48. The reduction involves the electrolysis of a mixture of beryllium oxyfluoride and barium-fluoride requiring 45 kilowatt-hours per pound, or of fused beryllium chloride requiring much less current.

BISMUTH

49. The bismuth produced in this country is recovered electrolytically from the slags of lead refineries. It is consumed in low-melting alloys and by the pharmaceutical industry. As the supply available if all were recovered from lead refining exceeds the demand, the United States Bureau of Standards is working on potential uses of the metal.

50. In the electrolytic refining, sheet lead covers the cell bottom and acts as the cathode. The anodes are in a basket lined with duck. Bismuth chloride and free hydrochloric acid solution form the electrolyte. The bismuth is deposited as nodules on the cathode and the deposits are broken down every 8 hours.

Metals Refined Electrolytically in Countries Other than the United States

51. *Nickel.*—Although nickel is fairly widespread in its occurrence, over 90 percent of the world's production comes from the Sudbury Field in the Province of Ontario, Canada. All production is by one company, The International Nickel Co. of Canada, Ltd. Refining of nickel is accomplished electrolytically at Port Colborne, where plants have a capacity of 43,200 short tons per annum. Platinum is recovered from such refining. This is shipped to a precious-metals refinery at Acton, England.

52. *Tin.*—Tin was refined electrolytically in the United States during and after the War at Perth Amboy, N.J. But in 1923 the industry was abandoned, as it was not commercially feasible to operate a tin smelter in this country. All virgin tin had to be imported, the Federated Malay States, Bolivia, and Netherlands East Indies, being the principal tin mining countries. And the mining and smelting industry was well controlled by British, Dutch, and German interests.

Appendix II

STUDY OF COST OF POWER TRANSMISSION FROM COLUMBIA RIVER PLANTS TO MARKET CENTERS (100 TO 250 MILES)

Prepared by E. A. Loew, *Professor of Electrical Engineering, University of Washington, Seattle, Wash.*

Introduction.—The investigation herein discussed was undertaken for the purpose of determining as closely as possible the probable cost of transmitting electrical energy from the several proposed generating sites on the Columbia River to adjacent markets. These markets include the Puget Sound region lying between Bellingham and Portland and the Inland region tributary to Spokane. Inspection of the map showing the locations of the proposed power plants covering the Columbia Basin project, indicates that to transmit power to these markets from the various proposed power sites on the river, will require transmission lines varying in length from perhaps 100 to 250 miles. The bulk of the power will probably not need to be transmitted more than 150 miles. It is therefore necessary to determine transmission costs for distances up to 250 miles.

DISCUSSION OF THEORY

Kelvin's Law.—When a line of given length is operated at some fixed voltage and is used to transmit a certain amount of power, the cost of delivering a kilowatt-hour of energy over the line depends upon the size of the conductor used. When the conductor is too small the line is relatively inexpensive, but owing to the high line resistance the losses are excessive and the cost of transmission is too high; when the conductor is too large the losses are greatly reduced but the investment in conductors is excessive; the interest and depreciation annually chargeable against the investment in conductors is a larger amount than the value of the losses annually saved will warrant, and hence the line is again uneconomical. Obviously, the condition of maximum economy for a particular line and a particular load occurs when the conductor used is the one for which the value of the energy annually wasted as line loss, added to the interest and depreciation on the sum of all items of line investment that vary with the size of the conductor used, is a minimum. This law of economics, as applied to transmission lines, is known as Kelvin's Law.

Kelvin's law of economy assumes a fixed line voltage. If the voltage on the line is raised, however, the line current is decreased and the line losses are reduced in proportion to the square of the in-increase in voltage. When the voltage is doubled the line losses are reduced to a fourth of their former value. On the other hand, if the losses are kept at the original level, the size of conductor may be reduced to one quarter of the original value, thereby effecting a large saving in the cost of conductors and supporting structures. The use of a higher voltage, however, entails additional outlay for transformers, switches and line insulation. The higher voltage is better than the lower one only when the saving in line loss annually effected by its use exceeds the increase in annual outlay chargeable to the additional investment required to make the saving possible.

Modified Kelvin's Law.—Kelvin's law is therefore not a complete statement of the law of economy affecting transmission-line design. A proper statement of the law must assume the line voltage to be variable and must express equality between the annual value of the energy wasted as line loss and all items of line cost whose values vary either with the conductor diameter or with the line voltage used. Such a statement of the law is found in the papers mentioned in references [25] and [26] below. A slightly modified form of expression is used herein as a basis for making line calculations.

Conductor size limited by corona.—Two other limiting conditions need to be mentioned as determining factors affecting line design, namely, corona and power limit. The latter will be briefly treated in a later paragraph.

When the voltage on a transmission line is gradually increased from a low to a high value, the voltage gradient at the conductor surface

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[25] Economy in the Choice of Line Voltages, by E. A. Loew. Journal, American Institute of Electrical Engineering, August 1928.

[26] Electrical Power Transmission, E. A. Loew. McGraw-Hill Book Co., January 1928.

increases. The absolute value which this gradient attains with a given impressed voltage varies inversely with the conductor size. The gradient is independent of the conductor spacing, provided the latter, as well as the conductor diameter, is proportional to the voltage, as it should be. When the voltage gradient finally reaches a critical value, corona forms on the line conductors and electrical energy escapes into the surrounding air. Practical transmission lines are so designed that the gradient at the conductor surface is held below the critical or corona-forming value. This means that for every line voltage there is a minimum size of conductor that can be used, independent of how little power is tranmitted over the line. For stranded cable the limiting conductor diameter in inch units is approximately equal to the line voltage (in kilovolts) divided by 210.

Based on the above criterion, the minimum conductor diameters that should be used with the several standard voltages above 100 kilovolts are roughly as follows:

TABLE I.—*Minimum cable diameters as determined by corona*

Voltage	Conductor diameter	Circular mils (A.C.S.R.) (nearest standard size)
Kilovolts		
110	0.523	211,600
132	.629	266,800
154	.735	336,000
220	1.050	715,500
330	1.570	1,590,000

Power limits.—The amount of power that can be transmitted successfully over a given transmission line is limited by conditions of operation, and by the constants of the circuit. The limit set by these conditions is quite independent of the size of the conductor used.

When the load on a line is gradually increased from a low to a high value, the excitation voltage vector of the receiver end motors gradually swings more and more out of exact phase opposition to the generator excitation voltage vector. The amount of this phase displacement is determined almost entirely by the load on the line and by the total amount of reactance in the circuit. This includes the synchronous reactance of the motors and generators, the reactance of step-up and step-down transformers and the reactance of the line itself. Theoretically, when the load is gradually applied, it may be increased until the angle of phase displacement between the excitation voltage vectors at the two ends of the line reaches 90°; beyond this any further increase of load will cause the synchronous machines at the two ends of the line to fall out of step. The load for which this condition prevails is called the steady-state power limit of the line.

Obviously, lines cannot be operated at or even very close to their steady-state power limits, for lines so operated would be very unstable and would lose synchronism under the slightest disturbance. An accidental short circuit may suddenly add a very heavy load to an already loaded line. If the line is operating near its steady-state power limit, a short circuit will so overload the line that the machines at the two ends will fall out of step before the circuit breakers can operate to open the circuit. Many factors influence the behavior of the system during the interval of time between the instant when the short circuit is first applied and the instant when either (*a*) the machines fall out of step, or (*b*) circuit breakers clear the line, and the system recovers. Some of these factors are the following:

(1) It is important that the voltages at the ends of the line should be maintained during and after the clearing of line faults. The system of excitation should be designed to respond quickly; that is, high-speed excitation is desirable.

(2) During the first moments of a fault, while the system frequency is dropping, energy is delivered by the energy of rotation (Wr^2) of the machines. The inertia of the rotating equipment is thus a factor in stability.

(3) The governors of the prime movers should respond quickly.

(4) The time elapsing between the beginning of the fault and the opening of the circuit breakers should be small. Improvement in the speed of operation of circuit breakers has made it possible to reduce this interval to a little over one tenth of a second.

The maximum load at which a line can be operated without having the machines lose synchronism at times of fault, is called the load limit of the line as determined by transient stability. This is the load limit that governs the practical operation of a line. The load thus found is less than the steady-state power limit mentioned above. It may roughly be calculated when all of the data for a given system are available. For the purpose of the present investigation average operating conditions are assumed and the power limits of the proposed lines are predicted on the basis of the performance of other existing lines whose approximate power limits are known.

