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SOME MECHANICAL CONSIDERATION OF TRANSMISSION SYSTEMS

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In any transmission system each of its elements, the supporting structures, the insulators and conductors, has a vital mechanical function and on each may rest the success or the failure of the system. In the early days of high voltage transmission these points were not given due consideration and there were many cases of the destruction of lines due to washouts, sleet and wind storms and frequent breakages of wires due simply to contraction at low temperatures. During later years, however, engineers have profited by these experiences and a greater study has been made of the details of mechanical construction, resulting almost entirely in the elimination of disasters except in cases of most unusual and severe conditions.

The purpose of this is to review in a general way the stresses which must be considered in the various elements of a transmission system and to point out some of the means which have been resorted to to meet certain special conditions. Consideration will be given chiefly to steel tower structures since they are by far the most important type of support for higher voltages. The wooden, steel and concrete poles have their field in the lower voltage range where they are able to compete against the built-up structure.

STRESSES

The stresses which a tower must be designed to withstand are (*a*) those acting in a vertical direction, due to the dead weight of the conductors and insulators, plus an allowance for ice covering; (*b*) in a horizontal direction at right angles to the line, due to wind pressure; (*c*) in a horizontal direction parallel to the line, due to wire breakages. All of these loads are applied at the ends of the cross-arms except a portion of (*b*) which is distributed over the entire tower.

The vertical load depends on the size, material and number of the conductors and ground wires, length of span and thickness of ice coating; the horizontal load at right angles to the line depends on these same elements which determine the exposed surface, and the wind velocity; the horizontal load in the direction of the line depends on the size and number of conductors, the amount of ice and the number of wires which may break at any one time. Each of these governing factors will be briefly discussed.

The size of conductor depends on electrical considerations, except where the length of span is the governing feature.

The length of span, except in river or gorge crossings, is dependent upon the designer and must be chosen so as to give the line

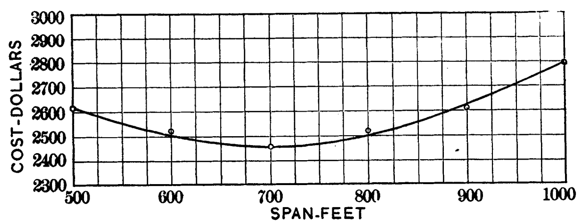

FIG. 1.—COST PER MILE OF TOWERS AND INSULATORS ERECTED.

the least cost. As the span increases, the number of towers and insulators per mile decrease, but on the other hand the height of the towers must be increased to care for the greater sag and at the same time they must be made proportionately stronger and heavier to care for the greater loads per span. The effect of these changes on the cost of a line is shown by the curve, Fig. 1. The length of a span affects the loads in the vertical direction and in the horizontal direction across the line and not that parallel to the line, since the latter is governed by the size of the conductor, it being necessary to adjust the sag so as not to exceed the safe stress for the wires.

For every size of conductor there is a practical limit of the length of span beyond which the sags and height of tower becomes excessive and there is danger of the wires swinging together. For the smaller sizes of conductor this limit is quite low (300 ft. (91 m.) for No. 4 cable) and in many cases it will be found more economical to increase the size of conductor so as to permit using a greater span. The following tabulation illustrates this:

	Size of Conductor	Span feet	Sag feet	No. of towers per mile	Cost of towers and insulators per mile erected	Cost of wire and freight per mile	Total per mile
Case I.	No. 4 B.&S.	300	10.5	17.6	$3080	$322	$3402
Case II.	No. 2 B.&S.	360	10.5	14.7	2570	514	3084
					Saving per	mile..........	$318

These figures are based on the assumption that the same towers and sags would be used in both cases, giving the same clearance to ground. The sag in Case I is the minimum sag at which wires may be strung on the basis of 0 deg. fahr., 8 lb. (3.6 kg.) wind, and $\frac{1}{2}$ in. (1.27 cm.) sleet and with these same conditions and sag the span for No. 2 wire is calculated and found to be 360 ft. (109 m.). With this tower spacing and No. 2 cable the cost of the line is $318 less than with No. 4 cable and 300 ft. (91 m.) span. It is allowable to assume that the same towers can be used in the second case as in the first since the lightest tower which it is practicable to build would be sufficiently strong for the second case. However, it would be possible to put $20.00 more into the cost of each tower and still have the cost of the second line a trifle less than that of the first and the gain would accrue from the electrical advantages of the larger size of conductor.

