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Technical Note N-448

CONCEPTS FOR VERY HIGH VERTICAL RADIATORS

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U. S. NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

CONCEPTS FOR VERY HIGH VERTICAL RADIATORS

Task No. Y-F006-03-001

Type C

by

P. J. Rush

CBJECT OF TAS

a. To determine the practicability of constructing a vertical radiator of 3000-ft height and above.

b. End Products Desired

1. Phase I - Conceptual studies for a vertical radiator of 3000-ft height.

2. Phase II - Conceptual studies for a vertical radiator of unlimited height (i.e., in the range of three miles).

ABSTRACT

The need for unconventional types of Very Low Frequency antenna systems as alternatives to the costly conventional systems is discussed. Possibilities of using very high vertical radiators of various structural types are explored. The loads and forces that must be sustained by 3000-ft high structures are described. Materials suitable for unusual structural concepts are set forth. Concepts encompassing 3000-ft high guyed towers, compression-tension towers, free-standing towers, mass structures, and retractible towers are briefly analyzed; and structural, erection, and economic feasibilities of the various concepts are presented.

It was concluded that 3000-ft high vertical radiators could probably be built and maintained at lesser cost than the best conventional systems which require great quantities of radiating wires supported aloft by many intermediate height towers emplaced over large expanses of ground. Much detailed study would have to be performed to define and elucidate the structural, erection, and economic factors relating to any specific 3000-ft high tower structure intended for a particular site.

It was concluded that the construction of an ideal VLF radiator system, which would be a quarter wave antenna of three miles height, is presently impossible because of practical engineering and economic reasons. It appears that if such a radiator would ever become practical

it would have to be of the so-called assisted type employing a lifting force of some sort. The present state of the art in air-buoyant, rotating plane and jet types of apparatus for supplying lift forces is such that no practical application to the problem of an assisted three-mile-high structure could be envisioned.

INTRODUCTION

The Naval Civil Engineering Laboratory (NCEL) was directed to conduct Phase I of a Research and Development task which involved studies of unconventional methods for providing vertical radiators of great heights.[1] Phase I of the investigation was limited to the study of prospects for 3000-ft high structures. This work was to include analyses of concepts and determinations of feasibility regarding construction methods and costs. Phase II of the R and D task would be dependent upon the results of Phase I and would be concerned with conceptual studies for a vertical radiator of unlimited height (i.e. in the range of 3 miles).

The task instructions[2] for an unconventional, 3000-foot antenna provided:

1. Wind loadings should be based on information contained in NAVDOCKS TP-Te-3.[3] The minimum wind velocity to be considered for purposes of this study should be 125 miles per hour.

2. The vertical radiator should have a minimum usable life of five years.

3. The radiator should be capable of continuous operation.

The principal reasons for considering the utilization of a very high monopole structure as a radiator in preference to a complex of wires supported by many medium-height towers are reduction of construction cost and increased electrical efficiency. The newest of the conventional antenna systems, at the North Atlantic VLF Transmitting Station at Cutler, Maine, is a complex of 26 towers and miles of lofty wires. This had a first estimated cost of 25 million dollars, although the final price tag was much greater, and a predicted electrical efficiency of 45 percent.[4] These figures may be taken as standards which must be met or bettered by any monopole radiator.

This report is to be confined to discussions of possible structural configurations capable of supporting at 3000-ft height an arrangement of radiating surfaces known as a top loading system. The top loading could possibly use tower guys as radiators but greater electrical efficiency could be obtained from a vertical mast with a cross-T or a Y-shaped extension. Another proposal would provide a helix of copper tubing atop a very high tower.[5]

While electrical considerations are not to be a part of this report, they do influence the structural concepts. One requirement, expressed by the Bureau of Ships, was for a radiator for operation at 15 kilocycles with power in the megawatt range and activating voltages of from 15 to 50 kilovolts. The antenna should be vertically polarized and the base should be close to the ground.

For a quarter-wave radiator this would require an antenna height of 3.13 miles and with a voltage of 15 to 50 KV applied at the base. The avoidance of corona effect from the radiating structure would necessitate the equivalent of a copper tube of at least 8-inch diameter extending the full height of the radiator.

To produce a signal equivalent to that of the idealized 3.13 mile high radiator, any 3000-ft tower would have to be surmounted by a top loading system that would have approximately 300-foot by 50-foot dimensions, and which would weigh about 100 tons. Thus, these figures were used in the calculations for the various structural concepts.

All work on this report was performed at the Naval Civil Engineering Laboratory (NCEL) at Port Hueneme, California. The work was accomplished under Task Y-F006-03-001, "Vertical Radiator".

APPROACH TO THE PROBLEM

By letting imagination take free flight and by temporarily ignoring the limitations imposed by the present states of the arts of electrical and structural engineering a number of unusual and perhaps bizarre ideas for a 3000-ft high vertical radiator evolved.

BUOYANT RADIATORS

The idea most often suggested involved supporting a radiating surface aloft with a buoyant lighter-than-air vehicle such as a balloon or a dirigible (Fig. 1a). Variants of this idea included vertical structures of hollow types such as stacks or cones, or articulated spheres or cylinders, filled with buoyant gas or heated air (Fig. 1b). A quick calculation presented some figures with which the practicality of a huge inflated structure could be evaluated. Helium, probably the safest gas that could be used, has a lifting capacity in the earth's atmosphere of 1.1 ounces per cubic foot. This implies an enclosed volume of the gas amounting to 35,200 ft^3 to support 1 ton. To support 100 tons would require a helium-filled sphere of 188 ft diameter, or a 3,000 foot high cylinder of 38 foot diameter. Atmospheric air heated to 100° C greater than the ambient temperature would have a lifting capacity of 0.472 ounces per cubic foot; requiring an enclosed volume of 68,000 ft^3 to support 1 ton. A 100-ton buoyant structure would require a hot-air-filled sphere of 226-foot diameter or a 3,000-foot high cylinder of 54-foot diameter. These dimensions would present tremendously large surface areas to the effects of wind loadings and the total wind force may range from 2 million to 3 million pounds. The restraining system needed would have to be extensive and complicated; the enclosing envelope would have to be of lightweight material that probably would be subject to fairly rapid deterioration; the problems of servicing and maintenance appear severe; and an installation of this type may offer hazards to nearby communities. The idea

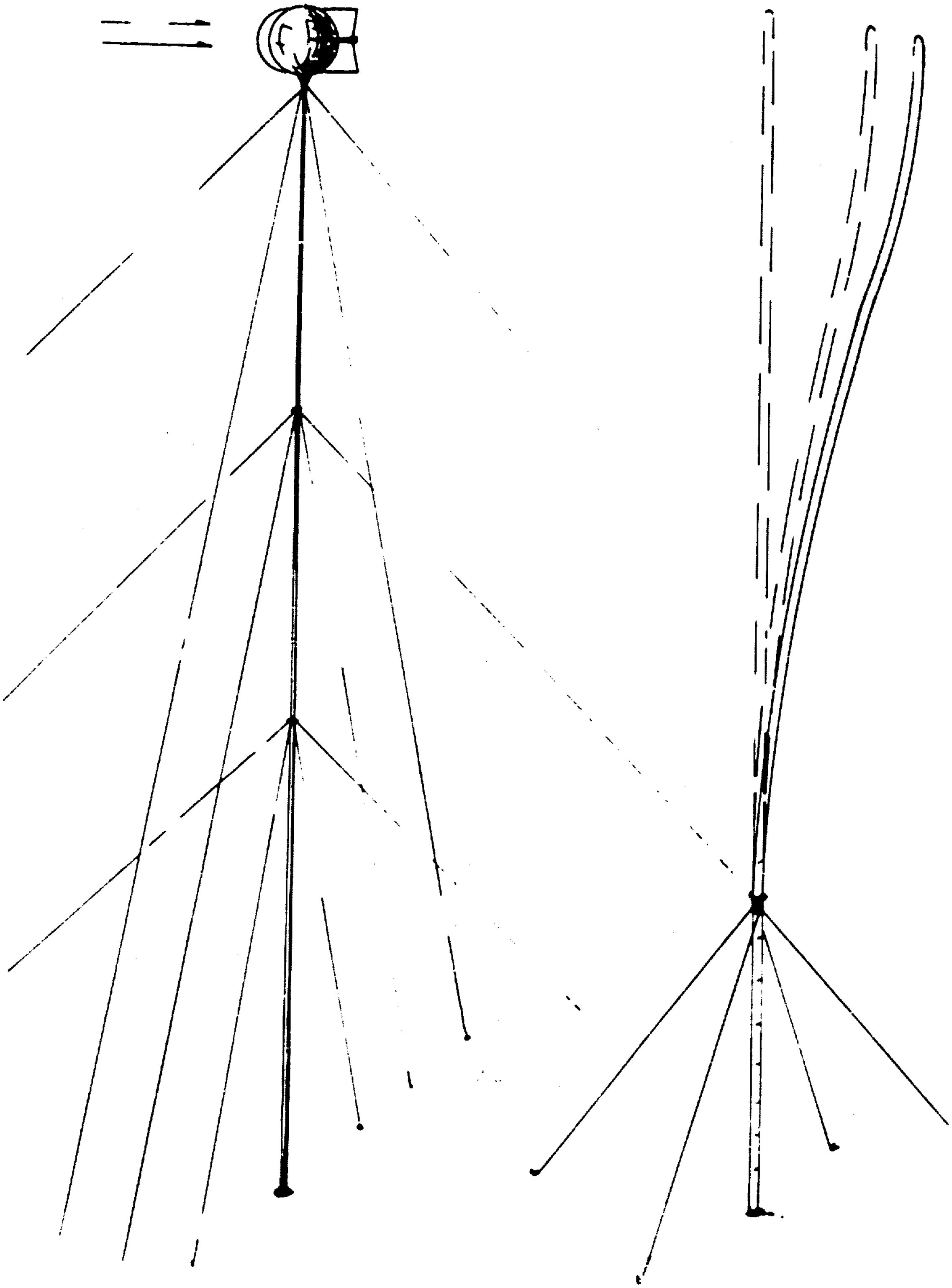

Figure 1a & 1b. Concepts for buoyant lighter-than-air supports for Vertical Radiator.

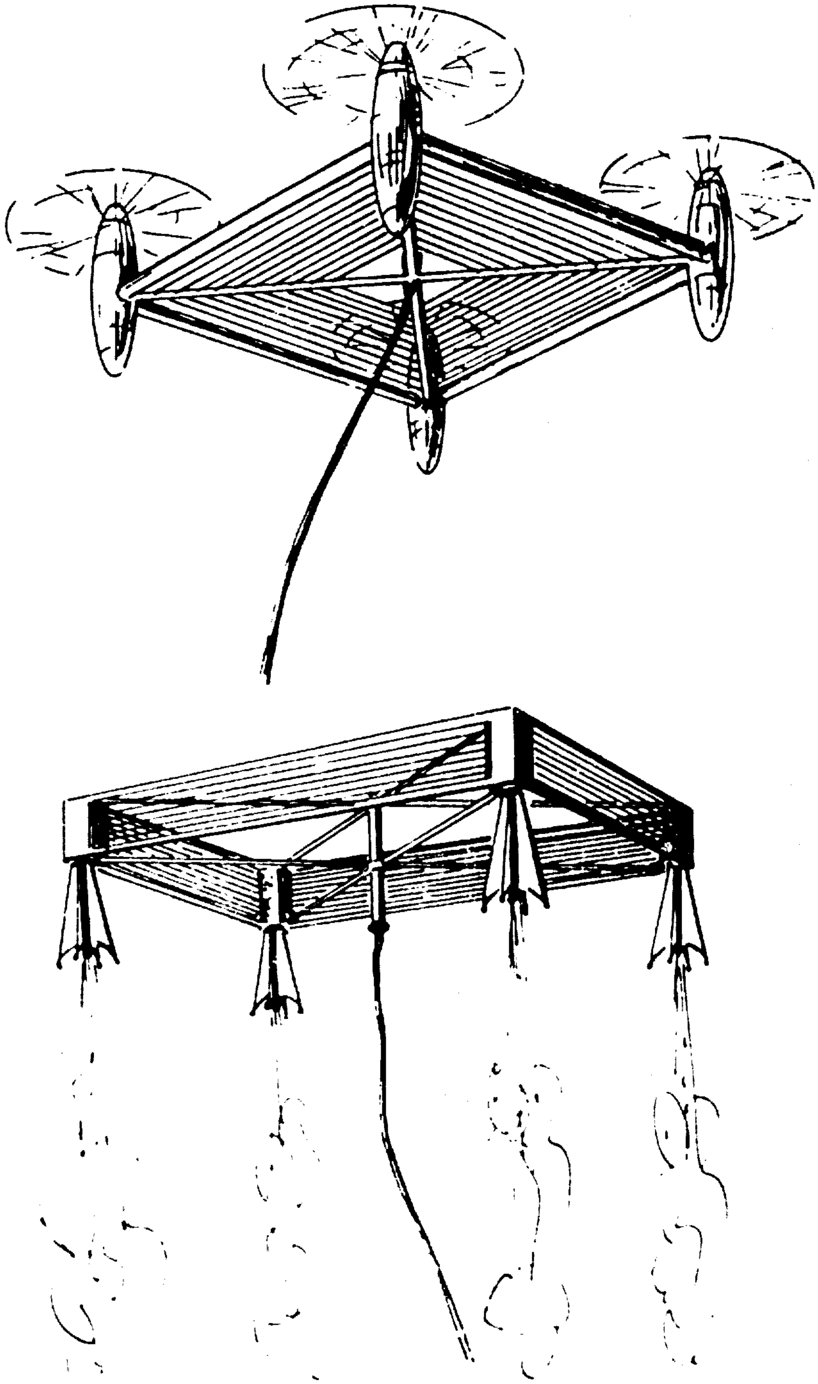

Figure 1c & 1d. Concepts for supporting Vertical Radiator aloft by mechanical aerodynamic means.

in general is thought to be imaginative, but impractical at the present time. Similar ideas for supporting a radiator system aloft proposed the use of captive helicopters, rotating planes, or jet-type apparatus, (Fig. 1c and 1d). The dimensions (300 x 50 ft) and the weight (100 tons) of a realistic transmitting antenna are greater than any existing aerodynamic equipment could carry and the prospects for vehicles of the required capacity appear to be far in the future.

