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THE OPTIMUM TURBINE EXHAUST PRESSURE FOR USE OF A SINGLE-EFFECT, VERTICAL-TUBE STILL DESALTING PLANT WITH A STEAM TURBINE-GENERATOR

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F. G. Welfare

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NUCLEAR DESALINATION PROGRAM

R. P. Hammond, Director

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
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CONTENTS

LIST OF FIGURES

LIST OF TABLES

THE OPTIMUM TURBINE EXHAUST PRESSURE FOR USE OF A SINGLE-EFFECT, VERTICAL-TUBE STILL DESALTING PLANT WITH A STEAM TURBINE-GENERATOR

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ABSTRACT

The optimum turbine exhaust pressure for a dual-purpose (power and water) plant employing a single-effect vertical-tube evaporator was calculated for a variety of economic conditions. The results show a possible saving due to the optimization of up to 2.5 millions of dollars or about 3.8 cents per thousand gallons of product water.

Keywords: AEC sponsored + nuclear desalination + dual-purpose plant + vertical-tube evaporator + economic evaluations + turbine-generators

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INTRODUCTION

A dual-purpose, electrical-power desalting plant consisting of a single-effect, vertical-tube still and a turbine-generator set with an output of about 1000 Mw(e) has been proposed by Jones and Anderson.[1] The desalting plant would have a capacity of about 20 million gallons per day. A process flow sheet for the vertical-tube still is shown in Fig. 1. As can be seen from Fig. 1, the vertical-tube still receives steam from the turbine exhaust and condenses this steam by evaporating brine. The condensate is returned to the turbine system and the vapor is condensed to form product water in a final condenser. The final condenser is cooled by seawater which, except for a small portion used for makeup, is returned to the sea. The brine blowdown is also returned to the sea with a concentration ratio of 2.

In the initial study[1] of the vertical-tube still concept, a turbine exhaust pressure of 2.5 inches of mercury was selected as a reasonable value but no studies were made of the economic significance of exhaust pressure. The possibility that the turbine exhaust pressure is of economic importance may be seen from the following: as one selects successively higher design values for exhaust pressure, the electrical

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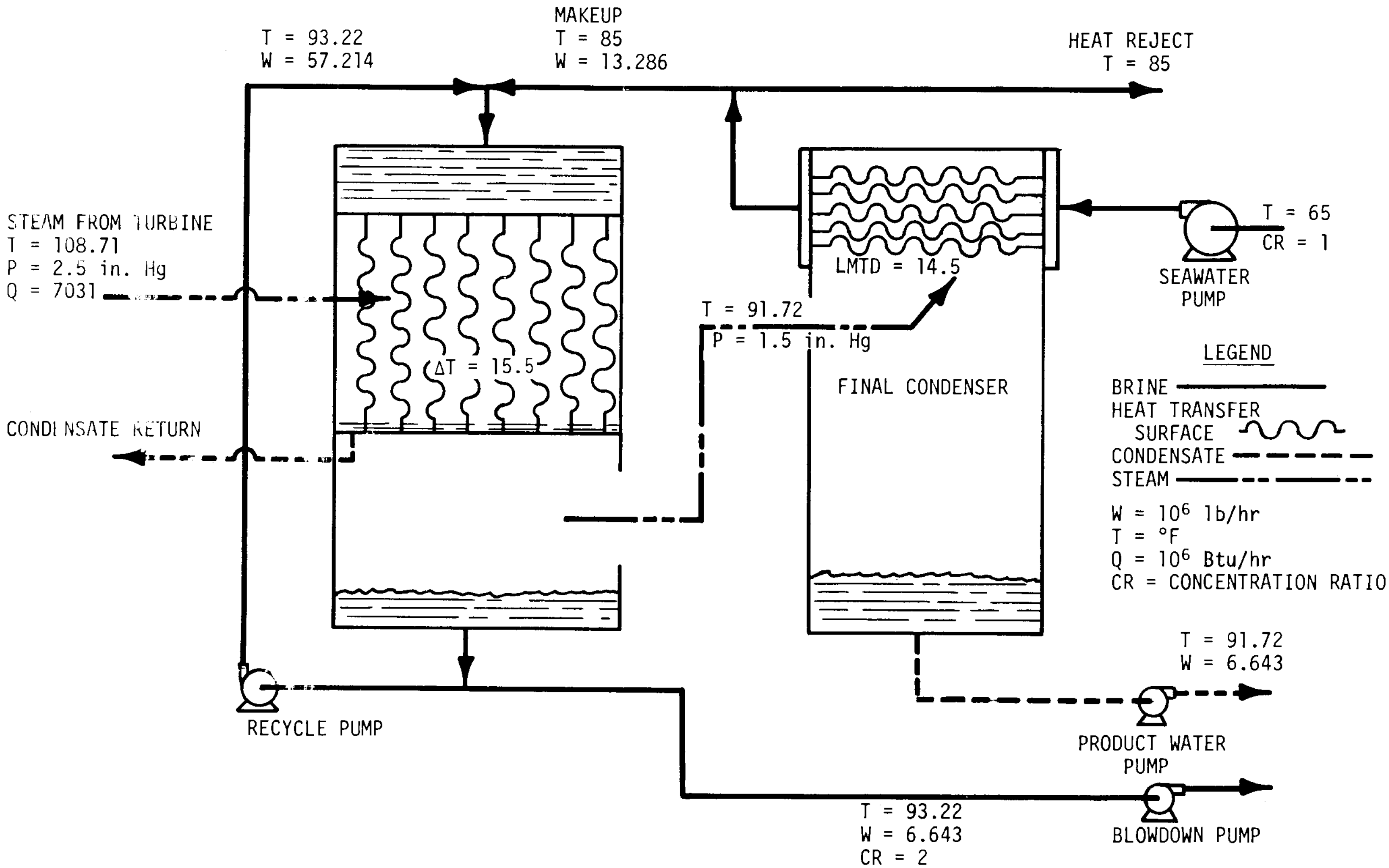