A span of 360 ft. (109 m.) is not necessarily the most economical span for the No. 2 conductor. Further calculation indicates that a 500-ft. (152 m.) span could be used with only a very slight increase in the cost of the towers. This limit cannot be extended beyond 500-ft. (152 m.) even though the line with greater spans would have a less cost. Here again the limit depends on mechanical considerations rather than on costs and is governed by the danger of lashing together of the wires in gusty winds.

In long spans over rivers, etc., the standard main line towers and conductors are frequently used. This practise may be permissible in some instances where the spans are not very much greater than normal but when the towers have been designed to closely meet the demands of the standard spacing it becomes dangerous to use them for any appreciably longer spans. It is advisable in these instances to use dead end anchor towers with strain insulators and thus isolate the crossing span and prevent any trouble in other parts of the line from being carried into it.

For very long spans it is, of course, necessary to use conductors of greater mechanical strength than are used in the main part of the line and the supporting structures must likewise be made correspondingly stronger. Too great care cannot be taken in planning such structures as unusual stresses are likely to occur and would result seriously unless properly cared for. More than average allowances should be made for wind, sleet and temperature and a greater factor of safety should be used in the design of the steel work.

Ice and Wind

The amount of ice which may form on wires has been a much-discussed topic and one which will probably never be settled to the satisfaction of all concerned. However, the various engineering bodies have about agreed that it is safe to consider $\frac{1}{2}$ in. (1.27 cm.) ice in conjunction with 8 lb. (3.6 kg.) wind pressure and 0 deg. fahr. as the worst combination of conditions likely to occur in the United States. It is conceded that there have been thicker formations of ice and greater wind pressures, yet the probability that they will occur simultaneously and with low temperature is so remote as to make it seem unnecessary to consider them. There is little doubt, however, that those engineers who have experienced destruction of their lines by sleet and wind storms will never use anything but the most conservative allowances. For spans crossing rivers, highways or railroads more liberal allowances are always made, the standard being $\frac{3}{4}$ in. (2 cm.) ice, 11 lb. (5 kg.) wind and 0 deg. fahr.

Ice and wind on the cables work together to increase all of the loads on a tower structure; the vertical load and the horizontal load in the direction of the line, by giving increased weight to the conductor, and the horizontal crosswise load by giving greater surface for the wind to act upon.

Wind on Towers

There is a great difference of opinion as to just how much wind pressure shall be allowed on the tower itself. It is certainly not sufficient to base this allowance on the same assumptions as are used for the conductors. Those assumptions are for wind velocities likely to occur simultaneously with heavy loading of ice and low temperature. Greater velocities may occur independent of these last factors. It is, therefore, advisable to allow for at least the highest recorded value. This value, as indicated by the Government anemometer is very nearly 100 mi. per hr., which corresponds to an actual velocity of 76.2 mi. per hr. and a pressure of 23.2 lb. (1005 kg.) per sq. ft. (=0.09 sq. m.) ($0.004 \times V^2$ for flat surface). The government anemometer records the velocities only at intervals and does not give all instantaneous values and these instantaneous values may be somewhat greater than those at the moment the record is taken, due to the gusty character of winds. It has been estimated that these gusts cause velocities 50 per cent greater than those which are recorded. Another feature enters, however, to somewhat counterbalance this effect, viz., the height above the earth surface. The anemometer records are taken well above the earth surface, while transmission structures are seldom higher than 75 ft. In consideration of these variables and uncertainties it is not possible to give one value of pressure to be used on all lines. A safe range of pressure though would be from 20 to 35 lb. (9 to 16 kg.) per sq. ft. (=0.09 sq. m.) depending on the general character of the country which the line traverses, *i.e.*, whether it is exposed to sweeping winds or protected.

