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Engineering

COMPUTATIONS ON THE PERFORMANCE OF A POWER STATION I

AUTOMATIC EXTRACTION TURBOGENERATORS

by
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Theoretical Physics Division

October 1955

E. I. du Pont de Nemours & Co.
Explosives Department - Atomic Energy Division
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ABSTRACT

A method is described in which an IBM 650 computer is used to determine the electrical output of a steam power station under all practical modes of operation. The output was calculated as a function of high- and low-pressure export steam and boiler output. The calculated and actual production of electricity differed by less than one per cent.

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TABLE OF CONTENTS

LIST OF FIGURES

COMPUTATIONS ON THE PERFORMANCE OF A POWER STATION I

Automatic Extraction Turbogenerators

INTRODUCTION

The performance characteristics of each piece of equipment in a power station are usually known from data supplied by the manufacturer. However, when export steam is obtained from either of two turbogenerators, or from both, it is difficult to predetermine the amount of electricity that can be generated. While an operator can change the distribution of steam to the various components of the system to meet the desired power output, he is not assured of meeting this condition with optimum economy. Thus, it is desirable to have performance curves for all situations likely to occur in the power station. This report explains how a medium-speed digital computer, the IBM 650, was used to predict the performance of a power station for all feasible modes of operation.

SUMMARY

To provide the data required to establish the most economical method of operation, the electrical output of a steam power station was computed as a function of high- and low-pressure export steam and boiler loads. The ranges of the independent variables were sufficient to cover all practicable modes of operation of the power station.

Standard operating procedures were established on the basis of these calculations.

To test the validity of the computational method, the electrical output of the power station was computed for April 1955 on the basis of the export-steam and boiler loads that existed during that month. The actual and the calculated production of electricity differed by less than one per cent.

The computation of each heat balance consumed ten seconds of IBM 650 time. Approximately 1000 balances were necessary for each of the many combinations of equipment. One man-month was required to code the problem. Ten hours of machine time were used for check-out and 40 hours for production runs. The estimated time for manual computation of these balances was six man-years.

This report describes computational methods only.

DISCUSSION

MATHEMATICAL METHOD OF COMPUTATION

The units of the power station are shown in Figure 1. The definitions of symbols appearing in Figure 1 are given in the Appendix. This figure has been simplified by showing only one unit of each type of equipment. However, the full complement of the station was considered in the equations shown in the Appendix.

The general method of solution was as follows. The symbols are defined in the Appendix.

1. Assume that steam is generated at the rate of A lb/hr-boiler.
2. Assume that high-pressure steam is exported at the rate of B lb/hr.
3. Assume that low-pressure steam is exported at the rate of C lb/hr.
4. Calculate all possible flows and enthalpies of the system from these three variables, and the fixed quantities such as the enthalpy of A, B, and C, the gland drawoff from the high-pressure turbogenerator (HP turbine), the enthalpy of the steam in the high-pressure header, etc. These calculations require only material and energy balances.
5. Assume a value for the extraction, x_{10}, from the low-pressure (LP) turbine to the low-pressure header. (The removal of steam from the periphery of a turbine at certain locations is termed an extraction.)
6. Continue calculating all flows and enthalpies through the turbine, condenser, heaters, and deaerator. The calculated enthalpy of the feed water leaving the deaerator must be equal to a constant determined by boiler feed conditions.
7. If this calculated enthalpy is not equal to the desired enthalpy, a correction must be made on x_{10}. For example, if the calculated enthalpy is too low, it can be increased by increasing x_{10}, and repeating steps (6) and (7) until the calculated enthalpy converges to the desired value.
8. Now that all flows and enthalpies are in balance, the electrical output from the turbines is calculated from the performance curves or formulas available for these turbines.
9. Net electrical output is obtained by computing losses within the power station, and subtracting these from the gross output.

This procedure was followed for approximately 1000 combinations of A, B, and C, covering the entire range. This large set of heat balances was made for each feasible combination of the power station equipment consisting of n boilers, n_H high-pressure turbines, and n_L low-pressure turbines.

