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COST ESTIMATES FOR SEVEN 200 MW TURBINE PLANTS FOR OPERATION WITH NUCLEAR REACTORS AT VARIOUS STEAM CONDITIONS

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COST ESTIMATES FOR SEVEN 200 MW TURBINE PLANTS FOR OPERATION WITH NUCLEAR REACTORS AT VARIOUS STEAM CONDITIONS

by

J. D. Maloney, Jr.

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SUMMARY AND CONCLUSIONS

Currently, as well as in the past, public utilities have been reaching for the highest temperature attainable at which to operate their steam plants. In considering only the turbine plant associated with power producing reactors, with little or no steam costs, is this highest temperature the most economical or is there some optimum lower temperature? This study is made in an attempt to answer the above question with the aid of a rather careful cost analyses of plants operating at various turbine throttle steam conditions.

At the present time reactor design determines the maximum steam conditions. Experience with aqueous homogeneous reactors sets these conditions at approximately 200 psi saturated. Reactors using liquid metal coolants, however, hold the possibility of producing steam at higher temperatures. In the future reactors may be designed and operated at temperatures approaching or even exceeding those currently used in steam power plants. With low cost steam to the turbine plant, an optimum operating temperature, if any, will be useful in establishing reactor design conditions.

Apparently modern power plants are approaching a minimum total investment cost per kilowatt as designers use higher and higher temperatures. Investment costs as a function of throttle conditions are presented in Figure 1, for the standard Federal Power Commission accounts modified to exclude the fuel handling equipment and the steam generators. The description of these accounts is given in Table II on page 16. Although the total investment curve does not include boiler or fuel handling equipment costs there is no reason to believe that its general shape would be changed if those costs were added. There is no optimum point below the 1000°F temperature. However, the cost of feedwater equipment, piping, etc. (account 312 less boilers and fuel handling equipment) does go through a minimum at approximately 800°F. At high temperatures, alloy steel

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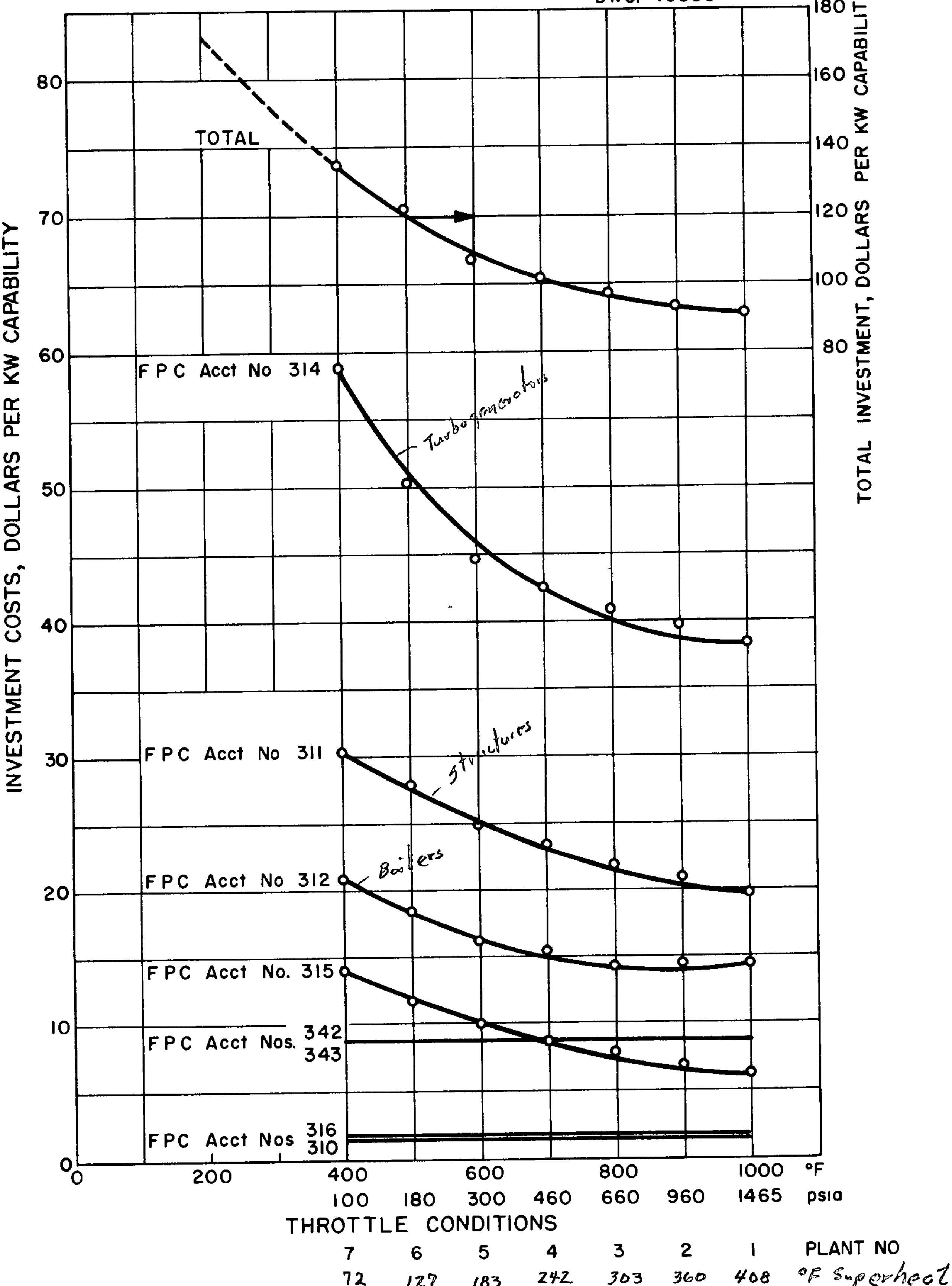

Fig. I. Investment Costs vs. Throttle Conditions (200 MW Steam Turbine Plant)

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piping, high pressure pumps and an increased number of feedwater heaters make this account high. On the other hand at the low temperatures large diameter steam lines and the multiplicity of equipment causes the curve to rise again. The influence of this minimum is not sufficient, however, (approximately 15% of total) to cause the total investment cost curve to go through a minimum. All of the other cost curves are either not a function of temperature or vary inversely with the temperature.

The operating cost of such a turbine plant can be evaluated on the basis of by product heat from a fissionable material producer or on the basis of a reactor primarily in the role of a power producer. In the first case the only cost that would be placed on the steam to the turbine plant would be a function of fixed charges for additional equipment in the reactor plant required to produce steam suitable for turbine operation less any saving in reactor cooling equipment that would otherwise have been necessary. In the second case steam cost would be figured on the total reactor plant investment. For every one-hundred dollars per kw generator capability invested in the reactor plant for power production

$$\text{Steam cost } (\$/10^6 \text{ Btu}) = \left(\frac{t}{100} + 5\right)/60$$

where t is the temperature of the turbine throttle steam.* On the same basis

$$\$100/\text{kw invested} = 2.14 \text{ mil/kwh power cost}$$

regardless of the efficiency of the turbine plant.

With a knowledge of steam cost in any given geographic location the curves in figure II can be used to estimate how much capital can be invested in the reactor plant chargeable to power production such that power can be produced economically. Cost of steam in public utility plants varies considerably over the country. In southwestern United States where natural gas is readily available in large quantities fuel costs are as low as $0.075 per million Btu which makes

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* Based on investment charged off at 15% per year, plant factor of 80% and efficiencies as shown in Table V page 23.