It will usually be found that the maximum wind pressure acting on the bare towers and wires will have a greater overturning moment than that caused by the maximum wind assumed to accompany ice formation, acting on the ice-coated wires and towers, *i.e.*, the greater pressure due to the higher velocity of the wind, even though exerted on a smaller surface, will overbalance the less pressure acting on the greater surface. For this reason the side pressure on towers should be figured for both conditions and the design should be based on the loads caused by the worst of the two.

In calculating the wind on the towers the entire projected area of two lateral faces should be used as the surface over which the wind acts.

Wire Breakages

The most serious stresses which a transmission tower is called upon to withstand are those due to the breaking of conductors. Lines are put up with a view of not having the conductors break but there are certain unavoidable conditions which frequently produce breaks. The most usual of these are (*a*) burning of the conductors due to short circuits or grounds started by lightning, large birds, swinging together of wires, etc., or through malicious intent; (*b*) breaking of conductors due to crystallization or fatigue of the metal produced by kinking during erection or by insufficiently rounded edges of cable clamps and (*c*) by overloading of conductors during extreme conditions of temperature, wind, etc.

The causes in (*a*) have been overcome to a great extent by the use of various devices, principally the arcing ground suppressor, the ground ring and metal sleeve. The swinging together of conductors occurs only when light conductors are used in too long a span where they will be likely to lash in the wind. Ordinarily in well designed spans the wires swing in unison so that there is no danger of their coming together.

The breaking of wires due to kinking is frequently not given due consideration and many lines erected by careless workmen have suffered from this cause. The elasticity and strength of the metal on the inside of the bend is decreased enormously by a short bend and when the wire is straightened out and drawn taught by frequent strains in the line it will finally weaken to the point of rupture. Likewise, many breaks have been caused by repeated bending of the conductor at the wire clamp on the pin type of insulator. The localization of the stress by a hard metal clamp finally makes the metal of the conductor brittle and rupture occurs well below the average tensile strength. A clamp may have well rounded edges and still cause trouble. It is the rigidity of the clamp as well as too sharp an edge which is harmful.

When all of the wires of a transmission line are intact there is no pull on the towers in the direction of the line (*i. e.*, on the intermediate towers, not the dead end or other special structures). As soon, however, as a conductor is broken the strain which it took to cause the break is thrown on the adjacent towers. Obviously, therefore, the maximum load which the cross arm must stand in the direction of the line is equal to the tensile strength of the conductor which is used. For the smaller sizes of conductor this rule is usually observed but for the larger sizes less liberal allowances are usually made. It is customary with the larger sized conductors to allow for a stress equal to one-half of the ultimate strength of the cables. This value is chosen since it is the maximum safe working stress, above which the cables are likely to stretch permanently.

With the suspension type of insulator the full length of an insulator string is thrown into the line when a break occurs and the strain in the conductor and on the cross arm is greatly reduced. But little consideration should be given to this fact, however, since there is a severe jerk when the insulator is drawn to its new position and the effect on the tower is not less and may be more than occurs when the pin type of insulator is used.

A question which naturally arises is how many conductors may break at any one time. This depends to a large extent on the cause of the breaks. If due to lightning or large birds it is probable that not more than one or possibly two conductors would break; but if due to poorly designed wire clamps, injury of wire during erection, or to excessive sleet and wind, it is conceivable that all might break. It is very rare, however, for all of the conductors to break, and further, it is hardly practicable to make such an assumption when considering main line towers since it would raise the cost of the line to a prohibitive value. It is usual to compromise by allowing for the breakage of only two cables of a three or six conductor line and to safeguard the system by interposing anchor towers at frequent intervals. These anchor towers would be capable of withstanding the strains due to the breakage of all of the cables and would thus divide the line into isolated sections so that any trouble in one could not be communicated to the other.

