded monopole antennas using numerical modeling techniques. Seven electrical properties, static capacitance, resonant frequency, effective height, radiation resistance, bandwidth-efficiency product, maximum radiated power and power-bandwidth product are determined, presented in the form of a series of design curves. Comparison is made with those obtained for the scaled test model studied in the Devaney report. Data used for plotting these design curves is normalized so that it can be universally applied.

The study validates that numerical modeling techniques can be used for monopoles used in the VLF-LF region of frequency spectrum. The effective height determined from the data obtained from NEC runs on computer model is twice the conventional value but easily corrected by applying 0.5 volt/meter incident field when operating over a ground plane. LF antenna engineers work with constraints of space, height and cost considerations. They should strive for a balanced design, by considering the effect of changes in the radial distance of anchor point of the guy wires from the base of the monopole, ρ, the number of top-hat radials, N, and the height of the center monopole on the electrical properties of VLF-LF antenna. The differences in the design curves of the computer model and the scaled test model are acceptable and the reasons for these are understood.

B. RECOMMENDATIONS

It is recommended that a study be undertaken to develop a NEC model of top-loaded monopole antenna and to carefully include the radius of the top-hat equal to that used in the Devaney report for comparison and to make an equivalent set of design curves for the exact model of antenna. This may require additional code developments to allow large radii changes at the junction of wires.

The Navy is the prime user of VLF and LF bands for its world wide broadcast. A need exists to improve the power handling capacity (limited due to corona) of VLF and LF antennas currently in use in the Navy. It is recommended that numerical modeling techniques be used to develop models of the existing antenna systems. These models can be used to study the effects of placing corona rings at the ends of top-hat radials and at the base of antenna to make it corona free for higher power handling capacity.

APPENDIX A
COMPUTER MODEL - DESIGN CURVES

The design curves shown from Figure A.1 to Figure A.7 are plotted for 12 top-hat radials and the Figures A.8 to Figure A.14 are plotted for 24 top-hat radials.

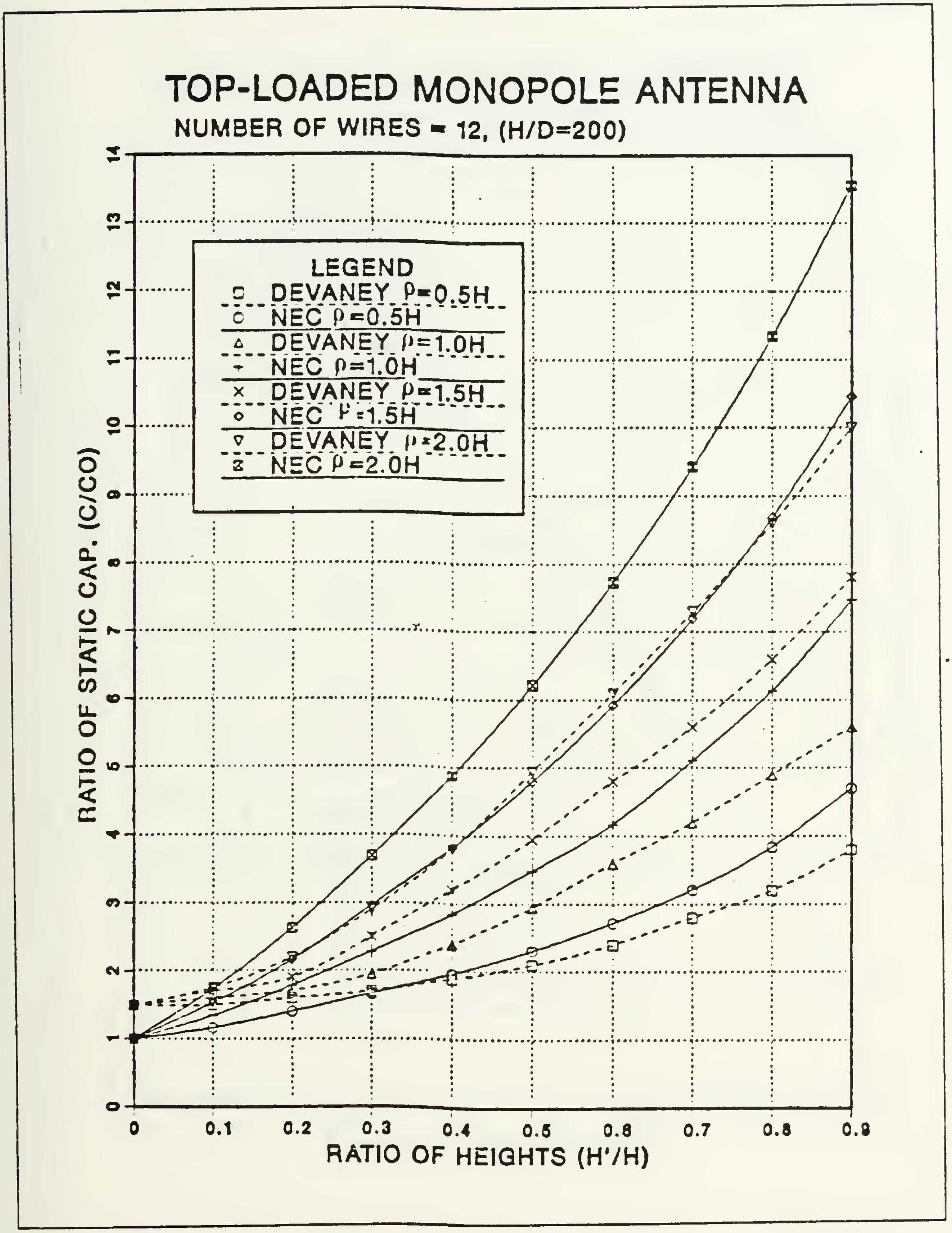


Figure A.1 Normalized Static Capacitance of Top-Loaded Antenna, the Number of Top-Hat Radials N = 12.