The practical design of short transmission lines (under 100 miles in length) is determined almost entirely by the principle of economy embodied in the modification of Kelvin's law, as discussed briefly in the earlier pages of this report. The total reactance in the circuit between the generating source and the point of consumption is so small that there is generally little likelihood of trouble from instability in the operation of such lines except for loads considerably in excess of those for which the lines are ordinarily designed. The design of long lines, on the other hand (lines from 100 to 300 miles long), cannot be based wholly on this simple principle. As the length of line increases, the load that a line can carry, with stability in operation, decreases quite rapidly. The load which a proper application of Kelvin's modified law predicts as the most economical one for a given line is then often in excess of the maximum load the line can carry without exceeding its limit of stability. The stability limit must then fix the maximum load for which the line is designed.

As previously pointed out, a minimum conductor diameter is required, independent of load, in order to eliminate excessive corona loss as well as to make possible the rigid construction needed to withstand heavy ice loads. The conductors of long lines therefore usually operate at low current densities and have correspondingly low losses per mile of circuit.

As a rough approximation one may state that the steady-state power limit of a line depends directly upon the square of the line voltage, and inversely upon the total reactance in the circuit. Components of the latter are the reactance of the line itself, the equivalent reactance of step-up and step-down transformers, and the reactances of the equivalent generators and motors representing the machines at the generating and receiving ends of the line, respectively.

The diameters of transmission line conductors (assuming a given type of cable) are proportional to the line voltages. The spacing between conductors is likewise generally proportional to the line voltage. When this is the case the total reactance per mile of transmission line is approximately constant, irrespective of the voltage or conductor size. The reactance per mile of line is in the neighborhood of 0.75 ohms; accordingly, the total reactance of a line is approximately equal to 0.75 L, where L is the length of line in miles.

Consider next the reactance introduced by the transformers and by the equivalent generator and motor representing the simplified system. If a fixed percent reactance be assumed for each of these (e.g., 40 percent for generators and 12 percent for transformers), the equivalent reactance of each will be inversely proportional to the rated capacity. The latter, in turn, should be inversely proportional to the length of line for all cases, however, since the steady-state power limit varies inversely as the length of line. Therefore, when the rating of the terminal machinery is proportioned to the steady-state power limit of the line, the total equivalent reactance which generator, transformer, etc., introduce is also proportional to the length of the line. Accordingly, when the above-outlined principles of design are employed, all lines operating under given conditions of stability will have approximately the same angular displacement between the voltage vectors at receiver and supply ends, regardless of the length of line or its operating voltage. This is the principle upon which the assumed loads for the several lines considered in the latter part of this report are determined.

Equation of transmitted power.—Equations (1) and (2) below are the familiar vector voltage equations of the transmission line. In (1) the receiver voltage (E_r) is the vector of reference, while in (2) the supply voltage (E_s) is the reference vector.

$$E_s = E_r A + I_r B \tag{1}$$
$$E_r = E_s A - I_s B \tag{2}$$

Let θ be the angular displacement between receiver-end and supply-end voltage vectors E_r and E_s. From equation (1), using the polar form of expression for E_s and writing I_r in terms of its two components, one obtains:

$$E_s \epsilon^{i\theta} = E_r A + \left(\frac{P_r}{E_r} + j\frac{Q_r}{E_r}\right) B$$

or

$$\frac{P_r}{E_r} + j\frac{Q_r}{E_r} = \frac{E_s \epsilon^{i\theta}}{B} - \frac{E_r A}{B} \tag{3}$$

Similarly, from (2), using E_s as reference

$$\frac{P_s}{E_s} + j\frac{O_s}{E_s} = \frac{-E_r \epsilon^{-i\theta}}{B} + \frac{E_s A}{B}$$

Let $k = E_s/E_r$, the ratio of supply to receiver voltage. Then in terms of receiver voltage, equations (3) and (4) above become

$$P_r + jQ_r = kE^2{}_r \epsilon^{i\theta}/B - E^2{}_r A/B \tag{5}$$
$$P_s + jQ_s = -kE^2{}_r \epsilon^{-i\theta}/B + k^2 E^2{}_r A/B \tag{6}$$

Equation (5) represents the line output in active and reactive power, while equation (6) represents the line input in similar terms. Adding these equations, dividing by 2, and multiplying and dividing by j yields

$$\begin{aligned} P_m+jQ_m &= jkE^2_r\ (\epsilon^{j\theta}-\epsilon^{-j\theta})/2jB+E^2_rA\ (k^2-1)/2B \\ &= E^2_r/B\left[kj\sin\theta+\frac{A}{2}\ (k-1)\right] \qquad (7) \\ &= \frac{E^2_r}{b^2_1+b^2_2}\left[kj\ (b_1-jb_2)\sin\theta+\frac{l}{2}\ (a_1+ja_2)\ (b_1-jb_2)\ (k^2-1)\right] \end{aligned}$$

whence

$$\begin{aligned} P_m &= E^2_r/(b^2_1+b^2_2)\left[kb_2\sin\theta+\frac{l}{2}\ (a_1b_1+a_2b_2)\ (k^2-1)\right] \\ &= E^2_r\left[kb_2n^2\sin\theta+\frac{l}{2}(k^2-1)\right] \qquad (8) \end{aligned}$$

P_m in equation (8) is approximately equal to the amount of power passing the midpoint of the line; it is greater than the receiver input by approximately one half the line loss and is less than the supply output by about the same amount. P_m is therefore only a few percent greater than the receiver input. The last term in (8) disappears when k is unity, and for any practical case is a small and quite negligible quantity. Omitting this term has the effect of bringing P_m nearer in value to the receiver input. Hence the receiver input is approximately

$$P_m=E^2_r\ b_2kn^2\sin\theta \qquad (9)$$

Since b_1 is small as compared with b_2, the quantity $b_2/(b^2_1+b^2_2)$ is approximately equal to $1/b_2$ and, hence, very closely

$$P_m=E^2_r/b_2\ (k\sin\theta) \qquad (10)$$

The values of b_1 and b_2 may be computed for any assumed length of line. For reasons already explained, b_2 and, therefore, n depend primarily upon the length of line, and are nearly independent of voltage and conductor size, even when calculated for the equivalent circuit, including transformers and generator.

Economical current density.—The most economical current to use with a given cable is determined by the law of economy already mentioned. When this law is correctly applied it turns out, as is to be expected, that the current is proportional to the size of cable. Stated in another way, the current density is approximately constant for all lines of a given length regardless of the line voltage. Since to prevent corona the diameter of the cable must also be proportional to the line voltage, the cable area, and hence the current carried, should be proportional, theoretically, to the square of the line voltage. Under this arrangement, assuming that no practical maximum operating load limit is reached, the transmitted kilovolt-amperes are porportional to the cube of the voltage.

As an example, consider five lines, each 200 miles long, one each operated at 110, 132, 154, 220, and 330 kilovolts. Let the cables used be the minimum sizes given in table I and let the conductor area per ampere of current be 2,000 circular mils in every case. The loads on the lines (at unity power factor) will then be those given in the last column of the following table:

TABLE II

;Line voltage (kv)	Circular mils A.S.C.R.	Amperes	Kw at unity P.F.
110	211, 600	106	20, 200
132	266, 800	133	30, 400
154	336, 000	168	44, 800
220	715, 500	358	136, 000
330	1, 590, 000	795	454, 000

Table II forcefully illustrates the advantage of using the higher voltages when large amounts of power are to be transmitted. This apparent advantage cannot always be fully realized, however, for the following reasons:

First. The theoretically most-economical load shown in the last column of table II may be greater than the permissible operating load limit of the line, as indicated in the curves of figures[27] 5, 6. When this is the case, the permissible load limit must control the design. The optimum condition prevails when the most economical load as determined by the modification of Kelvin's law is equal to the operating power limit of the line. As already pointed out, and as table II illustrates, in comparison with the curves of figures 6,[27] e.g., the theoretically most-economical loads for the extra-high-voltage lines are usually less than the permissible operating load limits, and the divergence increases with the line voltage. Thus the hoped-for increase in economy, which one might be led to expect would naturally accompany the use of higher and higher line voltages, does not exist in fact.