Fig. 1. Vertical Tube Still Process Flow Sheet

output of the turbine-generator is reduced but the size of the evaporator is also reduced (for a given water output) and this results in a lower capital cost for the evaporator. There is, therefore, the possibility of trading off electrical capability against water plant cost. The implication is that there is an optimum exhaust pressure for a given set of economic conditions. The purpose of the present study was to examine the parametric effects involved in such optimizations and to determine the economic importance of selecting an optimum exhaust pressure.

Salisbury[2,3,4] has previously considered the question of optimum exhaust pressure for this system and portions of his results are included for purposes of comparison.

SUMMARY AND CONCLUSIONS

The economic parameters of greatest importance in determining the optimum exhaust pressure were found to be (1) the value of a kilowatt of capacity and (2) the cost of the evaporator per unit of heat transfer area. The optimum exhaust pressure was determined over a broad range of the above parameters for four different commercial steam turbines. The economic optimization results in possible savings (capital cost saving minus penalty for loss of capacity) of up to 2.5 million dollars for extreme values of the economic parameters. This corresponds to a reduction in water cost of about 3.8 ¢/kgal.*

It is concluded that such potential savings justify a careful economic optimization of dual-purpose plants employing the single-effect vertical-tube still.

OPTIMIZATION RELATIONSHIPS

If we assume a constant output for the desalting plant and a constant thermal output for the reactor, then the problem is to select the turbine exhaust pressure for which an economic optimum occurs. As the turbine exhaust pressure is varied, the plant electrical capacity and the capital cost of the evaporator vary in such a way as to have opposing economic effects. For example, an increase in exhaust pressure reduces the

*This result was derived assuming a 10% annual charge rate and a plant factor of 0.9.

electrical capacity of the plant causing a reduction in income from energy sold, but it also reduces the required size of the evaporator resulting in a lower capital cost. The economic effect of these changes can be expressed quantitatively and a decision made as to whether or not the change results in improved economics. In their work, Jones and Anderson assumed as exhaust pressure of 2.5 inches of mercury. In the present work, 2.5 inches of mercury has been assumed as a reference and costs have been calculated relative to the cost for that pressure.

Define the following quantities:

Y = cost or benefit of a given change in evaporator pressure (or temperature) from the reference 2.5 inches of mercury

S = cost of the evaporator expressed in terms of $\$/ft^2$ of heat transfer surface

D = heat content of the turbine exhaust steam (BTU/hr)

U = heat transfer coefficient ($BTU/hr\text{-}ft^2\text{-}{}^\circ F$)

I = power change per unit temperature change ($kw/{}^\circ F$) = $\frac{dP}{dT}$

V = value of electrical capacity (\$/kw)

P_o = generator capacity at the reference temperature/pressure

$P(T)$ = generator capacity at temperature T

A_o = heat transfer surface required at reference

$A(T)$ = heat transfer surface required at temperature T

T_R = temperature measured from reference temperature of 108.7°F

C = change in turbine cost from reference

If we assume an increase in the exhaust pressure, then the economic effect of the capacity change is $[P(T_R) - P_o]V$ which correctly shows an economic loss. The economic effect of the change in evaporator size is $-[A(T_R) - A_o]S$ which shows an economic advantage. If a reduction in turbine cost takes place, it may be expressed as +C. Assuming that operating and maintenance costs are not effected by the pressure change, the total economic effect of a change in exhaust temperature is given by

$$Y = [P(T_R) - P_o]V - [A(T_R) - A_o]S + C$$

Taking the derivative of this expression with respect to T_R we get

$$\frac{dY}{dT_R} = V \frac{d}{dT_R} P(T_R) - S \frac{d}{dT_R} A(T_R) \ .$$

Substituting,

$$^{*}A(T_R) = \frac{D(T_R)}{U[T_R + 15.49]}$$

we get

$$\frac{dY}{dT} = VI(T_R) - \frac{S\{(T + 15.49)\ D'(T_R) - D(T_R)\}}{U[T_R + 15.49]^2} \ .$$

For Y equal to a maximum $\frac{dY}{dT} = 0$, which gives

$$VI(T_R) - \frac{S\{(T_R + 15.49)\ D'(T_R) - D(T_R)\}}{U[T_R + 15.49]^2} = 0 \ .$$

Rearranging we get

$$[T_R + 15.49]^2 = + \frac{S\{(T + 15.49)\ D'(T_R) - D(T_R)\}}{UVI(T_R)}$$

or

$$^{**}T_R = \left[\frac{+SD'(T_R)[T_R + 15.49]}{UVI(T_R)} - \frac{SD(T_R)}{UVI(T_R)} \right]^{\frac{1}{2}} - 15.49 \ .$$

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*The reference situation has a temperature difference of $15.49°$F in the evaporator. For any T_R the evaporator temperature difference is therefore $T_R + 15.49$.