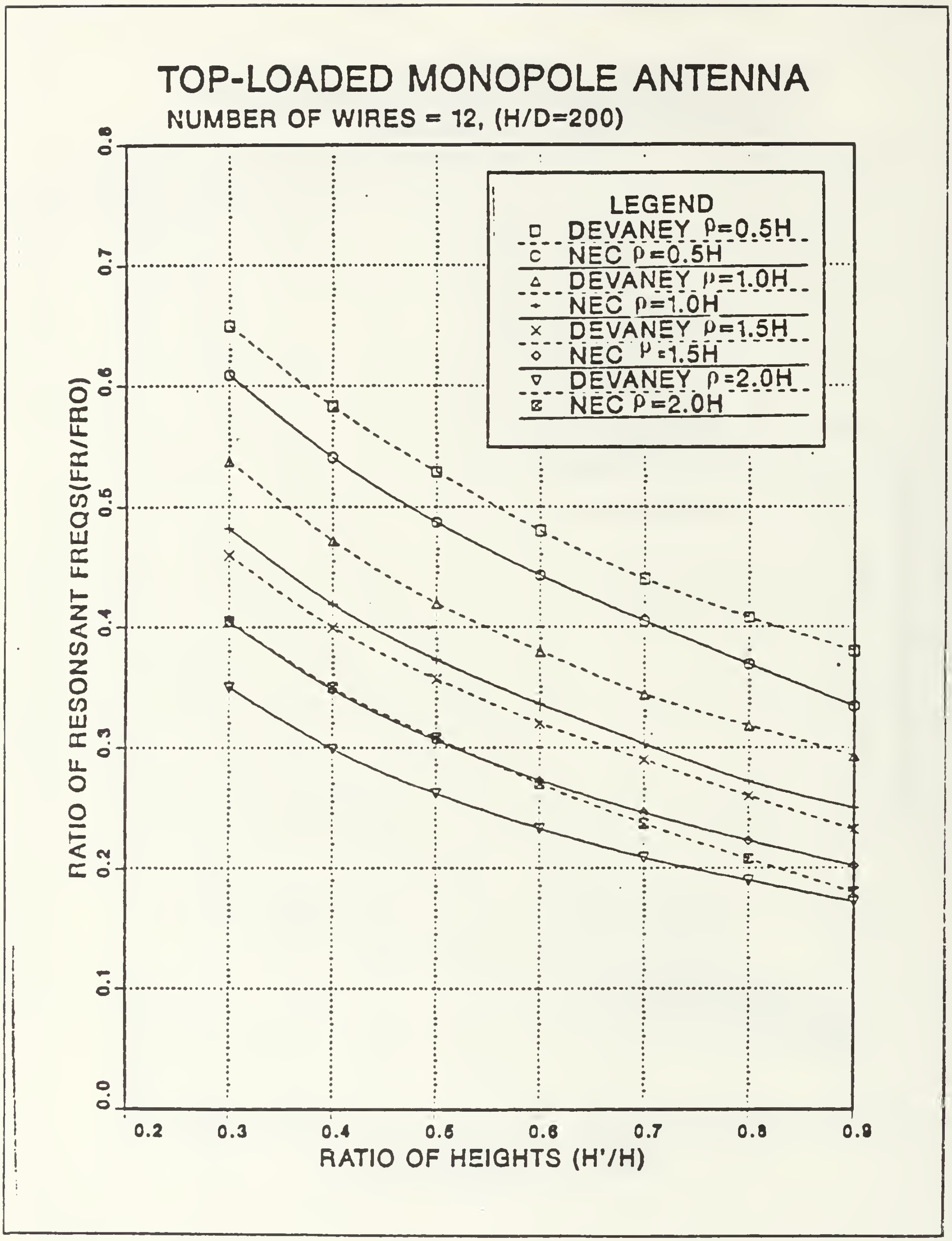


Figure A.2 Normalized Resonant Frequency of Top-Loaded Antenna, the Number of Top-Hat Radials N = 12.

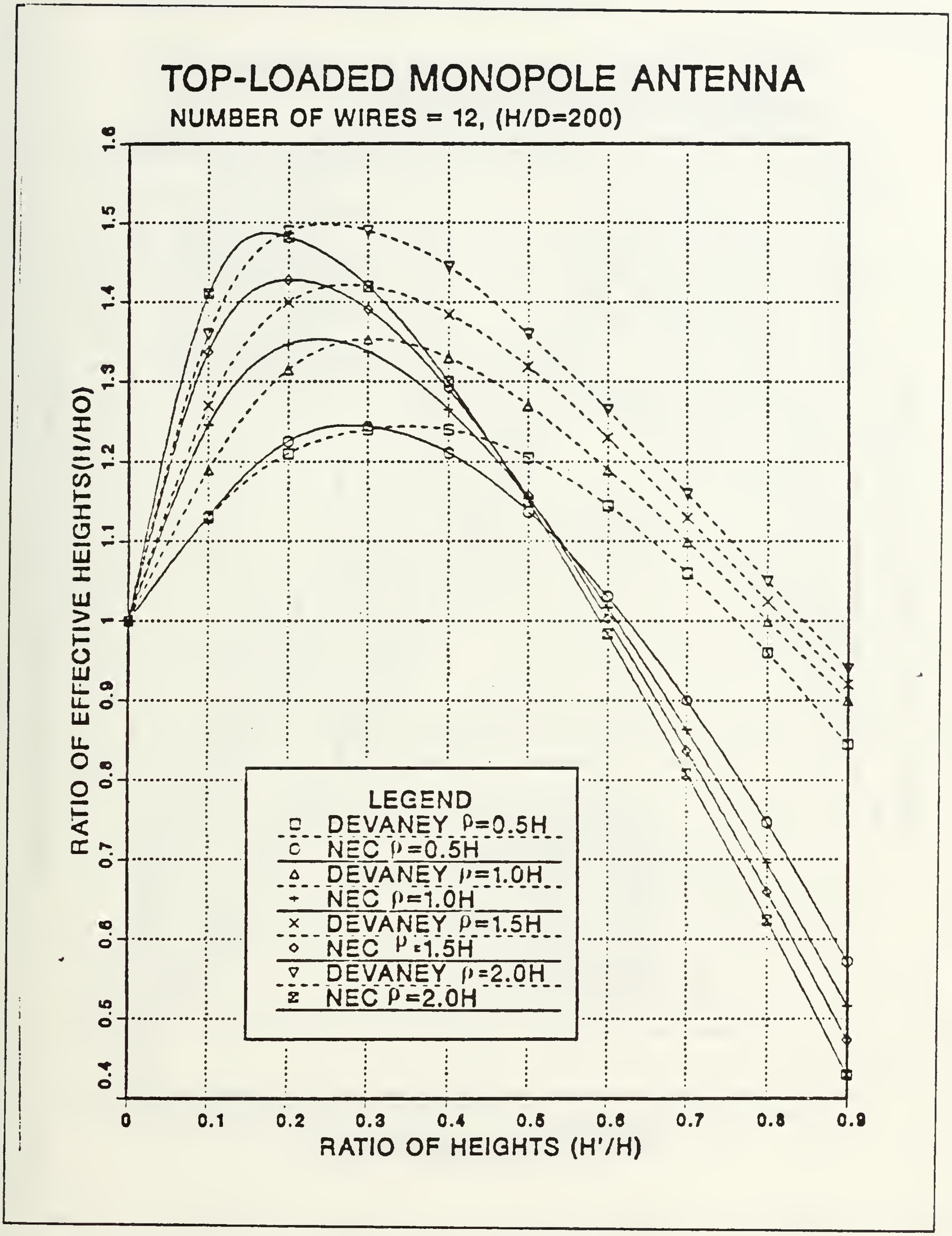


Figure A.3 Normalized Effective Height of Top-Loaded Antenna, the Number of Top-Hat Radials N = 12.