MACHINE PROCEDURES

Most of the equations used were simple algebraic equations. Fixed-decimal coding was used. Whenever the information was available only in graphical form, the Table-Look-Up feature of the IBM 650 was used. A maximum of 20 number pairs (ordinate and abscissa) was used for each group, with both numbers of a pair packed into one ten-digit storage.

The most intricate portion of the program was an interpolation routine. Since the electrical output was a fairly smooth function of boiler load A, it was possible to use a large increment in the values of A within most of the range. Smaller increments were used in the region where turbine limitations were encountered. For example, it was necessary that x_{11} remain between an upper and a lower limit. Suppose that for $A = A_o$ the heat balance forced x_{11} to become less than its minimum allowable value. Also, suppose that for $A = A_o + \Delta A$ the same was true, but for $A = A_o + 2\Delta A$, x_{11} became greater than the critical value. The program then reduced A to $A_o + \Delta A + 0.1(i)(\Delta A)$, and successively assigned to i the values 1, 2, 3, ... until x_{11} became greater than its critical value. A similar program was used for the case where x_{11} exceeded its maximum permissible value. In this manner the entire range of A was covered with a minimum number of balances, without sacrificing precision where it was needed.

The output information was printed on an IBM Type 402 Accounting Machine from cards punched by the IBM 650. To provide as many columns as possible with alphabetic printing, five pages of output were produced for each value of B, C, n, n_H, and n_L. A sample set of five such pages is shown in Figures 2 through 6. The numbers are fictitious, being for illustrative purposes only. The headings of each column, except the last, define the contents of that column. The last column contains a code word indicating an invalid problem. For example, the code 6666 was used in the last column when x_{11} was less than its minimum allowable value.

For a given n, n_H, and n_L, a family of curves of electrical output as a function of A, B, and C, was drawn from the printed output.

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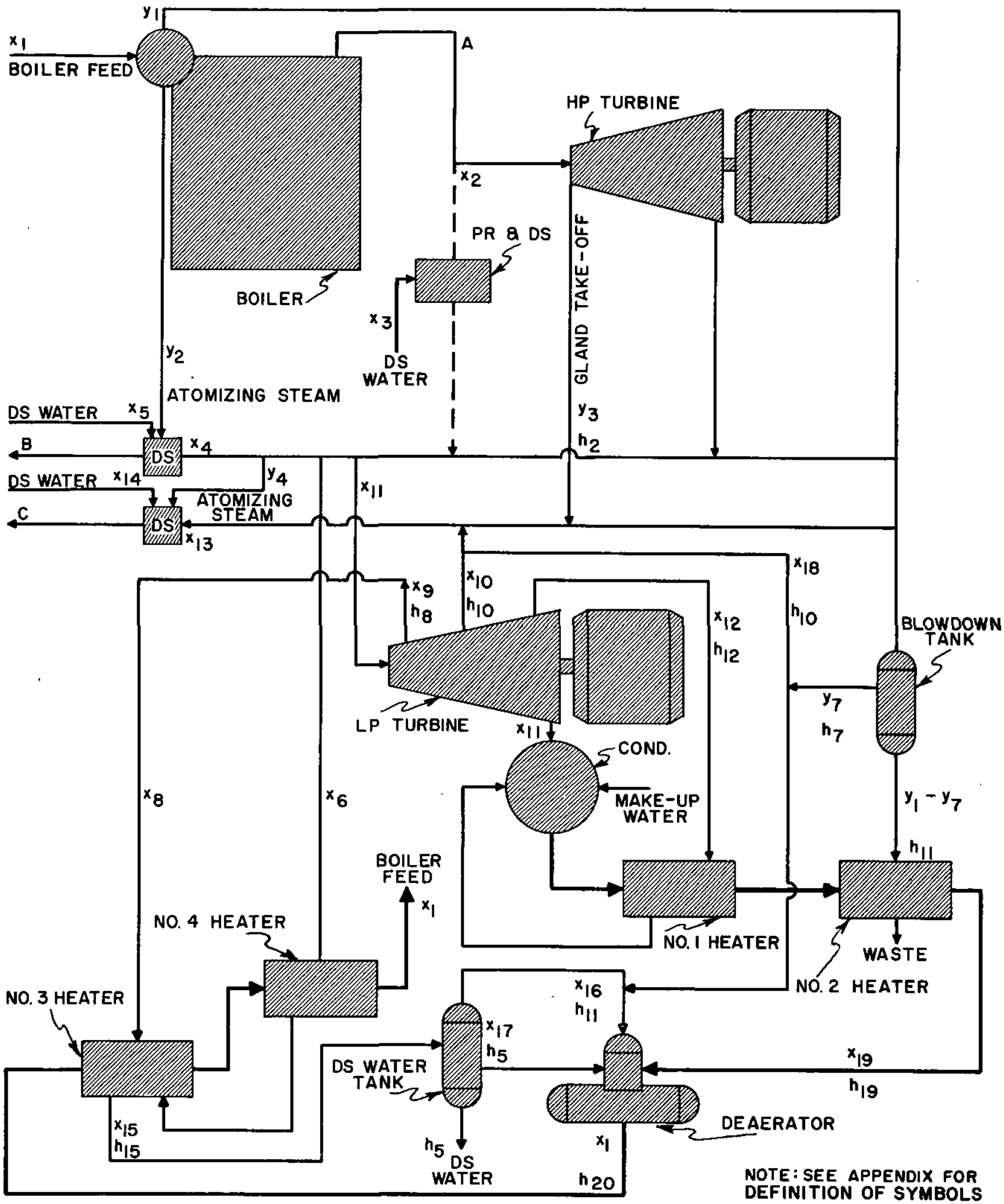
FIGURE 1



