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PLANT EFFICIENCY

AN ANALYSIS OF THE LOSSES OF A HYDROELECTRIC SYSTEM

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The following paper is an analysis of the losses and efficiencies of the Seattle Municipal Light and Power plant for the year 1911.

Great care has been taken in these measurements and the results have been checked in as many ways as possible and instruments have been frequently calibrated. These figures are therefore believed to be a close approximation to the true values.

GENERAL DESCRIPTION OF PLANT

The Seattle plant is a hydroelectric system delivering water to two 1,500 kw. Pelton units and two 5,000 kw. turbine units under 600-ft (183 m.) head through two pipes approximately $3\frac{1}{2}$ miles (5.6 km.) long, one of which is $67\frac{3}{4}$ (172 cm.) and the other 49 (124 cm.) inside diameter. The current is transmitted at 60,000 volts through two lines to Seattle, a distance of 38.7 miles (62.2 km.), and is there distributed at 15,000 and 2,400 volts for use by approximately 20,000 customers and for the city street lighting.

Pipe Lines and Penstocks. The $67\frac{3}{4}$ -inch (172 cm.) pipe consists of 15,865 ft. (4,835.6 m.) of wood stave pipe dividing at a point 951 ft. (289.8 m.) from the power house into two 48-in. (122 cm.) riveted steel penstocks. The 49-in. (124 cm.) wood pipe joins onto a 48-in. (122 cm.) riveted steel penstock at a point 1,008 ft. (307.2 m.) from the power house.

Careful tests were made on the $67\frac{3}{4}$ -in. wood stave pipe, using gages calibrated before and after. The pipe contains five steel elbows, where the curvature is greater than 20 deg. These elbows are made to a 15-ft. (4.57 m.) radius and have angles

respectively 92, 55, 60, 65, and 45 degrees. The loss in head of each elbow was measured by a differential pressure gage. The results of the test are given in detail in the following table:

LOSS OF HEAD IN FEET IN VARIOUS PARTS OF 67½-IN. (172 CM.) WOOD STAVE PIPE											
Vel- ocity in ft. per second	Loss in entry and screens	El- bow No. 1 92°	El- bow No. 2 55°	El- bow No. 3 60°	El- bow No. 4 65°	El- bow No. 5 45°	Total loss in pipe	Friction loss after deduct- ing entry and elbows	Loss in 67½" stave pipe per 1,000 feet	Value of C. in Kut- ters for- mula	Value of N. in Kut- ters for- mula
2½	.06	.03	.03	.03	.03	.01	4.1	3.91	.246	134.06	.01190
5	.25	.09	.08	.08	.08	.05	15.4	14.77	.931	137.96	.01175
7½	.54	.25	.18	.19	.20	.14	33.9	32.40	2.0425	139.71	.01165
10	1.14	.46	.34	.36	.37	.27	61.9	58.96	3.775	137.01	.011865

NOTE: 1 ft. = 0.3048 in.

FIG. 1

This pipe has been in operation since November 20, 1908. The loss in entry as given in the above table seems large and rises with the velocity more rapidly than it should. This is apparently due to the resistance of the screens, which are of wood bars. These were being changed before the test was made as it was noticed at times of heavy load that there was a difference of level on the two sides of the screens. The entry of the pipe is bell-mouthed. The total length of the wood pipe is 15,865 ft. (4,835.6 m.) The line was designed for a slope of four feet per thousand feet to give a velocity of ten feet (3.05 m.) per second.

The loss in the penstocks was computed from records taken by Bristol recording gages at the generating station, which were frequently calibrated. The results so obtained were checked by computing the loss from the efficiency shown under test, and agreed very closely. The maximum output of the two penstocks was 12,400 kw., with a loss of 6 per cent, and the average output for the year was 6,009 kw., with an average loss of 2.3 per cent. This loss was increased by the fact that the plant was supplied for thirty-three days in November and December by the larger pipe alone.