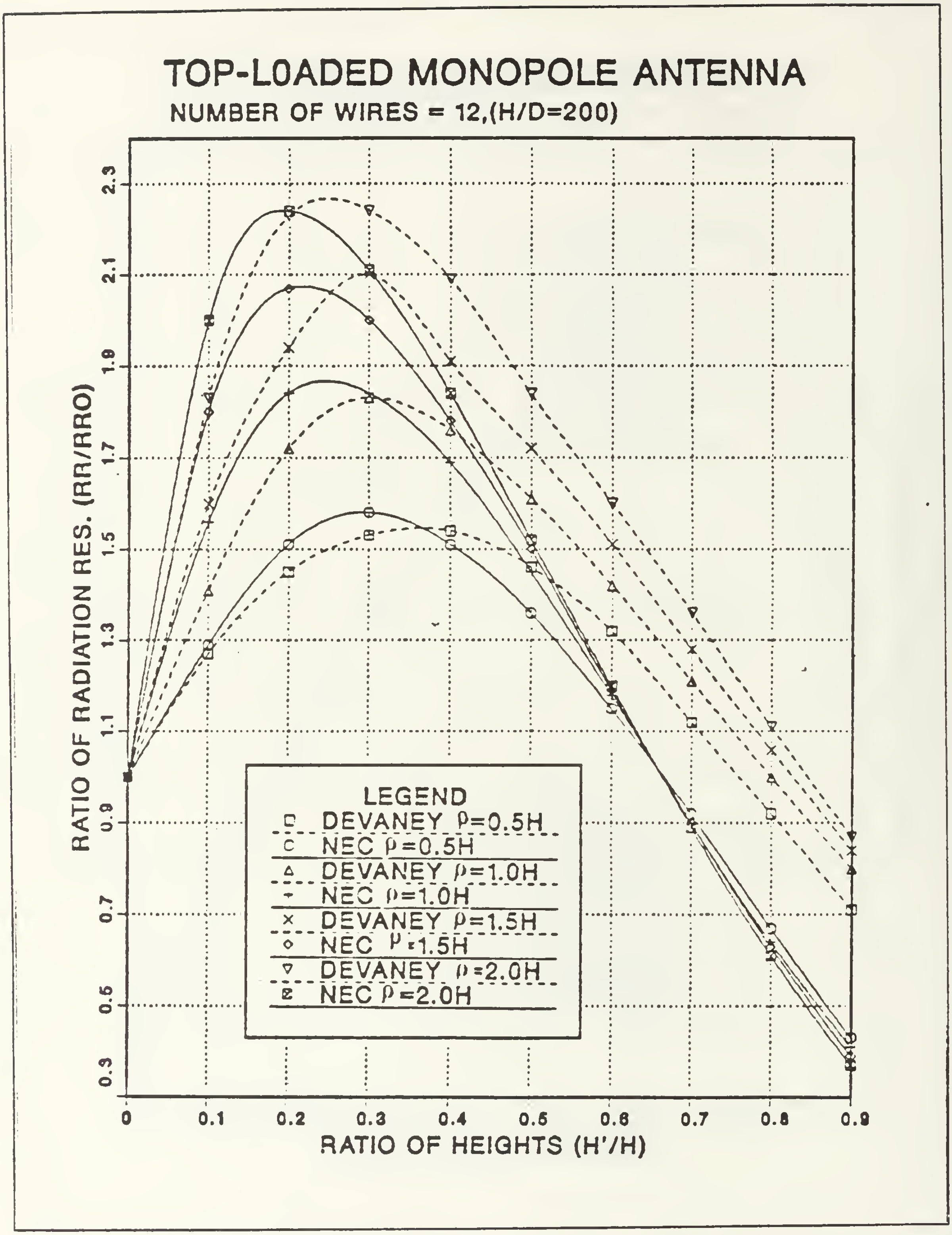


Figure A.4 Normalized Radiation Resistance of Top-Loaded Antenna, the Number of Top-Hat Radials N = 12.

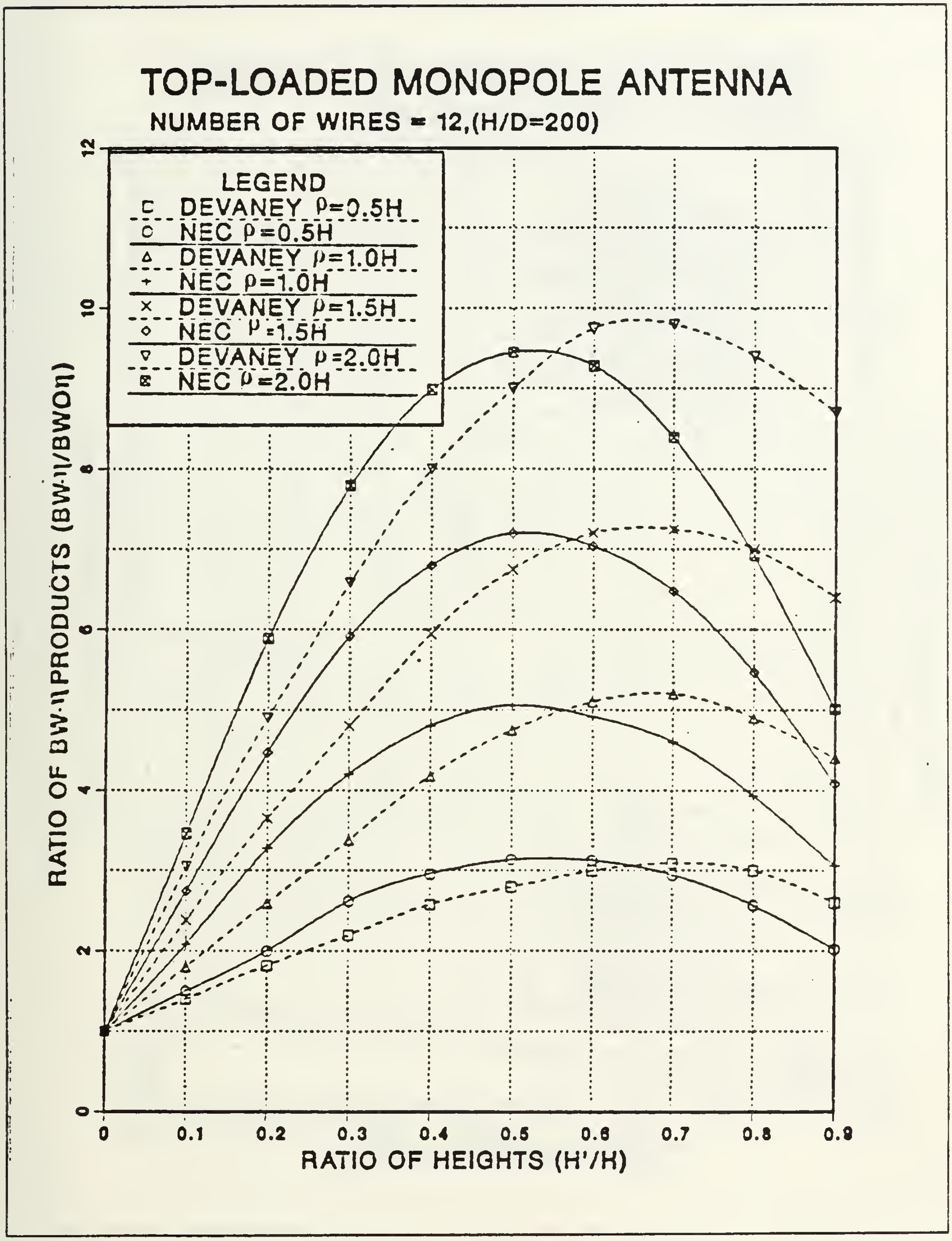


Figure A.5 Normalized Bandwidth-Efficiency Product of Top-Loaded Antenna, the Number of Top-Hat Radials N = 12.