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steam cost about $0.15 per million Btu.* The Johnsonville Steam Plant near the coal fields produces steam for about $0.27 per million Btu.[1] In the northeastern part of the country where fuels are scarce steam costs run as high as $0.50 per million Btu.[2] It can be seen from figure II that a 200 mw plant can be operated on low temperature steam and complete with fuel fired high temperature plants, even down near 200°F in some parts of the country, provided the steam costs are low enough.

If the 2.14 mil/kwh power costs for $100/kw invested in the reactor is added to the curve of zero steam cost, it can be seen from Figure 2 that a reactor built for $100/kw chargeable to power production and generating 400°F steam could only compete with a high temperature commercial plant where steam costs were in excess of $0.40 per million Btu, a figure near the top of the range for ordinary fuels. In 600°F steam, a $100/kw reactor would compete where steam costs were above $0.30/per million Btu and so on. Overall optimum operating temperatures can be determined by combining the results of this study of turbo-generator plant costs with other studies of the temperature dependence of reactor investment and operating costs.

The following report discusses the methods used to obtain the above results and presents some cost and space factors that may be useful in preliminary design and layout of future reactor turbine plants.

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* All steam costs are based on fuel costs, 85% boiler efficiency and fixed charges for the boiler plant at 15% per year. This investment is approximately 1/2 mil/kwh in a plant operating at 1450 psia 1000°F with a plant factor of 80%. This corresponds to about $0.05 per million Btu steam costs.

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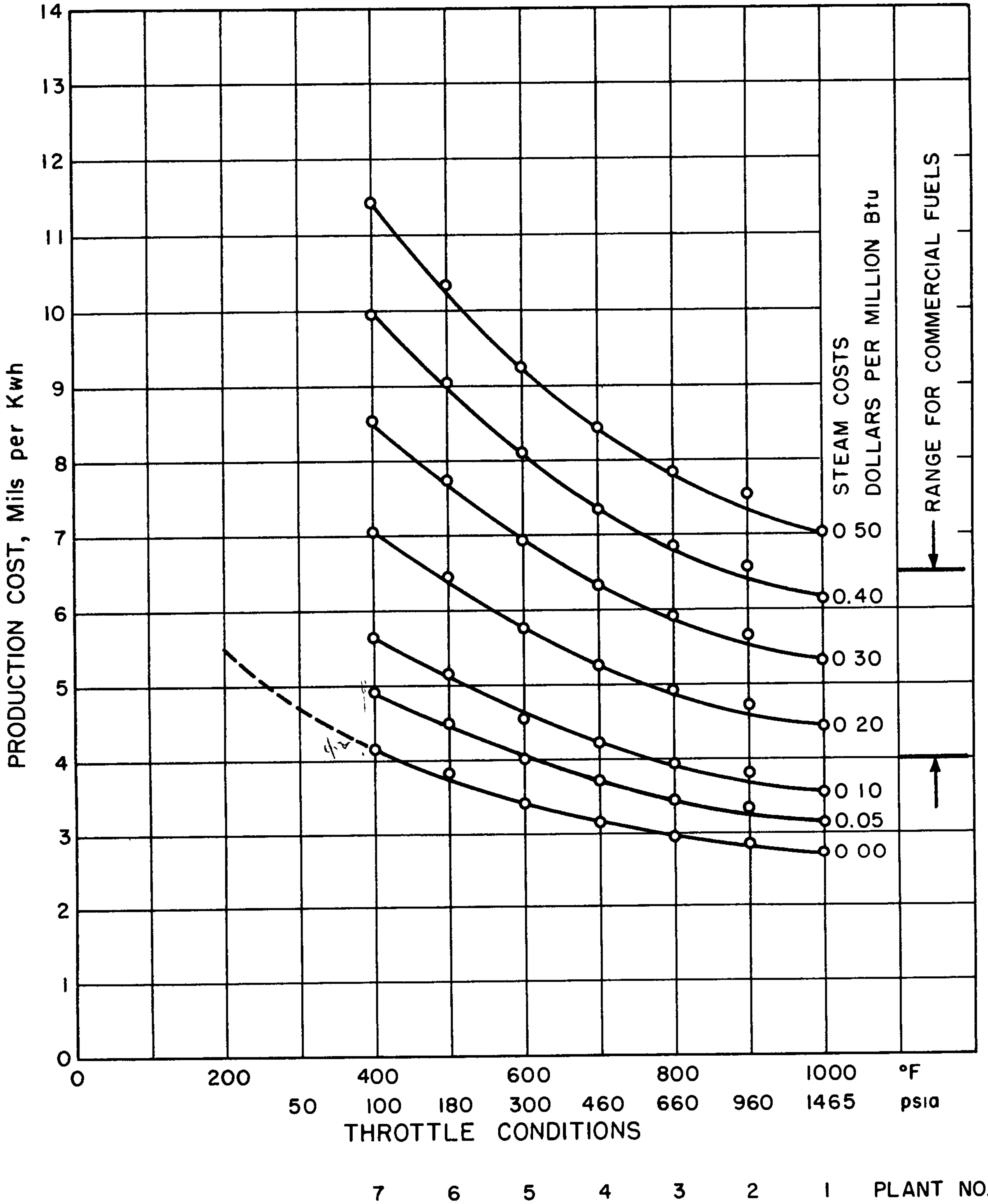

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Fig. 2. Yearly Operating Cost vs. Steam Conditions for Various Steam Costs (80% Plant factor, 200 MW Plants)

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I. INTRODUCTION

It is well known that in steam electric power plants using commercial fuels the optimum operating temperature is the highest temperature attainable. Availability of suitable high strength alloys has been one of the main limitations in increasing steam temperatures beyond the 1100°F ceiling used today. As fuel and other costs have been steadily rising, many public utilities have found it profitable to invest more capital into the physical plant such that over-all thermal efficiency will be increased. Higher initial temperatures, reheat cycle and additional regenerative feed water heating equipment have been a result of this trend.(3)

There has been some question with the advent of nuclear-thermal energy whether or not the optimum operating temperature of a related steam cycle is the maximum temperature attainable if there is little or no steam cost. In order to answer this question adequately, cost of a reactor plant directly chargeable to power production and cost of the turbine plant would have to be known as a function of steam conditions. As the design of power producing reactors is in its infancy, accurate costs of the reactor and its auxiliaries, particularly of large plants operating at high temperatures, are virtually nonexistant. For this reason only the turbine plant costs have been included in this study, with no charge being placed on the steam to the turbine. The results therefore do not reflect any effect of reactor costs whatsoever. When reactor costs are available, they can be combined with this study to determine some overall optimum steam condition.

Other studies have been made on this subject. One report indicates an optimum steam temperature of 600 - 800°F if no fuel costs are considered.(4) This result is based primarily on statistical data with extrapolation in the region of low throttle pressure and temperature where no information is readily

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available on the costs of turbogenerators. Any study attempted involving 50,000 kw and larger machines operating on low-pressure, low-temperature steam will meet with the common problem of obtaining turbogenerator estimating prices. The fact that this piece of equipment makes up nearly 35 percent of the total turbine plant costs makes it warrant careful consideration. In the following study the problem is attacked in a different manner with an attempt made to obtain accurate turbogenerator cost data.

In comparing costs of nuclear power plants operating at various steam conditions, either of two approaches may be taken. A constant reactor power level can be assumed with the steam and electrical systems varied to meet the requirements of the range of steam conditions selected, or a fixed electrical output can be assumed with reactor design power varied with changes in throttle conditions. The cost of the system that is varied is the most difficult to obtain; therefore, the selection between these two methods depends upon what equipment is being considered and the availability of equipment costs. Because reactor costs are not being considered, the second method becomes more desirable in this study.