GROUND SUPPORTED RADIATORS

Returning to the range of concepts that involved structural support eventually dependent upon the ground or water surfaces of the earth, certain unorthodox solutions were advanced. One fairly obvious answer was to locate the antenna systems atop mountains of appropriate height. This was done in the early 1950's at Jim Creek, Washington, where horizontal complexes of radiator wires were extended between low towers placed on adjoining hills. If a single mountain peak, intended to furnish an electrically efficient support to a top-loaded radiator complex, were to be used, it would have to be of the spire type rising steeply to a point. Here a special kind of geography would have to be found; and if it was, economic studies of construction at such a difficult site would affect its feasibility. Other suggestions for vertical radiators were: (1) a deep drilled hole in the ground with an antenna system of suitable length placed within it; and (2) an antenna system immersed in the sea; however, these earth-contained systems were found to be electrically impractical.

It was apparent that the best solution for a 3000-foot high radiator would be a ground-based supporting structure surmounted by a top-loading system of helical, cross-T or Y-shaped type; or by a system of horizontal or sloping wires ranging from the top of the support tower to the ground or to other towers of lesser height.

TYPES OF SUPPORT STRUCTURES

Classes of supporting structures that were considered in the early studies included vertical annular frames, spherical frames; domes of the radial, parabolic, or geodesic types; and single or crossed arches of the radial or parabolic types. The vertical annular, or wheel, concept envisioned a gigantic tension ring with the tension cables as part of the radiating system (Fig. 2a). The rim would require a cross-section of very substantial depth in order to prevent buckling and this part of the structure would most probably be of trussed construction. Such a solution would apparently require a greater cost than would vertical towers of lesser horizontal dimension. Further, with the average height of the radiating cables at one-half the diameter of the wheel, the effective electrical height of the system would be only a fraction of that for a spire tower with a top-load type radiating system.

The domical and arch type concepts (Fig. 2b and 3) were subjected to objections similar to those brought against the vertical wheel idea. Most of these would require large sites; the material costs would be higher than for spire towers; the necessity for curved members would complicate fabrication processes; erection methods would be necessarily unique and perhaps excessively expensive; and a very basic negative factor was that any supporting frame with sizeable horizontal dimensions would cause excessive ground losses in the electrical system.

Ideas for a prestressed metal supporting tower were advanced from several sources. These involved methods for engorging a suitably-shaped hollow chamber with gases or liquids so that initial tension forces would be created in the walls; and these forces would then counteract some portion of the compressive forces impinging on the structure. The action would be the reverse of that used in ordinary prestressing of concrete members. The prestressing schemes were not pursued because of certain obvious deficiencies in their applications to a tower of 3000 foot height that would be expected to support a 100-ton top load. Obviously a compressed gas or atmosphere would create a source of potential energy that might be exceedingly dangerous. If a non-compressible fluid was used as the engorging medium, very large hydrostatic forces would be created that would require many precautions to control.

Presently electrical engineers believe that the best support structure should be needle-shaped; and indeed if it were somehow possible to maintain the top-loading system at an appropriate altitude, the ideal connection to the ground would be a simple signal and power cable. Since the best conditions for ideal structural and electrical needs are mutually antipathetic, one factor must be traded off against another and a compromise reached. The solution for the supporting structure then is limited to a tower, mast, or stack of minimal horizontal dimensions and extremely large vertical dimensions. Such a supporting structure could be either free-standing or guyed. For the purpose of electrical efficiency a tower that is insulated from the ground would be best. Towers connected directly to the ground would have a practical electrical height of only 80 percent of the structural height.

TOP LOADING SYSTEMS

In the case of the 3000-ft tower it was implicit that a suitable top-loading system must be employed to satisfy the electrical requirements for a radiator. The radiating surfaces must be large to avoid corona effects. This top-loading system in itself would be a major structure. For instance, the top-loading system proposed for one version of a high antenna for VLF wave propagation employed a non-structural helix of 6-inch copper tubing, a top capacitance, a structural supporting framework, and a radome enclosure.[5] This entire complex involved a diameter of 45 feet, a vertical dimension of 300 feet, and an estimated

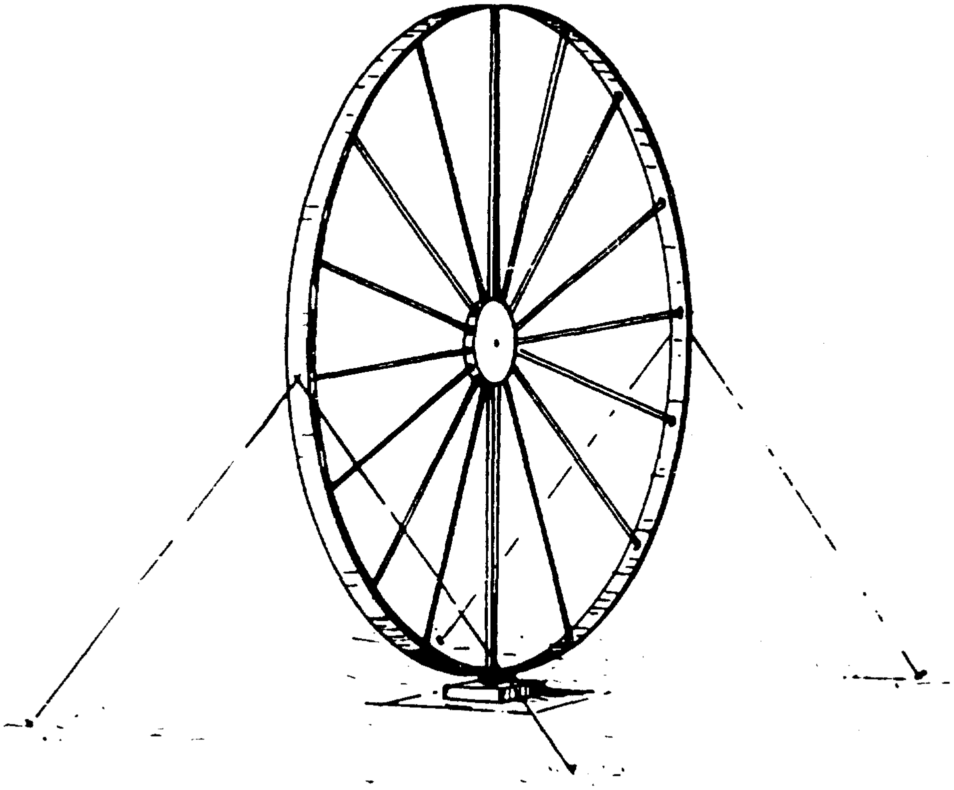

Figure 2a. Concept for vertical annular, or wheel structure type of Vertical Radiator.

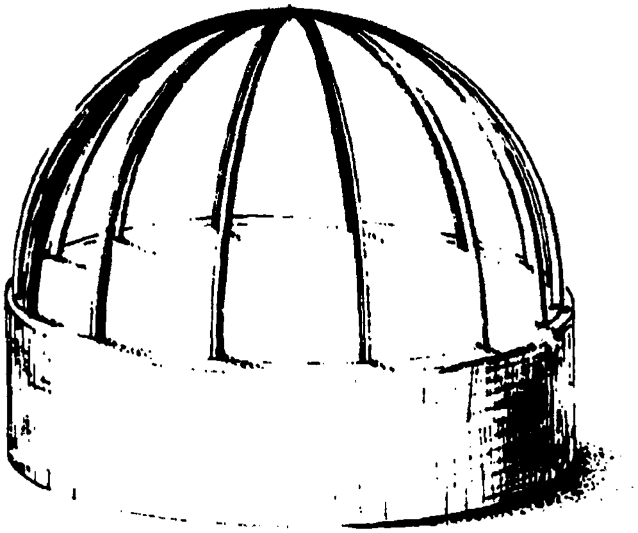

Figure 2b. Concept for domical or multiple-arch type structure for Vertical Radiator.

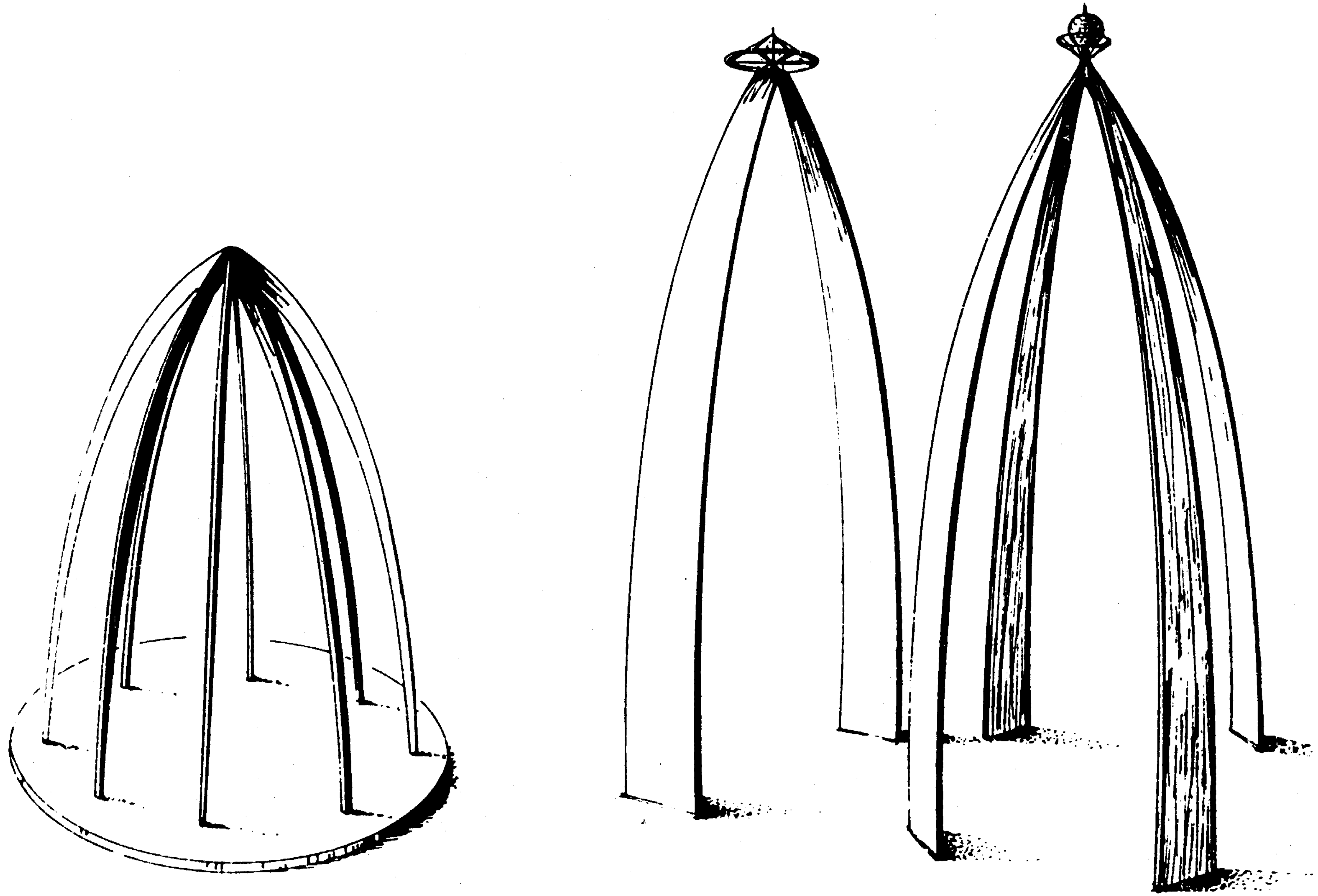

Figure 3. Concepts for arch-type structures to support Vertical Radiator system.

weight of 100 tons. Dimensions such as these would require inherent structural capacity or the need for a structural framework within the top-loading system. In another system, composed of horizontal and sloping radiating cables strung to many towers, lineal horizontal dimensions of many thousands of feet were involved.[4] Whether a monopole support is used or whether multiple towers are employed, it is apparent that the weight to be held aloft must be great.

LOADS AND FORCES

Regardless of the final configuration of a very high radiating or supporting tower certain loads and forces must be considered. Horizontal forces would chiefly be caused by wind loadings, although in some locations there is the possibility that seismic forces would also be encountered. Vertical forces would be certain live loadings such as those induced by ice formation, by the elevators within the structure, by servicing loads, by erection loads, by additional forces in the guys due to live load effects; and dead loads would include the weight of the top loading system and the tower structure plus the vertical components of the guy tension forces. All of these vertical or axial forces would ultimately be carried to the foundation and to the supporting soil.

If the considerable weights of the top-loading system and the upper parts of the tower were displaced horizontally for any appreciable distance the resulting eccentricity would cause large amplifications of the bending stresses within the structure. Any considerable tilting of the structure may impose the possibility of uplift of the foundation. Thus, the foundation may have to be of immense mass or may need to be tied to the earth by means of piling or other anchorages.

WIND FORCES

The wind forces would have the effect of causing bending stresses within the tower and, because of the great height of the structure, it is possible that these forces would be coming from different directions at separate elevations at a particular instant. Thus, torsional effects within the structure might be set up. In wind gusts at any instant actual velocity may be 50 percent greater than average velocity and within a second or two of time may change to 50 percent below average velocity.[6] The large and perhaps erratic horizontal forces induced by wind or seismic loading could be such as to threaten overturning of the entire structure.

Numerous authorities have investigated the phenomena of vertical wind gradients. It has been found that the layers of wind closest to the ground move at lesser velocity than the higher layers of air. This is attributed to the friction forces at the ground surface. The variation of wind velocity with height is expressed in the equation $v_z = v_o (\frac{z}{z_o})^x$ where v_z = velocity at base elevation z_o; z_o = the base elevation, commonly 30 to 50 feet; and z = the elevation greater than or equal to the base elevation z_o. The scalar exponent x is given various values by different authorities, with these values ranging from 1/8 to 1/4.

Many writers postulate that increasing wind velocity is not apparent beyond certain height limits. These height limits are not unanimously defined; in most cases 500 feet is considered to be the limit of wind velocity gradient. This figure of 500 feet, however, should not be considered as absolute because few observations have been made above this height; and further, local and time-dependent conditions of wind effects could cause wide variations in the observed data concerning the limit height of the wind velocity gradient.

For the wind loadings considered in this report we will use the data given in Reference 3, with the scalar exponent shown as 2/7, and assuming that the velocity gradient extends to 1500 foot heights. The wind forces will be assumed to create static loadings in the cases of the types of structures discussed here, although dynamic forces would have to be considered in any rigorous analysis.