Generating Station. There are four units in the power house, two of which consist of 8,000-h.p. Francis turbines direct-connected to 60-cycle, 2,300-volt, three-phase generators rated at 4,000 kw. at 35 deg. cent. rise, with a four hour overload capacity of 5,000 kw. at 40 deg. cent. rise. These units operate at 600 rev. per min. The other two units are driven by 2,400-h.p. Pelton impulse wheels direct-connected to 60-cycle, 2,300-volt, three-phase generators rated at 1,200 kw. at 35 deg. cent. rise, with a four hour overload capacity of 1,500 kw. at 40 deg. cent. rise. These units operate at 400 rev. per min. The wheels are each equipped with two runners, each of which is supplied from a needle and a deflecting nozzle. The combined capacity of the present installation is therefore 13,000 kw. on a 40 deg. cent. rating. The two machines last mentioned, however, exceed their rating and have been operated continuously without excessive heating at 1,750 kw., making the combined capacity 13,500 kw. Three water wheel exciter units are installed, two of which have a capacity of 75 kw. each, and the third 150 kw.

As the efficiency of each unit varies with the load, and it is obviously impossible to have all generators that are in use at any time carry their full load, the all-day efficiency of the generating station will depend on the number of units in use and the load which each carries, as well as on the power factor of the load and, in the case of this plant, where two types of wheels are used, it will also depend on the proportion of the load that the operator gives to each type of machine. In general, the greatest all-day efficiency can be had by keeping the machines as nearly as possible at the load of maximum efficiency, and by shutting down the machines without load as far as can conveniently be done.

While the combined maximum efficiency of generator and wheel was found in the case of the 5,000 kw. units to be 76.7

per cent, and in the case of the 1,500-kw. units to be 69.9 per cent, the all-day efficiency of the plant for 1911 was found to be 56.7 per cent. This does not include current for excitation and station lighting. By including this as a loss, the all-day efficiency of the plant drops to 55.7 per cent.

The reason for the difference in the same type of unit is found in the fact that the operators favor No. 1 and No. 4 machines, from habit rather than intention. The impulse wheels, being small, are operated under full load for a great part of the day and their all-day efficiency is greater than that of the turbines, notwithstanding the higher efficiency of the turbine sets at full

load. It will be readily seen from these facts that the efficiency of a plant depends very largely on the way it is handled by the operator and during low water periods it is possible to prepare a schedule showing which machines should be used for each load

FIG. 2

FIG. 3

which the plant carries. This schedule will be modified by the conditions of the plant, changes in load, and regulation.

Losses in the water wheels and generators were computed from the half-hour wattmeter readings on the generators as recorded in the station report. The input for each output

throughout the year was computed from efficiencies shown in tests made in 1909 and checked at the end of 1911. The results show all-day efficiencies for the year as follows:

EFFICIENCY			
	Wheel	Generator	Combined
Impulse Unit No. 1.....	70.8	93.0	65.8
Impulse Unit No. 2.....	66.3	92.2	61.1
Turbine Unit No. 3.....	57.1	93.0	53.1
Turbine Unit No. 4.....	63.6	94.1	59.8
Four units combined.....	60.7	93.5	56.7

The higher efficiency of the impulse units is due to the fact that they were nearly always loaded above 900 kw. and the regulating was done with the relief valves and governors on the turbines, so that there was little loss from the deflecting nozzles.

The power used in excitation was computed from the half-hour readings on the exciter outputs, and amounted to 399,120 kw-hr. or 1.3 per cent. of the output of the generators. The water input to the exciter units, computed similarly to that of the large units, was 665,200 kw-hr. Station lighting, including light for the employees' cottages, amounted to 175,000 kw-hr. for the year.