In the following analysis seven plants with the same net electrical output of 200 mw were established. The power required to operate the auxiliaries was assumed to be $5\frac{1}{2}\%$ of the generated energy for all plants making the gross output of each plant 212 mw.[5] Throttle steam conditions for each plant were selected in the range varying from 1465 psia and 1000°F to 100 psia and 400°F. (See Table V.) From this point two methods present themselves for the solution of the problem. Individual plants could be designed for the various throttle conditions to meet the above output, or a "basic" plant could be established operating at high pressures and temperatures and modified as a unit to be used in evaluating cost of the plants operating at the lower throttle conditions.

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The first method would yield a more accurate result if the design of each plant were carried to the point where adequate cost information could be obtained. The man-hours required for such an analysis preclude its use in this study. In the second method costs are established for one plant and then by making various assumptions, using the "7th Steam Station Cost Survey," and turbogenerator information obtained from a manufacturer, an attempt is made to estimate the cost of these modified units.(5) The cost of the total plant can be approximated by considering the number of units required to produce the plant output and the cost of each unit.

The TVA's Johnsonville Steam Plant was used in part as number one. This particular plant was chosen because, (1) it is currently under construction, (2) plant design details and costs were available, and (3) the turbines have moisture separators in the cross-over piping which eliminates reheat and appears to be a desirable feature for a nuclear-thermal plant.(1). Members of the TVA's Engineering Department were especially helpful in supplying design details and cost information.

II. Johnsonville Steam Plant

The Johnsonville Steam Plant of the TVA is located on the Tennessee River in middle Tennessee. It is a coal-fired plant with ultimate capability of 750 mw. At the present time, four of the six units are in operation with the last two in various stages of completion. Each of the first four units is an 1800 rpm double flow machine rated at 112,500 kw, while the last two are 3600 rpm triple flow machines of the same capacity. The plant is of the unit type design, with million-pound-per-hour steam generators and related auxiliaries per turbogenerator. The cost of all the equipment and structure connected with one of these units is used as a base cost in this study at the 1465 psia, 1000°F throttle condition. Major equipment considered in the basic plant is listed in Table I.

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A detailed cost estimate of the Johnsonville Steam Plant was studied and this information used to approximate costs of plants operating at lower temperatures. The cost estimate was made using the Federal Power Commission's account system for public utilities.(6) The use of this system is continued throughout the report.

Table II is a summary of the Johnsonville cost estimate stated as a percent of total cost and dollars per kilowatt of capability.* Table III reduces these costs to those of the basic plant, which excludes the steam generator and fuel handling equipment. Only the power plant equipment that is required after the steam has reached the throttle conditions and until it is returned to the source of heat was considered.

In order to make use of this plant as a base for studying the modified plants, it is necessary to study the turbine in some detail. Figure 3 is the turbine condition line showing the expansion of the steam in the turbine, extraction points, and effect of the moisture separator. Figure 4 is a heat balance diagram for an 1800 rpm, 112,500 kw machine operating at rated capacity with $1\frac{1}{2}$ in. hg. back pressure. Table IV shows the distribution of the heat converted to work in the turbine between extraction openings. It is made up from information taken from the heat balance.

* Capability is assumed in this report to be 1.111 x rated capacity

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TABLE I

Major Equipment Included in the Basic Plant

(Plant 1)

Major Equipment	Description	Number per Unit
Turbogenerator	Name plate rating - 112,500 kw Capability rating - 125,000 kw Back pressure - $2\frac{1}{2}$ in. Hg. H_2 pressure - 0.5 psig Throttle pressure - 1450 psig Throttle temperature - 1000°F Speed - 1800 rpm Type - single shaft tandem compound double exhaust	1
Condenser	Rating - condense 690,000 lb/hr. @ 2 in. Hg. back pressure with 79°F circulating water Type - horizontal single pass Surface - 70,000 sq. ft.	1
Circulating Pumps	Flow - 56,000 gpm Head - 21 feet	2
Regenerative Feedwater Heaters	5 closed heaters, one at each of the following extraction pressures - 490, 252, 93.5, 15.7, 5.43 psia 1 open heater @ 51.3 psia (see heat balance diagram for details, Figure IV)	6
Boiler Feed Pumps	Flow - 560,000 lb/hr (1209 gpm) Head - 4770 ft (1917 psia) Motor - 2000 hp Coupling - fluid (variable speed)	3

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Table II

Johnsonville Steam Plant Estimated Costs

Account No.		Cost % of Total		$/KW Capability
310	Land and land rights	0.04	0.04	0.005
311	General yard improvement	2.15		
	Powerhouse	16.12		
	Control building	0.31		
	Total account 311		18.58	22.41
312	Boiler and accessories	10.26		
	Draft equipment	4.31		
	Feedwater equipment	3.48		
	Coal handling and storing equipment	3.71		
	Pulverized fuel equipment	2.87		
	Ash handling equipment	1.18		
	Water purification and treating system	0.39		
	Boiler plant boards, instruments, and controls	1.24		
	Boiler plant piping	7.00		
	Total account 312		34.44	41.48
314	Turbogenerators	24.51 -- 30 (fr- 8/652)		
	Condensing and cooling water systems	4.23		
	Condensers	2.52 31 26		
	Central lubricating system	0.08		
	Instruments and meters	0.04		
	Turbine plant piping	0.19		
	Auxiliary equipment for generators	0.02		
	Other turbine equipment	0.10		
	Total account 314		31.69	38.15
315	Accessory electrical equipment	6.47	6.47	7.79
316	Miscellaneous power plant equipment	1.66	1.66	1.99
342, 343	Transmission plant	7.12	7.12	8.57
	Total	100.00	100.00	120.395

Table III

Basic Plant Estimated Cost

(Plant 1)

Account No.		% of Total		$/KW Capability
310	Land and land rights	0.06	0.06	.005
311	General yard improvements	3.14		
	Powerhouse*	10.21		
	Control building	0.45		
	Total account 311		13.80	11.38
312	Feedwater equipment	5.08		
	Water purification and treating system	0.57		
	Boiler plant boards, instruments, and controls	1.81		
	Boiler plant piping	10.22		
	Total account 312		17.68	14.58
314	Turbogenerators	35.78		
	Condensing and cooling water systems	6.19		
	Condensers	3.67		
	Central lubricating systems	0.11		
	Instruments and meters	0.06		
	Turbine plant piping	0.27		
	Auxiliary equipment for generators	0.03		
	Other turbine equipment	0.15		
	Total account 314		46.26	38.15
315	Accessory electrical equipment	9.45	9.45	7.79
316	Miscellaneous power plant equipment	2.41	2.41	1.99
242, 243	Transmission plant	10.39	10.39	8.57
	Total	100.00	100.00	82.46