FLOW DIAGRAM OF POWER STATION

FIGURE 2

A	B	C	n	n_H	n_L	D_H	x_1	x_4	x_6	
10	2	800	1	1	1	1.00	0000000	000000	000000	6666
15	2	800	1	1	1	1.00	0000000	000000	000000	6666
20	2	800	1	1	1	1.00	0000000	000000	000000	6666
25	2	800	1	1	1	1.00	0010234	020234	030234	
22.5	2	800	1	1	1	1.00	0009234	019234	029234	
30	2	800	1	1	1	1.00	0015234	025234	035234	
35	2	800	1	1	1	1.00	0020234	030234	040234	
40	2	800	1	1	1	1.00	0025234	035234	045234	
45	2	800	1	1	1	1.00	0030234	040234	050234	
50	2	800	1	1	1	1.00	0035234	045234	055234	
55	2	800	1	1	1	1.00	0040234	050234	060234	
60	2	800	1	1	1	1.00	0045234	055234	065234	
65	2	800	1	1	1	1.00	0000000	000000	000000	2222
61.5	2	800	1	1	1	1.00	0046234	056234	066234	
70	2	800	1	1	1	1.00	0000000	000000	000000	2222
75	2	800	1	1	1	1.00	0000000	000000	000000	2222
80	2	800	1	1	1	1.00	0000000	000000	000000	2222
85	2	800	1	1	1	1.00	0000000	000000	000000	2222