Step-Up Transformers. The station is equipped with nine transformers. Each bank of three has a normal capacity of 4,500 kw. at 35 deg. cent. temperature rise. These transformers step the voltage from 2,300 to 60,000 volts three-phase star connected. The neutral of the star connection is grounded. The manufacturers were requested to sacrifice efficiency for high insulation, if necessary, but the efficiency is found to be as high as is customary when using lower insulation. These transformers

FIG. 4

were all in circuit continuously to keep them in good condition, and their core losses were practically constant, amounting to 926,000 kw-hr., or an average of 11.7 kw. per transformer. The copper loss was computed from the readings on the reports, and

amounted to 200,00 kw-hr. or an average of 2.54 kw. per transformer.

	Kw-hr.	Average kw.
Core loss.....	926,000	106
Copper loss.....	200,000	23
Total loss.....	1,126,000	129
All-day efficiency.....	96.1 per cent.	

High-Tension Lines. There are two high-tension lines 38.7 miles (62.2 km.) in length strung on two different makes of insulators of practically the same size and type. One of the lines is of No. 2 solid medium hand-drawn copper, the wires being

FIG. 5

placed in a six-foot (1.83 m.) triangle. The other is built of No. 0000 seven-strand hard-drawn copper, the wires being placed in a seven-foot (2.13 m.) triangle.

The line loss was computed from the constants of the lines, taking the load data shown by the report sheets. The line resistances were measured by direct current, using the fall of potential method, and agreed very closely with the computed value. The inductance and capacity were calculated from the values given in the Standard Handbook, third edition. To simplify calculation for the all-day efficiency, a Perrine-Baum regulation diagram was drawn for both lines in parallel. To this

were added circles, taking as a center the end of the substation voltage vector, and as a radius the square of the voltage drop in the line, multiplied by the conductance of the line. The radii of these circles represent power loss. The power lost during 1911 on the two lines, figured from this diagram, using the half-hour readings at the substation for load data, amounted to 378,000 kw-hr. or an average of 43 kw. for the year.

	Kw-hr.	Average kw.
Line loss.....	378,000	43
All-day efficiency.....	98.6 per cent.	

Step-Down Transformers. The step-down transformers are placed on the first floor of the substation. There are at present eight of these, each of 1,500 kw. capacity at 35 deg. cent. temperature rise. All are made with a ratio of 54,000 volts, three-phase to 15,000 and 2,500 Scott connected two-phase, making four banks of transformers. The low-tension coils are connected in series for 15,000 and in multiple for 2,500 volts, two banks being used on each voltage.

The step-down transformer loss, computed in the same way as that of the step-up transformers, was as follows:

	Kw-hr.	Average kw.
Core loss.....	692,000	79
Copper loss.....	217,500	25
Total loss.....	909,500	104
All-day efficiency.....	96.6 per cent.	

The sum of the losses in line and transformers was checked against the difference in the watt-hour meter readings on the low-tension side of the transformers at each end of the line, and was about five per cent lower. This may not have been due to error but may be largely due to corona loss or other line leakage. No measurements have as yet been made to determine this point.

Main Substation. The main substation contains the step-down transformers, a distributing switchboard of the remote control type, and the necessary switching and control apparatus for the distributing feeders. The switchboard carries a complete set of curve-tracing meters for the high-tension lines, indicating ammeters and wattmeters and watt-hour meters for the transformers, and indicating ammeters, recording voltmeters and watt-hour meters for the feeders. Loss in meters and their instrument transformers was computed from tests

made on each type of meter and transformer. Current used for station light, heat and display lighting was metered.

	Kw-hr.	Average kw.
Loss in meters.....	29,000	3
Power for station light.....	317,400	37
Total loss.....	346,400	40
All-day efficiency.....	98.7 per cent.	

Motor-Generator Set. A motor-generator set consisting of a 750-h.p., two-phase synchronous motor direct-connected to two 250-kw. 250-volt direct-current compound-wound generators is used on a three-wire 500 and 250-volt system for operating elevators and other motors. The maximum load on this machine at the present time on the direct-current side is 300 kw. and the average load for 1911 was 30.2 kw. The surplus kilovolt-ampere capacity of the motor is utilized in regulating the voltage of the main system by varying the power factor by means of a Tirrill regulator controlling the field of the motor. There are at present 71 services connected on this system with a connected load of 772½ h.p. The main feeder is 750,000-cir. mil cable with a 400,000-cir. mil neutral, and the branches usually No. 4/0 with No. 2/0 neutral. In all, 27 miles (43.4 km.) of wire are used on this system.