* Only that required for turbine plant

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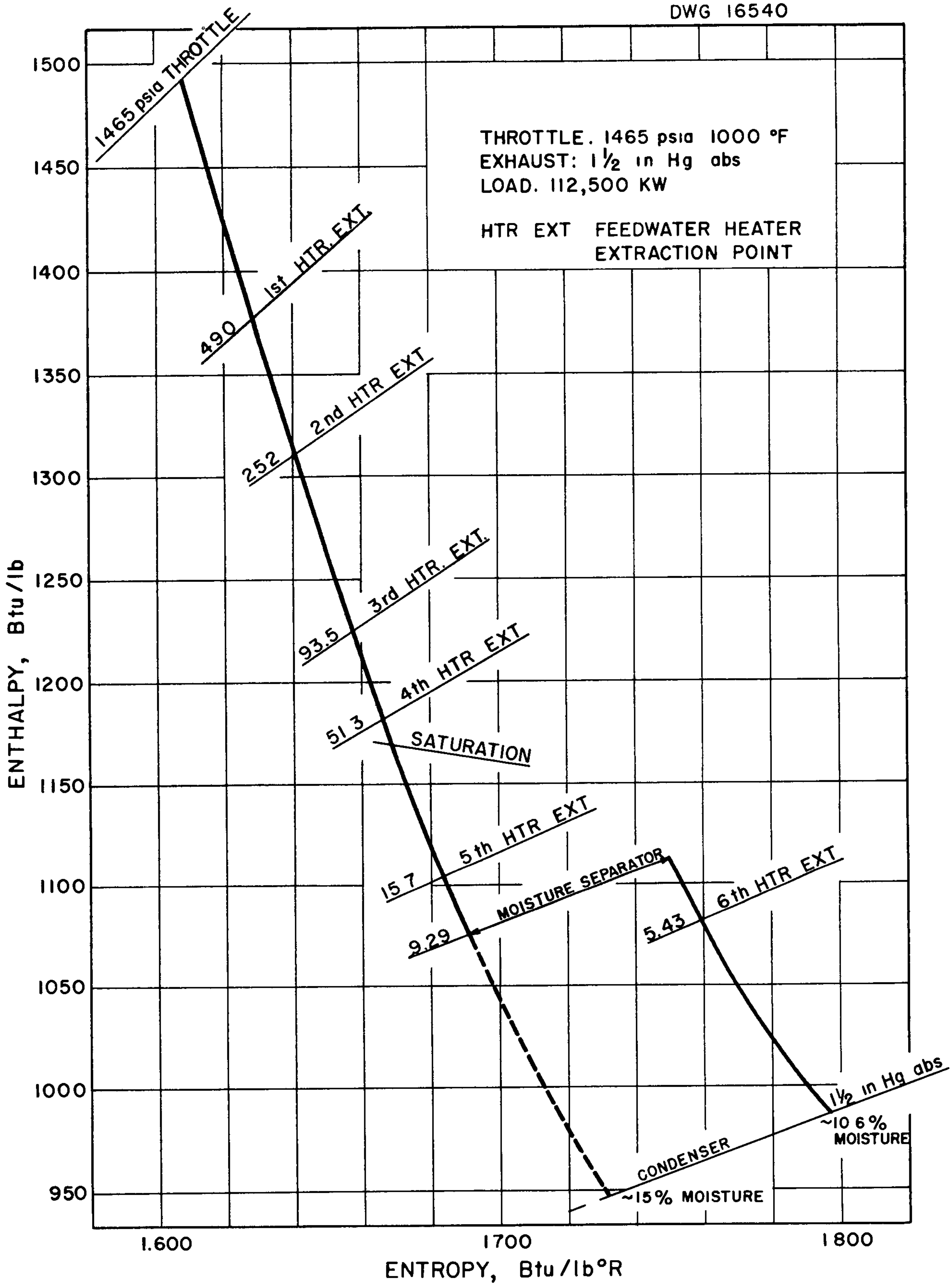

Fig 3. Condition Line (112,500 KW Steam Turbogenerator)

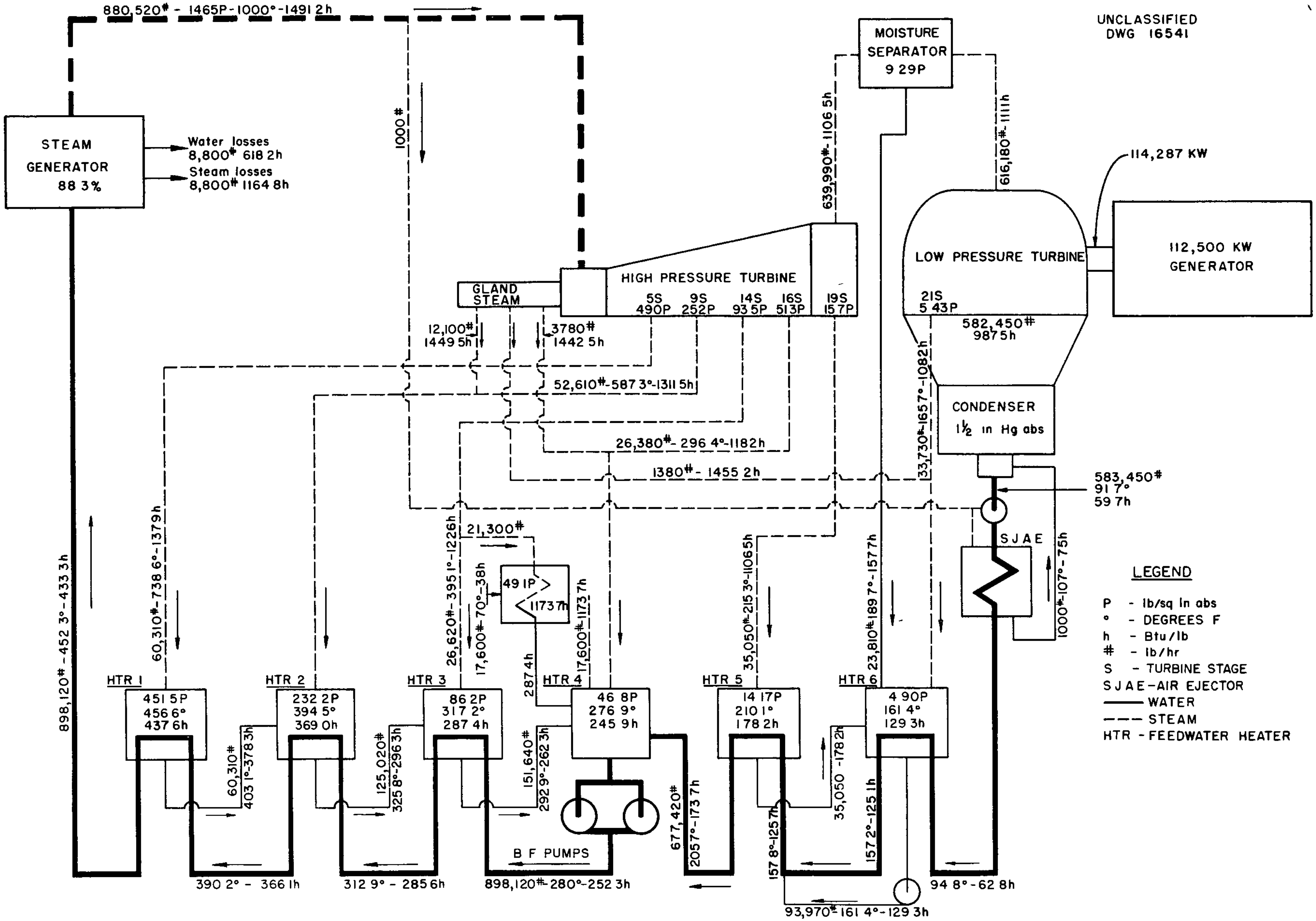

Fig 4 Heat Balance Diagram (112,500 KW Turbogenerator)

Table IV

Distribution of Work Contributed by the Stages of a 112,500 kw Turbine Between Extraction Openings

Steam Condition Entering Group: Pressure psia	Steam Condition Entering Group: Temperature °F	Stage Group Nos.	Inlet Stage No.	Outlet Stage No.	Steam Flow Through Stage Group 1000 lb/hr	Output of Stage Group at Generator kw	Cumulative Output kw	Extraction for Heater No.
5.43	166	1	22	24	582	15,875	15,875	6
9.29	190	2	21	21	616	5,154	21,029	Moisture Separator
15.7	215	3	20	20	640	5,815	26,844	5
51.3	296	4	17	19	675	14,700	41,544	4
93.5	395	5	15	16	701	8,902	50,446	3
252	587	6	10	14	749	18,479	68,925	2
490	739	7	6	9	802	15,613	84,538	1
1465	1000	8	1	5	862	27,904	112,442	

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III. Modification of Basic Plant

The fact that turbogenerator costs for plants operating at low throttle steam conditions are virtually nonexistant makes it necessary to devise a scheme by which some reasonable cost estimate can be made for these low pressure units.