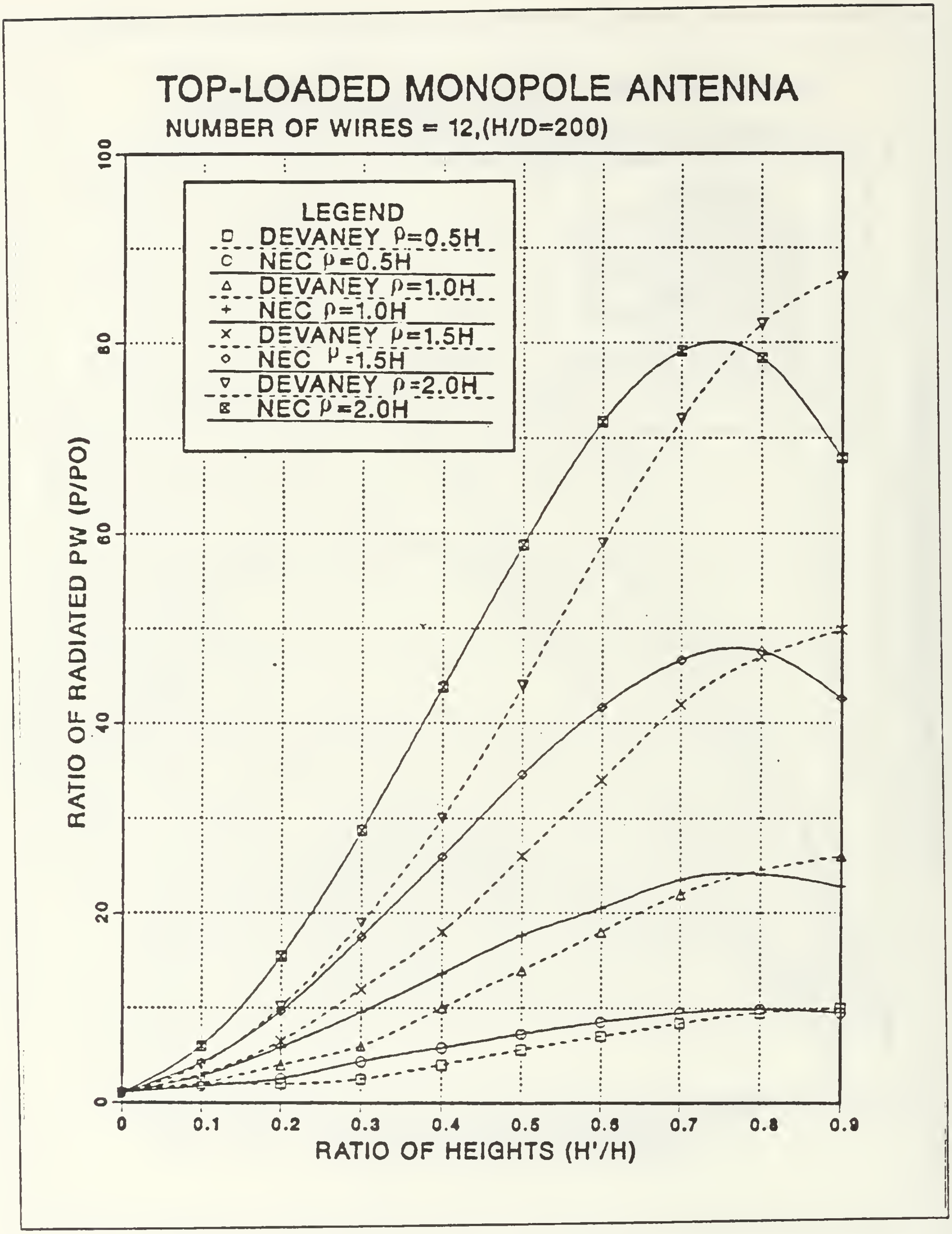


Figure A.6 Normalized Maximum Radiated-Power of Top-Loaded Antenna, the Number of Top-Hat Radials N = 12.

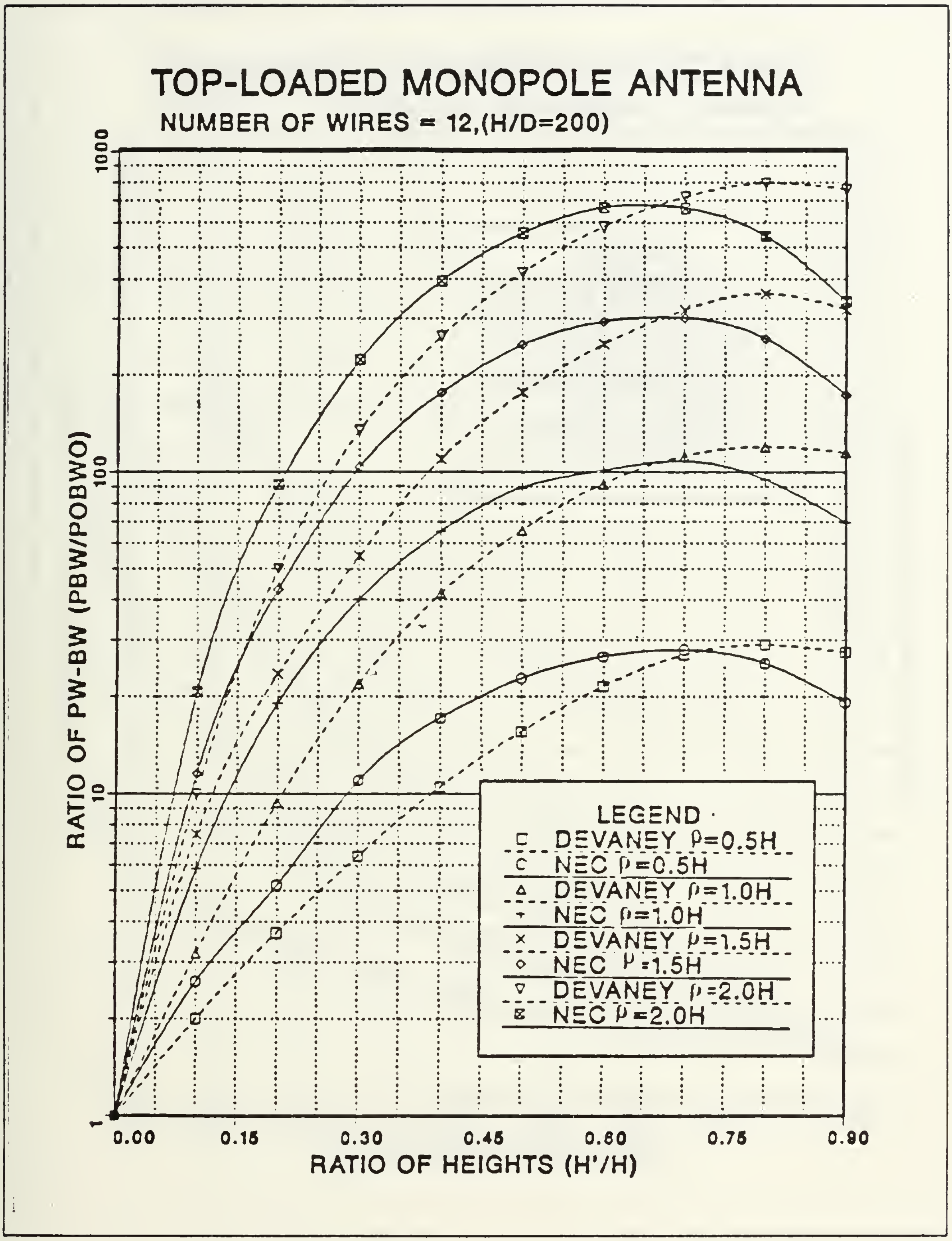


Figure A.7 Normalized Power-Bandwidth Product of Top-Loaded Antenna, the Number of Top-Hat Radials N = 12.