Using the basic wind velocity pressure equation:

$$q = 0.00256\ V^2$$

where q = velocity pressure, psf

V = wind velocity, mph,

and equation: $p = Cq$

where p = wind pressure,

C (Shape coefficient) = 1.20 for cylindrical surfaces with height diameter ratio greater than 40.

Assuming V = 125 mph at 50 ft height,

$$p = 0.00256\ (125)^2\ (1.20)$$
$$= 47.8 \text{ psf}$$

Utilizing velocity pressure correction coefficient for height, $C_h = (\frac{h}{50})^{\frac{2}{7}}$, and assuming wind velocity gradient does not reach beyond 1500 ft and that velocity is constant at greater height we get wind velocity pressures ranging from 47.8 psf at 50 ft height to 126 psf at 1500 ft height and thereafter maintaining 126 psf for the remaining height up to 3000 ft. For a particular structure the widths of the exposed surfaces, shape factors, and possible increased dimensions created by ice formation, would determine the areas upon which wind loads would impinge.

AERODYNAMIC FORCES

The production of wind vortices and eddies around structural members and the possibility of harmonic vibrations induced within the structure are factors that would require considerable detailed study. Drag coefficients for many of the structural elements and configurations proposed for towers are not precisely known. It is probable that the damping action of guys would minimize the possibility of harmonic vibrations and may permit analyses wherein wind forces could be treated as static loadings. Non-guyed towers, especially of the open-framed type, may require consideration of wind-imposed dynamic forces.

ICE LOADINGS

Reference 7 says, "In designing a tower built up relatively small members ice loads may be of importance. Ice having a density equal approximately to that of water may build up to a thickness of two or more inches on such members. It may also build up to a much greater thickness but have a lower density. When ice builds up, it alters the shape and the projected area of the member. This should be considered in computing wind loads." While the location chosen for the erection of a very high radiator structure may be out of the cold zones, it is possible even in temperate and sub-tropical areas to have local conditions or short-duration conditions wherein ice loads could build upon a very high structure. It should be assumed, therefore, that ice loadings of 2-inch thickness and of the density of water will build upon all exposed surfaces of the tower.

SEISMIC FORCES

During an earthquake the foundation of any structure undergoes accelerations which are largely horizontal. Vertical components are not usually significant. In most cases the structure is assumed to act as a rigid body and hence, it will accelerate horizontally at the same rate at its foundations. This assumption is quite approximate and not particularly valid. Actually the structure will undergo elastic distortions that will affect the acceleration of its various members. The type of framing, and relations of horizontal dimensions to vertical dimensions, could have important effects upon the responses of a particular structure. Various authorities have attempted to define the magnitude of the horizontal inertial forces which will act upon a structure. An example is given in Reference 3 wherein tower structures in the most susceptible earthquake zones of the earth are considered to be subjected to lateral forces equivalent to 0.20 times the weight of the structure. For the purposes of this study seismic loadings will not be considered. Practically, it may be advantageous to locate any very high tower structure in an area that would not be in the earthquake zones.

DEAD LOADS

Dead loads may be considered as the axial forces imposed by the weight of the top-loading system, the weight and tension of guy cables, and the weight of the tower structure itself.

The weight of the top-loading system may be approximated by considering the sizes and shapes of the systems already in use or proposed. The electrical requirements for adequate areas of radiating surface and the necessity of inherent self-support or framing within the top-loading equipment indicate the estimated weight should be about 100 tons.

A guyed tower may be thought of as a continuous beam gaining support from the horizontal components of the guy forces. The spacing of these horizontal supports should be such that adequate bending and buckling resistance in the tower would be maintained with the least possible number of guy levels. A reasonable first estimate may set the spacing of the guy levels at each 200 feet of the tower height. Thus for a 3000 ft tower, 15 levels would be necessary. Initial tensions in guys for high towers are usually about one-eighth to one-fourth of the ultimate strength of the cables.

MATERIALS

A very high radiator would be a complex structure and would, no doubt, include many different materials.

PROPERTIES OF MATERIALS

The physical properties of materials of construction that must be considered are briefly stated:

a. Strength is probably the most important physical property of materials. The types of stresses to be withstood; whether they be single or combinations of tension, compression and shear; whether they be uniform or concentrated; whether they are continuous or periodic; all these decide the strength characteristics of the materials.

b. Dimensional instability of materials due to applied stress or changes in temperature must be considered. This is especially true when several metals are used with each having different thermal expansion coefficients. Expansion or contraction as temperatures are changed, may produce secondary stresses over and above the normal forces in the system.

c. Conductivity of heat and electricity are important physical properties. Substances with low conductivity or insulators may be thought of as conductors with very low conductivity coefficients and in certain parts of antenna structures low conductivity may be the first essential.

d. Hardness is an important property which determines resistance to erosion and abrasion.

e. The elasticity of a material is an important property of both metallic and non-metallic substances. The elasticity of metals is relatively unaffected by environment; the elasticity of non-metals varies considerably with environmental conditions.

f. Formability is a measure of the ease with which a material can be produced in the proper dimensions for a particular purpose. This is a very complex property which is dependent upon the physical structure of the material.

g. Corrosion resistance is one of the most important properties. If the material is very resistant to corrosion, or if it can be readily and cheaply protected, it would be possible to avoid the necessity of overdesign to provide allowance for reduction in cross-sectional area of the members.

h. Economy in first cost and in maintenance is the primary factor in deciding the choice of structural materials in cases where more than one material has desirable qualities.

ELECTRICAL RADIATING SURFACES

The actual radiating surfaces of an antenna structure should have as their prime physical property the ability to conduct electricity. Copper or aluminum would be very suitable for this purpose. Although some of the more precious metals may have better properties of conductivity, economic considerations would prohibit their use. Copper would probably be ruled out because of its relatively great weight (556 lbs per cu. ft.) and thus aluminum (165 lbs per cu. ft.) although it has an electrical conductivity of only 0.6 that of copper, may be considered as the first choice of materials for the radiating surface. Requirements are for smooth surfaces in the radiating portions of the antenna and therefore the material must be resistant to pitting or roughening due to environmental causes. In one proposed structure it was intended that the aluminum helix used as a radiating element would be enclosed within a protective covering of acrylic or polyester plastic.

STEEL STRUCTURE

For the supporting framework of a very high tower structure, a metal would probably be given first consideration. Carbon steel of grades A 7-58T, and A 36-60T, are the most commonly used materials for major structural framing and have the advantage of relatively low cost, ready availability and high modulus of elasticity. Other steels such as A 440-59T, A 441-60T, and A 242-55, are of the high-strength type, have relatively high yield points which provide that working unit stress in tension may be one and one-half times greater than that used with structural carbon steel.[8,9] The use of higher working unit stresses permits reductions in the thicknesses of sections in the structure with a consequent decrease in weight. The high-strength steels also are characterized by a greater degree of resistance to atmospheric corrosion than carbon steel; this attribute permitting thinner sections without the hazard of shortening life in service. The mill price of high-strength low-alloy steels is about 50 percent more than that of structural carbon steel of the A 7-58T grade.[10] High-strength steels can be most economically used for columns where the slenderness ratio, l/r, is less than 90. At higher l/r ratios the A7, A373 and A 36 types of steel show the most favorable cost versus allowable-load figures.[11]

It should be noted that in members where buckling can occur the working unit stresses of the high-strength steels are modified to the extent necessary to insure stability. Reference 10 states:

"Since the modulus of elasticity for all grades of steel is essentially constant, within the elastic region, two members of equal length but with different average stresses, due to axial loads, will deform in the same ratio as the average stresses. Thus high-strength steels, which are usually employed at higher stresses than those for structural carbon steel, will naturally have the greater deformation. From this it is evident that, other factors remaining the same, an increase in the allowable stress, as would be the case when substituting a high-strength steel for structural carbon steel, will result in an increase in the deflection in proportion to the working stresses of the two steels. Deflection under a given total load may be decreased by any or all of the following methods:

1. Decrease the bending moment by:
    a. Changing the distribution of the load.
    b. Introducing restraining moments at the ends of the span.
2. Decrease the span length.
3. Increase the depth of the beam.

In general, stress and not deformation or deflection is the criterion for design."

ALUMINUM STRUCTURE

Aluminum should be considered as a structural material for a very high supporting tower.[11,12] The modulus of elasticity of aluminum is about one-third that of steel. It may at first be thought that excessively large deformations of the structure could take place since modulus of elasticity is important in the studies of structural stability as well as in the calculating of deformations and deflections caused by stress. Deflection, however, is dependent on dimensions and arrangement of parts as well as on the modulus of elasticity of the material. Desired stiffness can be provided by choosing suitable forms and sizes of members and by suitable distribution of metal.

Some of the chief advantages of the use of aluminum in the frame of a high antenna tower are:

a. Resists corrosion. Aluminum needs no protection in most ordinary environments.

b. Conducts heat. This could be of value in development of methods for melting ice loads.

c. Conducts electricity. For equal sections the conductivity of aluminum is 62 percent that of copper.

d. It is non-magnetic. Electrical losses and disturbances are reduced by this characteristic.

The claim is also made that the cost per pound of aluminum is advantageous when compared to steel but to fully evaluate this, an economic analysis involving the cost of material, fabrication, and erection of any particular structure would have to be made.

MAGNESIUM AS STRUCTURAL MATERIAL

Magnesium may have value as a material for a very high framed structure because of its very low weight (112 lbs per cu. ft.) but economic factors, difficulty of forming and joining of this material would probably make it impractical. Aside from steel, aluminum and magnesium, no other metals have the requisite combination of qualities needed in principal members for a major structure.

CONCRETE STRUCTURE

Concrete is rarely used in framed structures that are more than one hundred feet high. The strength/weight ratios of this material implies that for structures of great height the lower portions may be unduly massive, and the need for extensive steel reinforcement in vertical members may add largely to the costs.

Problems of forming and concrete placement may be difficult in a very high structure. However, clever design of a concrete supporting tower may mitigate some of the prejudices against the material.

PLASTICS

The technologies for the use of plastic materials as structural components have not yet been advanced far enough to justify its use in a major structure. Typical properties of a glass fiber reinforced polyester plastic acceptable for structural use are listed:

Flexural strength	60,000 psi
Flexural modulus of elasticity	3,000,000 psi
Compressive strength	30,000 psi
Elongation to failure 1 to 2 percent.	

Considering the techniques presently existing in the use of plastic structural members it would be necessary to use a large safety factor to account for possible poor workmanship, or inadequate material control. A serious objection to the use of plastic structural members is that when these parts are bolted, or otherwise joined, very high local stresses often occur which result in structural failure.

Guy lines made of Mylar, a polyester plastic, have been proposed for antenna structures. These lines are made of corded strips of tough, clear film and have good elongation and impact resistance with tensile strength of 17,000 to 21,000 psi. The material has a very low moisture absorption, and is dimensionally stable under extremes of temperature and humidity, with good retention of physical properties. It has a melting point of 250°C, and is slow burning. It has excellent resistance to acids, greases, oils, and organic solvents; but is affected by strong alkalies. It has electrical properties of good dielectric strength, high insulation resistance, and low dissipation factor. It does not become brittle or lose desirable properties with age. The material weighs about 90 lbs per cubic foot. This indicates no strength/weight advantage over stranded steel cables. A problem with Mylar lines is the development of adequate methods of gripping. The cost of this material shows no economic advantages over steel.

The design of the insulated sections for a structure of the dimensions and weight of the proposed 3,000-foot high supporting towers will involve evaluations of the various electrical insulating materials. No materials are absolute nonconductors; those rating lowest on the scale of conductivity are therefore the best insulators. An important quality of an insulator is that it will not absorb moisture which would lower its resistivity. Glass and porcelain are the most common insulators because they are cheap, hard, and not affected by moisture. Other materials suitable for insulation include hard rubber, slate, steatite, stone, glass-fiber reinforced or laminated synthetic resin plastics, resins, asphalt mixtures, asbestos, molded silica, mica, or certain specially compounded ceramics containing zirconia or beryllia. Certain commercially available insulation materials utilize combinations of some of the above-listed elements.

It is possible that the magnitudes of the imposed compressive and tensile loadings occurring in a 3000-ft high structure may limit the usefulness of conventional materials and require the development of new techniques for electrical insulating.

TYPES OF TOWERS

Because a tower connected directly to the ground has an effective electrical height of only 80 percent of its physical height it is imperative that an electrical insulating system be included in the total design for any very high radiator system.[13,14] When considering towers that must have electrical heights in the 3000-ft range, it can be seen that the penalties for an uninsulated tower would be inordinately complicated structural and economic problems.

GUYED TOWERS

The advantages of a guyed tower may be listed as: (1) small cross-section, (2) economy of material, (3) small exposed area, (4) acts as continuous beam, (5) built-in resistance to bending, (6) constant shape, (7) requires no special fabrication, (8) erection procedures are standard, and (9) resists overturning. The disadvantages may be listed as: (1) requires a large site, (2) the guys for a very high tower would have to be of very large diameter and weight, (3) there are great axial loads from guys, (4) buckling may be a problem in a slender tower, (5) foundation may offer problems in that the limiting bearing capacity of the supporting soil may require the use of an elaborate mat foundation, (6) large and heavy anchorages for the guys are required, (7) if guys are improperly adjusted large moments may occur through large relative displacements of guyed groups, (8) servicing of the guys may be a very difficult problem, (9) there may be large electrical ground losses because of the sloping guys, (10) insulation problem is difficult both for compression and tension insulators.

The design of a multi-guyed tower involves numerous cycles of proportioning and analysis; wherein the gross axial, bending, shear, and torsional stresses in all parts of the structure are kept within allowable limits. Thus, computations of a rigorous and refined sort must be made by those concerned with the planning for a specific structure. However, a few simple calculations can supply certain pertinent facts, delineate magnitudes and proportions of forces and structure for the general case, and serve to indicate feasibility and relative advantages of the structural philosophy.

The following are some assumptions for a hypothetical 3,000-ft high supporting tower of the multi-guyed type (Fig. 4):

1. Top load has projected dimensions of 400 ft by 40 ft and weight of 100 tons.

2. The supporting tower has projected dimensions of 2600 ft by 10 ft.

3. The cross-sectional shape of all elements is round, wind-loading shape factor = 0.6.

4. There will be four guys at each of 15 levels.

5. The guys will be initially tensioned to 1/8 ultimate strength.

6. All material will be steel, type A7, weight 490 lbs/ft^3.

7. Wind forces will be considered as static loadings.

8. Wind velocity will be considered at 125 mph at 50 ft height with a velocity gradient to 1500 ft and constant velocity at greater heights. This gives velocity pressures of 47.8 psf at the base and 126 psf at 1500 ft and higher.