This problem was approached by using the turbine from the basic plant, modifying it to operate on successively low pressures and temperatures, and then matching a generator to its output. The modification consists of successively removing the high pressure stages of the turbine and changing the throttle valve section to accommodate these low throttle conditions. The selection of pressures and temperatures throughout the range considered was made in such a manner that expansion through the remainder of the turbine was along the original condition line (See Figure III). The existing turbine, flows, and auxiliaries were maintained from this new throttle section on through the condenser and remaining feedwater heaters. No attempt was made to correct for an ever increasing percent exhaust loss inherent by using this procedure.*

The extraction steam conditions of the original turbine are not necessarily the conditions that should be used for the throttle steam of the modified plants. For this reason the curves in Figure 5 were plotted from the data in Table IV. Now from these curves a better spread of throttle conditions could be selected. The throttle conditions and output in Table V were obtained in this manner with no effort made to match exact stage pressures. By using the appropriate part of the information in Table IV a heat and steam rate was estimated for each plant. The number of feedwater heaters listed is that for the original plant,

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* For a given turbine and flow there is a fixed exhaust loss in Btu. This loss is generally expressed as a percent of available energy; hence, the increasing percent as the available energy is reduced.

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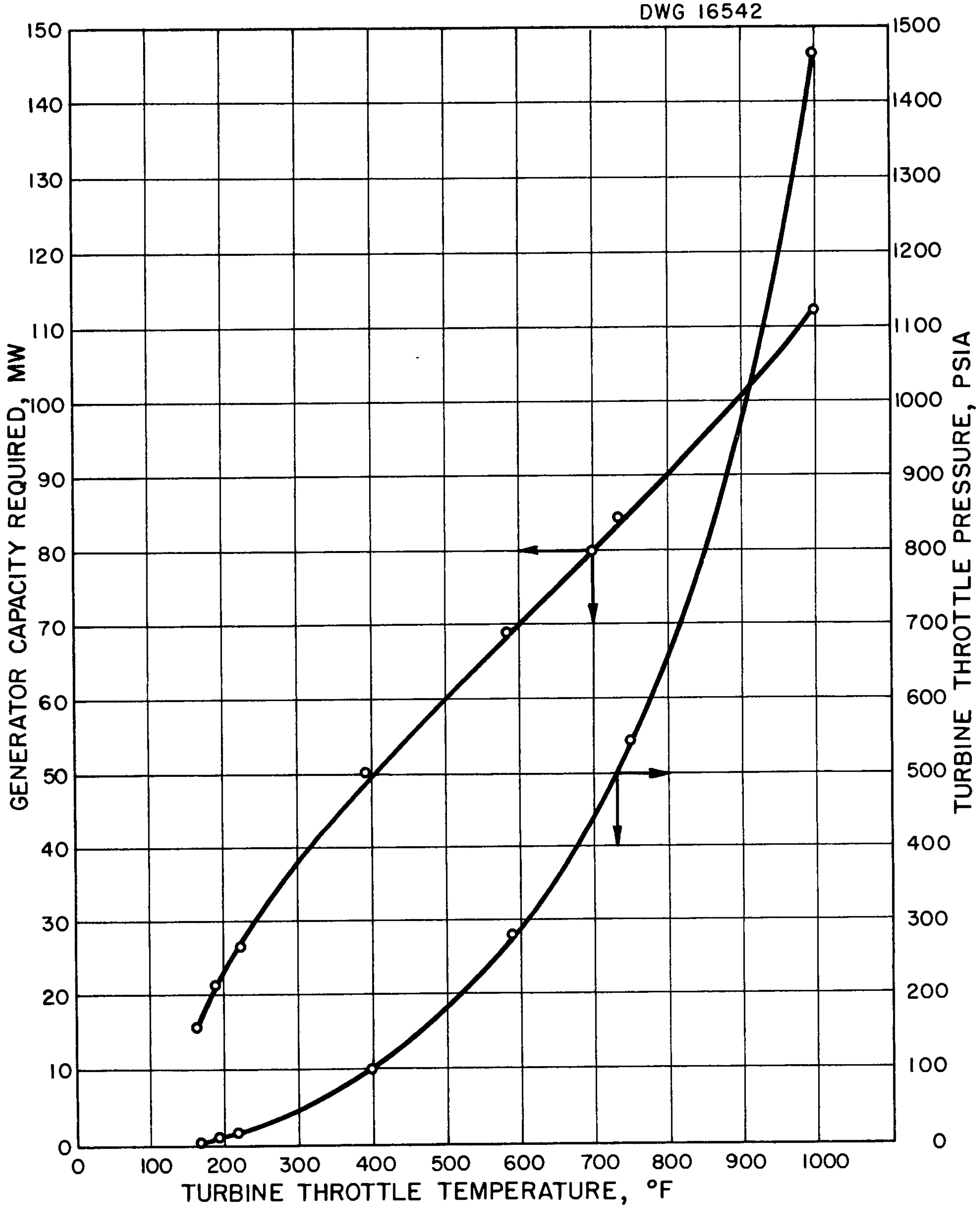

Fig. 5. Performance of Modified 112,500KW Turbine: Required Generator vs. Throttle Conditions (Plot of Data in Table IV)

TABLE V

Performance of Modified 112,500 KW Turbines used in the 7 Plants Analyzed

Plant No.	Throttle Pressure psia	Conditions Temperature °F	Steam Enters Turbine at Stage No.	Throttle Flow Required 1000 lb/hr	Feedwater Heaters Retained No.	Generator Output mw	Throttle Steam Rate-Gross Output lb/kwh	Turbine Heat Rate-Gross Output Btu/kwh	Overall Thermal Efficiency %	Units Required to Produce 200 mw Net Output No.
1	1465	1000	1	862	6	112.5	7.67	8119	39.6	1.89
2	960	900	2	862	6	100.0	8.62	8761	36.8	2.12
3	660	800	5	802	5	90.0	8.90	9249	34.8	2.35
4	460	700	7	802	5	80.0	10.02	9944	32.4	2.65
5	300	600	10	749	4	70.0	10.72	11027	28.7	3.03
6	180	500	12	749	4	60.0	12.48	12290	26.2	3.53
7	100	400	15	701	3	50.0	14.03	13678	23.5	4.24

with the higher pressure heaters being eliminated as the throttle pressures become lower than that for heater extraction. No attempt was made to justify the heaters economically or to make the best use of them thermodynamically. By dividing the gross plant output of 212 mw by each of the unit outputs, the number of units and fraction thereof required to make up the whole plant was obtained.