In the rigid type of tower practically all of the stress caused by the breaking of several conductors is cared for by the tower itself, *i. e.*, the movement of the top of the tower is not sufficient to permit an even distribution of stress between the unbroken cables of the damaged span and those in the adjacent spans. With the flexible type of tower, however, the effect is different. The tower is designed to be rigid in the plane across the line and flexible in the direction parallel to the line so that it will bend and allow an even distribution of stresses in the adjacent spans. For instance, consider a three-conductor system with one ground wire and assume that each cable has an ultimate strength of 6,000 lb. (2,721 kg.) and is strung to have a tension of one-half of its ultimate strength under the worst conditions likely to occur, and assume that these conditions prevail. Suppose that one of the conductors has been injured or is defective and that it breaks under this load. The tops of the towers on either side of the break will be pulled over by the four cables in the next span until the total tension in them would be just balanced by that in the remaining conductors of the damaged span.

This tension would amount to very nearly 12,000 lb. (5,443 kg.), *i. e.*, 4,000 lb. (1,814 kg.) per cable or 33 per cent more than the allowable stress. This load would not break the cables but it would stretch them beyond the elastic limit and permanently weaken them.

Suppose that two cables had broken instead of one. Each of the remaining two would be strained with nearly 6,000 lb. (2721 kg.), an amount almost equal to its ultimate breaking strength. The stress would not be quite 6,000 lb. because the tension in the adjacent spans would decrease rapidly as the cables in the damaged span are stretched to greater length. However, the example serves to illustrate that it is necessary to use very much greater factors of safety in stringing conductors in a flexible tower system than would be used in a rigid system.

FOUNDATIONS

The foundations of a tower are of prime importance, yet under average normal conditions they offer but a small problem. In ordinary straight line work, over fairly level country, where the soil is hard or rocky and where the smaller sized conductors are used no special foundations are necessary; the ground stub with cross piece or foot may simply be buried in the ground with a little rock filler and if the spread of the tower legs is normal there is little to fear from tilting. With the larger sizes of conductor and longer spans the overturning moment frequently reaches such proportions as to make it advisable to use concrete foundations and thereby eliminate the need of spreading the tower legs an excessive amount. When towers must be placed where the soil is loose or marshy or where they may be endangered by floods or landslides it is essential that special consideration be given to the design of their foundations. It may be necessary to resort to any one of several types of construction; steel or timber piling, crib work, rock filling or concrete, or a combination of two or more of these. Fig. 4 shows one of the best types of foundation, used to meet a very special condition where it was necessary in order to gain entrance to a city to extend the right of way along the lake front and place the tower footings in the water.

Angle, hillside and anchor on long spans present serious problems from the foundation standpoint and must be carefully and liberally designed so as to allow no motion or slip whatever. It frequently pays to make a long detour in order to avoid bad hillsides or crumbly crests.