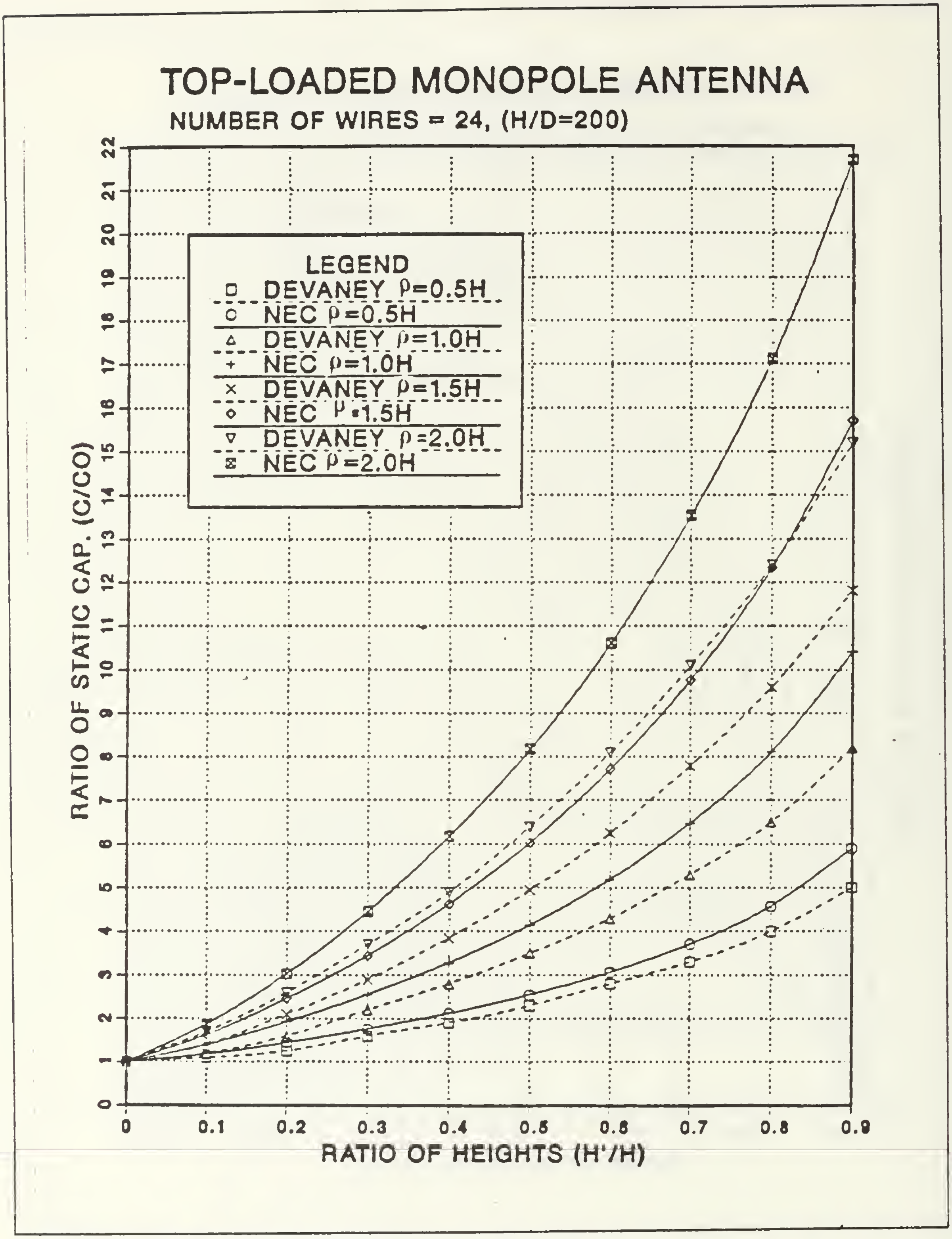


Figure A.8 Normalized Static Capacitance of Top-Loaded Antenna, the Number of Top-Hat Radials N = 24.

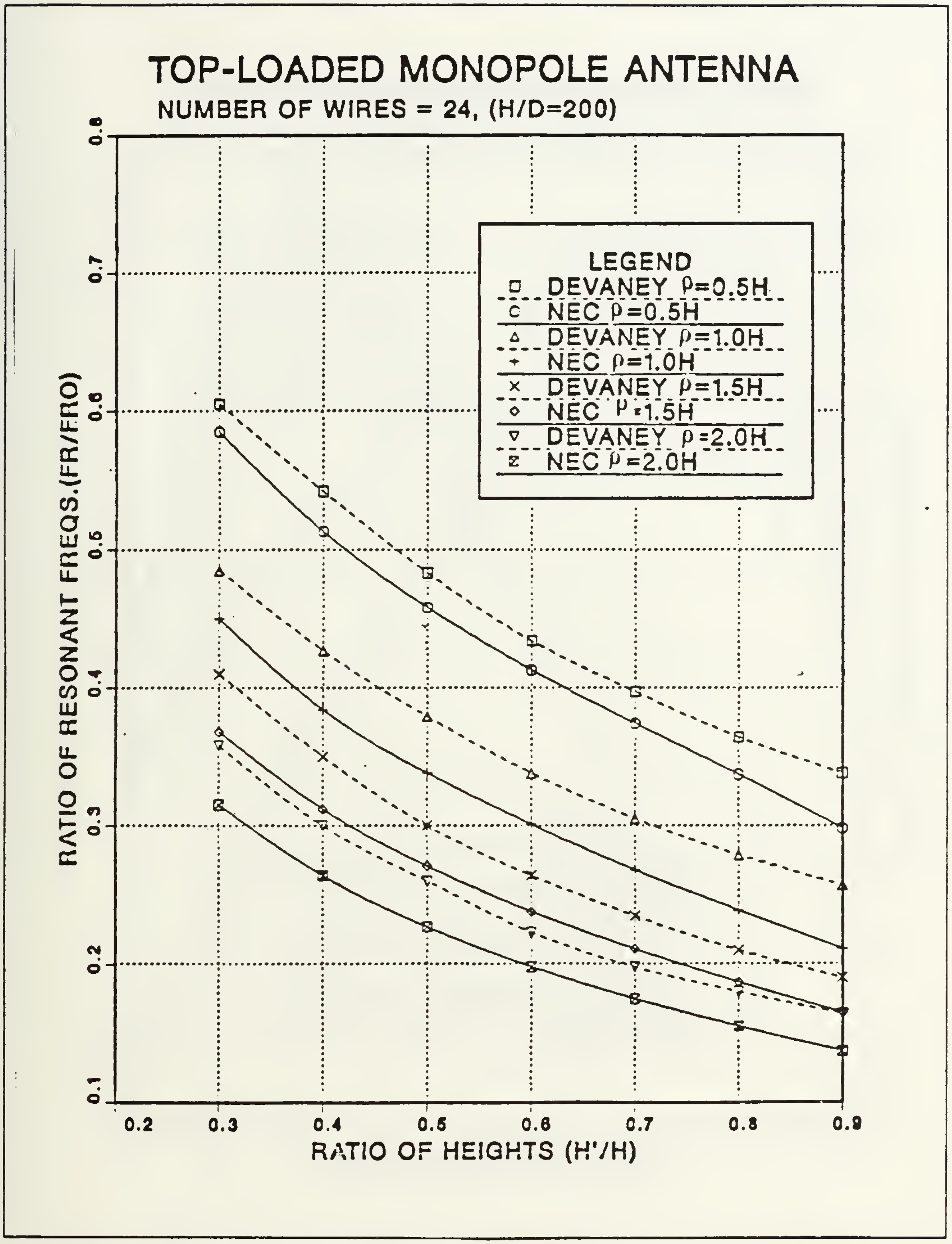


Figure A.9 Normalized Resonant Frequency of Top-Loaded Antenna, the Number of Top-Hat Radials N = 24.