IV. Evaluation of Costs of the Modified Plants

A. Investment Costs

Before using the Johnsonville Steam Plant costs, it was considered desirable to compare them with other plant costs. The "7th Steam Station Cost Survey" was used as a source for this information.(5) The average of 1950 costs was compiled for plants above 100 mw and was classified according to the Federal Power Commission's account numbers and also by auxiliary systems. This information corrected to 1951 costs is compared with the Johnsonville cost estimate in Table VI in the appendix. The 1950 costs were corrected to 1951 by multiplying the 1950 costs by 1.062. This factor was obtained by dividing the Engineering News - Record average construction cost index for 1951 by that of 1950.(7) Although in most cases Johnsonville's more detailed costs were used, use was made of the average tabulation where wide variations between the two existed.

The evaluation of costs listed in Table VII was accomplished in either of three ways:

(1) The fact that all the plants were established on the basis of a fixed net electrical output of 200 mw will cause some of the costs to be the same for all plants and not a function of temperature at which they operate. The transmission plant is very definitely of this character (accounts 342 and 343). Land and land rights and miscellaneous power plant equipment (accounts 310 and 316) were assumed to be of this nature also along with the water supply and treatment

equipment as shown in Table VII.

(2) The turbine, generator and their auxiliaries were established as a unit. The majority of the costs vary with the quantity of this equipment. Therefore, such things as the condenser circulating water system, the condenser, miscellaneous turbogenerator equipment and piping, and accessory electrical equipment were considered to vary directly as the number of units required as shown in the last column of Table V.

(3) Some special method was necessary to obtain some of the costs because the above methods were not altogether applicable. Piping and feedwater heaters and pumps fall into this category along with the turbogenerators. The method used to evaluate these costs are explained in the following paragraphs.

The following figures include installation costs and overhead and are the basis for the items in Table VII (in the appendix).

Account 310 -- Land and Land Rights

Because of the location of Johnsonville, land costs were much below the average. Therefore, instead of using the basic plant costs it was more appropriate to use the average figure of $1.29/kw. Although the powerhouse would increase somewhat in size with the lowering of plant operating conditions and land required by the AEC for reactor isolation would be enormous, no consideration was given these facts and consequently this account is shown the same for all plants.

Account 311 -- Structures and Improvements

In the Johnsonville Steam Plant the control building and miscellaneous buildings cost was approximately $950,000 per unit, or $1,795,000 total for Plant 1. As construction costs were below average at Johnsonville an arbitrary figure of $2,000,000 was used as a fixed cost of the powerhouse regardless of steam conditions with $1.00 per cubic foot added for the building required to

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house the turbogenerators etc. Only space for the turbine plant was considered and therefore the cost of housing the fuel handling equipment, boilers and its auxiliaries was not included. Distribution of space for Johnsonville, and average for plants above 100 mw is tabulated in Table VIII in the appendix.

Account 312 -- Boiler Plant

Although the boilers and fuel handling equipment were not included in this analysis, there is some equipment under this account that is necessary for turbine plant operation no matter what the heat source may be. The following paragraphs list this equipment and the determination of its cost.

Item 3 - Feedwater Equipment

Feedwater equipment was considered in detail only to the extent of evaluating boiler feed pump and high pressure heater costs as they vary the most with changes in throttle conditions. The remainder of this item was assumed the same for all seven plants.

Pumping unit costs were estimated assuming motor costs to be 35% of the unit cost, a figure obtained from the cost of this installation in the basic plant. As motor costs are available, a rough estimate of costs of feedwater pumps and drives was made. A summary of this study along with feedwater heater costs is found in Table IX in the appendix.

The three high pressure heaters were successively eliminated as the operating conditions were lowered, the deaerating heater and the two low pressure heaters were included in all seven plants. In the basic plant the first two high pressure heaters were approximately $40,000 each, the third $30,000 and the last two low pressure heaters $12,000 each. On a heating surface basis this amounts to about $8.00 and $4.50 per sq. ft. respectively for the high and low pressure heaters.

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A sum of $93,000 per unit was charged to all plants to cover the cost of the evaporator, miscellaneous heat exchangers, tanks, etc., common to all installations. This figure was obtained by difference from the known cost of this item for Plant 1.

Item 4 - Water Supply and Treatment

The cost of these facilities was taken as a constant for all plants at $111,000 as derived from Plant 1. This item includes all equipment necessary to supply raw water for power house and fire protection, filter plant etc. for treated water, and the chemical treatment system for boiler feed water.

Item 5 - Boiler Plant Boards, Instruments and Controls

This item includes mechanical control boards, heater control boards, and compressed air system boards. It is evaluated from the basic plant at $187,000 per unit.

Item 6 - Boiler Plant Piping

As there was no breakdown of the boiler plant piping cost by systems available for the Johnsonville Plant, it was necessary to use some other source for this information. The cost distribution for the piping at TVA's Watts Bar Steam Plant was obtained from their Technical Report No. 8.[8] Although there is a considerable difference in the design of the two plants, the Watts Bar distribution was used here for lack of a better figure.

Watts Bar Steam Plant Piping Costs

Main steam piping	14%
High pressure extraction	10%
Low pressure extraction	14%
Feedwater	29%
Condensate	8%
Drains and vents	15.5%
Miscellaneous	9.5%
	100.0%

[redacted]

The main steam line and high pressure feedwater heater piping were analyzed separately with the remainder of the piping cost common to all plants taken as $775,000 per unit as indicated by **Plant** 1 costs. Main steam piping costs were estimated by a method developed by R. A. Dickenson.(9) This line was assumed to consist of 160 ft of pipe with 4 bends and the turbine stop valve. Feedwater heater piping costs were evaluated according to the above table and proportionately eliminated as the number of feedwater heaters were reduced. Table X in the appendix is a summary of this study.

<u>Account 314</u> -- <u>Turbine Plant</u>

<u>Item 7</u> - <u>Turbogenerators</u>

Cost of turbogenerators based on an estimating price furnished by the General Electric Company are listed in Table XI in the appendix. The data were plotted and a smooth curve drawn through the points in Figure VI. Because of standardization of machines by the manufacturer this curve should be in steps by pressure as well as temperature at the throttle, however, for the method used here the smooth curve was thought to be more appropriate for the estimating of turbogenerator costs. No attempt was made to maintain the percentage exhaust loss a constant or below the conventional 4%. This would necessitate a different turbine for each throttle condition with successively large exhaust ends and hence a more costly turbine.

The cost of the remaining items are derived from the basic plant costs and are given in dollars per unit unless otherwise noted. Total cost is obtained by multiplying this unit cost by the number of units shown in the last column of Table V.