SAMPLE FORMAT OF RESULTS, PAGE 1

FIGURE 3

A	B	C	n	n_H	n_L	D_H	x_7	x_9	x_{10}	
10	2	800	1	1	1	1.00	0000000	000000	000000	6666
15	2	800	1	1	1	1.00	0000000	000000	000000	6666
20	2	800	1	1	1	1.00	0000000	000000	000000	6666
25	2	800	1	1	1	1.00	0010234	020234	030234	
22.5	2	800	1	1	1	1.00	0009234	019234	029234	
30	2	800	1	1	1	1.00	0015234	025234	035234	
35	2	800	1	1	1	1.00	0020234	030234	040234	
40	2	800	1	1	1	1.00	0025234	035234	045234	
45	2	800	1	1	1	1.00	0030234	040234	050234	
50	2	800	1	1	1	1.00	0035234	045234	055234	
55	2	800	1	1	1	1.00	0040234	050234	060234	
60	2	800	1	1	1	1.00	0045234	055234	065234	
65	2	800	1	1	1	1.00	0000000	000000	000000	2222
61.5	2	800	1	1	1	1.00	0046234	056234	066234	
70	2	800	1	1	1	1.00	0000000	000000	000000	2222
75	2	800	1	1	1	1.00	0000000	000000	000000	2222
80	2	800	1	1	1	1.00	0000000	000000	000000	2222
85	2	800	1	1	1	1.00	0000000	000000	000000	2222

SAMPLE FORMAT OF RESULTS, PAGE 2

FIGURE 4

A	B	C	n	n_H	n_L	D_H	x_{13}	LP KW	$10h_{20}$	
10	2	800	1	1	1	1.00	0000000	000000	000000	6666
15	2	800	1	1	1	1.00	0000000	000000	000000	6666
20	2	800	1	1	1	1.00	0000000	000000	000000	6666
25	2	800	1	1	1	1.00	0010234	020234	030234	
22.5	2	800	1	1	1	1.00	0009234	019234	029234	
30	2	800	1	1	1	1.00	0015234	025234	035234	
35	2	800	1	1	1	1.00	0020234	030234	040234	
40	2	800	1	1	1	1.00	0025234	035234	045234	
45	2	800	1	1	1	1.00	0030234	040234	050234	
50	2	800	1	1	1	1.00	0035234	045234	055234	
55	2	800	1	1	1	1.00	0040234	050234	060234	
60	2	800	1	1	1	1.00	0045234	055234	065234	
65	2	800	1	1	1	1.00	0000000	000000	000000	2222
61.5	2	800	1	1	1	1.00	0046234	056234	066234	
70	2	800	1	1	1	1.00	0000000	000000	000000	2222
75	2	800	1	1	1	1.00	0000000	000000	000000	2222
80	2	800	1	1	1	1.00	0000000	000000	000000	2222
85	2	800	1	1	1	1.00	0000000	000000	000000	2222

SAMPLE FORMAT OF RESULTS, PAGE 3

FIGURE 5

A	B	C	n	n_H	n_L	D_H	HP KW	HP KW	HP KW	
10	2	800	1	1	1	1.00	0000000	000000	000000	6666
15	2	800	1	1	1	1.00	0000000	000000	000000	6666
20	2	800	1	1	1	1.00	0000000	000000	000000	6666
25	2	800	1	1	1	1.00	0010234	020234	030234	
22.5	2	800	1	1	1	1.00	0009234	019234	029234	
30	2	800	1	1	1	1.00	0015234	025234	035234	
35	2	800	1	1	1	1.00	0020234	030234	040234	
40	2	800	1	1	1	1.00	0025234	035234	045234	
45	2	800	1	1	1	1.00	0030234	040234	050234	
50	2	800	1	1	1	1.00	0035234	045234	055234	
55	2	800	1	1	1	1.00	0040234	050234	060234	
60	2	800	1	1	1	1.00	0045234	055234	065234	
65	2	800	1	1	1	1.00	0000000	000000	000000	2222
61.5	2	800	1	1	1	1.00	0046234	056234	066234	
70	2	800	1	1	1	1.00	0000000	000000	000000	2222
75	2	800	1	1	1	1.00	0000000	000000	000000	2222
80	2	800	1	1	1	1.00	0000000	000000	000000	2222
85	2	800	1	1	1	1.00	0000000	000000	000000	2222