**If we assume that D is not a function of T then D' = 0 and we get the relationship

$$T_R = \left[\frac{SD}{UVI(T_R)} \right]^{\frac{1}{2}} - 15.49$$

which was used by Salisbury. The term $\frac{SD'[T_R + 15.49]}{UVI(T_R)}$ makes a difference of only a few tenths of a degree in the optimum temperatures obtained. The most important effect of this term is that it greatly reduces the number of iterations required for convergence in the Newton's Method solution.

This equation can be solved by iterative techniques, such as Newton's Method, for the optimum evaporator temperature. The quantities S and V representing the cost of the evaporator expressed in terms of dollars per square foot of heat transfer surface and the value of a kilowatt of capacity will be treated as parameters since they are not known exactly. The quantities $D(T_R)$ and $I(T_R)$ represent characteristics of the turbine-generator systems which must be calculated using appropriate techniques.

TURBINE-GENERATOR CHARACTERISTICS

Two closely related characteristics of the turbine-generator set must be known in order to find the optimum evaporator pressure. These characteristics are: (1) the derivative of the electrical output of the generator as a function of turbine exhaust temperature [$I(T_R)$], and (2) the heat content of the turbine exhaust as a function of turbine exhaust temperature [$D(T_R)$]. The program ORCENT[5] was used in this calculation. The techniques programmed into ORCENT were described in publications[6] by the General Electric Company. The optimization of exhaust pressure is extremely sensitive to the values obtained for loss per degree of temperature change. All of the turbine calculations done at ORNL were done using the techniques described in Reference 6. These techniques do not exactly describe some of the heat balances used in this work. In calculations of Westinghouse turbines, appropriate exhaust loss data were substituted for those built into the ORCENT code. In general, ORCENT seems to quite accurately describe the effect of changes in turbine exhaust pressure; however, it tends to overestimate turbine output compared with manufacturers heat balance data. The optimization of evaporator pressure is a function of the first of these quantities, so that the ORCENT results seem to be adequate for this work. Some small modifications in ORCENT would make it more directly applicable.

RESULTS OF OPTIMIZATION CALCULATIONS

Four different systems were analyzed for the optimum exhaust pressure. The systems (designated by the manufacturer and the last stage blade length) were (1) a 43-inch GE turbine, (2) a 38-inch GE turbine, (3) a 44-inch Westinghouse turbine and (4) a 40-inch Westinghouse turbine. Each company's turbines were analyzed and compared separately. In each case, the larger turbine operating at an exhaust pressure of 2.5 inches of mercury was assumed to be the reference situation. The optimum exhaust pressure was then found and economic comparisons were made between each condition and the reference situation. In the case of the smaller turbines, this comparison included the reduction in capital cost of the turbine and the reduced output of the turbine. In all cases, of course, the reduction in output resulting from a change in back pressure was considered.

Table 1 shows the results of the optimum pressure calculations for a General Electric 43-inch turbine. In addition, Table 1 shows the results obtained by Salisbury in Reference 2. The optimum values obtained for the pressure can be seen to be virtually identical with those obtained at ORNL.

In Table 2, some of the economic results of the optimization are summarized. This table shows the saving resulting from operation of the turbine at the optimum instead of the reference (2.5 in. Hg) back pressure. The results shown are the algebraic sum of the effect of capacity changes and the effect of changes in the required heat transfer surface. The agreement between the results calculated by Salisbury and those calculated at ORNL is not as good for the economic effects as was the case for the calculation of optimum pressure. The calculation of the saving is extremely sensitive to the accuracy obtained in the calculation of turbine output. Small differences in the model assumed will generate economic differences of the order of those observed.

The second calculation performed considered replacement of the 43-inch General Electric turbine with a 38-inch General Electric turbine. The capital cost saving in going to the smaller turbine was assumed to be $1,850,000. The reference situation was still considered to be the 43-inch turbine operated at an exhaust pressure of 2.5 inches of mercury. Tables 3 and 4 summarize the results obtained. The negative entries in Table 4 are of particular interest. These negative entries show that for low values of evaporator cost and/or high values of the worth of a kilowatt the use of the small turbine results in a net cost rather than a saving. On the other hand, if the evaporator is expensive and the value of a kilowatt is low then the use of the smaller turbine becomes economical.

TABLE 1

OPTIMUM EXHAUST PRESSURE* FOR THE OPERATION OF A 43-INCH GENERAL ELECTRIC TURBINE WITH A SINGLE EFFECT VTS

Value of Capacity	$100/kw		$150/kw		$200/kw		$250/kw	
SOURCE	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL
Cost of Heat Transfer Surface $/ft^2								
4	2.50	2.51	2.37	2.38	2.29	2.29	2.23	2.23
6	2.66	2.67	2.50	2.51	2.41	2.41	2.34	2.34
8	2.79	2.81	2.61	2.62	2.50	2.51	2.43	2.43
10	2.91	2.92	2.71	2.72	2.59	2.60	2.50	2.51
12	3.02	3.03	2.79	2.81	2.66	2.67	2.57	2.58
14	3.11	3.13	2.87	2.89	2.73	2.74	2.63	2.64

*Pressures are in inches of mercury absolute.