Second. From a practical standpoint it is necessary to have several lines feeding a given important load center in order that continuity of service may be assured. Suppose, for example, that four similar equally loaded 220-kilovolt lines supply a given load center. Should one line accidentally fail, the load which it originally carried may be divided among the remaining three by increasing the load on each by one third without endangering their satisfactory performance and until such time as the faulty line is again put into service. Thus service is maintained. If, on the other hand, 330-kilovolt lines were used, two lines, each carrying twice as much power as one of the 220-kilovolt lines would be electrically equivalent to the latter. These two lines cannot, however, supply service equivalent to that supplied by the four 220-kilovolt lines. Should one line fail, the load on the remaining line would have to be doubled to maintain service. This additional load, however, would probably be more than the remaining line could satisfactorily carry, and accordingly, service would be partly interrupted or it must be supplied from some other source until it may again be renewed over the faulty line.

The two above-mentioned reasons constitute very strong arguments against the use of line voltages in excess of 220 kilovolts and will probably make them impractical, at least until such time as the

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[27] Not printed.

amounts of power to be transmitted to a given load center reach the order of 600,000 to 800,000 kilowatts.

COMPUTATIONS

Curves for economical RI drop.—For conditions of maximum economy, the root-mean-square of transmitted current should be that given by equation (11)[28] below. This equation reduces to equation (12) when the conductor resistance per mile is substituted in terms of conductor diameter. The constants used have the values given in the tabulation; thus:

$$I' = d^2_s\left[\frac{1}{\rho A}\left(\frac{0.03}{bc^2}\cdot Bp_1+\frac{0.01\ p_2{}^M}{b}+\frac{0.01\ p_3{}^{k_{11}}}{bl}\right)\right]^{\frac{1}{2}} \tag*{(11)[29]}$$

But the resistance per mile of one conductor is

$$R/\text{mi} = \frac{5280\ \rho c^2}{10^6 d_s}$$

and, hence,

$$RI/\text{mi.} = \frac{5280\ \rho c^2}{10^6}\left[\frac{1}{\rho A}\left(\frac{0.03}{bc^2}\cdot Bp_1+\frac{0.01\ p_2{}^M}{b}+\frac{0.01\ p_3{}^{k_{11}}}{bl}\right)\right]^{\frac{1}{2}} \tag{12}$$

Assume that steel-reinforced aluminum cable (A.C.S.R.) will be used, and assign the following values to the constants:[30]

$p_1 = p_2 = p_3 = p = 6.83$ for the case of public money;
$= 8.77$ for the case of private money
$A =$ value of 1 kw-hr. of energy at receiver bus $=$ \$0.005.
(The reason for choosing this figure is found on the following page.)
$l =$ length of line in feet
$L =$ length of line in miles
$c^2 = \overline{1.23}^2 = 1.51$ for aluminum cable (A.C.S.R.)
$p = 17.9$ the resistivity of aluminum in ohms per mil-foot
$k_{11} = 3k_{11}v^2 = 3\times 20\times 10^{-6}\times 122^2\times 10^6$ (the terminal equipment constant)
$M = 0.30$ the tower constant
$b = 40\times 10^{-6}$
$B = 0.265$ for 15¢ copper
$= 0.30$ for 17¢ copper
$k_r^2 = p/A$ or $k_r = \sqrt{p/A}$

Substituting the above values in equation (12) and solving yields the following forms of the equation:

$$RI/\text{mi.} = 0.925\ k_r\ (0.275+55/L)^{1/2} \text{ (for 15¢ copper)} \tag{13}$$
$$RI/\text{mi.} = 0.925\ k_r\ (0.300+55/L)^{1/2} \text{ (for 17¢ copper)} \tag{14}$$

It is apparent from equations (13) and (14) that 2 cents difference in the price of copper affects the results obtained from the equations only slightly. The curves of figures 5 and 6,[31] which are drawn for an assumed price of 17 cents per pound for copper, may be used without appreciable error for all prices of copper between 15 and 19 or 20 cents per pound. These equations show that the economical *RI* drop per mile of conductor depends upon the length of line (*L*), upon the value of a kilowatt-hour of energy (*A*), upon the interest

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[28] See footnote 25, p. 457.

[29] It is important to note that the current I used in this and the following equations is the root-mean-square value as obtained from the average annual day-load curve and is not one third of the power delivered to the receiver divided by the receiver voltage to neutral.

[30] These values of p are derived in the manner shown on a later page.

[31] Not printed.

and depreciation rate (p) and upon the cost per pound of conductor material (B). With the help of one of these equations the curves of figure 1[31] were prepared. From these the economical size of conductor for any assumed conditions may quickly be obtained.

As an illustration, assume a line 200 miles long, let $p=6.83$ and $A=0.005$. Then $k_r^2=6.83/0.005=1{,}366$, and from the curve the economical RI drop per mile is seen to be approximately 26 volts. When I_{RMS} is known, the resistance per mile of conductor is found from the quotient $26 \div I_{RMS}$.

For the purpose of this investigation it is assumed that energy must be sold in competition with steam-generated energy, which latter is available at the load center for 5 mils per kilowatt-hour. Accordingly, a kilowatt-hour of energy transmitted over the line is assumed to be worth 5 mils, or $0.005 = A. If the transmission system is to be built with public money, it is assumed that 6.83 percent is a fair rate to cover interest, depreciation, and amortization; while if private money is to be used in the construction, the corresponding rate to cover interest, depreciation, and Federal and State taxes is 8.77 percent. These rates are made up approximately as follows:

Public money	Percent
Interest	4.00
Amortization	1.05
Depreciation reserve	1.78
Total	6.83

Private money	Percent
Interest	6.00
Depreciation reserve	1.27
Taxes	1.50
Total	8.77

The following values of k_r^2 therefore apply:

$$\text{For public money } k_r^2=\frac{6.83}{0.005}=1{,}366$$

$$\text{For private money } k_r^2=\frac{8{,}77}{0.005}=1{,}754$$

Economical transmission voltage.—The economical RI drop obtained from the curves of figure 1[31] may be used to calculate the most economical voltage suitable to transmit any assumed load over a line of any length. The formula in which the relating of these factors is shown is derived below.

I = R.M.S value of the average line current at full load
R = ohms resistance per mile of 1 conductor
d_s = diameter of stranded conductor in inch units
l = number of feet per mile = 5,280
ρ = resistivity of A.C.S.R. = 17.9 ohms per mil-foot
kw = root-mean-square kilowatts transmitted over the line at full load
E_n = average line voltage to neutral in kv.
E = $\sqrt{3}E_n$, the average line-to-line voltage
v = a constant $\left(\frac{1}{1000}\times\right.$ constant in table 23, p. 259, of reference in footnote 26 on. p. 457 of this document.$\left.\right)$
= 122.5
= $E_n \div d_s$
p.f = average line power factor at full load—assumed to be 0.90.

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[31] Not printed.

Then

$$\begin{aligned} RI &= \frac{R \times kw}{3 \times 0.9\ E_n} \\ &= \frac{\rho l\ c^2 \cdot kw}{10^6 d^2{}_s \cdot 2.7\ E_n} \\ &= \frac{\rho l\ c^2 v^2\ kw}{10^6 \times 2.7\ E^3{}_n} \end{aligned}$$

or

$$E^3{}_n = \frac{\rho l\ c^2 v^2\ kw}{10^6 \times 2.7\ RI} \qquad \begin{bmatrix} \rho = 17.9 \\ l = 5280 \\ c^2 = 1.51 \\ v^2 = 15.000 \end{bmatrix}$$

$$E_n = \sqrt[3]{793 \times \sqrt[3]{\frac{kw}{RI}}}$$

$$= 9.26\ \sqrt[3]{\frac{kw}{RI}} \qquad (15)$$

$$E = 16\ \sqrt[3]{\frac{kw}{RI}} \qquad (16)$$

With the help of equation (16) and the curves for the economical *RI* drop per mile (in figure 1),[31] the line voltage which it is most economical to use for any assumed transmitted load in root-mean-square kilowatts can be found approximately.