9. The l/r ratio for main and secondary compression members will be placed at 120, which, for mild steel, indicates allowable stress of 10,000 psi.

10. The weight of bracing and other secondary members will be 50 percent of the weight of the main compression members.

Figure 5 shows a diagram of the maximum wind forces imposed on the hypothetical structure and Figure 6 indicates the stresses that could be expected in the guy lines under these wind loading conditions. Since the calculated wind load stresses in the guys must be multiplied by the safety factor of 3.5 and these products represent seven-eighths of the ultimate strength of the strands, while initial tension requires one-eighth of the ultimate strength, the total required capacity of the cables was determined. By referring to catalogs of bridge strands, a rough estimate of the sizes of guy lines was obtained. The weights of the strands were not included in these rough first calculations. By applying the rule-of-thumb that each square inch of cross-sectional area of bridge strand supplies an ultimate strength of 100 tons, determination was made of the total cross-sectional area for each of the four directions of guy supports at each guy level. Single lines or combinations of lines may make up the necessary guy cross sections. Table I lists data concerning the separate guy strands for each of 15 levels of the tower.

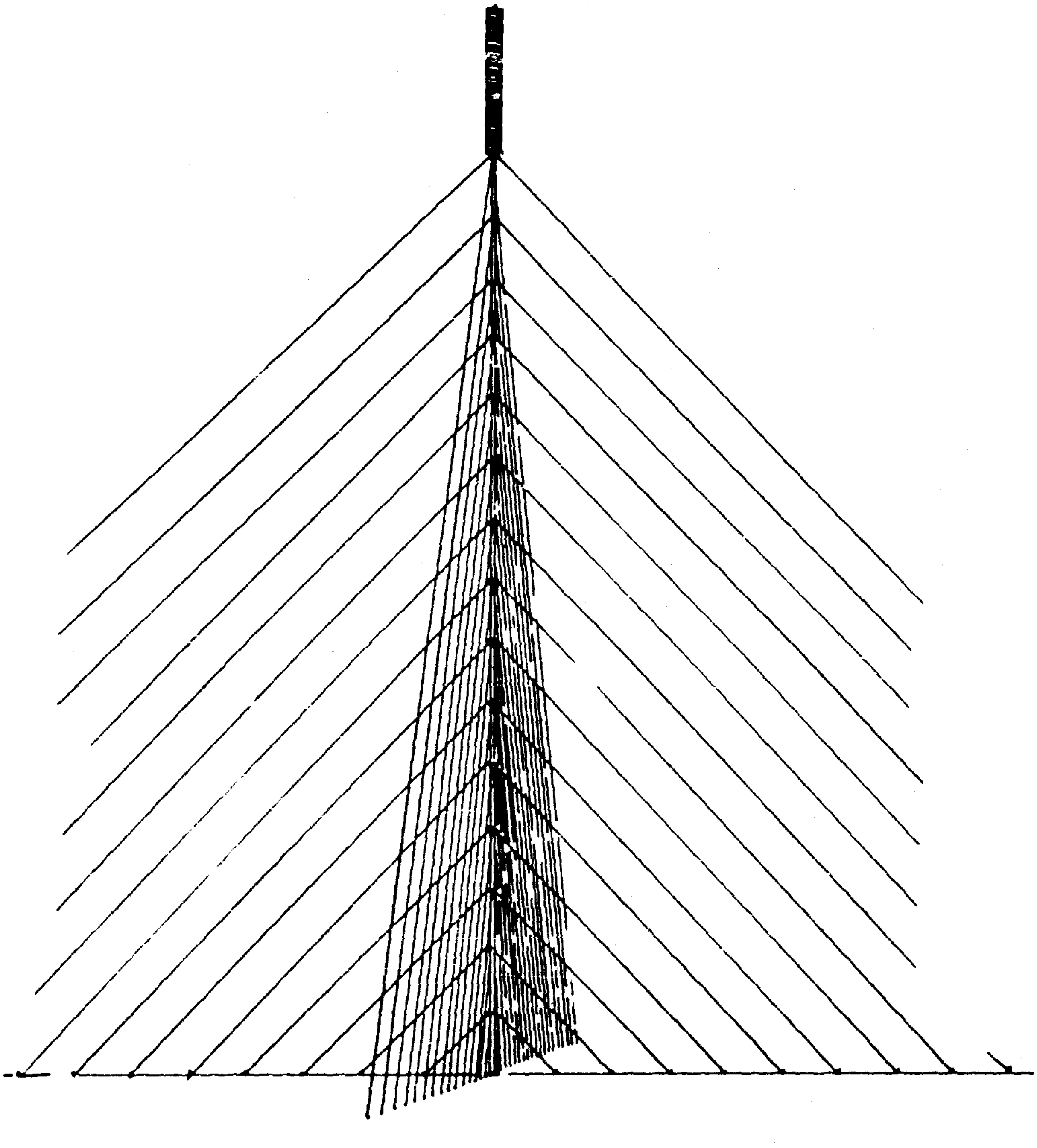

Figure 4. Concept for 3,000-ft supporting tower of multi-guyed type.

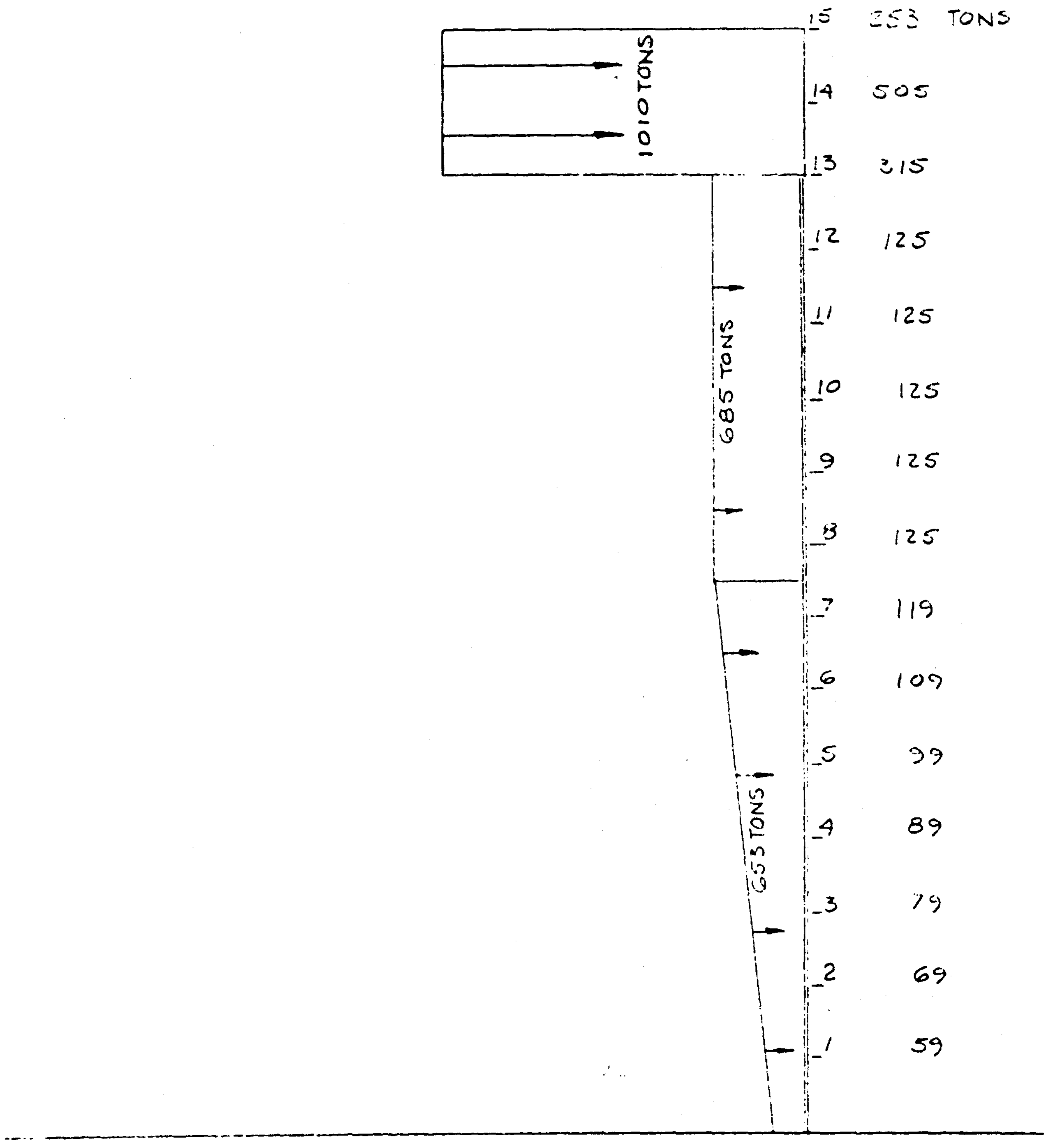

Figure 5. Wind forces on hypothetical guyed cylindrical tower 2600 ft height, with 400 ft high top loading apparatus.

Utilizing the previous assumptions and data from Table I the weights of the various tower sections and the cumulative axial loads were estimated as shown in Table II.

The final cross-sectional shape of the tower need not be deduced at this time. It could be a single cylinder, or have three, four, six, or any number of cylindrical legs suitably disposed and braced for stability against bending and buckling stresses.

The weight of steel in the guyed tower would then be 15,000 tons for the main structure, 7,500 tons secondary structure, guys 700 tons; which gives a total of 23,000 tons. At an average price of $450.00 per ton, the basic cost of a top-loaded guyed tower of 3,000-ft height is estimated at 10 million dollars, plus real estate and foundations. Fabrication and erection processes should be straightforward and well within the capacities of many mills, shops, and heavy construction contractors.

COMPRESSION-TENSION TOWERS

Another type of structure suggested for a very high antenna is the so-called compression-tension concept which would have a vertical central compression core, a series of horizontal booms or rings extending outward at various elevations, and tension lines joined to the outer edges of the horizontal members. Thus all compressive forces would be carried by the central core and tension forces would be accepted by whichever vertical lines are appropriate for any particular bending condition. One example of this concept is shown in Figure 7.

A system such as this might permit lesser cross-sectional dimensions in the central core as compared to the dimensions of an unguyed structure, and would require much less real estate for the site as compared to a conventionally guyed tower. The vertical tension lines would enhance the stability of the structure against bending forces; and by shortening the unbraced length of compression sections mitigate the buckling tendencies of the compression core.

A typical compression-tension structural system was investigated to determine the suitability of the concept. The following assumptions were made:

1. tower of 3,000-ft height.

2. No top load system. Guys act as radiators.

3. Projected width of central core: 12 feet.

4. Cross-sectional shape of elements is round, wind-loading shape factor = 0.6.

Table I. Guys for Each of Four Directions at Each Elevation

Elevation No.	Wind load Stress x 3.5 (tons)	Initial Tension (tons)	Ultimate Strength (tons)	Cross-section Area (in.^{2})	Diameter (in.)
3000	1250	180	1430	14.30	4.25
2800	2500	360	2860	28.60	6.00
2600	1560	220	1780	17.80	4.75
2400	620	90	710	7.10	3.00
2200	620	90	710	7.10	3.00
2000	620	90	710	7.10	3.00
1800	620	90	710	7.10	3.00
1600	620	90	710	7.10	3.00
1400	590	85	675	6.75	2.92
1200	540	80	620	6.20	2.80
1000	490	70	560	5.60	2.66
800	440	65	505	5.05	2.52
600	390	55	445	4.45	2.37
400	350	50	400	4.00	2.25
200	290	40	330	3.30	2.05

Table II. Axial Dead Loads Imposed by Guy Forces at Each Level, Plus Weight of Top-Loading System and Tower Structure

Elevation (ft)	Single Guy Weight (tons)	Single Guy Vertical Component, Initial Tension (tons)	Total Dead Load 4 Guys (tons)	Weight Top-load System (tons)	Weight, Structure Section (tons)	Cumulative Axial Dead Load (tons)
3,000	106	127	930		0	930
2,800	200	254	1810	50	98	2,888
2,600	116	155	1080	50	289	4,299
2,400	43	64	428		430	5,157
2,200	37	64	404		516	6,077
2,000	36	64	400		608	7,085
1,800	32	64	384		709	8,178
1,600	28	64	368		818	9,364
1,400	24	60	336		936	10,636
1,200	19	57	310		1064	12,010
1,000	14	50	256		1201	13,357
800	10	46	224		1346	15,027
600	7	39	184		1503	16,714
400	4	35	156		1671	18,541
200	2	28	120		1854	20,515
0					2052	22,567
	678		7390		15,095	22,567

5. Average wind load: 100 psf (static force).

6. Booms at 300 foot elevations of the tower.

7. Booms extend in four directions, horizontally, at right angles.

8. Booms were all of 100 foot length.

9. Safety factor of 3.5 for guy cables, based upon ultimate tensile strength of 100 tons/sq in.

10. Initial guy tension equals one-eighth ultimate strength.

11. $\frac{L}{r}$ ratio of core = 120.

12. Allowable column stress = 10,000 psi.

The moment forces in the tower, which may be imposed from any direction, were computed. The required resistance forces in the vertical guys were based upon moment arms of 100 foot length. Since the booms extended in four directions, four separate guy systems would be involved. In these guy systems initial tension was one-eighth of the ultimate strength of the cables; and seven-eighths ultimate strength equalled design wind load stresses multiplied by a safety factor of 3.5. The cross-sectional area of the guy cables was based upon an ultimate strength for bridge strands of 100 tons per square inch. Cross-sectional area of the central compression core was determined by adding the loadings at each 300-ft section of the structure.

The calculations employed were approximate and would need to be greatly refined for the design of any particular structure; but they did serve to indicate important facts concerning the compression-tension tower concept.