TABLE 2

SAVING* RESULTING FROM OPTIMUM+ USE OF THE 43-INCH GENERAL ELECTRIC TURBINE

Value of Capacity	$100/kw		$150/kw		$200/kw		$250/kw	
SOURCE	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL
Cost of Heat Transfer Surface $/ft^2								
4**			.0499	.0705	.2135	.2387	.4366	.4658
6	.0587	.0768			.0214	.0497	.1441	.1775
8	.2436	.2646	.0285	.0542			.0019	.0380
10	.5030	.5272	.1656	.1941	.0085	.0418		
12	.8176	.8452	.3654	.3969	.1175	.1535		.0339
14	1.176	1.207	.6144	.6492	.2804	.3193	.0834	.1270

*In millions of dollars.

**In several cases, the calculated optimum pressure was too near the reference pressure for the calculation of saving to have significance. The blank positions in the table correspond to those cases.

+The reference is the 43-inch turbine operated at 2.5 inches of mercury exhaust pressure.

TABLE 3

OPTIMUM EXHAUST PRESSURE* FOR THE OPERATION OF A 38-INCH GENERAL ELECTRIC TURBINE WITH A SINGLE-EFFECT VTS

Value of Capacity	$100/kw		$150/kw		$200/kw		$250/kw	
SOURCE	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL
Cost of Heat Transfer Surface $/ft^2								
4	2.66	2.70	2.52	2.55	2.43	2.46	2.37	2.39
6	2.83	2.88	2.66	2.70	2.55	2.59	2.48	2.52
8	2.98	3.01	2.78	2.82	2.66	2.70	2.58	2.62
10	3.11	3.14	2.88	2.93	2.75	2.80	2.66	2.70
12	3.22	3.25	2.98	3.02	2.83	2.88	2.73	2.78
14	3.33	3.35	3.07	3.10	2.91	2.95	2.80	2.84

*Pressures are in inches of mercury absolute.

TABLE 4

SAVING* RESULTING FROM OPTIMUM** USE OF THE 38-INCH GENERAL ELECTRIC TURBINE

Value of Capacity	$100/kw		$150/kw		$200/kw		$250/kw	
SOURCE	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL
Cost of Heat Transfer Surface $/ft^2								
4	.9272	.8713	.3887	.2763	-.0759	-.2444	-.4979	-.7205
6	1.123	1.091	.4658	.3819	-.0886	-.2288	-.5834	-.7803
8	1.410	1.397	.6432	.5845	.0044	-.1074	-.5590	-.7269
10	1.761	1.761	.8905	.8529	.1718	.0857	-.4570	-.5968
12	2.159	2.168	1.191	1.170	.3958	.3324	-.2958	-.4095
14	2.593	2.609	1.532	1.526	.6648	.6209	-.0871	-.1772

*In millions of dollars.

**Reference is 43-inch General Electric turbine operated at 2.5 inches of mercury exhaust pressure.

The next systems analyzed consisted of the single-effect vertical-tube still operated with Westinghouse turbines. With one exception, the procedure used was identical to that used in the calculations with General Electric turbines. This exception consisted of replacing the exhaust loss calculation in the ORCENT code with a calculation suitable for the Westinghouse turbines. Exhaust losses (per pound of dry steam) as a function of exhaust velocity were derived from information included in Reference 4.* Fifth order polynomials were then fitted to these data and the calculation of exhaust loss in ORCENT was then replaced by these polynomials. As before, the reference situation was taken to be the larger turbine operated at an exhaust pressure of 2.5 inches of mercury. The results of these calculations are shown (and compared with Salisbury's information) in Tables 5, 6, 7 and 8.

Several results are immediately apparent. In Table 8, we can see that the range over which the use of the small turbine is uneconomical extends to lower values of a kilowatt than was the case in the earlier results. The change from the large to the small turbine is less economical for the Westinghouse unit than for the GE because of the larger loss per degree of temperature change in the case of the Westinghouse unit.

As expected, increasing the value of a kilowatt of capacity causes the optimum pressure to decrease. That is, as the value of a unit of capacity goes up the system tends toward reduced pressure where the capacity is larger. The companion result can be seen in the case of evaporator cost. As the cost of the evaporator goes up, the optimum pressure goes up because higher evaporator pressures reduce the required size of the evaporator.

Examination of the optimization relationship shows that the quantities V and S, corresponding to the value of a kilowatt and the cost of the evaporator expressed in terms of dollars per square foot of heat transfer area occur only in ratio. This raises the possibility of a correlation of optimum pressure with the ratio of V over S. Figure 2 presents the

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*The data thus obtained are tabulated in Appendix V.