If it be assumed that the generating plant output is at all times proportional to the system demand, then the root-mean-square kilowatts delivered by a given generating station is the product of the following factors:

1. Kilowatts of installed generating capacity
2. Average annual day-load factor
3. Form factor of the average day-load curve for the year

The 1929 average day-load curves for the city of Seattle, the Puget Sound Power & Light Co., and the Washington Water Power Co. are shown in figures [31] 2, 3, and 4, respectively. From these curves the following data are obtained:

	Average annual load factor	Form factor
	Percent	
City of Seattle	44.8	1.04
Puget Sound Power & Light Co	58.5	1.06
Washington Water Power Co	58.7	1.00+

In the calculations that follow, a load factor of 55 percent and a form factor of 1.05 were assumed. Figure 5 [31] contains a set of curves computed on the assumption that public money is used ($p = 6.83$); while figure 6 [31] is a similar set of curves for the assumption of private money ($p = 8.77$).

With the aid of these curves it is possible very quickly to obtain the most suitable voltage to use for a given length of line and a given load. From figure 6,[31] for example, it is clear that to transmit a load of from 25,000 to 45,000 root-mean square kilowatts over a 100-mile line it is more economical to use 154 kilovolts than it is to use either 110 kilovolts or 220 kilovolts. On the other hand, 220 kilovolts should be used to transmit loads in excess of 50,000 root-mean-square kilowatts over a line 200 miles long. The curves clearly show that the

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[31] Not printed.

use of 110 kilovolts is limited to loads under 25,000 root-mean-square kilowatts except for distances under 50 miles.

The curves of these figures (theoretically) may be applied throughout the entire range of the figure, but operating practice sets a limit of load for every system as already pointed out in the paragraphs on power limits. This limit determines the maximum load that a given line may carry, and hence fixes a cut-off line for the curves of figures[31] 5 and 6 beyond which it is impractical to use them. Such cut-off lines have been calculated for the several standard operating voltages between 110 kilovolts and 330 kilovolts and have been superimposed on the load curves. The method used to compute these lines will now be described.

Estimation of power limits.—Experience with certain 220-kilovolt 50-cycle lines seems to indicate that approximately 120,000 kilowatts is the practical upper load limit of a 250-mile line operating at the above voltage and frequency; while for a 200-mile line at the same voltage and frequency the corresponding limit is in the neighborhood of 160,000 kilowatts. When corrected to a frequency of 60 cycles this indicates that the angular displacement between the voltage vectors at the two ends of the line should not exceed from 15° to 20°. For the purpose of this report, the limiting angle for the line alone is therefore assumed to be about 18°, or $\sin \theta = 0.31$.

The so-called approximate power limits of lines of various lengths and for the several standard transmission voltages were calculated in conformity with the theory discussed in the earlier pages of this report, using equation (8). The constants a_1, a_2, b_1, and b_2 are found in appendix D of footnote 26, page 457, the ratio $Es/Er = k$ was assumed to be 1.05 and $\sin \theta = 0.31$, as already stated. The values resulting from these calculations are found in figure 7.[31]

One realizes that the values of power limit found in this manner involve certain assumptions as to uniformity in different power systems that can be realized only approximately. Nevertheless, it is believed that the limits found are quite close to those that may be expected in practice and that they may safely be used as a guide in the present investigation.

Relative economies of 154-, 220-, and 330-kilovolt lines.—The question that must next be answered is, "Which of the three voltages—154-, 220-, or 330-kilovolt—is the most economical one to use?"

It has already been shown that extra-high transmission voltages can be economically used only when large amounts of power are to be transmitted over a line of considerable length. When large amounts of power are involved, however, it will usually be impractical to entrust the entire load to a single line.

To guard against the failure of service due to line outage, a minimum of at least two lines would be required for an important market like the Puget Sound region, as soon as the load supplied by the hydroelectric plants on the Columbia River became a considerable percentage of the system load. Thus, before 330-kilovolt lines could be considered on a really favorable basis, the total amount of power to be transmitted to the Puget Sound area would have to be in the neighborhood of 500,000 kilowatts. Studies of the probable growth of power load in this district show that additions of load of this order of magnitude will probably be required in the not-far-distant future.

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[31] Not printed.

Assumptions of the order of 250,000 kilowatts per line therefore seem reasonable.

Let it be assumed that in a given plant 500,000 kilowatts of generating machinery is available and that at full load the station power factor is 90 percent. The full-load station kilovolt-ampere is then 555,555. Let the distance of transmission be 200 miles, and assume losses as follows:

	Percent
1. Line loss at full load	10
2. Step-up transformers	1
3. Step-down transformers	1
4. Synchronous condensers [32]	1.5

The full-load receiver input is then 0.865×500,000, or 432,500 kilowatts.

Examination of the power-limit curves of figure 7 [31] shows that the estimated maximum receiver loads that can be delivered by 200-mile lines operating at the several standard voltages above 100 kilovolts are approximately those given in column 4 of table III below. The number of lines required to deliver the output of a 500,000-kilowatt generating station, less losses, for each of the voltages considered, is found in column 3 of the table.

TABLE III

Assumed voltage	Receiver input	Number of lines	Receiver load per line
Kilovolts	*Kilowatts*		*Kilowatts*
110	432,500	16	27,000
132	432,500	14	30,900
154	432,500	8	54,200
220	432,500	4	108,000
330	432,500	2	216,000

From the electrical standpoint the several methods of delivering the assumed amount of power to the load are taken to be equivalent. The lines operating at the lower voltages (110 and 132 kilovolts) are obviously uneconomical in the present instance, but they are included in the table in order to give a better picture of the problem and of the principle underlying its solution. Stated in words, the desired transmission of power may be accomplished in any one of the following ways:

1. By the use of a relatively large number of comparatively inexpensive, low-voltage lines, each carrying a relatively small load.
2. By the use of a minimum number (two) of very expensive, high-voltage lines, each carrying a relatively large load.
3. By the use of an intermediate number of moderately expensive, intermediate-voltage lines, of intermediate carrying capacity.

If it be assumed, for the sake of argument, that the operating advantages are equal for all of the arrangements to be considered (namely, the 154-, 220-, and the 330-kilovolt lines), the choice will fall to that arrangement for which the cost of transporting a kilowatt-hour of energy is minimum. There are certain obvious advantages favoring the use of 220 kilovolt rather than 330 kilovolt for example, but these need not now be considered.

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[32] The synchronous condenser capacity required at the end of the line is roughly 50 percent of the receiver input, and the condenser loss is assumed at 3 percent.

[31] Not printed.

To arrive at a solution, cost estimates must now be made for transmission of the assumed amount of power at each of the voltages, 154, 220, and 330 kilovolts. The 110- and 132-kilovolt lines obviously do not need to be considered further.

Itemized estimates of line costs follow. The unit costs used for towers and fittings, insulators, transformers, switches, synchronous condensers, etc., were furnished by manufacturers' representatives. Most of the original data used in making the estimates are found in an appendix to this report. The costs of substation buildings and auxiliary equipment were independently estimated. Costs of conductors are based on an assumed price of 17 cents per pound for copper cable. Present prices (March 1931) are from 15 to 20 percent under this value. Lines are assumed to be operated without the use of any intermediate sectionalizing substations. In case of the longest lines it is probable that the use of such stations would reduce the estimated transmission costs by about 15 percent.

Estimates were first made of the cost of transmitting the output of a 500,000-kilowatt generating plant a distance of 200 miles by each of three methods, namely, over 154-kilovolt lines, over 220-kilovolt lines, and over 330-kilovolt lines. Various load factors from 55 to 85 percent were assumed. The results of these comparative estimates are shown graphically in figure 8.[31] It is seen from this figure that the 220-kilovolt transmission is more economical than is either the 330-kilovolt or the 154-kilovolt transmission. The theoretically most economical transmission voltage is only slightly above 220 kilovolts, and the 154-kilovolt transmission is quite a bit less economical than either of the other two. As the length of line and the amount of power to be handled are increased, the conditions of maximum economy would tend to bring the 330-kilovolt transmission into a more favorable position. It is to be remembered, however, that from an operating standpoint two 330-kilovolt lines carrying the very large loads here assumed are far from being equivalent to the four 220-kilovolt lines, and accordingly they could hardly be considered on an equal basis even though the cost estimates were the same for both. With this in mind, it is difficult to see where there is any likelihood of the need arising for 330-kilovolt transmission.