The total loss in the direct-current feeders and the motor-generator was obtained from the difference in the motor watt-hour meters and the customers' meters. From recording volt-meter charts taken at various distributing points and at the substation and from computations, using the load data and line resistance, the line loss is placed at 5 per cent. The details of losses and efficiencies follow:

	Efficiency, 1911	Loss, kw-hr.	Average loss, kw.
Motor-generator.....	38.	417,000	48
Direct-current lines.....	95.0	12,800	1
Customers' meters.....	98.8	3,000	..
Total direct-current system.....	35.7	432,800	49

15,000-Volt System. Current is distributed at 15,000 volts from the main substation to two smaller substations and to

about twelve mills and factories which use large amounts of power. This system is two-phase, with the center point of each

FIG. 6

phase grounded. For mechanical reasons, No. 2 is the smallest wire used on the 15,000-volt lines. There are about 105 miles (169 km.) No. 2, nine miles (14.5 km.) of No. 1, and two and one-half miles (4.02 km.) of No. 0 wire. There are 30 transformers connected, ranging in size from 750 kw. to 50 kw., with a combined capacity of 6,250 kw.

Loss in the 1,500-volt system was found by taking the difference in the meter readings at substation and at the various receivers, and checked closely by calculation from the line constants and load data. The transformer losses on this system were computed from the load data on the station reports and the tests taken on each size and type of transformer under actual operating conditions.

Copper loss is small compared to core loss because the transformers were lightly loaded; an installation of 6,250 kw. carried an average load of 1,323 kw. The detail losses were:

	Efficiency, 1911	Loss, kw-hr.	Average loss, kw.
15,000-volt lines.....	99.2	93,500	11
15,000-volt transformers.....	93.2	775,100	88
Core loss.....		694,000	79
Copper loss.....		81,100	9
Total for system.....	92.5	868,600	99

2,400-Volt Distributing System. Power is distributed from the substations by means of seventeen 2,400-volt primary feeders. Of these, twelve are fed from the main substation at Seventh Avenue and Yesler Way, three from Fremont substation and two from West Seattle substation. The more heavily loaded

circuits were designed for 200 amperes and the lighter ones for 150 amperes. Number 4/0 wire was used at first, but the economic size for a 200-ampere feeder has been computed at 350,000 cir. mils, which size is now used on the heavier feeders.

An area of 28 square miles (72.5 sq. km.) is served by this system extending seven miles (11.2 km.) south and six miles (9.6 km.) north of Yesler Way. A distributing point is established at the approximate center of distribution for each feeder, and the automatic regulators in this station are set to give the desired voltage at this point.

Connected to the 2,400-volt feeders are 1,082 distributing transformers, ranging in size from $2\frac{1}{2}$ kw. to 50 kw., and with an aggregate full-load capacity of $9,268\frac{1}{2}$ kw. They are connected to give a 240-120-volt three-wire low-tension winding, with the neutral grounded. To aid regulation, a number of transformers of the same size and type are usually connected together on the low tension side where conditions will permit. The secondary wire is generally No. 4 for the outside wires and No. 6 for the neutral, with No. 8 for the services. The maximum voltage drop from transformer to customer is kept within 2 volt whenever possible, since there is no way of regulating for voltage between these points. The pressure at the service is kept as near 120 volts as possible. Although standard 2,200-110-volt transformers are used, the pressure has been raised to 2,400 volts, and it is planned to raise it still further to 2,500 volts. This gives about 25 per cent higher core loss, but lowers the copper loss in both transformers and feeders about 29 per cent, and in addition gives nearly 14 per cent better regulation. The 2,400-volt system used 545.4 miles (877.7 km.) of high-tension wire, ranging in size from No. 6 to 350,000 cir. mils, and 1,137.7 miles (1,830.9 km.) of low-tension wire, varying from No. 6 to No. 4/0.