TABLE 5

OPTIMUM EVAPORATOR PRESSURE SINGLE-EFFECT VTS OPERATED WITH 44-INCH WESTINGHOUSE TURBINE
(Pressures in In. Hg)

Value of Capacity	$100/kw		$150/kw		$200/kw		$250/kw	
SOURCE	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL
Cost of Heat Transfer Surface $/ft^2$								
4	2.42	2.40	2.29	2.26	2.22	2.18	2.17	2.13
6	2.58	2.57	2.42	2.40	2.33	2.30	2.27	2.24
8	2.72	2.71	2.53	2.52	2.42	2.40	2.35	2.32
10	2.86	2.84	2.63	2.62	2.50	2.49	2.42	2.40
12	2.98	2.96	2.72	2.71	2.58	2.57	2.49	2.47
14	3.11	3.08	2.81	2.80	2.65	2.64	2.55	2.54

TABLE 6

SAVING* RESULTING FROM OPTIMUM** USE OF THE 44-INCH WESTINGHOUSE TURBINE

Value of Capacity	$100/kw		$150/kw		$200/kw		$250/kw	
SOURCE	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL
Cost of Heat Transfer Surface $/ft^2								
4	.0266	.0343	.2297	.2740	.5468	.6465	.9310	1.099
6	.0185	.0133	.0400	.0515	.2185	.2631	.4888	.5803
8	.1516	.1416	.0038	.0002	.0533	.0687	.2181	.2647
10	.3824	.3705	.0748	.0638	.0019	.0009	.0667	.0859
12	.6900	.6737	.2274	.2124	.0370	.0266	.0058	.0078
14	1.056	1.035	.4454	.4273	.1414	.1252	.0173	.0083

*In millions of dollars.

**Reference is the 44-inch Westinghouse turbine operated at 2.5 inches of mercury.

TABLE 7

OPTIMUM EVAPORATOR PRESSURE SINGLE-EFFECT VTS AND 40-INCH WESTINGHOUSE TURBINE
(Pressures in In. Hg)

Value of Capacity	$100/kw		$150/kw		$200/kw		$250/kw	
SOURCE	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL	Salisbury	ORNL
Cost of Heat Transfer Surface $\$/ft^2$								
4	2.72	2.67	2.57	2.50	2.48	2.41	2.42	2.34
6	2.92	2.90	2.72	2.67	2.61	2.54	2.53	2.46
8	3.09	3.11	2.86	2.82	2.72	2.18	2.63	2.57
10	3.24	3.27	2.98	2.97	2.83	2.79	2.72	2.67
12	3.38	3.40	3.09	3.11	2.92	2.90	2.81	2.76
14	3.51	3.51	3.20	3.22	3.01	3.00	2.88	2.85