Since most of the power to be developed on the Columbia River will require transmission of less than the assumed 200 miles, and in view of figure 8,[31] it is clear that the best transmission voltage to use is 220 kilovolts. In order to make it possible to estimate the cost of transmission from any site on the river to the load center, additional cost estimates of 220-kilovolt lines were made for lines varying in length from 100 to 250 miles. For these estimates it was assumed that the lines would always be designed to carry the loads indicated by the 200-kilovolt power-limit curve of figure 7,[31] when fully loaded. The transmission costs resulting from these estimates are shown by the curves of figure 9[31] for each of a number of load factors and for lines of various lengths.

Finally, it should be emphasized that the cost of transmitting a kilowatt-hour of energy over a given line depends not only upon the load factor and upon the length of line, but is greatly influenced as well by the amount of the transmitted load. The greatest transmission economy is secured when a line is loaded to the limit of its carrying capacity, as determined by conditions of stability.

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[31] Not printed.

To illustrate, consider the double-circuit, 220-kilovolt, 100-mile line whose cost estimate begins in column 1 on page 474. This line is assumed to have a capacity of a little over 200,000 kilowatts (fig. 7),[31] and is designed to transmit one half of 375,000 kilowatts, or 187,500 kilowatts per circuit. The cost of transmitting a kilowatt-hour of energy over this line at an assumed load-factor of 55 percent is about 0.5 mill (fig. 9).[31] Had the line been designed to carry only 100,000 kilowatts per circuit, the cost of the line itself, including towers, right of way, conductors, etc., would have been substantially the same as that given for the 187,500-kilowatt circuit, except for some saving in the cost of conductors due to their reduced size. There would have been a considerable saving in the cost of transformers and other terminal equipment, substation structures, etc., but this saving would have been far less than proportional to the reduction in the line output. The cost of transmitting a kilowatt-hour of energy would therefore have been increased from about 0.5 mill to perhaps 0.8 mill. If only 50,000 kilowatts per circuit were transmitted the cost would be further increased to perhaps 1.1 or 1.2 mills per kilowatt-hour. The same principle holds for the longer lines.

When using the curves of figure 9[31] to estimate transmission costs, therefore, one must bear in mind that the costs there given hold only for the assumed loads and load factors. Assuming the load-limit curves of figure 7[31] to be correct, the costs given are the minimum transmission costs that may be expected. For loads less than those assumed, the costs are increased in the manner explained above.

COST ESTIMATE

330-kilovolt, 200-mile line

Generator output per line (4×62,500 kilowatts)	kilowatts	250, 000
Full-load losses assumed (see p. 467)	percent	13. 5
Low-tension receiver full-load input per line (1−0.135)250,000	kilowatts	216, 250
Average full-load power transmitted ((250,000+216,250)÷2)	do	233, 100
Average full-load kilovolt-ampere transmitted (0.90 pf.)	kilovolt-amperes	259, 000
Generator current per terminal	amperes	1, 830

The transformer capacity for both ends of the line is based on the average kilovolt-amperes transmitted. Generators are assumed to be 22,000-volt, three-phase machines, and low-tension oil circuit breakers are rated at 34.5 kilovolts, 3,000 amperes, and 1,500,000 kilovolt-amperes.

1. Transformers, switches, circuit breakers, and synchronous condensers:	
(*a*) 2- by 4-low-tension oil circuit breakers at $7,200	$57, 600. 00
(*b*) 2- by 4-low tension dis. switches at $525	4, 200. 00
(*c*) 2- by 6-transformers (44,000 kilovolt-amperes) at $3 per kilovolt-ampere	1, 584, 000. 00
(*d*) 2- by 2-330-kilovolt oil circuit breakers (2,500,000 kilovolt-amperes) at $113,000	452, 000. 00
(*e*) 2-by 2-three-pole dis. switches at $4,900	19, 600. 00
Subtotal	2, 117, 400. 00
Freight and handling at 7 percent	148, 200. 00
Subtotal	2, 265, 600. 00
Synchronous-condenser capacity (60 percent received kilowatt at $2.50 per kilovolt-ampere)	325, 000. 00
Freight and starting equipment	30, 000. 00
Total electrical items (subtotal 1)	2, 620, 600. 00

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[31] Not printed.

2. Right of way:	
75-foot strip per circuit, at $3,000 per mile	$600, 000. 00
Roads and bridges, at $200 per mile	40, 000. 00
Subtotal (2)	640, 000. 00
3. Towers in place + insulators (see curves, fig. 11)[31], at $10,800 per mile. Subtotal (3)	2, 160, 000. 00
4. Conductors:	
600 miles 1,590,000 C.M.A.C.S.R., at $0.30 per foot per 10^6 cir. mils (copper, at 17 cents)	1, 510, 000. 00
Freight and hauling	80, 000. 00
Stringing and placing insulators, at $175 per cond.-mile	105, 000. 00
Two ⅝-inch ground cables, at 8 cents per pound, plus freight	130, 000. 00
Stringing ground wire, at $75 per cond.-mile	30, 000. 00
Subtotal (4)	1, 855, 000. 00
5. Telephone line, at $800 per mile	160, 000. 00
6. Substation and auxiliary equipment (receiver end):	
Site	50, 000. 00
Substation building	300, 000. 00
Warehouse and garage	50, 000. 00
Outdoor structure	50, 000. 00
Storage batteries and charging sets	3, 000. 00
Cooling-water system	5, 000. 00
Transformer oil system	10, 000. 00
Control equipment	20, 000. 00
Miscellaneous equipment	40, 000. 00
Installation and wiring	80, 000. 00
Freight on miscellaneous items	5, 000. 00
Subtotal (6)	613, 000. 00

Summary

1. Transformers, switches, etc	2, 620, 600. 00
2. Right of way	640, 000. 00
3. Towers and insulators	2, 160, 000. 00
4. Conductors, ground wires, and stringing	1, 855, 000. 00
5. Telephone line	160, 000. 00
6. Substation and auxiliary equipment	613, 000. 00
Subtotal	8, 048, 600. 00
7. Contingencies, at 15 percent	1, 207, 300. 00
Subtotal	9, 255, 900. 00
8. Overhead, engineering supervision, etc., at 12½ percent	1, 115, 300. 00
Subtotal	10, 371, 200. 00
9. Interest during construction:	
Private money (8 months, at 6 percent)	414, 800. 00
Public money (8 months, at 4 percent)	276, 500. 00
10. Total cost:	
Private money	10, 786, 000. 00
Public money	10, 647, 700. 00
11. Annual charge on investment:	
Private money, at 8.77 percent	947, 000. 00
Public money, at 6.83 percent	728, 000. 00
12. Operating charge per annum, at $150 per circuit-mile	30, 000. 00
13. Total yearly operating expense:	
Private money	977, 000. 00
Public money	758, 000. 00
14. Cost per kilowatt of generator capacity:	
Private money	43. 10
Public money	42. 60
15. Receiver-kilowatt input per line = 250,000 (1.00 − 0.135) kilowatt	216, 000

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[31] Not printed.

16. Receiver kilowatt-hours per year:	
55 percent load factor	$1{,}042\times10^6$
65 percent load factor	$1{,}232\times10^6$
75 percent load factor	$1{,}422\times10^6$
85 percent load factor	$1{,}610\times10^6$

17. Cost of transmission per kilowatt-hour.

L.f.	Public money	Private money
Percent	*Mills*	*Mills*
55	0.937	0.737
65	.793	.615
75	.687	.533
85	.607	.471

One double-circuit (200-mile) 220-kilovolt line

Generator output per double-circuit line kilowatts	250,000
Receiver input per double-circuit line do	216,300
1. Transformers, circuit-breakers, switches, and synchronous condensers:	
(*a*) 2 by 4 oil circuit breaker, at $7,200 ampere	$57,600.00
(*b*) 2 by 4, 22-kilovolt, 3,000-ampere disconnecting switches, at $525	4,200.00
(*c*) 2 by 6, 220-kilovolt (44,000 kilovolt-amperes) transformers, at $1.95 per kilovolt-ampere	1,029,600.00
(*d*) 2 by 2, 220-kilovolt, oil circuit breaker (1,200 amperes, 2,500,000 kilovolt-amperes), at $45,000	180,000.00
(*e*) 2 by 2 disconnecting switches with operating mechanism, at $2,600	10,400.00
Subtotal	1,281,800.00
Freight, at 7 percent	89,700.00
Subtotal	1,371,500.00
Synchronous condensers 60 percent of recorded kilowatts, at $2.50/kilovolt-ampere	325,000.00
Freight and starting equipment for synchronous condensers	30,000.00
Total electrical equipment (1)	1,726,500.00
2. Right of way (100-foot strip), at $3,500/mile	700,000.00
Roads and bridges, at $200/mile	40,000.00
Subtotal (2)	740,000.00
3. Towers in place plus insulators, at $9,300/mile (see curve, fig. 11.)[31] Subtotal (3)	1,860,000.00
4. Conductors (1,200 miles, 795,000 circular mils, A.C.S.R.), at $0.30 foot, per 10^6 circular mils (copper, at 17 cents)	1,512,000.00
Freight and hauling	96,000.00
Stringing and placing insulators, at $150/conductor-mile	180,000.00
Ground cables plus freight	130,000.00
Stringing ground cables, at $75 per conductor-mile	30,000.00
Subtotal (4)	1,948,000.00
5. Telephone line (same for 330-kilovolts) (5)	160,000.00
6. Substation and auxiliary equipment (same as for 330-kilovolts) (6)	613,000.00

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[31] Not printed.