Losses in the feeder regulators were computed from tests made on each type used, in conjunction with load data from the station reports. Losses in distributing transformers were computed in the same way, using also recording ammeter charts taken at distributing points. Losses in the high-tension line were computed from the load data and line resistances of each feeder, and checked by recording voltmeter charts taken at the station and at each distributing point. Loss in low-tension line was estimated from line resistances and load data, and checked by recording voltmeter at the customers' services. Loss in the customers' meters was computed from tests on each type of meter in use.

A check on the various distributing losses is furnished by the difference in the power metered to the customer and that delivered to the distributing system. This amount proved to be slightly greater than the sum of the losses as computed, and the difference was added to the loss in low-tension system, since that loss was most difficult to determine with accuracy. There is also probably a small amount of stolen current included in the low-tension loss. The details of losses on the 2,400-volt commercial system follow:

	Efficiency, 19	Loss, kw-hr.	Average loss, kw.
Feeder regulators.....	98.6	178,500	20
Primary feeders.....	96.0	521,600	60
Distributing transformers.....	88.8	1,391,000	159
Core loss.....		960,000	110
Copper loss.....		431,000	49
Secondaries.....	92.9	782,600	89
Customers' meters.....	97.6	250,000	29
Total for system.....	76.2	3,123,700	357

Cluster Light System. The cluster light system comprises 1,631 poles, lighting 25 miles (40.2 km.) of street and carrying 6,851 lamps of a total of 335,700 watts. This system is supplied from 720 kw. in transformers using 23 miles (37 km.) of primary wire carrying 2,400 volts and 98.4 miles (158.3 km.) of secondary wire in a 240- and 120-volt three-wire system. The voltage is changed from 120 volts to 8 volts in the base of the pole and 8-volt multiple lamps are used. Losses on this system were computed in a similar manner to those on the other distributing systems. They lack the check of integrating meters at the lamp, but were easier to compute on account of the constancy of the load. The transformer losses contain those from the pole-base transformers, which are 250-watt, 8-volt transformers.

	Efficiency, 1911	Loss, kw-hr.	Average loss, kw.
Cluster light primaries.....	97.0	42,500	5
Cluster light secondaries.....	93.0	86,500	10
Cluster light transformers.....	87.8	181,000	21
Core loss.....		117,500	13
Copper loss.....		63,500	7
Total for system.....	79.1	310,000	35

Series Street Lighting System. The series street light system comprises 683 miles (1,099 km.) of No. 6 wire divided into 29 circuits, lighting 601 miles (967.2 km.) of street. The circuits are connected two in series to 100-light air-cooled constant-

FIG. 7

current transformers. The voltage on the circuits varies with the number and kind of lamps from 2,500 volts to 5,000 volts. Altogether there are 692 6.6-ampere arc lamps, 5,315 40-candle-power tungsten lamps, and 199,300-candle-power tungsten lamps.

OUTLINE OF LOSSES AND EFFICIENCIES FOR 1911, SEATTLE MUNICIPAL LIGHT AND POWER PLANT.