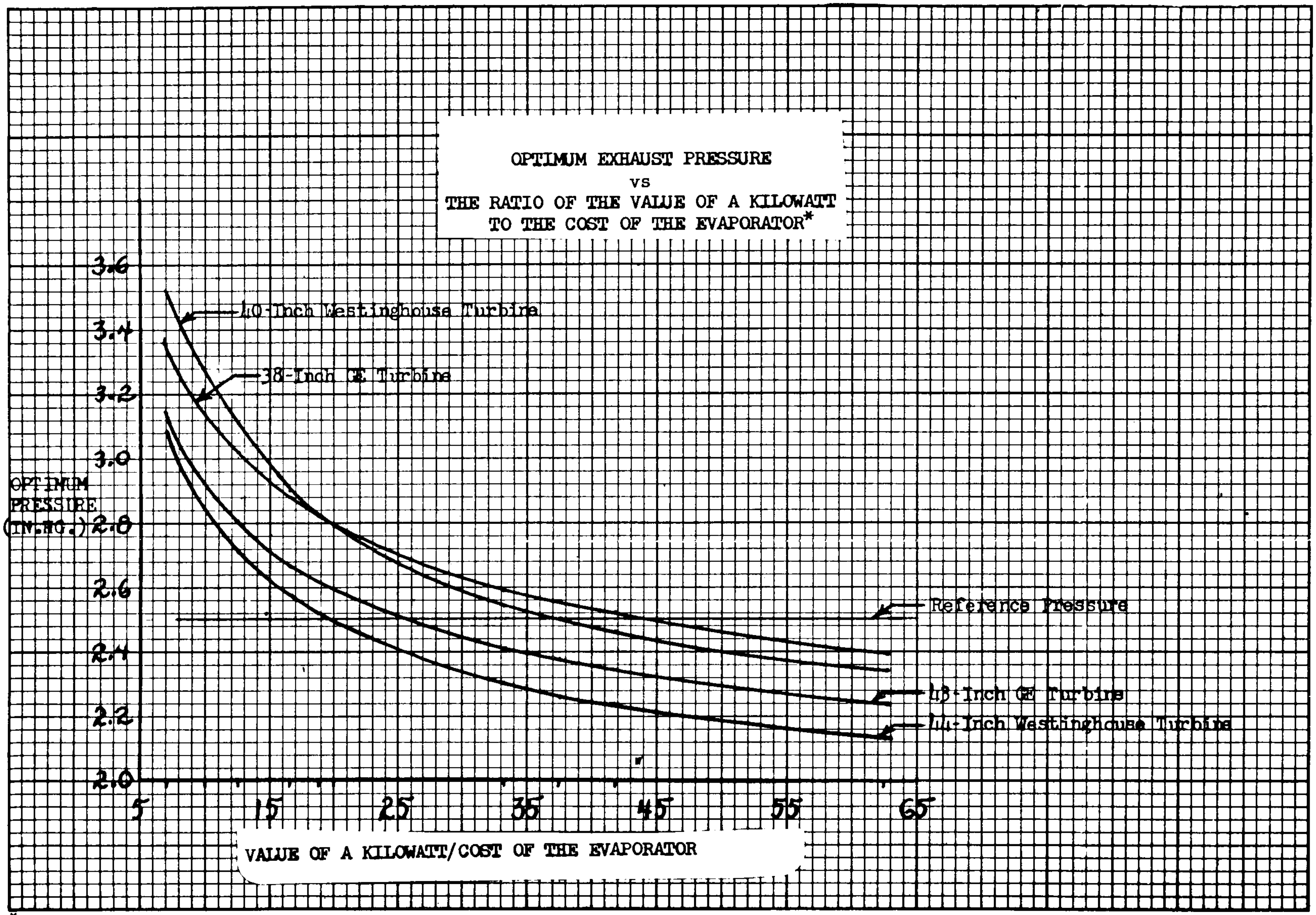
TABLE 8

SAVING* RESULTING FROM OPTIMUM** USE OF THE 40-INCH WESTINGHOUSE TURBINE

Value of Capacity	$100/kw		$150/kw		$200/kw		$250/kw	
SOURCE	Salisbury	ORNL	Salisbury	Welfare	Salisbury	Welfare	Salisbury	Welfare
Cost of Heat Transfer Surface $\$/ft^2$								
4	.1831	.2381	-.7803	-.6385	-1.668	-1.422	-2.512	-2.154
6	.4367	.4639	-.6513	-.5688	-1.631	-1.466	-2.549	-2.287
8	.7883	.8139	-.4172	-.3679	-1.486	-1.376	-2.475	-2.284
10	1.207	1.244	-.1086	-.0721	-1.262	-1.188	-2.320	-2.183
12	1.676	1.726	.2564	.2948	- .9785	- .9242	-2.103	-2.003
14	2.185	2.242	.6661	.7147	- .6468	- .5990	-1.836	-1.760

*In millions of dollars.

**Reference is the 44-inch Westinghouse turbine operated at 2.5 in. hg.



*The value of a kilowatt is expressed in dollars and the cost of the evaporator is expressed in dollars per square foot of heat transfer area.

Fig. 2

optimum pressure data in this way. Figure 2 indicates that the optimum pressure is independent of the particular combination of values by which a given V/S ratio was obtained. The economic parameters V and S do not have to be considered independently if the optimum pressure is in question. These parameters must be considered independently, however, if the cost or saving due to operation at the optimum pressure is being considered.

For reference purposes complete results of the optimization calculations are shown in Appendices I through IV.

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APPENDIX I

COMPLETE CALCULATED RESULTS FOR THE SINGLE-EFFECT VTS OPERATED WITH THE 43-INCH GENERAL ELECTRIC TURBINE

Cost of Surface ($/ft^2)	Optimum Pressure (In. Hg)	Evaporator Temp. (°F)	Evaporator Temp. Diff. (°F)	Total Surface (ft^2 x 10^5)	Capacity Change (kw)	Value of Capacity Change ($ x 10^6)	Change In Surface Cost ($ x 10^6)	Total Saving Due to Change ($ x 10^6)
				Value of a kilowatt = $100.				
4	2.51	108.78	15.57	5.8351	- 114.7	- .01147	+ .01100	- .0004
6	2.67	110.92	17.71	5.1361	- 3591.	- .35914	+ .43590	+ .07675
8	2.81	112.64	19.43	4.6902	- 6733.	- .67337	+ .93799	+ .26462
10	2.92	114.09	20.88	4.3705	- 9649.	- .96495	+1.49218	+ .52723
12	3.03	115.36	22.15	4.1250	-12400.	-1.23997	+2.08521	+ .84524
14	3.13	116.50	23.29	3.9280	-15017.	-1.5018	+2.7085	+1.2067
				Value of a kilowatt = $150.				
4	2.38	106.89	13.68	6.6313	2519.8	.377963	- .30746	+ .07051
6	2.51	108.77	15.56	5.8373	- 106.1	- .015916	+ .01523	- .00069
8	2.62	110.27	17.06	5.3303	- 2478.2	- .37173	+ .42589	+ .05416
10	2.72	111.54	18.33	4.9675	- 4674.	- .70110	+ .89515	+ .19405
12	2.81	112.64	19.43	4.6895	- 6739.0	-1.0109	+1.40777	+ .39692
14	2.89	113.63	20.42	4.4665	- 8702.6	-1.3054	+1.9546	+ .64917
				Value of a kilowatt = $200.				
4	2.29	105.68	12.47	7.2676	+ 4003.4	+ .80068	- .56199	+ .23869
6	2.41	107.41	14.20	6.3923	+ 1837.3	+ .36745	- .31777	+ .04968
8	2.51	108.77	15.56	5.8369	- 107.6	- .02151	+ .02059	- .00092
10	2.60	109.92	16.71	5.4395	- 1907.	- .38140	+ .42317	+ .04177
12	2.67	110.93	17.72	5.1352	- 3597.3	- .71946	+ .87295	+ .15349
14	2.74	111.83	18.62	4.8913	- 5202.9	-1.0406	+1.3599	+ .31933
				Value of a kilowatt = $250.				
4	2.23	104.83	11.61	7.8019	+ 4965.9	+1.2415	- .77568	+ .46579
6	2.34	106.43	13.22	6.8601	+ 3103.6	+ .77591	- .59846	+ .17745
8	2.43	107.70	14.49	6.2633	+ 1433.9	+ .35849	- .32048	+ .03801
10	2.51	108.77	15.56	5.8364	- 109.53	- .02738	+ .02623	- .00115
12	2.58	109.71	16.50	5.5098	- 1558.2	- .38956	+ .42344	+ .033878
14	2.64	110.54	17.33	5.2481	- 2933.4	- .73336	+ .86037	+ .12702