Summary

1. Transformers, switches, etc		$1,726,500.00
2. Right of way, etc		740,000.00
3. Towers and insulators, etc		1,860,000.00
4. Conductors and ground cables in place		1,948,000.00
5. Telephone line		160,000.00
6. Substation and auxiliary equipment		613,000.00
Subtotal		7,047,500.00
7. Contingencies, at 15 percent		1,057,100.00
Subtotal		8,104,600.00
8. Overhead (engineering, supervision, clerical help, etc.) at 12½ percent		1,013,100.00
Subtotal		9,117,700.00
9. Interest during construction:		
Private money, 8 months, at 6 percent		364,700.00
Public money, 8 months, at 4 percent		243,400.00
10. Total cost:		
Private money		9,482,400.00
Public money		9,361,100.00
11. Annual charge on investment:		
Private money, at 8.77 percent		831,600.00
Public money, at 6.83 percent		647,600.00
12. Operating charge per annum, at $150 per circuit-mile		60,000.00
13. Total yearly operating expense:		
Private money		891,600.00
Public money		707,600.00
14. Cost per kilowatt of generator capacity:		
Private money		37.90
Public money		37.40
15. Receiver input per line of towers (216,300 kilowatts)		
16. Receiver kilowatt-hours per year:		
55 percent load factor	1042×10^{6}	
65 percent load factor	1232×10^{6}	
75 percent load factor	1422×10^{6}	
85 percent load factor	1610×10^{6}	
17. Cost of transmission per kilowatt-hour (in mills)		

Percent of load factor	Private money	Public money
55	0.856	0.679
65	.724	.574
75	.627	.498
85	.554	.440

Two double-circuit (200-mile) 154-kilovolt lines

Generator output per 4 circuits	kilowatts	250,000
Receiver input	do	216,300
1. Transformers oil circuit breaker disconnecting switches and synchronous condensers:		
(*a*) 2 by 4 oil circuit breaker, at $7,200		$57,600.00
(*b*) 2 by 4 disc. switches, at $525 each		4,200.00
(*c*) 2 by 12, 22,000-kilovolt-ampere transformers, at $1.65 kilovolt-ampere		871,200.00
(*d*) 2 by 4, 154-kilovolt disconnecting switches with operating mechanism, at $2,150		17,200.00
(*e*) 2 by 4, 154-kilovolt oil circuit breakers, at $20,000		160,000.00
Subtotal		1,110,200.00
Freight, at 7 percent		77,700.00
Subtotal (1)		1,187,900.00
(*f*) Synchronous condensers, at $2.50 per kilovolt-ampere		325,000.00
Freight and starting equipment		30,000.00
Subtotal (1)		1,542,900.00

2. Right of way (200-foot strip), at $6,000 per mile		$1, 200, 000. 00
Roads and bridges, at $250 per mile		50, 000. 00
Subtotal (2)		1, 250, 000. 00
3. Towers in place plus insulators (see curve fig. 11),[31] at 2 multiplied by $7,600 per mile		3, 040, 000. 00
4. Conductors (2,400 miles, 500,000 circular mils, A.C.S.R.), at $0.30 per foot, per 10^6 circular mils		1, 900, 800. 00
Freight and hauling		122, 000. 00
Stringing and placing insulators, at $130 per conductor-mile		312, 000. 00
Ground cables plus freight		260, 000. 00
Stringing ground cables		60, 000. 00
Subtotal (4)		2, 654, 800. 00
5. Telephone line (same as for 220-kilovolt)		160, 000. 00
6. Substation and auxiliary equipment		400, 000. 00

Summary

1. Transformers and switches		1, 542, 900. 00
2. Right of way		1, 250, 000. 00
3. Towers and insulators		3, 040, 000. 00
4. Conductors		2, 654, 800. 00
5. Telephone line		160, 000. 00
6. Substation and auxiliary equipment (receiver end)		400, 000. 00
Subtotal		9, 047, 700. 00
7. Contingencies, 15 percent		1, 357, 200. 00
Subtotal		10, 404, 900. 00
8. Overhead (engineering, supervision, clerical help, etc.), 12½ percent		1, 300, 600. 00
Subtotal		11, 705, 500. 00
9. Interest during construction:		
Private money, 8 months, at 6 percent		468, 200. 00
Public money, 8 months, at 4 percent		312, 500. 00
10. Total cost:		
Private money		12, 173, 700. 00
Public money		12, 018, 000. 00
11. Annual charge on investment:		
Private money, at 8.77 percent		1, 067, 600. 00
Public money, at 6.83 percent		820, 800. 00
12. Operating charge per year, $125 per circuit-mile		100, 000. 00
13. Total yearly operating expenses:		
Private money		1, 167, 600. 00
Public money		920, 800. 00
14. Cost per kilowatt of generator capacity:		
Private money		48. 70
Public money		48. 10
15. Receiver input (4 circuits), 216,300 kilowatts		
16. Receiver kilowatt-hours per year:		
55 percent load factor	$1{,}042\times10^6$	
65 percent load factor	$1{,}232\times10^6$	
75 percent load factor	$1{,}421\times10^6$	
85 percent load factor	$1{,}611\times10^6$	
17. Cost of transmission per kilowatt-hour of energy (mills)		

Percent load factor	Private money	Public money
55	1. 12	0. 883
65	. 948	. 747
75	. 821	. 648
85	. 725	. 571

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[31] Not printed.

220-kilovolt double-circuit lines of various lengths

[Each line is assumed to be designed for a full load equal (approximately) to that indicated by the power-limit curves]