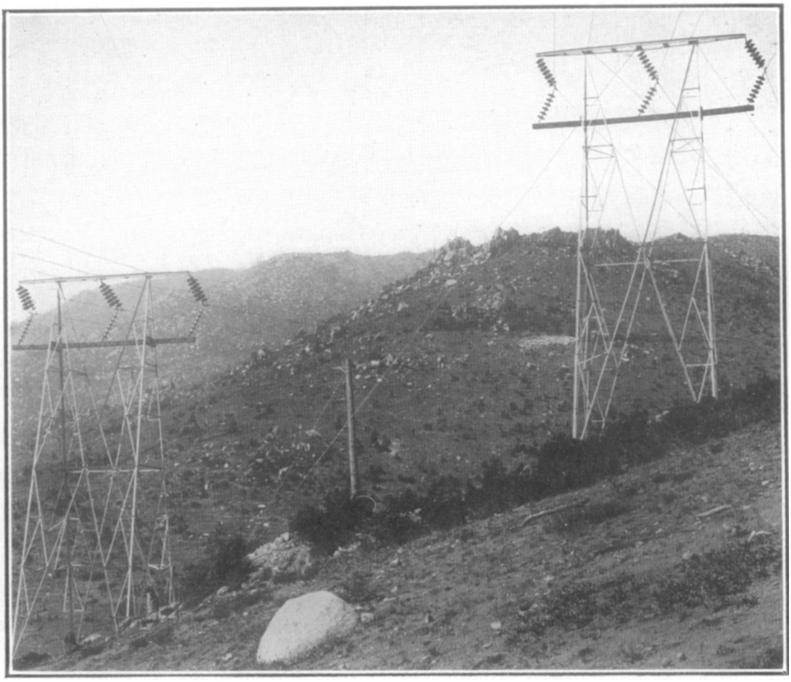

FIG. 2.—DIFFICULT ANGLE AND HILLSIDE CONSTRUCTION. [WORCESTER]
Great Falls Water Power and Townsite Company.

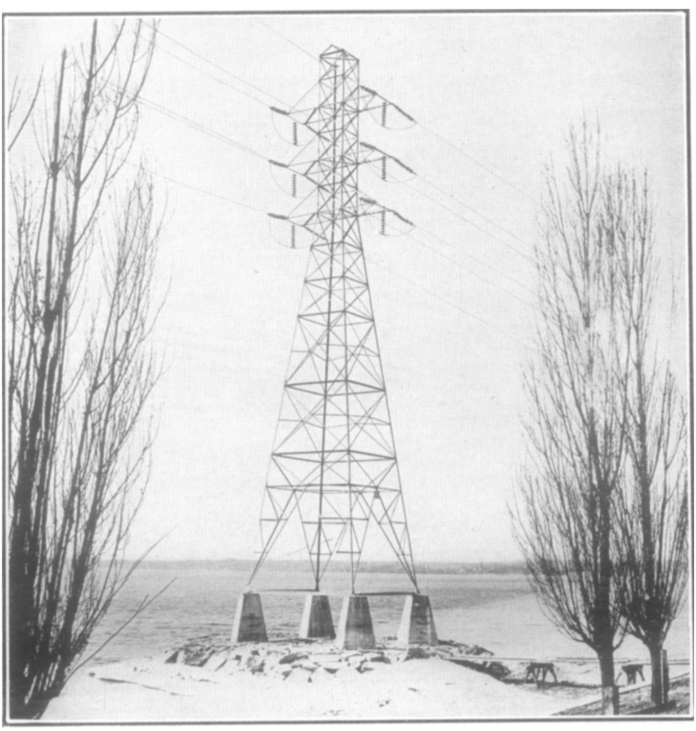

FIG. 3.—INTERMEDIATE STRAIN ANCHOR TOWER. [WORCESTER]
Hydro-Electric Power Commission of Ontario.

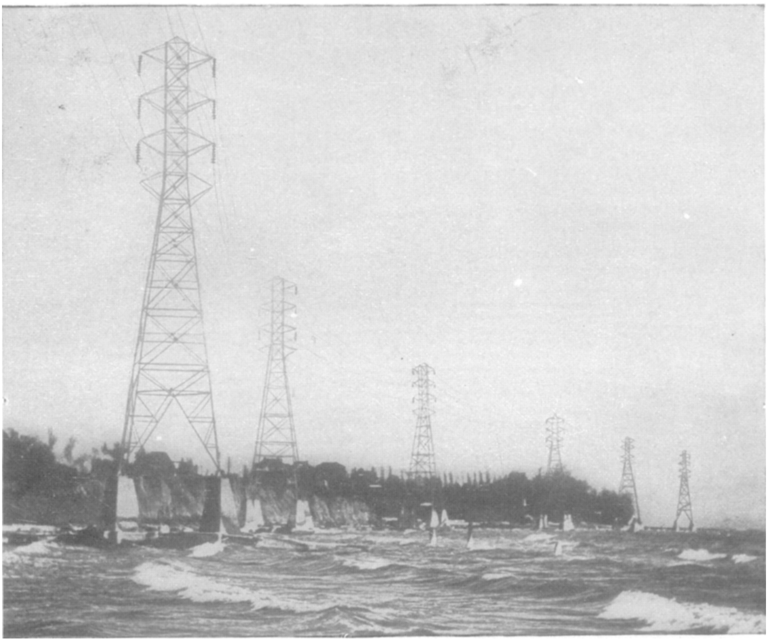

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FIG. 4.—TRANSMISSION LINE ENTERING TORONTO.
Hydro-Electric Power Commission of Ontario.