APPENDIX II

COMPLETE CALCULATED RESULTS FOR THE SINGLE-EFFECT VTS OPERATED WITH THE 38-INCH* GENERAL ELECTRIC TURBINE

Cost of Surface ($/ft²)	Optimum Pressure (In. Hg)	Evaporator Temp. (°F)	Evaporator Temp. Diff. (°F)	Total Surface (ft² x 10⁵)	Capacity Change (kw)	Value of Capacity Change ($ x 10⁶)	Change In Surface Cost ($ x 10⁶)	Total Saving Due to Change ($ x 10⁶)
				Value of a kilowatt = $100.				
4	2.70	111.33	18.12	5.0416	-13072	-1.3072	+ .32849	+ .87128
6	2.88	113.53	20.32	4.5009	-15760.	-1.5760	+ .81715	+1.0912
8	3.01	115.25	22.04	4.1532	-18209.	-1.8209	+1.3677	+1.3968
10	3.14	116.69	23.48	3.9034	-20488.	-2.0488	+1.9594	+1.7606
12	3.25	117.91	24.70	3.7142	-22606.	-2.2606	+2.5784	+2.1678
14	3.35	119.00	25.79	3.5603	-24644.	-2.4644	+3.2236	+2.6091
				Value of a kilowatt = $150.				
4	2.55	109.34	16.13	5.6556	-11044.	-1.6566	+ .08291	+ .27633
6	2.70	111.32	18.11	5.0441	-13062.	-1.9593	+ .49124	+ .38194
8	2.82	112.87	19.66	4.6505	-14902.	-2.2354	+ .96990	+ .58452
10	2.93	114.15	20.94	4.3683	-16611.	-2.4917	+1.4946	+ .85290
12	3.02	115.24	22.03	4.1566	-18182.	-2.7272	+2.0475	+1.1703
14	3.10	116.20	22.99	3.9848	-19688.	-2.9533	+2.6294	+1.5261
				Value of a kilowatt = $200.				
4	2.46	108.09	14.88	6.1295	- 9939.	-1.9877	- .10664	- .24441
6	2.59	109.89	16.68	5.4723	-11566.	-2.3131	+ .23433	- .22881
8	2.70	111.32	18.11	5.0422	-13070.	-2.6140	+ .65653	- .10743
10	2.80	112.53	19.31	4.7318	-14477.	-2.8953	+1.1310	+ .08572
12	2.88	113.52	20.31	4.5021	-15753.	-3.1505	+1.6329	+ .33238
14	2.95	114.41	21.20	4.3158	-16975.	-3.3950	+2.1660	+ .62096
				Value of a kilowatt = $250.				
4	2.39	107.15	13.94	6.5404	- 9197.8	-2.2995	- .27101	- .72047
6	2.52	108.86	15.65	5.8309	-10598.	-2.6495	+ .01919	- .[illegible]8029
8	2.62	110.21	17.00	5.3704	-11884.	-2.9709	+ .39394	- .72696
10	2.70	111.33	18.11	5.0415	-13073.	-3.2681	+ .82134	- .59679
12	2.78	112.28	19.07	4.7909	-14183.	-3.5458	+1.2863	- .40948
14	2.84	113.12	19.91	4.5920	-15226.	-3.8064	+1.7792	- .17724

*Capital cost saving compared to the 43-inch GE turbine is $1,850,000.

APPENDIX III

COMPLETE CALCULATED RESULTS FOR THE SINGLE-EFFECT VTS OPERATED WITH THE 44-INCH WESTINGHOUSE TURBINE

Cost of Surface ($/ft^2)	Optimum Pressure (In. Hg)	Evaporator Temp. (°F)	Evaporator Temp. Diff. (°F)	Total Surface (ft^2 x 10^5)	Capacity Change (kw)	Value of Capacity Change ($ x 10^6)	Change In Surface Cost ($ x 10^6)	Total Saving Due to Change ($ x 10^6)
				Value of a kilowatt = $100.				
4	2.40	107.27	14.06	6.8071	+ 2834.2	+ .28342	- .24906	+ .03436
6	2.57	109.57	16.36	5.8603	- 1812.2	- .18122	+ .19452	+ .01330
8	2.71	111.46	18.25	5.2636	- 5951.1	- .59511	+ .73761	+ .14161
10	2.84	113.10	19.89	4.8378	- 9761.8	- .97618	+1.3466	+ .37046
12	2.96	114.54	21.33	4.5176	-13265.	-1.3265	+2.0002	+ .67366
14	3.08	115.91	22.70	4.2511	-16716.	-1.6716	+2.7067	+1.0351
				Value of a kilowatt = $150.				
4	2.26	105.32	12.11	7.8877	6368.8	+ .95532	- .68129	+ .27404
6	2.40	107.27	14.06	6.8043	2823.0	+ .42345	- .37191	+ .05155
8	2.52	108.86	15.65	6.1214	- 334.7	- .05020	+ .05045	+ .000244
10	2.62	110.21	16.99	5.6448	- 3171.7	- .47576	+ .53963	+ .06387
12	2.71	111.46	18.25	5.2636	- 5950.8	- .89263	+1.1050	+ .21241
14	2.80	112.55	19.34	4.9711	- 8476.4	-1.2715	+1.6988	+ .42733
				Value of a kilowatt = $200.				
4	2.18	104.11	10.90	8.7544	8372.3	+1.6745	-1.0280	+ .64648
6	2.30	105.86	12.65	7.5572	5434.0	+1.0868	- .82366	+ .26314
8	2.40	107.27	14.06	6.8043	2822.9	+ .56458	- .49585	+ .06873
10	2.49	108.46	15.25	6.2792	478.3	+ .09566	- .09471	+ .00095
12	2.57	109.57	16.36	5.8603	- 1812.0	- .36241	+ .38901	+ .02660
14	2.64	110.54	17.33	5.5387	- 3894.6	- .77892	+ .90414	+ .12522
				Value of a kilowatt = $250.				
4	2.13	103.26	10.05	9.4902	9688.9	2.4222	-1.3223	+1.0999
6	2.24	104.86	11.65	8.1949	7146.0	1.7865	-1.2062	+ .58027
8	2.32	106.16	12.95	7.3818	4890.4	1.2226	- .95784	+ .26474
10	2.40	107.25	14.04	6.8150	2865.9	.71646	- .63057	+ .08589
12	2.47	108.26	15.05	6.3639	892.4	.22310	- .21531	+ .07783
14	2.54	109.14	15.93	6.0173	- 902.8	- .22570	+ .23399	+ .08289