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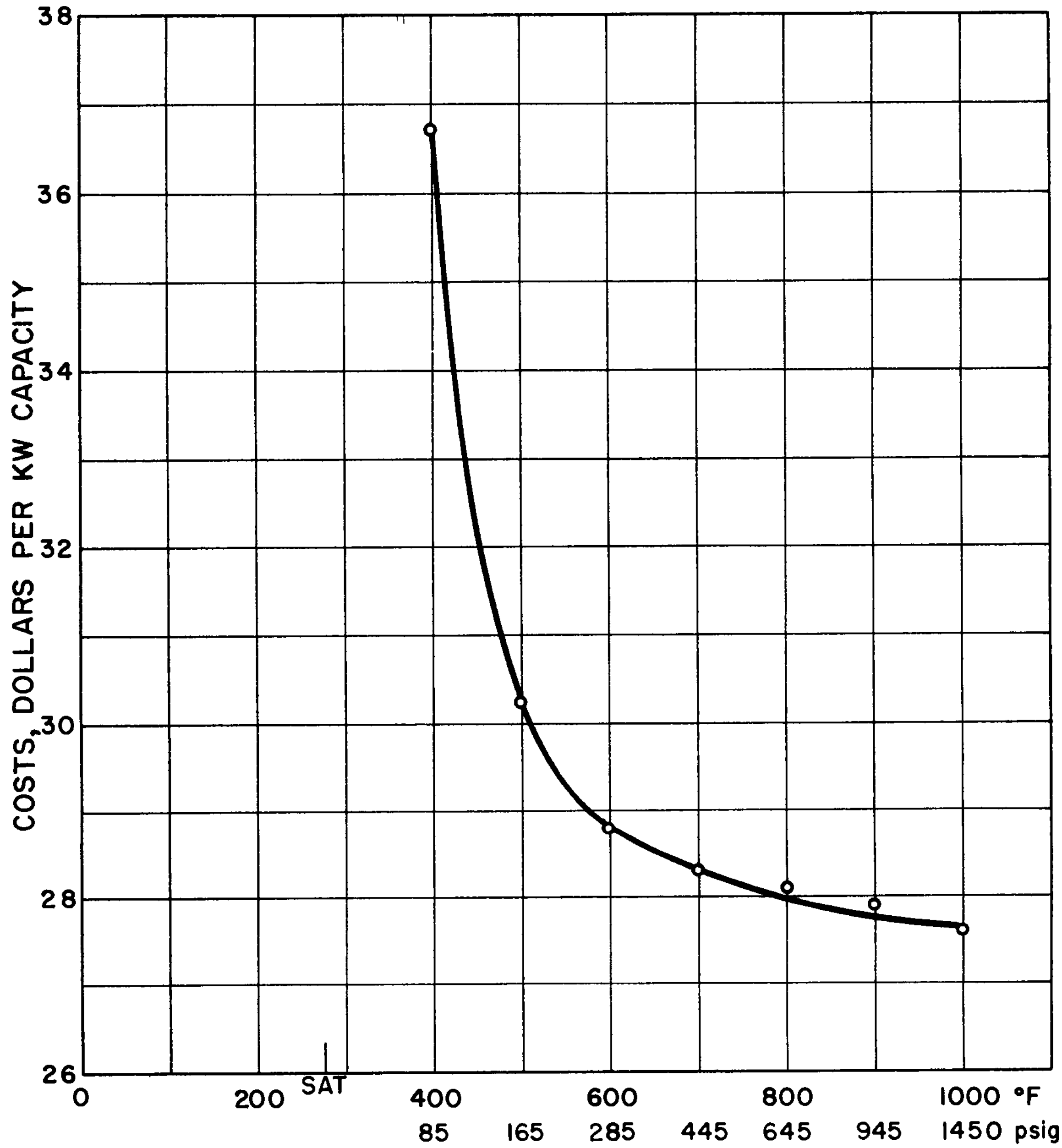

Fig. 6. Turbogenerator Costs vs. Throttle Temperature (Plotted from Table XI)

Item 8 - Circulating Water System - $637,000/unit

The circulating water system includes intake structure; main supply pumps, valves and piping; traveling screens, trashracks, and screen washing system; cranes and hoists; condenser supply and discharge piping; and discharge conduit. It can be seen by the items involved in this water system that the cost depends a great deal on the local conditions at the plant. The basic plant costs were used here as no comparative information was available.

Item 9 - Condenser - ($5.41 per sq. ft. of surface, installed) - $379,000/unit

Item 10 - Miscellaneous Turbogenerator Equipment and Piping - $63,500/unit

Central lubricating system	$11,700
Instruments and meters	6,000
Turbine plant piping	28,500
Auxiliary equipment for generator	3,000
Other turbine plant equipment	14,300

Account 315 -- Accessory Electrical Equipment - $775,000/unit

This item includes switchgear, switchboards, protective equipment, electrical structures, conduit, power and control wiring, and station service equipment.

Account 316 -- Miscellaneous Power Plant Equipment - $424,000 (all plants)

This account includes station maintenance equipment, all cranes and hoisting equipment, compressed air system, and other miscellaneous equipment. The cost of this item was considered the same for all plants.

Accounts 342 and 343 -- Transmission Plant - $2,018,000 (all plants)

This account includes all costs encountered in establishing the transmission plant. These costs were evaluated for Plant 1, and assumed to be the same for all plants.

Curves in Figure 1 as well as the figures in Table VII summarize the investment costs for all seven plants.

D. Operating Costs

Operating costs were evaluated in a similar manner as those in the "7th Steam Station Cost Survey" except fuel and boiler plant cost were modified.

Fixed charges at 15%

Production charges

Wages and superintendence

Water, lubrication, and supplies

Maintenance, repairs

Buildings and structures

Boiler plant

Prime movers and auxiliaries

Electrical equipment

Supervision, engineering, miscellaneous

An average for the above items was computed for 100 mw stations and larger - using an 80% plant factor. The boiler plant costs found in this manner were cut in half in attempt to exclude boiler maintenance and yet retain cost of maintaining feedwater equipment etc. Table XII in the appendix is a summary of estimated steam plant yearly production costs with no charge being placed on the steam to the turbine. Table XIII is a summary of yearly steam cost at various cost per million Btu added to the steam ranging from $0.05 to $0.50. And, finally, Figure II in the summary is a plot of yearly operating costs $ per kwh produced vs throttle conditions for a variety of steam costs to the turbine.

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BIBLIOGRAPHY

1. Petersen, H. J., "Johnsonville Steam Plant of the TVA," Combustion, December 1950, pp. 44 - 50

2. Federal Power Commission, "Steam-Electric Plant Construction Cost and Annual Production Expenses - 1950."

3. Anon., "Design Trends in 92 of the Newest Power Plants," Electrical World, April 7, 1952, p. 119.

4. Elliott, R., "Economic Factors in the Selection of Steam Temperatures in Nuclear Power Plants", Atomic Energy Research Department, North American Aviation, Ind., NAA-SR-145.

5. Knowlton, A. E., "7th Steam Station Cost Survey," Electrical World, August 27, 1951, pp. 97 - 108.

6. Federal Power Commission, "Uniform System of Accounts Prescribed for Public Utilities and Licensees," January 1, 1937.

7. "Engineering News Record Cost and Volume Indexes", Engineering News-Record, November 1, 1951.

8. Tennessee Valley Authority, "The Watts Bar Steam Plant", Technical Report No. 8, 1949 p. 250.

9. Dickson, R. A., "Pipe Cost Estimation", Chemical Engineering, V57M1, January 1950, pp. 123 - 135

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APPENDIX

[redacted]

Table VI

1951 Power Plant Investment Costs

Account No.		Average Unit Cost $/kw Capability	Johnsonville Unit Cost $/kw Capability
310	Land	1.29	.005
311	Structures and improvements	32.32	22.41
312	Boiler plant equipment	49.65	41.48
314	Turbogenerator plant	32.65	38.15
315	Accessory electrical equipment	11.66	7.79
316	Miscellaneous plant equipment	1.86	2.03
	Total station	129.36	111.83
	Outdoor switch yard	9.21	8.57
	Total station and switch yard	138.57	120.40
	Building	24.70	19.40
	Condensing supply works	8.86	5.09
	Fuel handling	10.77	7.92
	Ash handling	2.62	1.42
	Draft system	4.22	5.20
	Feedwater system	5.99	4.19
	Piping system	10.15	8.65
	Condensers	3.96	3.03
	Switchgear and station wiring	13.11	--

[redacted]