It was shown that the tension elements, vertical cables, would require large cross-sectional areas. The total weight of the cables was 5,000 tons. The compression core of 12-foot diameter would need a wall thickness of 3 feet at the bottommost section to provide enough metal to resist the tremendous compressive forces set up by dead load of the tower, initial tension in the vertical guys, and wind-induced moment loads. The weight of the core was 20,000 tons. Probably 50 percent should be added to this core weight to take care of the weight of the horizontal booms and secondary members. Thus the total weight of structural steel would be in the neighborhood of 30,000 tons. Based on an average unit price of $450.00 per ton for all steel, tension cables, compression core, and miscellaneous structural parts. the total basic cost of a typical compression-tension tower of 3,000-ft height is estimated at 16 million dollars,

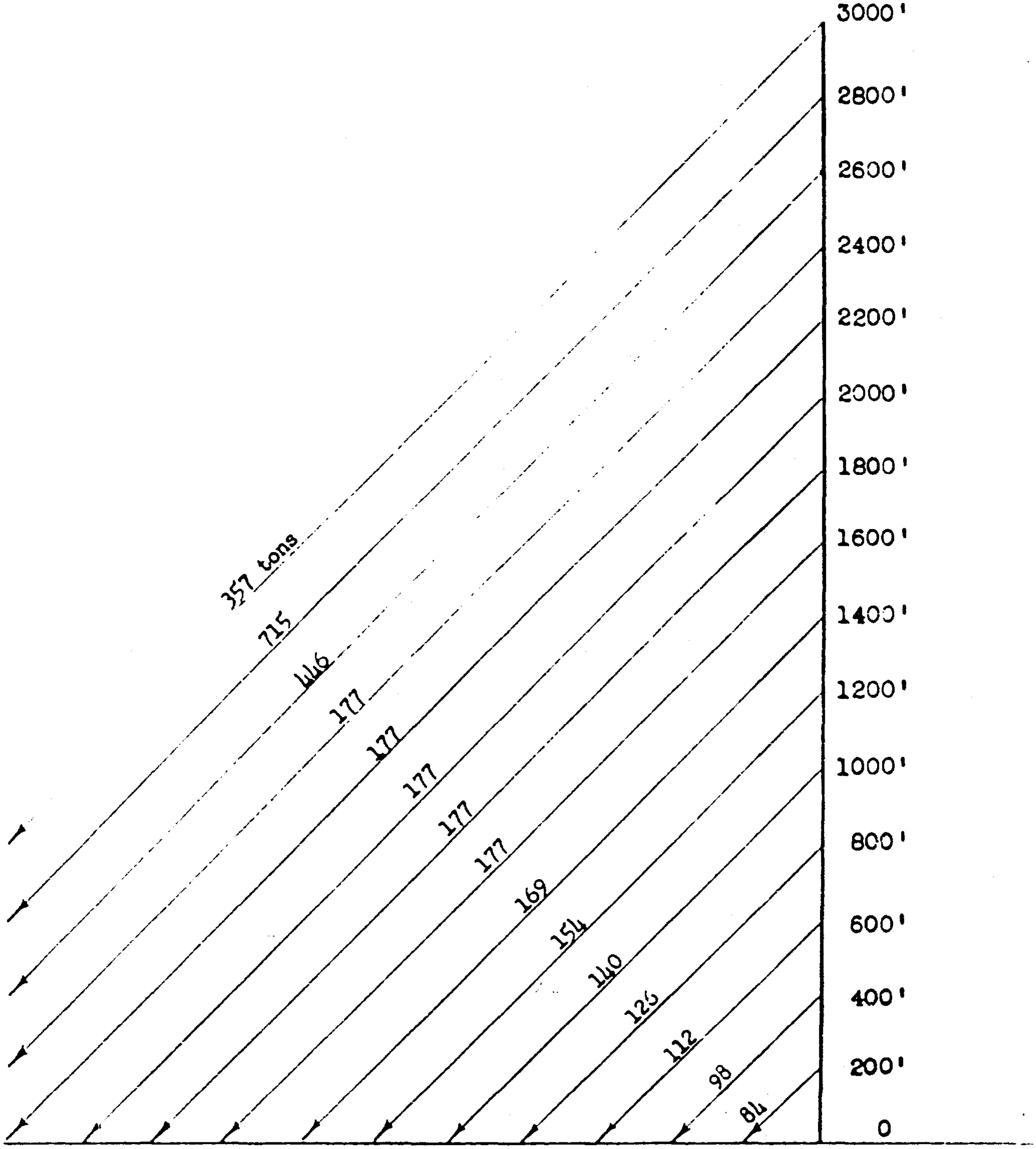

Figure 6. Stresses in guys for hypothetical tower subjected to wind forces.

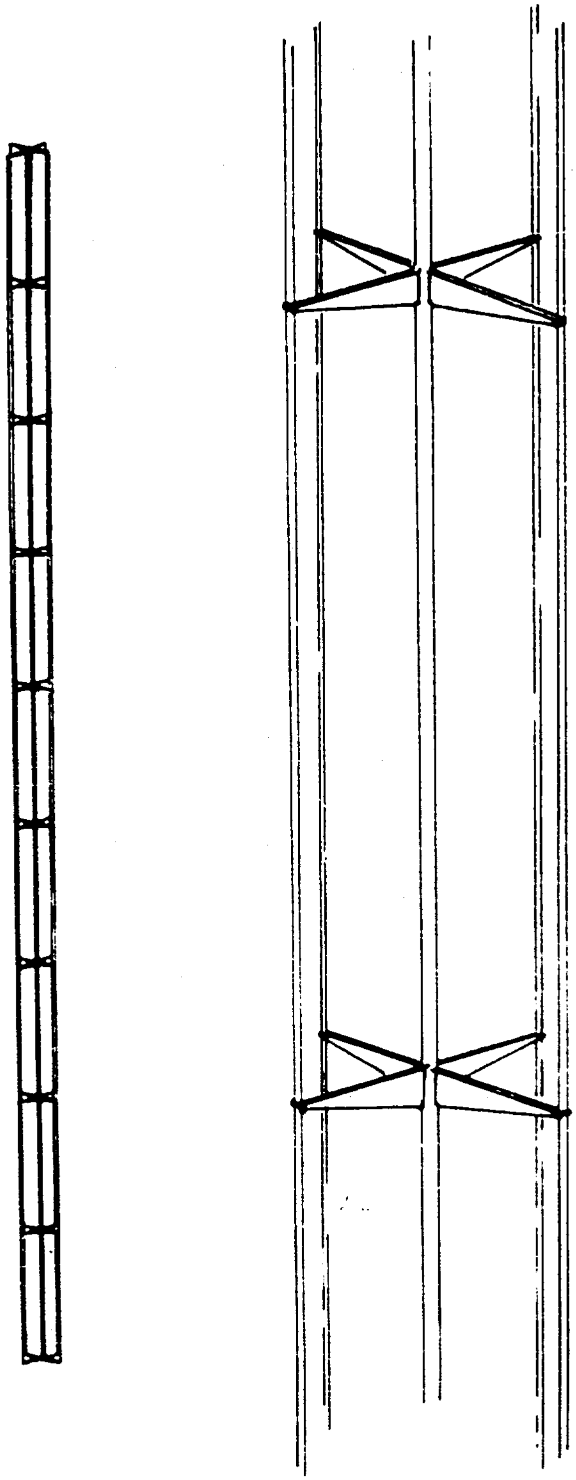

Figure 7. Concept for compression-tension structure for Vertical Radiator.

plus real estate and foundations. It is not expected that the fabrication and erection of such a structure would offer any extreme difficulties; although some interesting problems of construction techniques would probably be encountered.

FREE-STANDING TOWER

The advantages of a free-standing or cantilever tower may be listed as: (1) the site could be relatively small, perhaps having a maximum dimension of approximately one-quarter that of the tower height. Thus, the real estate needed for a free-standing tower may be only about one-fiftieth of that required by a guyed tower of similar height; (2) a self-supporting tower would be free of additional axial loads such as those imposed by vertical components of guy forces; (3) there would be no need for additional foundation structures such as heavy guy anchorages; (4) the insulation problem would be minimized because axial loads would be less than for a guyed tower and there would not be any tension members that would have to be insulated; (5) if it is assumed that a free-standing structure would have varying cross section, then buckling problems would be minimized; (6) servicing of a cantilever structure should not be difficult; (7) though the tower cross section may be larger than that of a guyed structure the overall horizontal dimensions would be much less than for the case of a tower where the guy cables may extend for large distances in a horizontal or sloping direction, thus electrical ground losses would be minimized.

Some of the disadvantages of a cantilever-type tower are: (1) a varying cross sectional shape with relatively large bottom sections compared to the topmost sections would require more complicated component fabrications, be more difficult to erect, and require a greater quantity of materials; (2) in the lower portions large areas of exposed surface would be subject to wind loading; (3) the entire structure would act as a cantilever beam, thus resistance to great bending forces would imply sizeable cross-sectional area; (4) in order to resist overturning the structure would need a very heavy lower section or base or otherwise be tied to tension piles or other types of anchors in the foundation soil.

As with the guyed tower, the design of a free-standing tower of very great height would require a great number of inter-related computations and would have to be keyed to the circumstances of a particular structure. But again certain premises concerning the scope and practicality of the general concept of a very high cantilever structure, Figure 8, can be deduced from an enumeration of some basic data. Assume:

1. A free-standing truncated cone surmounted by a helical type top-loading system.

2. The total height of the structure to be 3,000 feet, with a base diameter dependent upon the requirements for resistance to overturning moment.

3. The top-loading will comprise the upper 300 feet of structure height, will have a diameter of 40 feet, and a weight of 100 tons.

4. The supporting tower may be solid-surfaced stack, or alternatively could be composed of numerous columns with appropriate cross-bracing. If separate columns were used, these would individually diminish in cross-section as height increased.

5. Cross-sectional shape of the structural elements is round. This gives a wind-loading shape factor of 0.60.

6. The wind loadings impinge on a projected surface of trapezoidal shape. The projected width is 10 feet at the top of the supporting tower and increases with the required resisting moment to the base of the structure.

7. Wind forces will be considered as static loadings.

8. Wind velocity will be 125 mph at 50 feet elevation with a velocity gradient to 1500 feet and constant velocity at greater heights. This gives velocity pressures of 47.8 psf at base and 126 psf at 1500 feet and higher.

9. Material will be steel A7, allowable tensile and compressive stress, 20,000 psi; weight 490 lbs/ft^3.

In a rough calculation the overturning moment caused by the wind velocity pressures on the projections of the top loading systems and the supporting tower of varying cross-section was found. The force on the top-loading system was considered to be 126 psf; and the tower, with the major portions of its surface in the lower half of elevation, was assigned an average wind loading of 75 psf. By varying the base diameter relative to the weight of the entire system a number of combinations for appropriate moments resistant to overturning were found.

The overturning moments were calculated by:

M_o = Average wind velocity pressure x shape factor x projected area x moment arm

For top-loading system,

$$M_{tp} = (126 \text{ psf})\,(0.60)\,(40 \text{ ft.} \times 300 \text{ ft.})\,(2850 \text{ ft})$$

$$= 2.58 \times 10^9 \text{ ft-lb}$$

For tower structure,

$$M_{ts} = (75 \text{ psf})\,(0.60)\left[\frac{h^2}{3}\,(R + 2r)\right]$$

where,

r = radius of cone top, 5 ft

R = radius of cone base, various values ranging from 20 to 200 ft

h = 2700 ft.

The resisting moment was calculated by:

M_r = Total weight x base radius = WR

Table III lists the weights required for overturning-resistant structures for the case where the supporting tower is a solid surfaced truncated cone. If the tower were in the form of an open framework with a general trunce-conical shape but with much less exposed surface than the solid cone it would be possible to drastically reduce the total weight of the structure.

For instance, consider the total exposed surface to be the equivalent of a solid truncated cone of 80-foot base diameter but use this amount of surface in an open-framed tower of 400-foot base diameter. The main compression elements were assumed to have a ratio of unbraced length to radius of gyration, $\frac{L}{r}$, of 120. The allowable compression stresses were than calculated by:

$$17{,}000 - 0.485\,(120)^2 = 10{,}000 \text{ psi.}$$

The section modulus to resist bending was then calculated:

$$\text{Section Modulus, } S = \frac{\text{Moment, } M}{\text{allowable stress, } f_s}$$

$$\text{for a hollow circle, } S = \frac{0.098}{d}\left(d^4 - d_1^4\right)$$

where: d = diameter, outside = 400 feet

d_1 = diameter, inside

Solving the above equations for d_1 it was found that an average shell thickness of steel equivalent to 0.49 inches was required. This thickness indicated a weight per square foot of shell surface of 20 pounds. The shell surface area was 1.695×10^6 square feet and thus 17,000 tons of steel to resist moment forces was required.

This amount of steel disposed at the perimeter of the truncated-cone-shaped frame would probably be most efficient in the form of solid round compression members suitably spaced and braced to provide the

Table III. Weights for Overturning-Resistant, Solid Surfaced, Truncated Cone Structures

Base Diameter Ft	Base Radius Ft	Overturning Moment Ft-lb $\times 10^9$	Resisting Weight lbs $\times 10^8$	Resisting Weight tons
20	10	4.76	4.76	238,000
40	20	5.85	2.93	147,000
60	30	6.93	2.31	116,000
80	40	8.03	2.00	100,000
100	50	8.83	1.77	89,000
120	60	10.2	1.70	85,000
140	70	11.3	1.62	81,000
160	80	12.4	1.55	77,500
180	90	13.4	1.49	74,500
200	100	14.6	1.46	73,000
240	120	16.8	1.40	70,000
280	140	18.9	1.35	67,500
320	160	21.1	1.32	66,000
360	180	23.3	1.30	65,000
400	200	25.4	1.27	63,500

required $\frac{L}{r}$ ratio of 120.

The additional steel required to sustain axial loads was computed by adding the dead loads at various elevations, and by using the allowable column stress of 10,000 psi based upon an $\frac{L}{r}$ ratio of 120. This was showed that the weight of steel to sustain axial loadings was 6700 tons. By adding this figure to the previously determined 17,000 tons needed for bending resistance the total steel weight amounted to 24,000 tons. Since this open-framed conical structure of 400-foot base diameter was assumed to have the same amount of projected exposed surface as a solid-surfaced cone of 80-foot base diameter, the over-turning moment for the 80-foot case, which is 8.03×10^9 ft-lb was used to determine resistance to overturning. The total weight of steel was 24,000 tons and this on a moment arm of 200 feet gave a resisting moment of 9.6×10^9 ft-lb; proving the structure safe against overturning from wind forces.

At $450.00 per ton the basic supporting structure of 24,000 tons weight would cost about 11 million dollars. To this would be added the cost of real estate, a foundation, a top-loading system, and the necessary auxiliary construction for the entire complex. Some complications may occur in the fabrication of the component members due to their curved shapes, although judicious design could minimize the problems. Erection should be straight-forward and require no special techniques.