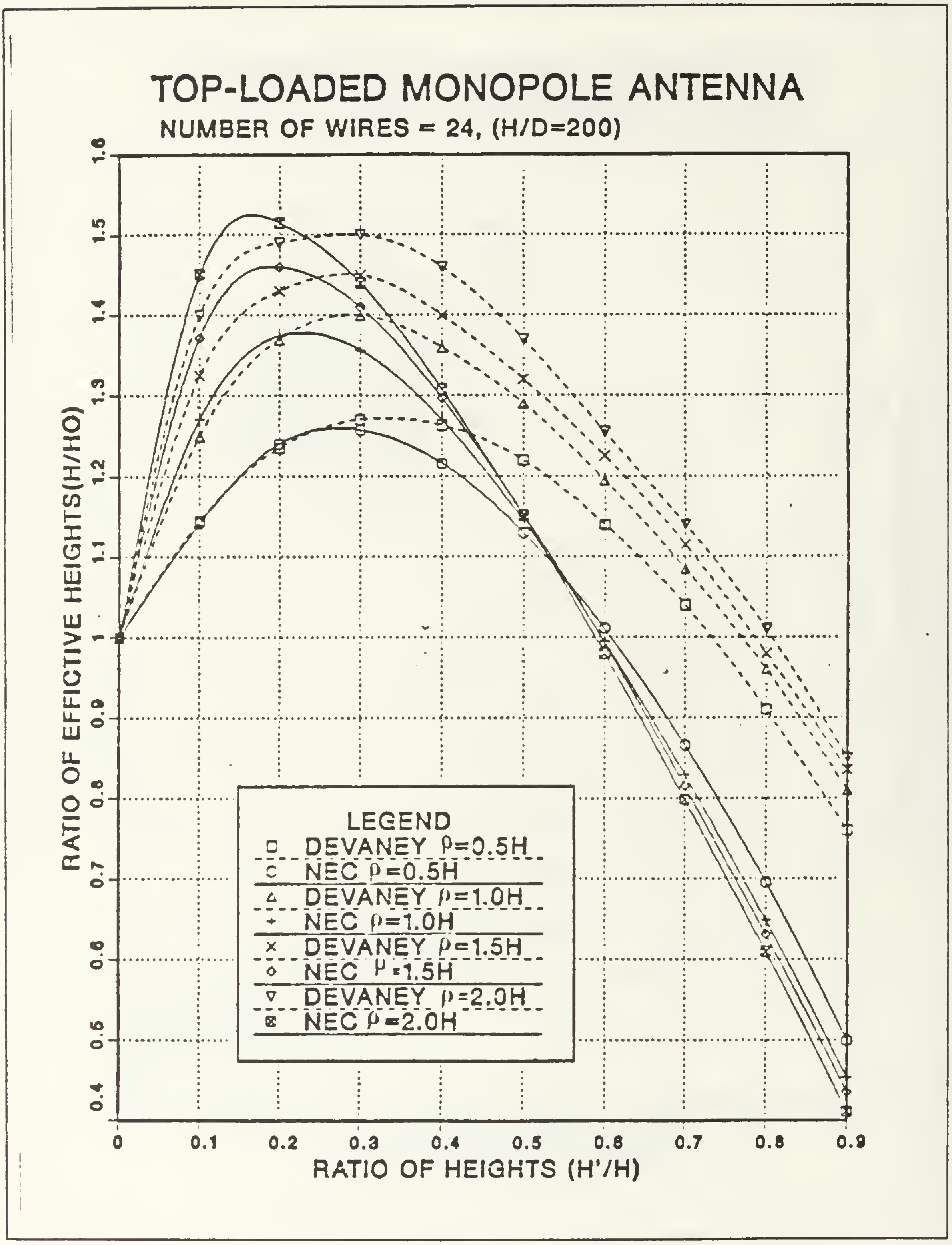


Figure A.10 Normalized Effective Height of Top-Loaded Antenna, the Number of Top-Hat Radials N = 24.

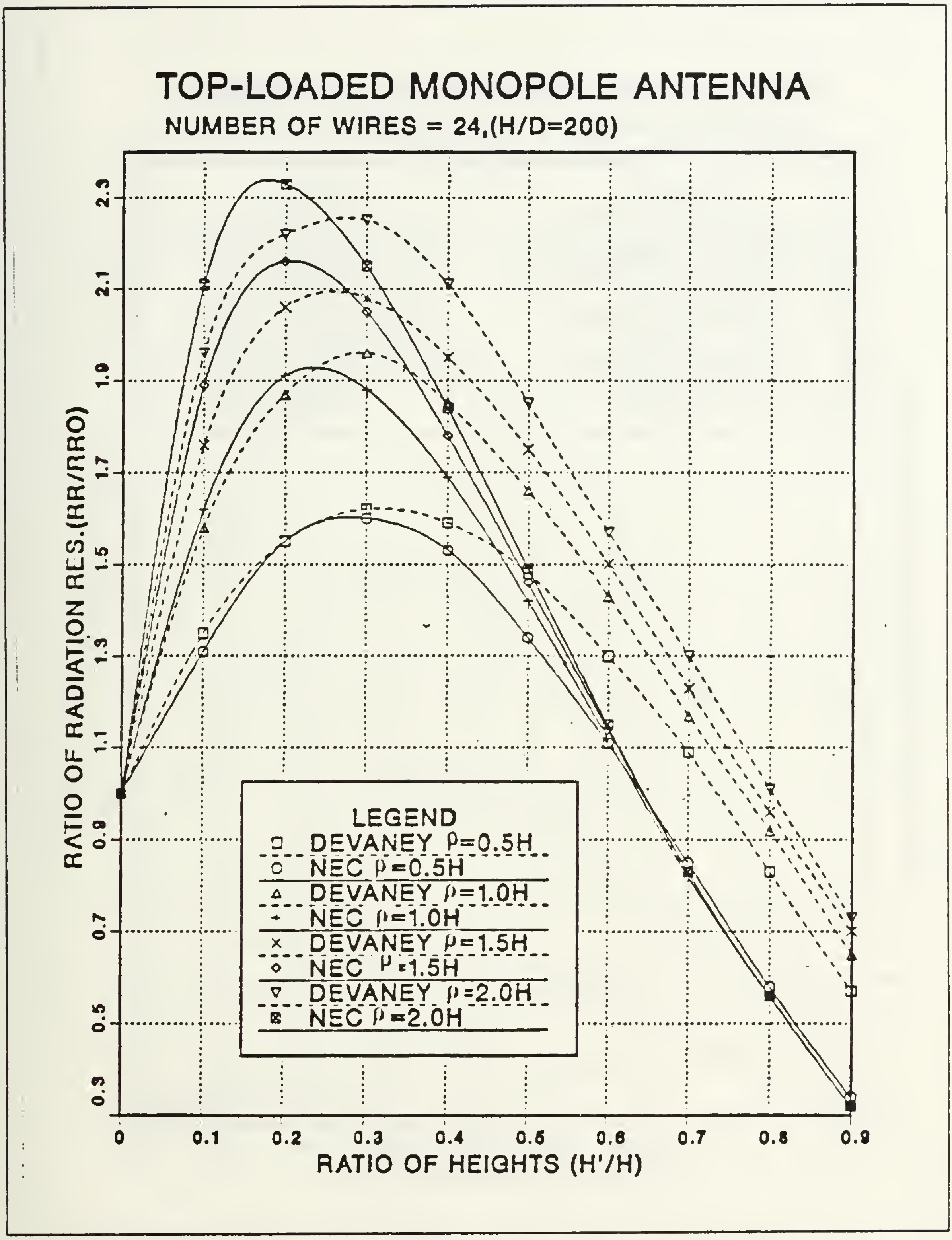


Figure A.11 Normalized Radiation Resistance of Top Loaded Antenna, the Number of Top-Hat Radials N = 24.