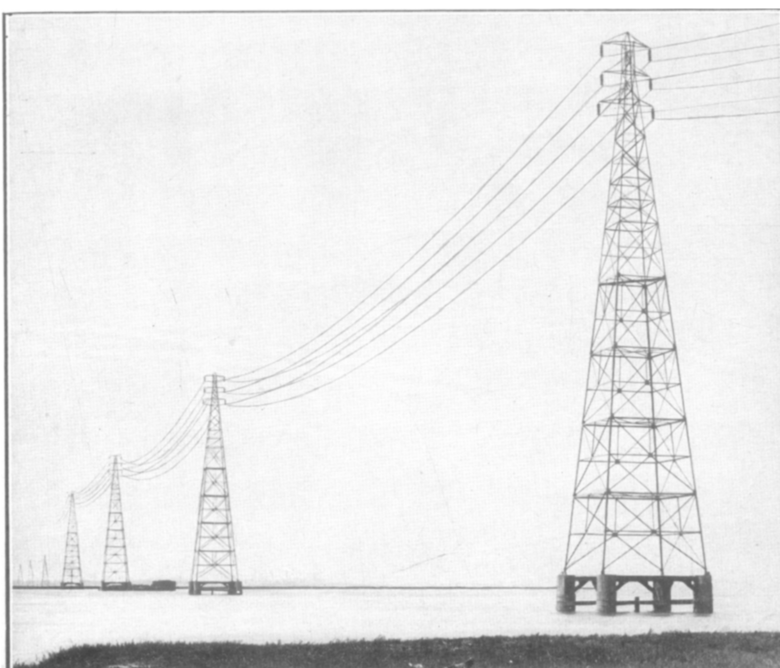

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FIG. 5.—STANDARD 50-FOOT TOWERS ON 87-FOOT LOWER EXTENSION—SPANS, 750 FEET.
Sierra and San Francisco Power Company's Line Crossing San Francisco Bay.

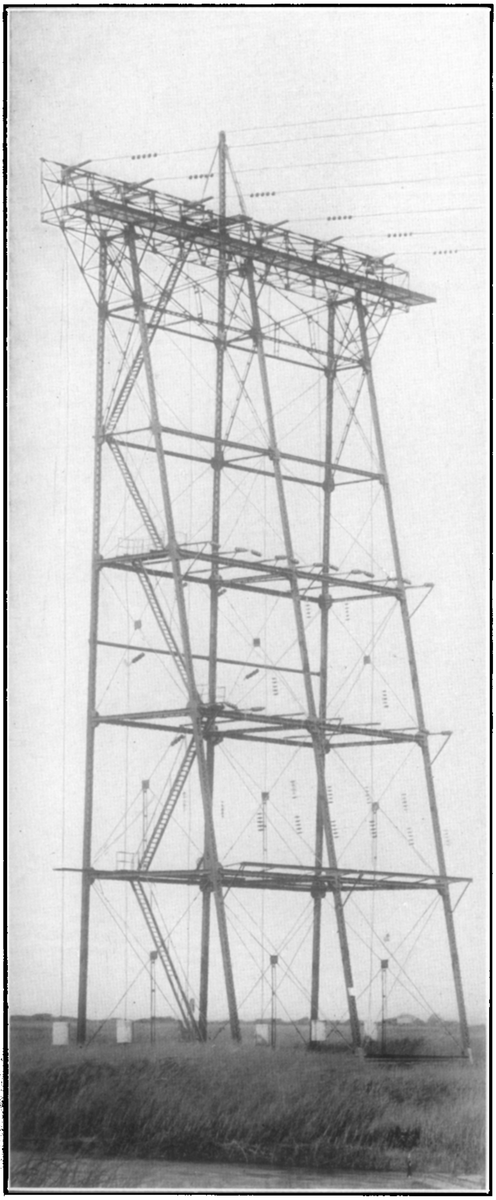

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FIG. 6.—LONG SPAN STRAIN TOWER.
Great Western Power Company.
(Note Balance Weights to Insure Uniform Tensionin Conductors.)