CONCRETE TOWER

Since no natural mountains of the right size and shape are available to support a radiating complex at great heights it has been suggested that a huge concrete mass structure in the shape of a tall peak be constructed. A 3,000-foot conical column, rising to a point, if it were of solid concrete of 150 pounds per cubic foot density, would require a base diameter of only 41 feet to provide sufficient mass against the overturning forces of wind pressures.

A more practical configuration would be a hollow truncated cone constructed of concrete which might be surmounted by and/or engirded by an appropriate radiating system of metal. This cone could be in the form of a prestressed or reinforced concrete silo, Figure 9, and the interior space could be utilized to contain the mechanical and electrical equipment necessary for the entire complex.

If the concrete conical structure be assumed to support a top loading system of 40 by 300 feet dimensions; and have a height of 2700 feet, a top diameter of 10 feet and a bottom diameter of a certain dimension, then the data in Table III is pertinent. For example, consider a solid-surface truncated cone of 400 foot base diameter.

Assuming wall thickness of 2-1/2 feet, the section modulus at the tower base was calculated,

$$S = 0.098 \left(\frac{d^4 - d_1{}^4}{d} \right)$$

$$= 2.45 \times 10^6 \text{ ft}^3$$

The overturning moment for this size and shape of tower was obtained from Table III,

$$M = 25.4 \times 10^9 \text{ ft - lb.}$$

Bending stress was,

$$f_B = \frac{M}{S} = 10380 \frac{\text{lbs}}{\text{ft}^2} = 72 \frac{\text{lbs}}{\text{in.}^2}$$

The axial stress was determined,

$$f_A = \frac{P}{A} = 1470 \text{ psi}$$

where

P = Weight of concrete cone and top load

$= 5.28 \times 10^8$ lbs

A = Area in bearing at bottom of tower

= Perimeter x thickness

$= 2500 \text{ ft}^2 = 360{,}000 \text{ in.}^2$

Total unit stress,

$$f_c = f_A + f_B = 1542 \text{ psi}$$

$$\frac{f_A + f_B}{F_A + F_B} = .9844 < 1$$

$$F_A = 0.25 \, f_c'$$

$$F_B = 0.45 \, f_c'$$

This would indicate that for 2-ft wall thickness of the tower cone the concrete should have a f_c' value of 6180 psi. This is high but possible and, if required, lower strength concrete could be used

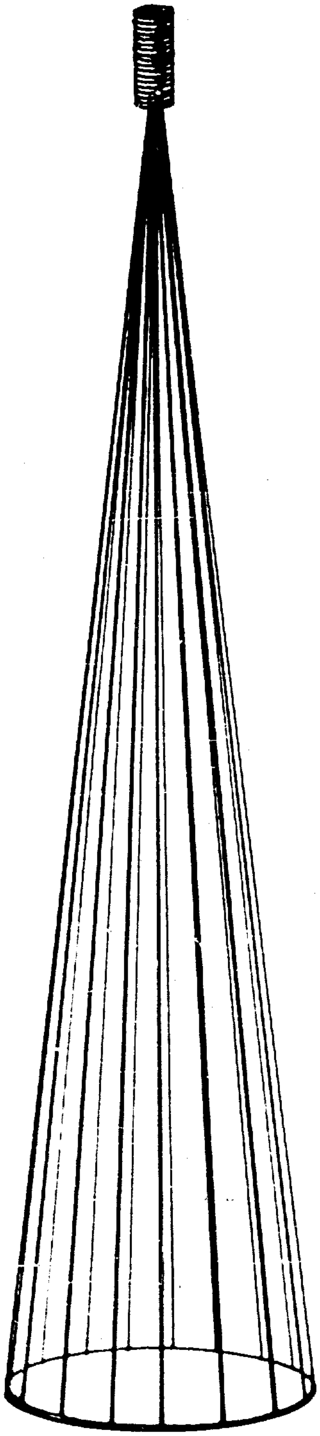

Figure 8. Concept for a free-standing type structure for Vertical Radiator.

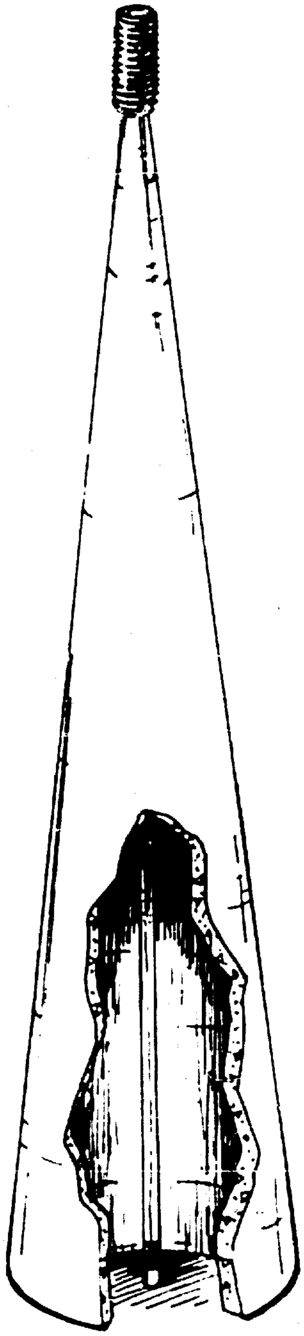

Figure 9. Concept for free-standing concrete cone structure for Vertical Radiator.

by increasing wall thickness. For the very low bending stresses indicated, no steel reinforcement would be needed; but a rough estimate of required temperature and shear reinforcing steel would be about 1000 tons.

The total weight of 255,000 tons times the moment arm of 200 feet gave a resisting moment of 102 x 10^9 ft-lbs which is much greater than the overturning moment of 25.4 x 10^9 ft-lbs.

The costs may be roughly estimated by considering 255,000 tons of concrete to be 128,000 cubic yards which at $50.00 per yard amounts to $6,400,000. The required 1000 tons of reinforcing steel at $400.00 per ton adds another $400,000 for a total cost, exclusive of real estate, foundation, electrical system and auxiliary equipment, of about $6,800,000.

Probably the forming problems for a vast conical-shaped concrete structure would be complicated and costly. It would be economically impractical to erect working staging for the full height of such a tower. Concrete emplacement would require advanced techniques of materials handling. To fully evaluate the concrete tower concept studies of proposed construction practices as well as economic, structural and electrical feasibilities for a particular structure would have to be performed.

RETRACTABLE TOWERS

One of the greatest factors contributing to the difficulty of designing an adequate monopole supporting tower of 3000-foot height is the electrical necessity for a top-loading system weighing about 100 tons and presenting a projected wind-loaded surface in the neighborhood of 12,000 square feet. This could result in bending and overturning moments of the magnitude of 2.58 x 10^9 ft-lb. A possible solution to the problem would involve a top-loading system that would be demountable or retractable during periods of very severe environmental conditions.

One proposal is that a 3000-foot supporting tower be surmounted by an inflatable radiating surface of metallized fabric, of spherical or cylindrical shape, filled with helium gas. It has been suggested that the supporting tower be designed to hold the inflated radiator against the forces caused by winds up to 40 mph. When wind velocities were greater than this figure the radiator would be partially deflated and reduced in size; with the deflated portions withdrawn into the tower, Figure 10a. A variation of this idea would provide a number of inflated radiator balloons attached to the tower top by shear linkages, Figure 10b. In the event of wind velocities greater than the design load these inflated spheres would successively be loosed from the tower and be allowed to float away. This would mean, of course, that each of the released spheres would have to be replaced when wind conditions return to normal. It is realized that electrical adjustments would have to be made within the system so that the proper wave length could be maintained and it is also recognized that in the event of reduced radiating surfaces power output of the system would have to be reduced. However, judicious study of sites for the proposed antenna should provide maximum efficiency at least at 90 percent of the time.

Other methods for minimizing wind loadings would provide mechanical means for reducing the exposed area of the top loading systems at times of dangerous wind velocity. This could be accomplished by a method for reefing or folding the upper portion of the antenna, perhaps in the inverted umbrella fashion shown in Figure 11. A variation of this scheme would provide for a movable top load that could be lowered from its position during hazardous periods, Figure 12. A telescoping mast would provide another method of reducing exposed surface area, and would also greatly reduce bending moments and buckling stresses during periods of adverse environmental conditions, Figure 13. For any of the above-mentioned schemes it would be prudent that the structure be located where the possibility of peak weather hazards would be infrequently experienced.

Schemes employing demountable or folding positions of the top-loading systems or the tower structure would require electric or hydraulic power and hoisting methods that may increase costs by large factors. However, by making possible lighter construction through elimination of the worst loading conditions, some portion of this additional cost may be recovered. A demountable or folding structure would possibly include certain parts projecting from the main radiating surfaces. These could result in corona discharges which would impair the efficiency of the transmitting system. The principal drawback to a variable dimension radiator is that the transmitting efficiency of the antenna would be drastically reduced during the periods when the structure would be retracted.

DISCUSSION

The information presented in the foregoing sections of this report indicates that the structural design problems for a conventional tower structure of 3000-foot height are indeed formidable.

The dead weight of a tower structure is a principal factor. It is not possible to materially reduce the axial loads in any high tower that must support a top loading system weighing 100 tons such as has been proposed in certain radiator systems. The weight of the supporting tower could be reduced to some degree by the use of high-strength steels or aluminums but the controlling consideration in any column structure would be buckling stress rather than compression stress and here the lesser cross-sectional area of the high-strength materials would limit their usefulness. Thus, reduction of dead weight

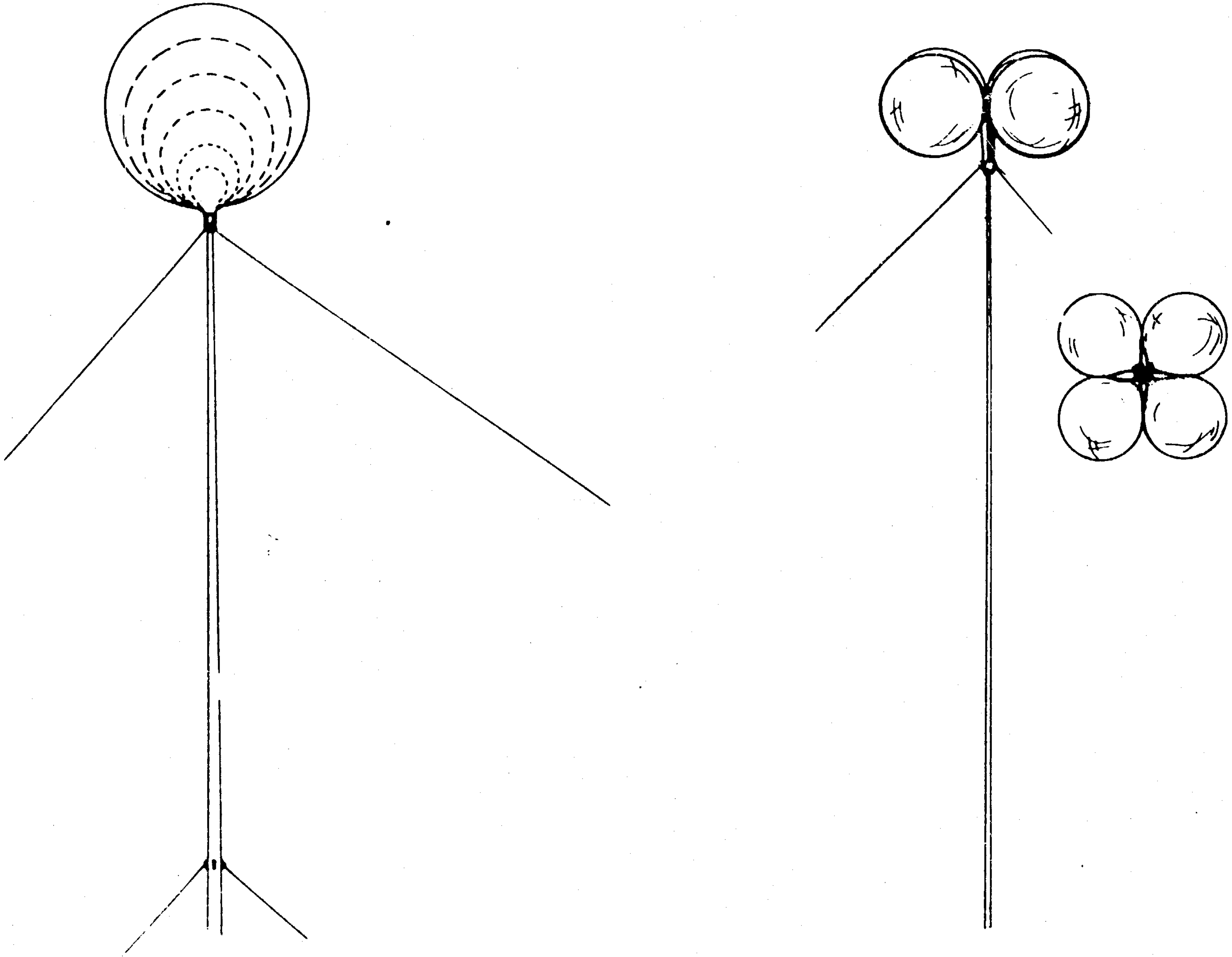

Figure 10a & 10b. Concepts for variable volume inflatable top loaded radiator systems.