Item	Circular mils of A.C.S.R.			
	1,113,000	795,000	715,000	715,000
	Length of line (miles)			
	100	150	200	250
Assumed load per double-circuit line	375, 000	312, 500	250, 000	187, 000
1. Transmitter switches, oil-circuit breakers and synchronous condensers:				
(*a*) Oil-circuit breakers (line tension)	$86, 400	$72, 000	$57, 600	$43, 200
(*b*) Disconnecting switches	6, 300	5, 250	4, 200	3, 150
(*c*) Transformers	1, 544, 400	1, 287, 000	1, 029, 600	772, 200
(*d*) High-tension oil-circuit breakers	180, 000	180, 000	180, 000	180, 000
(*e*) Disconnecting switches with operating mechanism	10, 400	10, 400	10, 400	10, 400
Subtotal	1, 827, 100	1, 554, 600	1, 281, 800	1, 008, 900
Freight 7 percent	127, 900	108, 800	89, 700	70, 600
Subtotal	1, 955, 000	1, 663, 400	1, 371, 500	1, 079, 500
(*f*) Synchronous condensers	487, 000	405, 000	325, 000	245, 000
Freight and starting equipment	45, 000	37, 500	30, 000	22, 500
Subtotal (1)	2, 487, 000	2, 105, 900	1, 726, 500	1, 347, 000
2. Right-of-way at 3,500 miles per tower line	350, 000	525, 000	700, 000	875, 000
Roads and bridges ($200 per mile)	20, 000	30, 000	40, 000	50, 000
Subtotal (2)	370, 000	555, 000	740, 000	925, 000
3. Towers in place+insulators at $9,300 per mile. Subtotal (3)	930, 000	1, 395, 000	1, 860, 000	2, 325, 000
4. Conductors	1, 057, 800	1, 133, 000	1, 359, 000	1, 699, 000
Freight and hauling	67, 000	72, 000	86, 000	107, 000
Stringing and placing insulators at $150 per circuit-mile	90, 000	135, 000	180, 000	225, 000
Ground cables and freight	65, 000	97, 500	130, 000	163, 000
Stringing ground cables at $75 per conductor-mile	15, 000	22, 500	30, 000	37, 500
Subtotal (4)	1, 294, 800	1, 460, 000	1, 785, 000	2, 231, 500
5. Telephone line	80, 000	120, 000	160, 000	200, 000
6. Substation and auxiliary equipment	920, 000	760, 000	613, 000	450, 000
Summary				
1. Transfer switches, etc	2, 487, 000	2, 105, 900	1, 726, 500	1, 347, 000
2. Right-of-way	370, 000	555, 000	740, 000	925, 000
3. Towers, insulators, etc	930, 000	1, 395, 000	1, 860, 000	2, 325, 000
4. Conductors and ground cables	1, 294, 800	1, 460, 000	1, 785, 000	2, 231, 500
5. Telephone line	80, 000	120, 000	160, 000	200, 000
6. Substation and auxiliary equipment	920, 000	760, 000	613, 000	450, 000
Subtotal	6, 081, 800	6, 395, 900	6, 884, 500	7, 478, 500
7. Contingencies at 15 percent	912, 300	959, 400	1, 032, 700	1, 122, 000
Subtotal	6, 994, 100	7, 355, 300	7, 917, 200	8, 600, 500
8. Overhead (engineering, clerical, etc., 12½ percent)	874, 300	919, 400	989, 700	1, 075, 100
Subtotal	7, 868, 400	8, 274, 700	8, 906, 900	9, 675, 600
9. Interest during construction:				
Private money	314, 700	331, 000	356, 300	387, 000
Public money	209, 800	221, 000	237, 500	258, 000
10. Total cost:				
Private money	8, 183, 100	8, 605, 700	9, 263, 200	10, 062, 600
Public money	8, 078, 200	8, 495, 700	9, 144, 400	9, 933, 600
11. Annual charge on investment:				
Private money, 8.77 percent	717, 700	754, 700	812, 400	882, 500
Public money, 6.83 percent	551, 700	580, 300	624, 600	678, 500
12. Annual operating expense at $150 per circular mil	30, 000	45, 000	60, 000	75, 000
13. Total annual operating cost:				
Private money	747, 700	799, 700	872, 400	957, 500
Public money	581, 700	625, 300	684, 600	753, 500

220-kilovolt double-circuit lines of various lengths—Continued

Item	Circular mils of A.C.S.R.			
	1,113,000	795,000	715,000	715,000
	Length of line (miles)			
	100	150	200	250
14. Cost per kilowatt general capitalization:				
Private money	21.80	27.60	37.00	53.70
Public money	21.50	27.20	36.50	53.10
15. Receiver input per tower line	325,000	271,000	216,000	162,000
16. Received kilowatt-hours per year:				
55 percent load factor	$1,566\times10^6$	$1,306\times10^6$	$1,041\times10^6$	780.5×10^6
65 percent load factor	$1,851\times10^6$	$1,543\times10^6$	$1,230\times10^6$	922.4×10^6
75 percent load factor	$2,135\times10^6$	$1,780\times10^6$	$1,419\times10^6$	$1,064\times10^6$
85 percent load factor	$2,420\times10^6$	$2,018\times10^6$	$1,608\times10^6$	$1,206\times10^6$
17. Cost of transmission per kilowatt-hour in mills:				
Private money:				
55 percent load factor	0.477	0.615	0.838	1.225
65 percent load factor	.403	.518	.709	1.037
75 percent load factor	.350	.449	.615	.898
85 percent load factor	.309	.396	.542	.797
Public money:				
55 percent load factor	.372	.479	.657	.965
65 percent load factor	.314	.405	.556	.817
75 percent load factor	.272	.351	.483	.707
85 percent load factor	.241	.310	.426	.625

UNIT PRICES USED FOR ESTIMATING

The principal cost data used in making the foregoing estimates are given in this appendix.

Steel towers and insulators.—The weight of steel per mile of tower line is given in the tabulation entitled "Analysis of Tower Cost Per Mile of Line" and in the curves of figure 10.[31]

All suspension towers are designed for the assumption of one conductor broken, ½-inch ice load, an 8-pound wind load, and conductor stressed to a maximum tension equal to 75 percent of the elastic limit. The weights given in the figure are for standard suspension towers, including steel earth anchors. Anchor towers for double-circuit lines are assumed to be 75 percent heavier than the corresponding suspension towers; while for single-circuit lines anchor towers are assumed to be only 20 percent heavier than the suspension towers.

The cost of steel towers is estimated on the basis of $100 per ton of steel f.o.b. cars at the nearest station. Cost of erection of towers is estimated at $50 per ton of steel. Handling and hauling costs are separately estimated as indicated in the tabulation.

Costs of insulators and fittings were estimated, and these costs were added to the appropriate tower costs to obtain the total cost of towers and insulators in place per mile of line for each assumed span length. Total costs per mile of line, including insulators, are shown graphically in figure 11.[31] The most economical spans and the costs appropriate thereto were used in making the final estimates of tower costs.

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[31] Not printed.

Analysis of tower cost per mile of line—Continued

Item	Assumed span length			
	700 feet	1,100 feet	1,700 feet	2,100 feet
Number of towers per mile	7.54	4.8	3.1	2.51
Number of suspension towers per mile (suspension towers equal 90 percent of total)	6.78	4.32	2.79	2.26
Number of anchor towers per mile (anchor towers equal 10 percent of total)	.75	.48	.31	.25
Weight [1] of steel per suspension tower (pounds):				
110 kilovolts, 2-circuit	8,200	10,300	16,300	23,200
154 kilovolts, 2-circuit	9,800	12,700	20,700	30,300
220 kilovolts, 2-circuit (average)	12,500	15,500	24,200	34,300
220 kilovolts, 1-circuit	7,500	10,700	17,800	25,000
275 kilovolts, 1-circuit	10,800	14,000	22,200	31,600
330 kilovolts, 1-circuit	15,300	19,300	29,800	41,300
Total weight [1] of steel per mile (in M pounds):				
110 kilovolts, 2-circuit	66.4	53.2	54.4	62.6
154 kilovolts, 2-circuit	79.3	65.6	69.0	81.8
220 kilovolts, 2-circuit	101.0	80.0	80.8	92.8
220 kilovolts, 1-circuit	60.7	55.3	59.4	67.5
275 kilovolts, 1-circuit	87.5	72.3	74.0	85.5
330 kilovolts, 1-circuit	124.0	99.7	99.5	111.7
Cost of erection per mile, at $50 per ton:				
110 kilovolts, 2-circuit	$1,660	$1,330	$1,360	$1,565
154 kilovolts, 2-circuit	1,980	1,640	1,725	2,045
220 kilovolts, 2-circuit	2,530	2,000	2,040	2,320
220 kilovolts, 1-circuit	1,515	1,382	1,485	1,687
275 kilovolts, 1-circuit	2,180	1,807	1,850	2,137
330 kilovolts, 1-circuit	3,110	2,492	2,487	2,792

Item	Assumed line voltage				
	2 circuits 110 kilovolts	2 circuits 154 kilovolts	2 circuits 220 kilovolts	1 circuit 220 kilovolts	1 circuit 330 kilovolts
Insulators per suspension string	7	10	14	14	22
Insulators per suspension tower	42	60	84	42	66
Insulators per anchor-tower string	9	12	16	16	24
Insulators per anchor tower	108	144	384	192	288
700-foot span:					
Disks per mile on suspension towers	286	408	570	286	448
Disks per mile on anchor towers	82	108	288	144	216
Total number disks per mile of line	368	516	858	430	664
1,100-foot span:					
Disks per mile on suspension towers	182	260	364	182	286
Disks per mile on anchor towers	52	70	186	92	140
Total disks per mile of line	234	330	550	274	426
1,700-foot span:					
Disks per mile on suspension towers	118	168	236	118	186
Disks per mile on anchor towers	34	46	120	60	90
Total disks per mile of line	152	214	356	178	276
2,100-foot span:					
Disks per mile on suspension towers	96	136	190	96	150
Disks per mile on anchor towers	28	36	96	48	72
Total disks per mile of line	124	172	286	144	222
700-foot span:					
1. Cost of disks per mile at $2.40	$885	$1,240	$2,060	$1,032	$1,593
2. Suspension clamps per mile at $3.60 per suspension string	147	147	147	74	74
3. Strain clamps per mile at $7.85 per strain string	71	71	71	35	35
4. Arcing horns per mile at $3 per suspension string	122	122	122	61	61
5. Suspension grad. rings per mile at $8 per suspension string	327	327	327	164	164
6. Attachment clevises equal total strings multiplied by 0.50	21	21	21	11	11

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[1] Weight of anchor tower is assumed at 1.75 by weight of suspension tower.