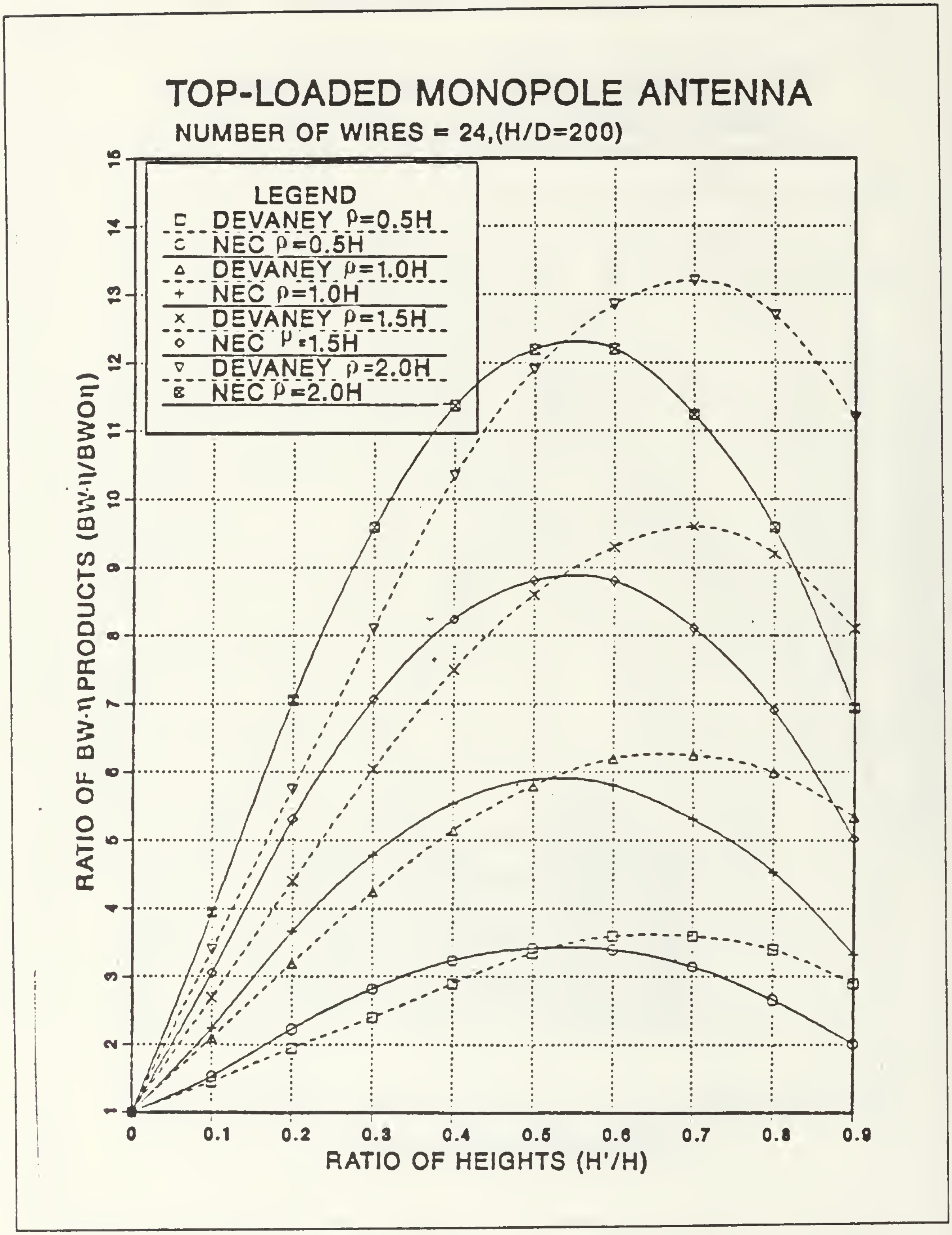


Figure A.12 Normalized Bandwidth-Efficiency Product of Top-Loaded Antenna, the Number of Top-Hat Radials N = 24.

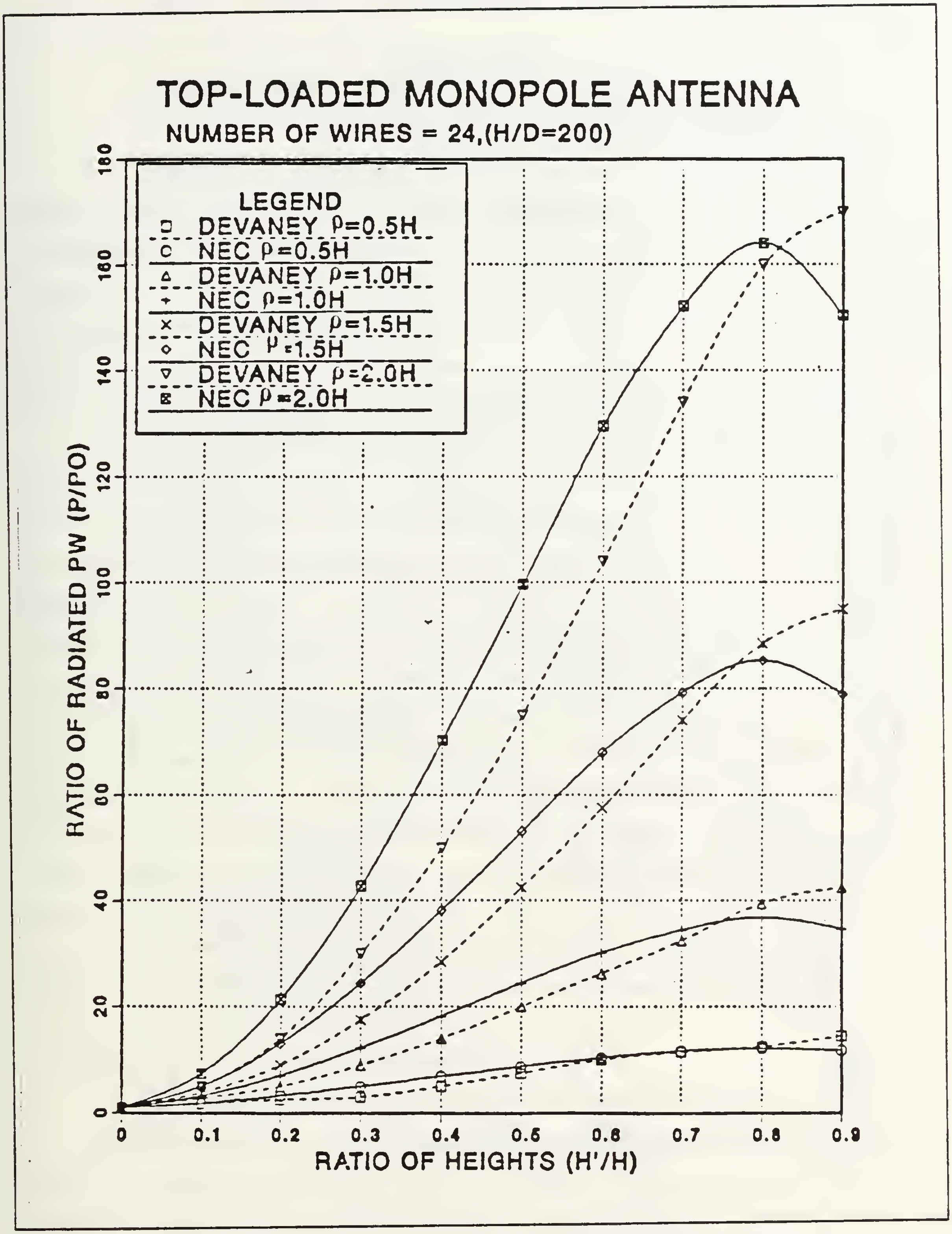


Figure A.13 Normalized Maximum Radiated-Power of Top-Loaded Antenna, the Number of Top-Hat Radials N = 24.