[WORCESTER]

FIG. 7.—FLEXIBLE TOWER TRANSMISSION LINE.
Rochester & Sodus Bay Elec. Ry. Co.

It must be remembered that a very slight tilt at the base of the tower means large displacement at the top which may exert considerable extra tension in the conductors and in the case of the suspension insulator may bring the conductors dangerously near the tower.

Factors of Safety

In the design of all mechanical structures it is customary after assuming certain conditions of loading to allow a factor of safety; in other words, to design the parts so that their ultimate strength will be several times their assumed loading. The amount of this factor of safety depends on (*a*) the character of the load—whether steady, intermittent, or otherwise—(*b*) on the knowledge one has relative to the amount of load; (*c*) on the ease or difficulty of calculating the structure to care for the assumed loadings; (*d*) on the possibility of faults in construction and (*e*) on the risk to life and property. In a transmission structure the load is intermittent and reversing and our knowledge as to its amount is not definite. These features tend to demand a relatively large factor of safety. However, this tendency is more than counterbalanced by the facts that it is not difficult to calculate the stresses when a definite load is assumed, that the chance for faults in manufacture are but few and that the risk to life and property is a minimum.*

Another feature which makes it possible to use a small factor of safety is that a sample tower may easily be tested with the assumed loadings and with ultimate breaking loads. Obviously if a factor of safety is used which will permit the tower to be strained with the assumed loads without being permanently deformed then such factor of safety will be satisfactory, provided the assumed loads correspond with the actual loads. The factor of safety for these conditions would be two if it is considered that the elastic limit of the metal is one-half of its ultimate strength. Many transmission towers have been built on this basis with a consequent saving in the cost of the line. On the other hand more conservative engineers have used values of three and even four, these higher values being chosen to care for the uncertainty of load conditions. In one line recently built a factor of safety of 4 was used for all of the main line towers and three for all the strain or dead end structures. This at first sight seems illogical, but it is justified, since the strain towers are figured for a very definite condition; *i. e.*, of all cables

*Except at railroad and highway crossings, etc.

being broken in one span and with a maximum load of wind and ice on all those in the next span; whereas the intermediate towers are figured on an indefinite assumption; *i. e.*, of having only two cables break while the others are heavily loaded. The use of these large values, however, makes the cost of the line excessive and for this reason it is common practise to use smaller values, two, two and one-half, or three for the intermediate towers and three or three and one-half for the strain towers. With this arrangement the main part of the line will be safe except in case of some unusual condition which produces worse loads than those assumed and in event of such an accident the strain towers will prevent the trouble from traveling to the next section of the line.

For the conductors themselves a factor of safety of two is sufficient except for very long spans and crossings, in which cases slightly larger values should be used unless a greater allowance is made for ice and wind than in other parts of the line. Larger factors of safety also must be used in conductors in flexible tower systems, as pointed out under "Wire Breakages."

Flexible Towers

The flexible tower was discussed above with special reference to the stresses induced in the unbroken cables when one or two cables should break in one span and it was found necessary to string the cables with less tension than in a rigid tower system. When this is done the flexible system immediately becomes mechanically stable and is of value. Economy is secured by the small weight and cost of the towers without unduly sacrificing the safety of the system.

A special field for the flexible tower appears to be for the higher voltage systems in which a double tower line of three conductors each is desired. There are a number of advantages in using such a system in preference to the six-conductor single tower system, the principal ones being that there is less liability to complete shut-down in case of accident to a tower and that there is greater safety for linemen when repairing damaged towers, conductors or insulators. The reason for the present limited use of double tower lines is the high cost of such a system when made up of the rigid type of tower. If engineers would look more into the possibilities and cost of the flexible structures there would undoubtedly be a more general use of double tower lines.