APPENDIX IV

COMPLETE CALCULATED RESULTS FOR THE SINGLE-EFFECT VTS OPERATED WITH THE 40-INCH* WESTINGHOUSE TURBINE

Cost of Surface ($/ft²)	Optimum Pressure (In. Hg)	Evaporator Temp. (°F)	Evaporator Temp. Diff. (°F)	Total Surface (ft² x 10⁵)	Capacity Change (kw)	Value of Capacity Change ($ x 10⁶)	Change In Surface Cost ($ x 10⁶)	Total Saving Due to Change ($ x 10⁶)
				Value of a kilowatt = $100.				
4	2.67	110.87	17.66	5.4703	-18996.	-1.8996	+ .28568	+ .23813
6	2.90	113.79	20.58	4.7012	-22781.	-2.2781	+ .88994	+ .46389
8	3.11	116.26	23.05	4.2042	-26223.	-2.6223	+1.5842	+ .81387
10	3.27	118.18	24.97	3.8860	-29064.	-2.9064	+2.2985	+1.2441
12	3.40	119.61	26.40	3.6789	-31328.	-3.1328	+3.0067	+1.7259
14	3.51	120.71	27.50	3.5356	-33184	-3.3184	+3.7085	+2.2421
				Value of a kilowatt = $150.				
4	2.50	108.60	15.39	6.2697	-16376.	-2.4564	- .034089	- .63852
6	2.67	110.87	17.66	5.4703	-18996.	-2.8493	+ .42852	- .56881
8	2.82	112.87	19.66	4.9198	-21544.	-3.2316	+1.0118	- .36786
10	2.97	114.67	21.46	4.5109	-23985.	-3.5977	+1.6736	- .07208
12	3.11	116.27	23.06	4.2032	-26231.	-3.9347	+2.3775	+ .29480
14	3.22	117.60	24.39	3.9767	-28188.	-4.2281	+3.0909	+ .71474
				Value of a kilowatt = $200.				
4	2.41	107.31	14.10	6.8413	-15058.	-3.0116	- .26273	-1.4224
6	2.54	109.22	16.01	6.0281	-17058.	-3.4116	+ .09382	-1.4658
8	2.67	110.88	17.67	5.4687	-19002.	-3.8004	+ .57262	-1.3758
10	2.79	112.39	19.18	5.0414	-20916.	-4.1832	+1.1431	-1.1881
12	2.90	113.80	20.59	4.7008	-22783.	-4.5567	+1.7805	- .92423
14	3.00	115.07	21.86	4.4293	-24541.	-4.9082	+2.4572	- .59900
				Value of a kilowatt = $250.				
4	2.34	106.44	13.23	7.2884	-14259.	-3.5647	- .44157	-2.1542
6	2.46	108.12	14.91	6.4691	-15873.	-3.9683	- .17075	-2.2870
8	2.57	109.57	16.36	5.9019	-17449.	-4.3623	+ .22604	-2.2843
10	2.67	110.88	17.67	5.4686	-19002.	-4.7506	+ .71587	-2.1827
12	2.76	112.10	18.89	5.1189	-20536.	-5.1340	+1.2787	-2.0034
14	2.85	113.25	20.04	4.8283	-22044.	-5.5110	+1.8987	-1.7603

*Capital cost saving compared to the 44-inch Westinghouse turbine is $1,852,000.

APPENDIX V

EXHAUST LOSS DATA FOR THE WESTINGHOUSE TURBINES
(Derived from Reference 4)

Exhaust Velocity (ft/sec)	40" Westinghouse Turbine (Btu/lb of Dry Flow)	Exhaust Velocity (ft/sec)	44" Westinghouse Turbine (Btu/lb of Dry Flow)
1347.2	45.10	1117.02	27.57
1049.1	29.02	869.81	14.95
863.2	19.08	715.73	9.48
736.5	12.91	610.68	7.28
656.4	9.02	544.29	6.43
573.6	6.61	475.57	6.25

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