Analysis of tower cost per mile of line—Continued

Item	Assumed line voltage				
	2 circuits 110 kilovolts	2 circuits 154 kilovolts	2 circuits 220 kilovolts	1 circuit 220 kilovolts	1 circuit 330 kilovolts
700-foot span—Continued.					
7. Double strain yokes per mile equals $10 multiplied by double strings per mile			90	45	45
8. Double string rings equals double strings multiplied by $12			108	54	54
9. Freight at $0.015 per pound	91	128	213	107	165
10. Hauling and handling at $0.40 per ton-mile	15	21	35	18	27
Total cost per mile	1,679	2,077	3,194	1,601	2,229
1,100-foot span:					
1. Cost of disks per mile at $2.40	562	792	1,320	658	1,022
2. Suspension clamps per mile at $3.60	93	93	93	47	47
3. Strain clamps per mile at $7.85	43	43	43	21	21
4. Arcing horns per mile at $3	93	93	93	47	47
5. Suspension grad. rings at $8	207	207	207	104	104
6. Attachment clevises at 50 cents	15	15	15	8	8
7. Double-strain yokes at $10			54	27	27
8. Double-string rings at $12			65	38	38
9. Freight at $0.015 per pound	58	82	136	68	105
10. Hauling and handling	10	14	23	12	18
Total	1,081	1,339	2,048	1,030	1,437
1,700-foot span:					
1. Cost of disks per mile at $2.40	367	510	860	430	665
2. Suspension clamps per mile at $3.60	61	61	61	30	30
3. Strain clamps per mile at $7.85	30	30	30	15	15
4. Arcing horns per mile at $3	50	50	50	25	25
5. Suspension grad. rings at $8	135	135	135	68	68
6. Attachment clevises per mile at 50 cents	9	9	9	5	5
7. Double strain yokes at $10			38	19	19
8. Double string rings at $12			45	23	23
9. Freight at $0.015 per pound	38	53	88	45	69
10. Hauling and handling	5	7	11	6	9
Total	695	855	1,327	666	928
2,100-foot span:					
1. Cost of disks per mile at $2.40	300	412	686	343	531
2. Suspension clamps per mile at $3.60	49	49	49	25	25
3. Strain clamps per mile at $7.85	44	44	44	22	22
4. Arcing horns per mile at $3	42	42	42	21	21
5. Suspension grad. rings at $8	109	109	109	55	55
6. Attachment clevises per mile at 50 cents	7	7	7	4	4
7. Double-strain yokes at $10			30	15	15
8. Double-string rings at $12			36	18	18
9. Freight at $0.015 per pound	31	43	71	36	55
10. Hauling and handling at $0.40 per ton-mile	4	6	9	5	7
Total	586	712	1,083	542	753

Item	Tower-line items of cost per mile for the several spans noted below			
	700 feet	1,100 feet	1,700 feet	2,100 feet
110-kilovolt, 2-circuit line:				
Cost, steel, f.o.b. nearest station at $100 per ton	$3,320	$2,660	$2,720	$3,130
Hauling and handling average of 10 miles at $0.40 per ton-mile	123	106	109	123
Erection at $50 per ton	1,660	1,330	1,360	1,570
Digging and back filling at average of $3 per yard	1,780	1,360	1,310	1,410
Cost, insulators and fittings at site	1,679	1,081	695	586
Total	8,562	6,537	6,194	6,819
154-kilovolt, 2-circuit line:				
Cost, steel, f.o.b. nearest station, at $100 per ton	3,965	3,280	3,450	4,090
Hauling and handling	159	122	138	164
Erection at $50 per ton	1,980	1,640	1,725	2,045
Digging and back filling at $3 per yard	2,140	1,670	1,660	1,840
Cost, insulators and fittings at site	2,077	1,339	855	712
Total	10,320	8,051	7,828	8,851

Analysis of tower cost per mile of line—Continued

Item	Tower-line items of cost per mile for the several spans noted below			
	700 feet	1,100 feet	1,700 feet	2,100 feet
220-kilovolt, 2-circuit line:				
Cost, steel, f.o.b. nearest station, at $100 per ton	5, 050	4, 000	4, 040	4, 640
Hauling and handling	202	160	162	185
Erection at $50 per ton	2, 525	2, 000	2, 020	2, 320
Digging and back filling at $3 per yard	2, 720	2, 040	1, 940	2, 090
Cost, insulators and fittings at site	3, 194	2, 048	1, 327	1, 083
Total	13, 691	10, 248	9, 489	10, 318
330-kilovolt, 1-circuit line:				
Cost, steel, f.o.b. nearest station, at $100 per ton	6, 200	4, 985	4, 975	5, 585
Hauling and handling	248	200	200	223
Erection at $50 per ton	3, 100	2, 493	2, 488	2, 792
Digging and back filling at $3 per yard	3, 360	2, 520	2, 390	2, 520
Cost, insulators and fittings at site	2, 229	1, 437	928	753
Total	15, 137	11, 635	10, 981	11, 873

NOTE.—Yards excavation equals *k* multiplied by weight of steel in pounds; *k* varies from 0.75 to 0.90 percent.

Right of way.—Experience with right-of-way costs in the areas considered in this report indicates that average costs about as given below may be expected. These costs contemplate the purchase of an easement only, including the right to place and to maintain the necessary towers and fixtures on a 100-foot strip, and to cut all trees that endanger the line. They include the cost of clearing and of burning limbs and brush and of otherwise preparing the right of way for use.

1. Through open, semidesert country east of the Cascade Mountains where little or no clearing is required, $1,000 per mile.
2. Through logged-off land or light second-growth timber, $2,000 per mile.
3. Through light stands of timber, such as one finds in the mountains, $3,500 per mile.
4. Through moderately heavy to heavy stands of virgin timber, $10,000 to $20,000 per mile.
5. Through valuable cultivated lands in regions west of the Cascade Mountains, $3,000 to $7,000 per mile.

Terminal equipment.—The unit costs used in estimating the principal items of terminal equipment are given below. These are exclusive of freight.

Transformers (single-phase):	
154 kilovolts, 22,000 kilovolt-amperes____per kilovolt-ampere	$1. 65
220 kilovolts, 44,000 kilovolt-amperes____do	1. 95
330 kilovolts, 44,000 kilovolt-amperes____do	3. 00
Oil circuit breakers:	
34.5 kilovolts, 3,000 amperes, 1,500,000 kilovolt-amperes	7, 200. 00
161 kilovolts, 600 amperes, 1,500,000 kilovolt-amperes	20, 000. 00
230 kilovolts, 1,200 amperes, 2,500,000 kilovolt-amperes	45, 000. 00
345 kilovolts, 1,200 amperes, 2,500,000 kilovolt-amperes	113, 000. 00
Disconnecting switches with operating mechanism:	
22 kilovolts, 600 amperes	525. 00
161 kilovolts, 600 amperes	2, 150. 00
230 kilovolts, 600 amperes	2, 600. 00
330 kilovolts, 600 amperes	4, 900. 00

Synchronous condensers:	
10,000 kilovolt-amperes	35, 000. 00
20,000 kilovolt-amperes	58, 000. 00
30,000 kilovolt-amperes	78, 400. 00
40,000 kilovolt-amperes	96, 750. 00

To these costs must be added about 5 percent for freight and from $2,000 to $5,000 per unit for starting equipment.

REPORT BY THE BUREAU OF RECLAMATION, DEPARTMENT OF THE INTERIOR

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