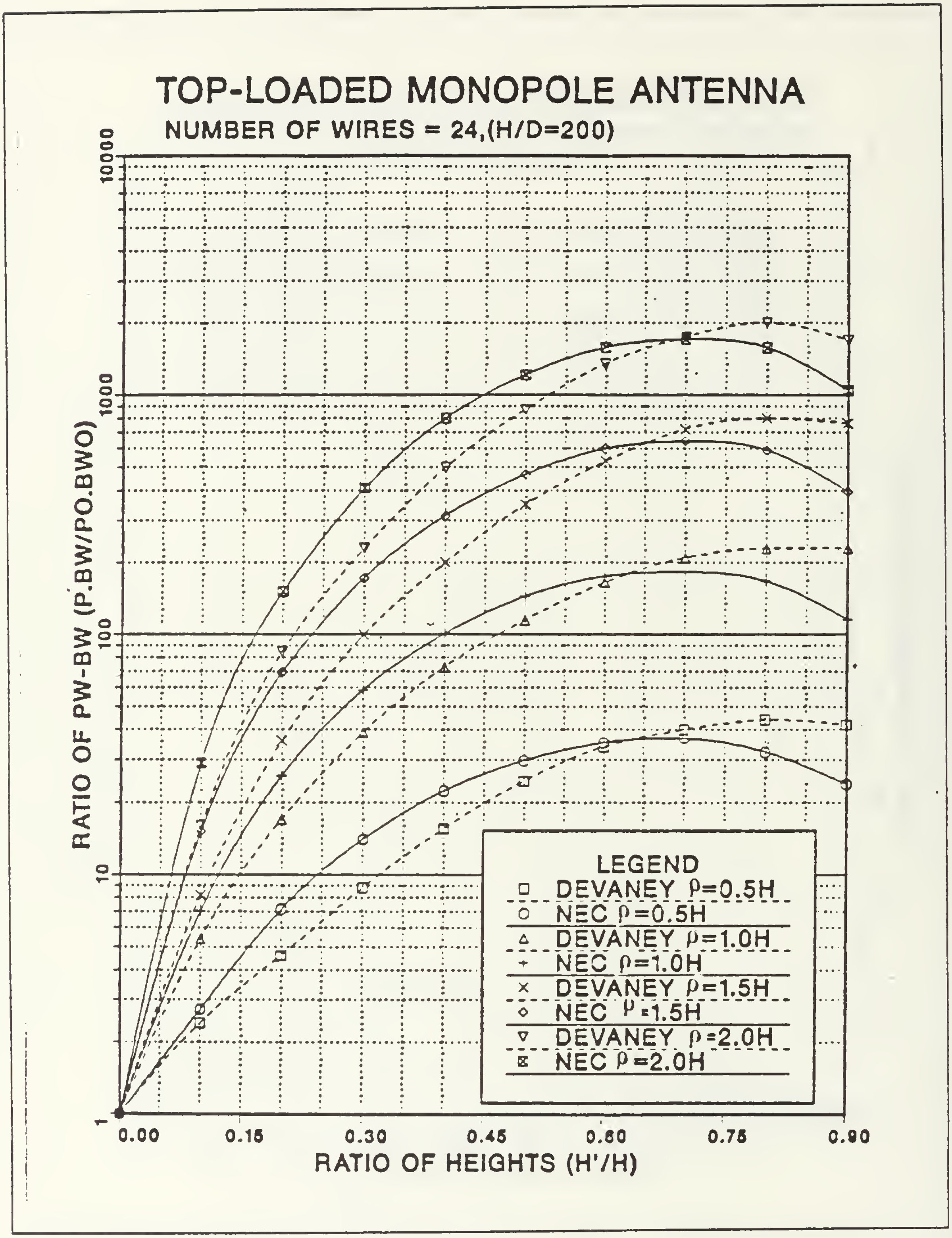


Figure A.14 Normalized Power-Bandwidth Product of Top-Loaded Antenna, the Number of Top-Hat Radials N = 24.

APPENDIX B
THE NUMERICAL ELECTROMAGNETIC CODE (NEC)

The Numerical Electromagnetic Code (NEC) is an advanced version of a computer code available for the analysis of performance of antenna models. It offers comprehensive capabilities for analyzing the electromagnetic response of an arbitrary antenna structure consisting of wires or surfaces in free space or above perfectly conducting ground or over finite conductivity earth. The program is based on numerical solution of integral equations for the currents induced in the antenna structure by the exciting field.

The NEC program uses both an electric-field integral equation (EFIE), and a magnetic-field integral equation (MFIE), to model the electromagnetic response of antenna/general structures. A numerical electromagnetic code model may include nonradiating networks and transmission lines, perfect and imperfect conductors and lumped element loading. The effect of realistic ground conditions is achieved by including radial ground wires and the electromagnetic response of the structure is also incorporated. The excitation may be an applied voltage source or an incident plane wave of linear or elliptical polarization or generated by a Hertzian source. The output may include currents and charges, near or far zone electric or magnetic fields and impedance or admittance. Many other commonly used parameters such as gain and directivity, power budget and antenna to antenna coupling are also available. In order to save computer time NEC utilizes structural symmetry about a plane or rotation about a reference axis.

EFIE is well suited for thin wire structures, with application towards modeling surfaces of thin structures with small separation and is expressed in Equation 1.5.

$$-\hat{s}.\bar{E}_i(\bar{r}) = (j\eta/4\pi k)\int_L I(\hat{s}')(k^2\hat{s}.\hat{s}'-\partial^2/\partial s\partial s')g(\bar{r},\bar{r}')ds' \qquad \text{(eqn 1.5)}$$

The EFIE in numerical electromagnetic code utilizes thin wire approximations; ie. only axial currents are considered with transverse currents neglected, axial current circumferential variation is neglected, current is represented by a filament on the wire axis and the boundary conditions on the electric field is enforced only in the axial direction.

Studies in thin wire approximations reflect error of less than 1% when segment length (Δ) and the wire radius (a) selection results in a ratio (Δ/a) greater than eight. For short thick wires, where the thin wire approximation fails, NEC provides an extended thin wire approximation to reduce the error to less than 1%.

MFIE fails for thin wire applications, but is useful for voluminous structures, especially those having large smooth surfaces. Additionally, MFIE requires that only closed conducting surfaces are modeled. It is expressed in Equation 1.6.

$$\bar{J}_s(\bar{r}) = 2\hat{n}x\bar{H}^i(r) + (1/2\pi)\hat{n}x\int_s \bar{J}_s(\bar{r}')x\nabla' g ds' r\varepsilon s \qquad \text{(eqn 1.6)}$$

Double precision version of NEC programs 32-bit implementation are used when handling low frequency and very low frequency antenna structures. This is necessary because the low frequency limit depends upon the wire segment length with respect to the wavelength and the numerical precision of the computer. Double precision version of NEC programs give adequate results for segment length as small as 10^{-15} wavelength. During this study double precision version of NEC programs are used for computation of data.

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c.1
A study top-loaded monopole antennas using numerical modeling techniques comparison to scaled model measurements.