SAMPLE FORMAT OF RESULTS, PAGE 4

FIGURE 6

A	B	C	n	n_H	n_L	D_H	GR KW	NT KW	Btu	
10	2	800	1	1	1	1.00	0000000	000000	000000	6666
15	2	800	1	1	1	1.00	0000000	000000	000000	6666
20	2	800	1	1	1	1.00	0000000	000000	000000	6666
25	2	800	1	1	1	1.00	0010234	020234	030234	
22.5	2	800	1	1	1	1.00	0009234	019234	029234	
30	2	800	1	1	1	1.00	0015234	025234	035234	
35	2	800	1	1	1	1.00	0020234	030234	040234	
40	2	800	1	1	1	1.00	0025234	035234	045234	
45	2	800	1	1	1	1.00	0030234	040234	050234	
50	2	800	1	1	1	1.00	0035234	045234	055234	
55	2	800	1	1	1	1.00	0040234	050234	060234	
60	2	800	1	1	1	1.00	0045234	055234	065234	
65	2	800	1	1	1	1.00	0000000	000000	000000	2222
61.5	2	800	1	1	1	1.00	0046234	056234	066234	
70	2	800	1	1	1	1.00	0000000	000000	000000	2222
75	2	800	1	1	1	1.00	0000000	000000	000000	2222
80	2	800	1	1	1	1.00	0000000	000000	000000	2222

SAMPLE FORMAT OF RESULTS, PAGE 5

APPENDIX

DEFINITION OF TERMS

A	steam flow at the superheater outlet of the boiler, lb/hr-boiler
B	flow of high-pressure export steam, lb/hr
C	flow of low-pressure export steam, lb/hr
n	number of boilers in service
n_H	number of high-pressure (HP) turbines in service
n_L	number of low-pressure (LP) turbines in service
x_1	total flow of feed water to the boilers, lb/hr
x_2	total flow of superheated steam to the pressure-reducing and desuperheating stations, lb/hr. x_2 is greater than zero only when the boiler output exceeds the allowable HP turbine input
x_3	total desuperheating water to the pressure-reducing and desuperheating stations, lb/hr
x_4	steam flow from the HP header to the desuperheating station for HP export steam, lb/hr
x_5	flow of desuperheating water to the HP export steam desuperheater, lb/hr
x_6	steam flow lb/hr-boiler from the HP header to No. 4 Heater of the boiler feed water
x_7	steam flow to the throttle of the LP turbine, lb/hr-LP turbine
x_8	flow of steam to the No. 3 Heater, lb/hr-LP turbine
x_9	high-pressure extraction from the LP turbine, lb/hr-LP turbine
x_{10}	low-pressure extraction from the LP turbine, lb/hr-LP turbine
x_{11}	steam flow to the low-pressure section of the LP turbine, lb/hr-LP turbine
x_{12}	uncontrolled extraction from the LP turbine, lb/hr-LP turbine
x_{13}	flow of steam from the LP header to the LP export steam desuperheater, lb/hr
x_{15}	total condensate flow from the No. 3 Heaters to the desuperheating water tanks, lb/hr
x_{16}	total flash steam flow from the desuperheater storage tanks, lb/hr
x_{17}	total overflow from the desuperheater water storage tanks, lb/hr

x_{18}	total flow of steam from the low-pressure header to the deaerators, lb/hr
x_{19}	total feed water flow to the deaerators from the blowdown heat exchangers, lb/hr
y_1	liquid flow to the blowdown tank, lb/hr-boiler
y_2	total atomizing steam to the desuperheater stations for HP export steam
y_3	gland take-off from the HP turbine, in lb/hr-HP turbine
y_4	atomizing steam flow from the HP header to the LP export desuperheater, lb/hr
y_5	steam flow to the air ejector, lb/hr. (not shown in diagram)
y_7	flow of flash steam from the blowdown tank to the deaerator, lb/hr-boiler
h_1	enthalpy of the LP export steam, Btu/lb
h_2	enthalpy of the gland take-off, Btu/lb
h_3	increase in enthalpy of the boiler feed water passing through the No. 3 Heater
h_4	decrease in enthalpy in the No. 3 Heaters of the condensate from the No. 4 Heaters
h_5	enthalpy of the desuperheating water, Btu/lb
h_6	enthalpy of the steam in the HP header, Btu/lb
h_7	enthalpy of the flash steam from the blowdown tank, or desuperheater water storage tank, Btu/lb
h_8	enthalpy of the high-pressure extraction steam, Btu/lb
h_9	difference in enthalpy between the feed water entering No. 2 Heater, and the waste water leaving that heater, Btu/lb
h_{10}	enthalpy of low-pressure extraction, Btu/lb
h_{11}	enthalpy of the exit liquid from the blowdown tank, Btu/lb
h_{15}	enthalpy of the condensate from the No. 3 Heaters
h_{19}	enthalpy of the feed water entering the deaerator, Btu/lb
h_{20}	calculated enthalpy of the feed water leaving the deaerator, Btu/lb
D_H	enthalpy of the feed water leaving the condenser, Btu/lb
α_1	ratio of desuperheating water flow to steam flow in the pressure-reducing and desuperheating station