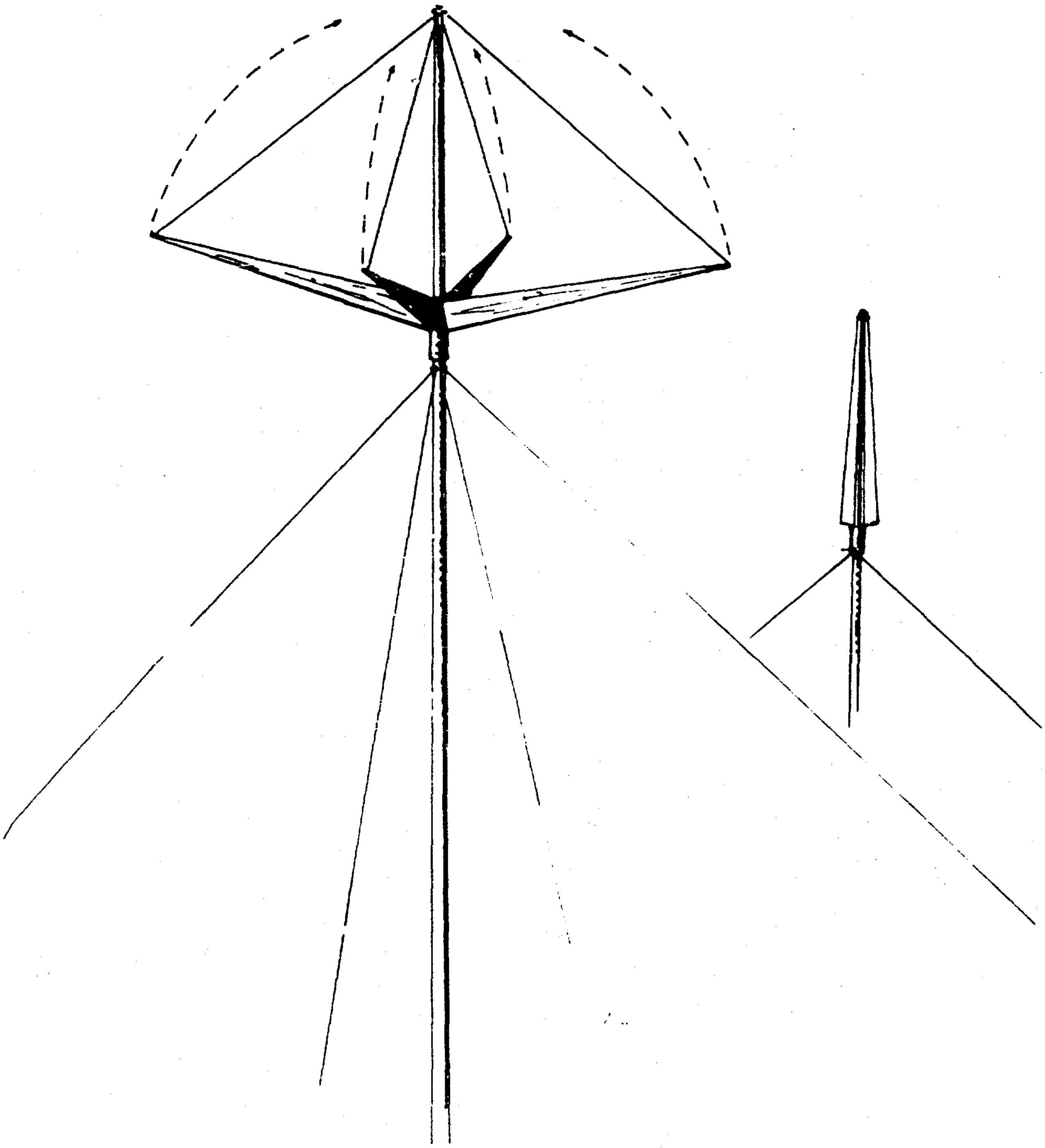

Figure 11. Concept for folding type of top loading system for Vertical Radiator.

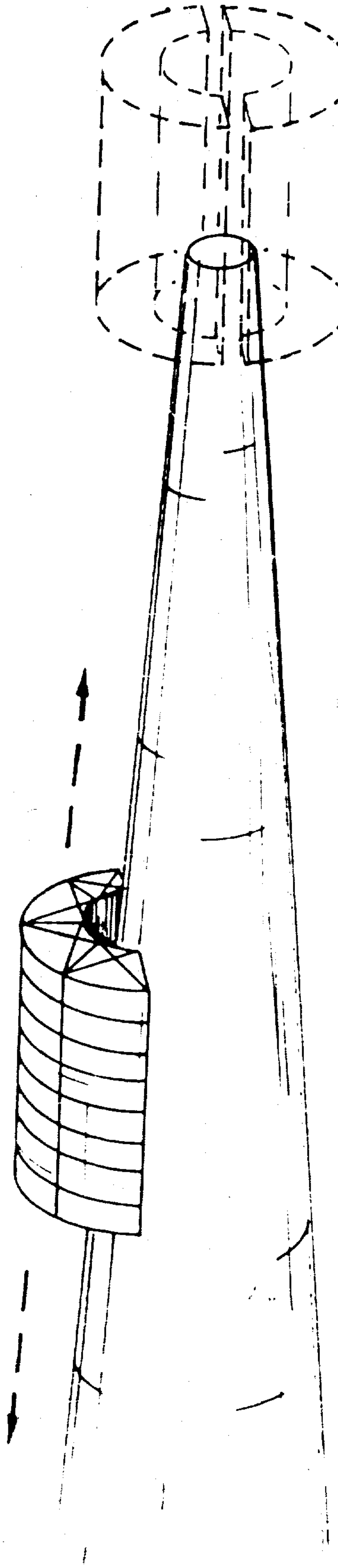

Figure 12. Concept for movable top load system for Vertical Radiator.

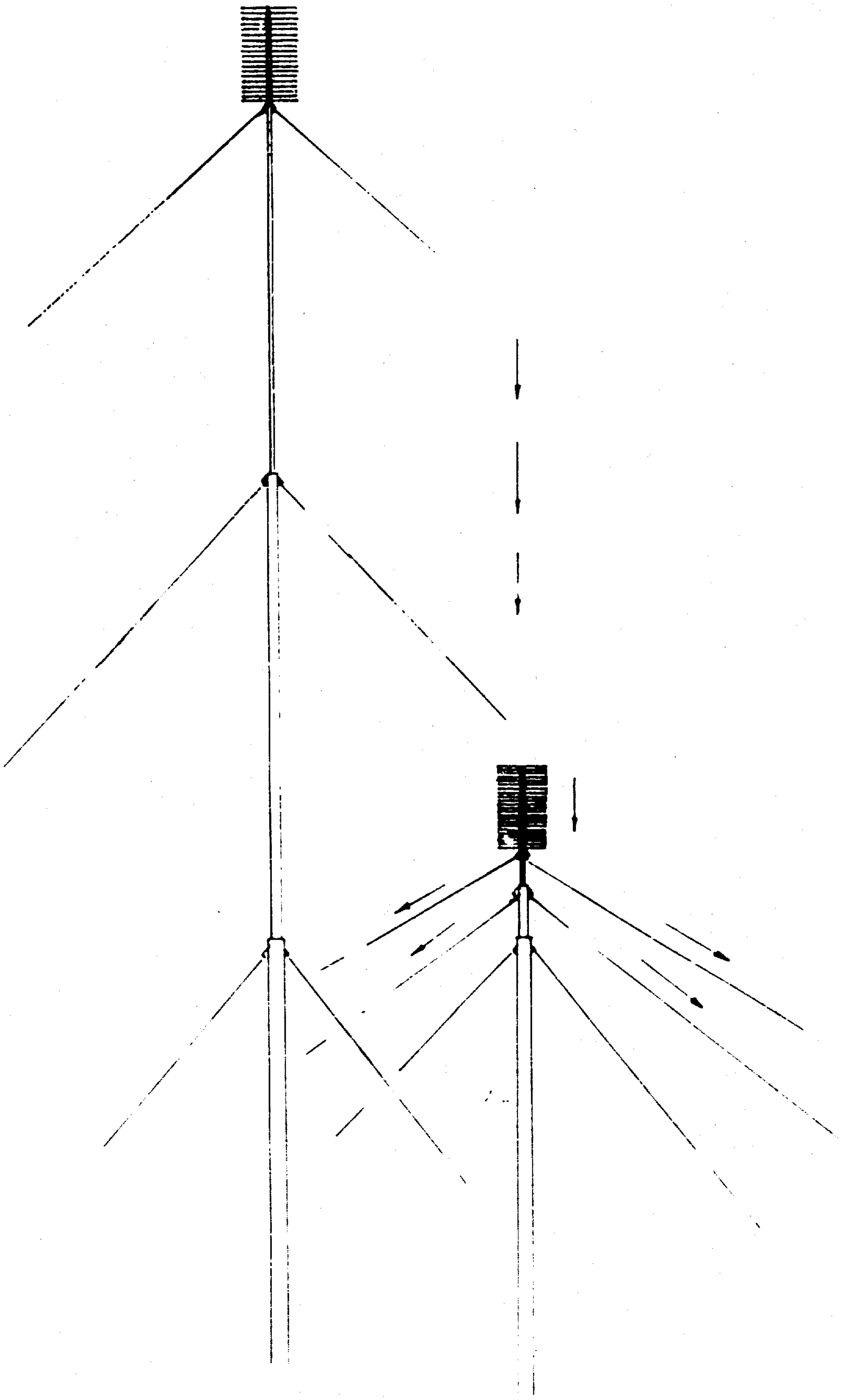

Figure 13. Concept for telescoping mast structure for Vertical Radiator.

comes to mean that a structural configuration should be devised that would reduce the buckling tendency of the structure; a requirement that is imcompatible with the necessity for small horizontal dimensions. The most logical shape (of those listed herein) for a very high tower is trunce-conical where a circular cross-section widens toward the base.

Another most serious factor in the consideration of a very high structure is the need for minimizing or compensating for horizontal forces caused by wind pressures. Top-loading systems of the types recommended for best electrical efficiency expose large surface areas to wind pressures, and the resulting loads at the topmost portions of the tower would require great resistance to bending within the structure. With a slender column of very great height, significant horizontal displacements of the upper portions could not be tolerated; less the amplified bending stress induced by eccentric positions of the heavy top load become so great as to cause failure of the structure. There does not seem to be any logical way in which horizontal displacement or sway can be completely restrained except by using very large cross-sectional dimensions and massive construction, which creates additional surface areas subject to wind forces. A guyed tower system can offer a considerable resistance against sidewise movements, but additional surface areas are exposed and tremendous axial forces are produced within the tower by the vertical components of initial and working loadings in the guys. It is probable that some side sway would have to be accepted, but it is questionable whether any large elastic recovery capacity could be built in as an inherent feature of any practical tower. A somewhat improbable solution to the side sway problem might involve a mechanical system of wind propellers or jets to counteract excessive horizontal forces impinging on the tower. Nature furnishes a good example of a tall structure with side sway characteristics in the bamboo, which sometimes reaches a height of 120 feet and has ratio of height to radius of gyration, $\frac{L}{r}$, of about 500.

These natural structures have been known to withstand tropical winds of very great force even though very large horizontal displacements of the plant tops occurred. The plant has a slender stem which is hollow, with well-marked nodes or joints in which the cavity is closed by a strong diaphragm. The tensile strength of bamboo fibers is from 40,000 psi to 60,000 psi. It may be that a man-made structure based upon the principle of nature's most efficient slender column would have application to the purposes of a high antenna system.

Where the total weight of a structure of minimized horizontal dimension may be as much as 250,000 tons a foundation design will be complicated. Selection of a site will involve exhaustive soil studies and a mat or piling foundation system may have to be devised. The necessity of providing anchorages against uplift forces will occur in the case of certain structural configurations.

FABRICATION AND ERECTION

The fabrication of the component parts for a 3,000-foot high supporting structure of steel or aluminum are well within the abilities of forming, joining, and inspection as practiced in modern well-equipped shops. Strict quality control of the various fabrication operations would have to be maintained. No doubt many sub-assemblies for the structure could be made in the shops. Care would have to be taken that these component parts should not be subjected to any unusual stresses during fabrication, transport, and installation.

Erection of a very high guyed or free-standing tower would mostly involve the same types of operations presently employed for the erection of major metal-framed structures. For joinings that would be made on the ground welding could be performed with adequate control and inspection. However, for joinings that must be made aloft it is probable that riveting or bolting methods would be most appropriate from the standpoints of speed, safety, and simplicity.

Construction of a concrete tower of great height would present a number of interesting problems, but probably none that were insuperable. Slip forms might be useful for such a structure or perhaps precasting of certain elements would be employed. Reinforcing or prestressing techniques would possibly be novel but present methods would have useful application.

The bringing of men, materials, and equipment to the working areas on any type of growing tower structure would merely involve extensions of the present methods which employ derricks or booms that move upward as the structural frame does. It is possible that new high-speed hoisting equipment may have to be used to reduce the times of vertical transit to the upper reaches of the structure. No doubt temporary guys would be necessary during the construction of any kind of tower, but it would probably be uneconomical to construct any great amount of falsework or staging for the erection operation.

SERVICING AND MAINTENANCE

It would be necessary to construct various elevators, lifts, passages, catwalks, and ladders within and on the outside of any tower structure so that servicing and maintenance may be performed. Servicing and maintenance of guy lines may offer difficult problems of access. Some of the guys may be at angles of 45° and may have lengths of about 1/2 mile. They will not be continuous strands but may be interrupted at various points by insulator assemblies or other hardware.

It may be that the principal factor in the maintenance program, control of corrosion, could be minimized by judicious design. Certain more expensive grades of steel or aluminum have inherent corrosion resistance and the employment of such materials would have to be based upon economic studies. Design of a structure to minimize collecting places for moisture would reduce corrosion effects. By arbitrarily increasing the thickness of materials the effects of corrosion can be delayed. Application of coatings such as paints, galvanizing, tin-plating, asphaltic, plastic, or other compounds, interposes essentially neutral substances between the steel and the corroding media and delays inevitable attack as long as an unbroken protective coating can be continuously maintained. Where cyclic loadings or mechanical effects such as bending occur the probability of protective coating failure is greater. Methods of corrosion surveillance employing electrical or electronic equipment may be of great value, but periodic inspection and upkeep by skilled technicians would have to be the basis for any maintenance program. Techniques of inspection and repair must provide a minimum of interruption to the operational status of the antenna system.

ECONOMICS

Both guyed towers and free-standing towers have inherent advantages and disadvantages. Probably economics would be the deciding factor in the choice of one of these types of structures. Reference 5 contains data based upon experiences with towers in the lower height ranges (100-700 feet) and extrapolations to greater height ranges, which indicate that in general the guyed tower is cheaper to construct than a free-standing tower; and that the cost differential becomes more pronounced as height increases. It is doubtless true that the relative costs of sites, material and labor for construction of either type of tower could vary largely depending upon location; and that in certain locations around the world the variations in price for one or all of the prime cost factors would influence the final decision.

The best existing VLF antenna system, a multi-tower complex at Cutler, Maine, which has an electrical efficiency of about 50 percent, may have cost 50 million dollars. Any of the estimates listed in previous sections of this report are necessarily very rough, but they do give an indication of the cost of certain monopole radiator structures. The guyed tower, estimated basic cost $10,000,000; the compression-tension tower, basic cost $16,000,000; the open-frame truncated cone, basic cost $11,000,000; and the concrete solid-surfaced truncated cone, estimated basic cost $6,800,000; all seem to have promise of economic feasibility.