TABLE VII

Estimated Steam Plant Investment Costs

			1000 Dollars						
		Plant Numbers -------------------	1	2	3	4	5	6	7
		Throttle Conditions psia/°F -----------	1465/1000	960/900	660/800	460/700	300/600	180/500	100/400
Item No.	Account								
1	310	Land and land rights	354	354	354	354	354	354	354
2	311	Structures and improvements	4656	4920	5144	5490	5872	6562	7160
3	312	Feedwater equipment	990	953	744	747	648	668	605
4		Water supply and treatment	111	111	111	111	111	111	111
5		Boiler plant board, instruments, and controls	354	397	440	496	567	661	794
6		Boiler plant piping	1900	1923	2005	2251	2479	2903	3377
7	314	Turbogenerators	6972	7038	7064	7120	7266	8105	9256
8		Circulating water systems	1203	1350	1496	1687	1929	2248	2700
9		Condensers	716	803	890	1004	1083	1261	1606
10		Miscellaneous turbogenerator equipment and piping	119	135	149	168	193	224	269
11	315	Accessory electrical equipment	1466	1644	1822	2055	2350	2737	3290
12	316	Miscellaneous power plant equipment	424	424	424	424	424	424	424
13	342,343	Transmission plant	2018	2018	2018	2018	2018	2018	2018
14		TOTAL	21283	22070	22661	23825	25294	28276	31964

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Table VIII

Powerhouse Space Distribution

Johnsonville

	1000 ft^3/unit	ft^3/kw
Boiler room	708	5.66
Air preheaters, fans	230	1.84
Coal handling system	340	2.72
Boiler feed pumps	44	0.35
440 and 4160 V switchboards	46.5	0.37
Control room	68.5	0.55
Deaerating heaters, storage tanks, evaporator	80.8	0.65
2nd and 3rd feedwater heaters (9 and 14th stage)	36.8	0.29
1st feedwater heater (5th stage), evap. preheater	39.3	0.31
Condenser and miscellaneous equipment	324.3	2.59
Turbogenerator	534.5	4.28
Turbogenerator service	66	0.53
Control building	161	1.29
Total	2,679.7	21.43

Space Factor ft^3/kw

	Average 1950	Johnsonville
Boiler plant	11.21	11.48
Turbine plant	8.97	6.7
Switch house	0.76	-
Office, etc.	1.21	1.74
Total	22.15	21.43

Building Ground Area ft^2/kw*

Average 1950	Johnsonville
0.37	0.22

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* Capability 1 unit = 125,000 kw capability

[redacted]

TABLE IX

Boiler Feed Pump and Feed Water System Costs

Press./Temp	Flow m lb/hr	Head psi	Motor Required hp	Cost 3 Motors $	Estimated Unit Cost	No. Feedwater Heaters	Feedwater Heater Costs	Unit Installation, etc., Cost	Total per Unit	Total 200 mw Plant
1450/1000	560	1900	2000	98,400	287,900	6	143,000	93,000	523,800	990,000
960/900	560	1250	1500	72,900	213,300	6	103,300	93,000	449,300	953,000
660/800	500	850	850	41,100	120,200	5	103,300	93,000	316,500	744,000
460/700	500	600	600	29,300	85,700	5	103,300	93,000	282,000	747,000
300/600	470	375	400	20,400	59,700	4	61,200	93,000	213,900	648,000
180/500	470	325	200	12,000	35,100	4	61,200	93,000	189,300	668,000
100/400	450	125	100	6,000	17,600	3	32,100	93,000	142,700	605,000

TABLE X

Boiler Plant Piping Cost Estimate

Thousands of Dollars							
Press./Temp.	1465/1000	960/900	660/800	460/700	300/600	180/500	100/400
Main steam piping	248	70	28	22	29	50	89
High pressure feedwater heating piping	187	209	155	174	100	116	0
Miscellaneous ($775,000/unit)	1,465	1,644	1,822	2,055	2,350	2,737	3,288
Total	1,900	1,923	2,005	2,251	2,479	2,903	3,377
Main steam pipe size 5% pressure drop	16.5" O.D. 12.5" I.D.	16" Sch. 100	18" Sch. 60	20" Sch. 40	24" Sch. 40	24" Sch. 40	30" Sch. 30
Velocity, ft/sec	171	177	163	164	144	214	205

Table XI

Turbogenerator Estimating Prices

Turbine: Tanden compound - double flow - 1800 rpm - 30-inch last stages buckets.

Plant No.	Throttle Conditions Press./Temp. psig/^{o}F	Throttle Flow 1000 lb/hr	Feedwater Heaters No.	Generator Rating mw	Estimating Price* $1000	Cost per kw of Capability $/kw
1.	1450/1000	860	6	112.5	3460	27.6
2.	945/900	860	6	100	3103	27.9
3.	645/800	800	5	90	2809	28.1
4.	445/700	800	5	80	2511	28.3
5.	285/600	750	4	70	2241	28.8
6.	165/500	750	4	60	2146	32.2
7.	85/400	700	3	50	2040	36.7

* From letter from General Electric Company dated April 12, 1952 and G. E. price sheet 4711, page 11.

TABLE XII

Estimated Steam Plant Yearly Production Costs
(Less Fuel)

Item No.	Plant Number / Throttle conditions psia/°F	1 1465/1000	2 960/900	3 660/800	4 460/700	5 300/600	6 180/500	7 100/400
		1000 Dollars per Year						
1	Fixed charges at 15 percent	3192	3311	3399	3574	3794	4241	4495
2	Production charges (less fuel)	634	706	779	873	992	1152	1376
3	Total	3826	4017	4178	4447	4786	5393	5871
	80 Percent Plant Factor	Mils per kwh						
4	Fixed charges at 15 percent	2.277	2.362	2.425	2.550	2.707	3.026	3.207
5	Production charges (less fuel)	0.452	0.504	0.556	0.623	0.708	0.822	0.982
6	Total	2.729	2.866	2.981	3.173	3.415	3.848	4.189

Distribution of Item 5* (80% Plant Factor)	Mils/kwh
Wages and superintendence	0.292
Water, lubrication and supplies	0.051
Maintenance	
Building and structure	0.017
Boiler plant**	0.027
Prime movers and auxiliaries	0.032
Electrical equipment	0.007
Supervision, engineering, misc.***	0.026
Total (Plant 1)	0.452

* Average from reference 3
** Only one-half was used
*** Assumed constant - all others vary with number of units

TABLE XIII

Yearly Steam Cost at Various Cost per Million Btu of Heat

80% Plant Factor

Plant Number ------------------	1	2	3	4	5	6	7
Throttle conditions psia/°F ---	1465/1000	960/900	660/800	460/700	300/600	180/500	100/400
Dollars per Million Btu add to Steam	Millions of Dollars per Year						
.05	0.603	0.652	0.687	.736	0.820	0.911	1.016
.10	1.205	1.303	1.374	1.472	1.640	1.822	2.032
.20	2.410	2.606	2.748	2.944	3.280	3.644	4.064
.30	3.615	3.909	4.122	4.416	4.920	5.466	6.096
.40	4.820	5.212	5.496	5.888	6.560	7.288	8.128
.50	6.025	6.515	6.870	7.360	8.200	9.110	10.160
	Mils per KW-H						
.05	0.43	0.47	0.49	0.53	0.59	0.65	0.73
.10	0.86	0.93	0.98	1.05	1.17	1.30	1.45
.20	1.72	1.86	1.96	2.10	2.34	2.60	2.90
.30	2.58	2.79	2.94	3.15	3.51	3.90	4.35
.40	3.44	3.72	3.92	4.20	4.68	5.20	5.80
.50	4.30	4.65	4.90	5.25	5.85	6.50	7.25

Industrial range - 0.15 to 0.50 $/million Btu