α_2 ratio of the flow of desuperheating water to the high-pressure steam flow at the HP export desuperheater

α_3 fraction of atomizing steam which acts as desuperheating water at the HP export desuperheater

α_4 ratio of steam flow to the No. 4 Heaters to the boiler feed flow through those heaters

α_5 efficiency of the No. 3 Heaters

α_7 weight fraction of input to the desuperheater storage tanks that becomes flash steam

α_8 efficiency in heat transfer by x_{18}

EQUATIONS

$$x_1 = (A + y_1)n + y_2$$

$$x_2 = nA - 473{,}000\ n_H \quad \text{if } na \geq 473{,}000\ n_H$$

$$= 0 \quad \text{if } na < 473{,}000\ n_H$$

$$x_3 = \alpha_1\ x_2$$

$$x_4 = B - x_5 - y_2 = \frac{1}{1 + \alpha_2}\left[B - (1 - \alpha_3)y_2\right]$$

$$x_5 = \alpha_2\ x_4 - \alpha_3\ y_2$$

$$x_6 = \alpha_4\ x_1$$

$$x_7 = \frac{nA + x_3 - x_4 - x_6 - y_3\ n_H - \begin{Bmatrix} 0 \\ y_4 \end{Bmatrix}}{n_L} \text{ for} \begin{Bmatrix} C = 0 \\ C \neq 0 \end{Bmatrix}$$

$$x_8 = \frac{h_3\ x_1 - h_4\ x_6}{n_L\ (\alpha_5 h_8 - h_{15})}$$

$$x_9 = x_8 + y_5$$

$$x_{11} = x_7 - x_9 - x_{10}$$

$$x_{12} = \alpha_6\ x_{11} - \alpha_9 \quad \left[\text{Curve of } x_{12} = f(x_{11}) \text{ from manufacturer of turbine}\right]$$

$$x_{13} = \frac{(h_1 - h_5)C - (h_2 - h_{10})\ y_3\ n_H - (h_6 - h_5)\ y_4}{h_{10} - h_5}$$

$$x_{14} = C - x_{13} - y_4$$

$$x_{15} = x_6 + n_L\ x_8$$

$$x_{16} = \alpha_7 x_{15}$$

$$x_{17} = (1-\alpha_7) x_{15} - x_5 - x_{14} - x_3$$

$$x_{18} = n_L x_{10} + y_3 n_H - x_{13}$$

$$x_{19} = x_1 - x_{17} - x_{16} - x_{18} - y_7 n$$

$$h_{19} = D_H + \Big\{ (y_1 - y_7)n \left[h_{11} - D_H\right] - \frac{(y_1 - y_7)n\, n_L\, x_{12}}{x_{19}} (h_{12} - D_H - h_9) + n_L x_{12} (h_{12} - D_H - h_9) \Big\} \div x_{19}$$

$$h_{20} = \frac{x_{19}h_{19} + y_7 h_7 + \alpha_8 x_{18} h_{10} + x_{16} h_7 + x_{17} h_5}{x_1}$$

The values of h_8, h_{10}, and h_{12} were obtained from empirical curves. The values of electrical output from the turbogenerators were obtained from curves supplied by the manufacturer.