	Per cent all-day efficiency	Total 1911 input, kw-hr.	Average 1911 input, kw.	Total 1911 loss, kw-hr.	Average 1911 loss, kw.	Per cent loss	Per cent of penstock input	Per cent of total loss
GENERATING SYSTEM.	54.4	52,639,000	6009	23,990,300	2739	45.6	45.6	75.3
Penstocks.....	97.7	52,639,000	6009	1,214,900	139	2.3	2.3	3.8
Generating station.....	55.7	51,424,100	5870	22,775,400	2600	44.3	43.2	71.5
Water wheels.....	60.7	50,758,900	5795	19,944,400	2277	39.3	37.9	62.6
Generators.....	93.5	30,814,500	3518	1,990,800	227	6.5	3.8	6.2
Excitors.....	.....	665,200	76	665,200	76	.....	1.3	2.1
Station lights and control.....	.....	175,000	20	175,000	20	.....	0.3	0.5
TRANSMISSION SYSTEM.	91.6	28,648,700	3270	2,413,500	276	8.4	4.6	7.6
Step up transformers.....	96.1	28,648,700	3270	1,126,000	129	3.9	2.1	3.5
Transmission lines.....	98.6	27,522,700	3141	378,000	43	1.4	0.7	1.2
Step-down transformers.....	96.6	27,144,700	3098	909,500	104	3.4	1.7	2.9
DISTRIBUTING SYSTEM.	79.2	26,235,200	2994	5,448,700	622	20.8	10.3	17.1
City substations.....	98.7	26,235,200	2994	346,400	40	1.3	0.7	1.1
S. Lights and control.....	.....	317,400	37	317,400	37	1.2	0.6	1.0
Switchboard meters......	.....	.....	.....	29,000	3	.....	0.1	0.1
15,000-volt system.....	92.5	11,587,000	1323	868,600	99	7.5	1.6	2.7
15,000-volt lines.....	99.2	11,587,000	1323	93,500	11	0.8	0.2	0.3
15,000-volt transformers.....	93.2	11,493,500	1312	775,100	88	6.8	1.5	2.4
Series street lights.....	86.3	2,672,800	305	367,200	42	13.7	0.7	1.2
Transformers.....	95.0	2,672,800	305	133,700	15	5.0	0.3	0.4
Series circuits.....	90.8	2,539,100	290	233,500	27	9.2	0.4	0.7
Cluster street lights.....	79.1	1,486,000	170	310,000	35	20.9	0.6	1.0
Cluster transformers.....	87.8	1,486,000	170	181,000	21	12.2	0.3	0.6
Underground cables.....	90.1	1,305,000	149	129,000	15	9.9	0.2	0.4
2400-volt commercial system.....	76.2	13,178,400	1612	3,123,700	357	23.8	5.9	9.8
Feeder regulators.....	98.6	12,999,900	1592	178,500	20	1.4	0.3	0.6
Primary feeders.....	96.0	12,999,900	1592	521,600	60	4.0	1.0	1.6
Transformers.....	88.8	12,478,300	1332	1,391,000	159	11.2	2.6	4.4
Secondaries.....	92.9	11,087,300	1373	782,600	89	7.1	1.5	2.5
Customers' meters.....	97.6	10,304,700	1284	250,000	29	2.4	0.5	0.8
Direct-current system.....	35.7	673,200	77	432,800	49	64.2	0.8	1.4
Motor-generator.....	38.0	673,200	77	417,000	48	62.0	0.8	1.3
D-C. circuits.....	95.0	256,200	29	47,800	5	5.0	.....	.....
Customers' meters.....	98.8	243,400	28	12,800	1	1.2	.....	.....
SUMMARY:								
Total power loss.....				31,852,500 kw-hr.		Average 3,636 kw.		
Total power delivered to customers.....				17,304,900 "		" 1,975 "		
Total power delivered to street lamps.....				3,481,600 "		" 398 "		
Total delivered power.....				20,786,500 "		" 2,373 "		
Over-all efficiency, 39.5 per cent.....								

[1 kw-hr. at the customers' premises requires 1,364 gallons (5,163 liters) of water from Cedar Lake at average head of 590 feet (179.8m.).]

Losses were computed in a similar manner to those on the cluster light system, and were as follows:

	Efficiency, 1911	Loss, kw-hr.	Average loss, kw.
Series lines.....	90.8	233,500	27
Constant current transformers.....	95.0	133,700	15
Core loss.....	....	63,900	7
Copper loss.....	....	69,800	8
Total for system.....	86.3	367,200	42

The table on the preceding page, shows the losses and efficiencies for each part of the system, and the accompanying diagram shows each loss expressed in per cent of penstock input.

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