THREE-MILE HIGH RADIATORS

Although a 3,000-foot high tower with top-loading system seems the present limit of a feasible solution to the VLF electrical radiator problem, it is hoped that some day it will be possible to achieve maximum electrical efficiency in the form of a 1/4 wave antenna which would extend skyward to a height of about three miles. The scale of such a structure may be visualized by contrasting a mammoth structure of 3-mile height with the Empire State Building (Fig. 14).

At the present time it appears that any 3-mile high radiator system would have to be something other than an ordinary gravity-type structure and that it would have to be assisted in maintaining its position, equilibrium and structural integrity by some means other than by utilizing the inherent strength of the material or the structural qualities of its dimensions.

A number of unusual concepts for this 3-mile high antenna system have been proposed. Most of these are highly speculative. They may be listed and briefly considered as follows:

a. A balloon or dirigible lighter-than-air-type vehicle which could be moored at an appropriate height or maintained in position by propeller or jet-propulsion units. From this buoyant vehicle a line of flexible cables could be lowered and connected to a transmitting station on the ground, (Fig. 15).

b. Another proposal envisions a convection current of hot air passing through a slender lightweight tube to a large balloon-like upper section (Fig. 16). The entire surface would be metallized and act as the radiator. A variation of this was a gigantic fabric cone based on the ground and engorged with gas or hot air that would have sufficient upward pressure to maintain its shape and support an appropriate radiating system.

c. Other ideas involve a vertical dirigible, an articulated stack of buoyant balloons, (Fig. 17), and an unconfined particulate column.

The problems of heating sufficient volumes of air or of confining tremendous volumes of lighter-than-air gases would seem to militate against these ideas.

Variations on the above-mentioned sky-supported systems would employ helicopters or rotating planes, (Fig. 18). These present the problem of delivering a continuous supply of fuel to maintain the helicopter in position for a long period of time. One proposal is to make the combined tether line and radiating medium of hollow lightweight metallized fabric and deliver the fuel through this in the form of gas. Obviously no present types of vehicles would do the lifting and supporting jobs so these concepts may have to be deferred until aeronautical developments have progressed further.

The development of an operational VLF radiator of 3-mile height and great power capacity is a task of tremendous scope and appears to be a practical impossibility considering the present states of the various technologies that would contribute to a solution. Apparently no ordinary engineering or applied research effort could be expected to

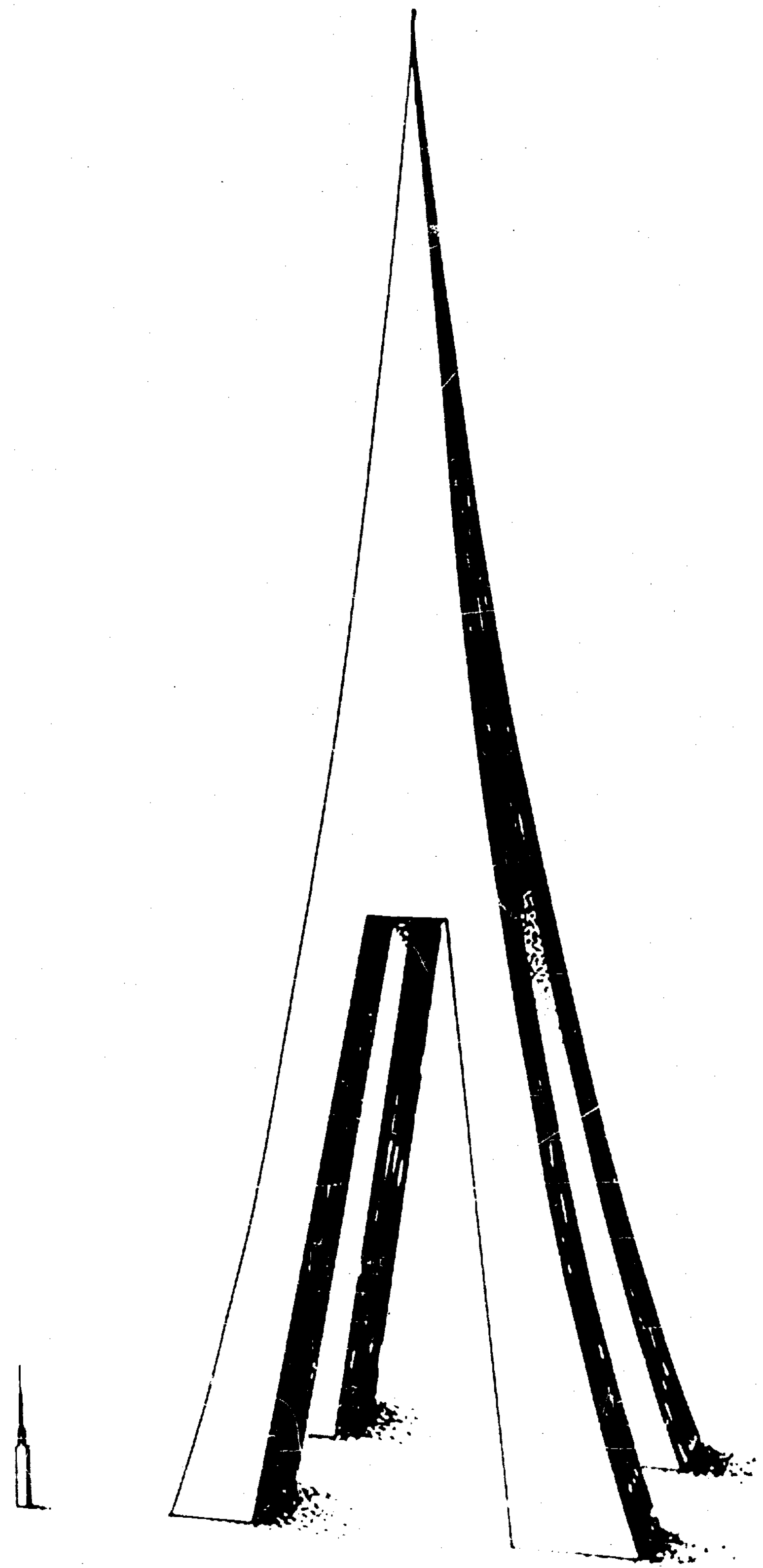

Figure 14. Comparison of Empire State Building with hypothetical 3-mile-high structure.

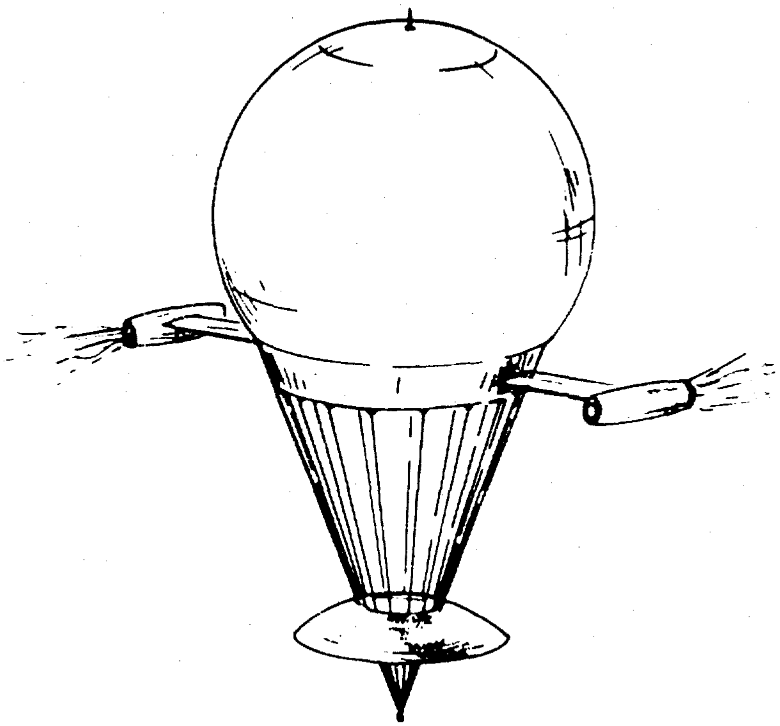

Figure 15. Concept of lighter-than-air supporting vehicle for 3-mile-high radiator system.

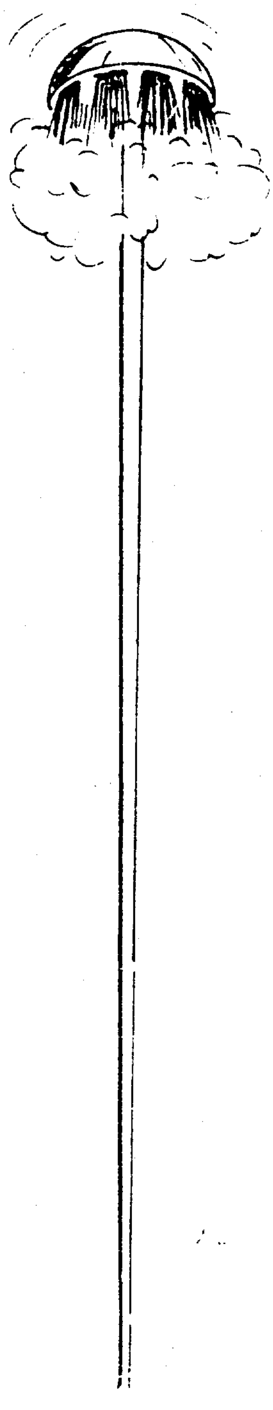

Figure 16. Concept for convection current type of supporting structure for 3-mile-high radiator system.

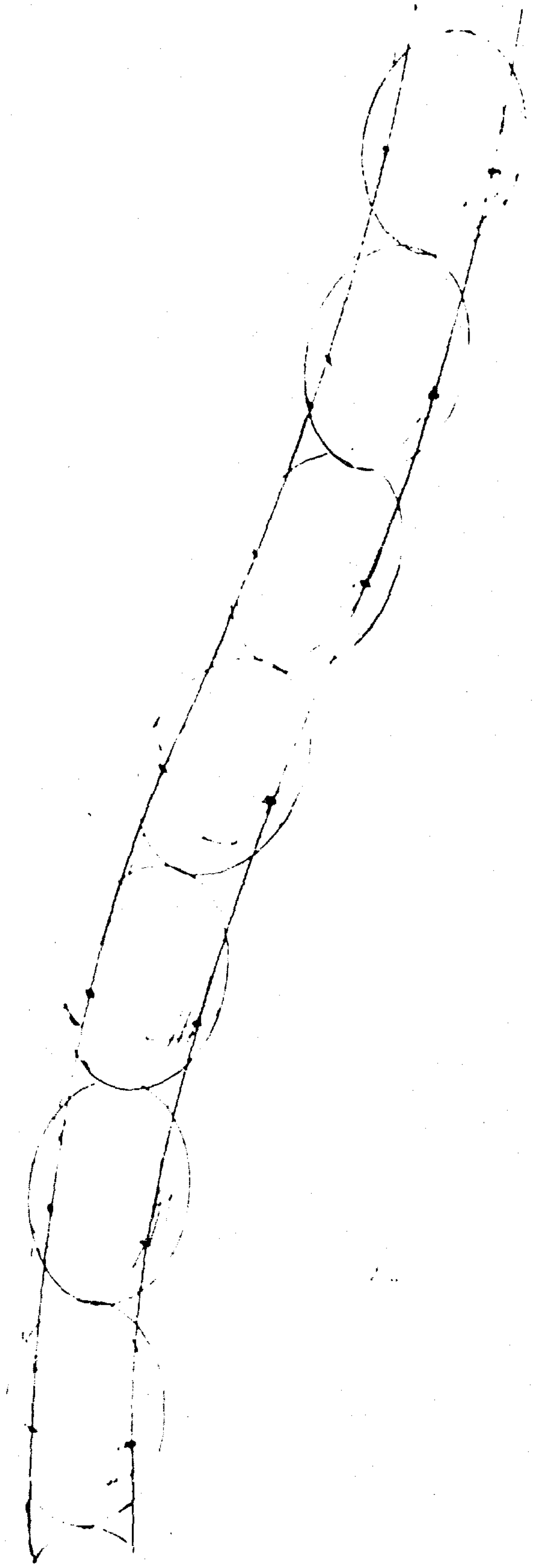

Figure 17. Concept for articulated stack of buoyant balloons to support 3-mile-high radiator system.

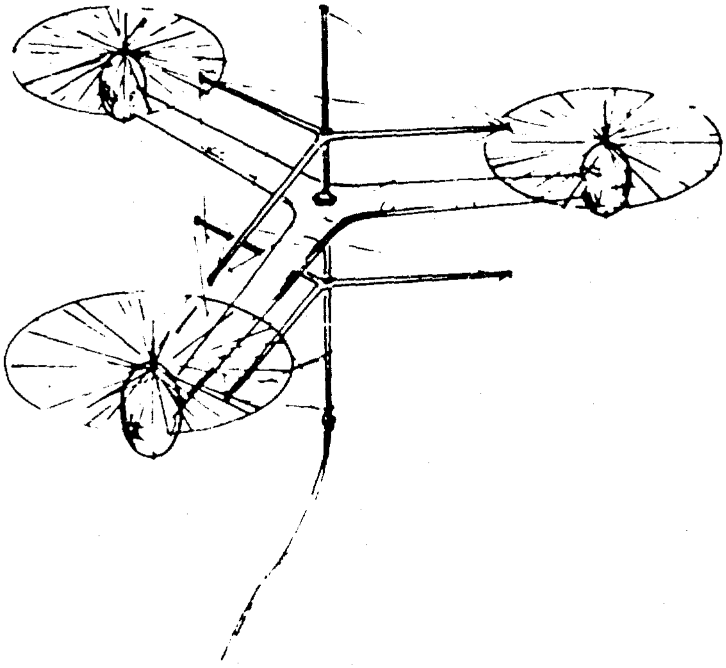

Figure 18. Concept for mechanical aerodynamic machine to support 1-mile-high vertical radiator system.

solve the problem. An ultimate solution would be a synthesis of many scientific advances brought together by someone's genius.

CONCLUSIONS

The foregoing studies have indicated the following conclusions:

1. The design of a 3000-ft high monopole radiator is structurally feasible.
2. The erection of a 3000-ft high supporting tower with a top-loading system is feasible.
3. The total cost of a 3000-ft high monopole radiator complex would probably be less than 25 million dollars.
4. Judicious site selection should minimize problems of wind loadings, ice loadings, seismic forces, corrosion, and soil bearing; and maximize electrical efficiency.
5. Prospects are remote for the development of a 1/4 wave antenna of 3-mile height. Present concepts for such a VLF radiator are fanciful and none are manifestly worthy of further study.

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