Output:

The heat content of the slag at 1,450 deg. C .is given by:

$$12{,}500 \times 945 = 11{,}800{,}000 \text{ B.T.U.}$$

The heat content of the ferrophosphorus is given by:

$$436 \times 555 = 242{,}000 \text{ B.T.U.}$$

The heat of reduction of P_2O_5 is given by:

$$4{,}325 \times 4{,}630 = 20{,}000{,}000 \text{ B.T.U.}$$

Out:

The heat of reduction of Fe_2O_3 is given by:

$$347 \times 2{,}200 = 763{,}000 \text{ B.T.U.}$$

The heat of reduction of H_2O is given by:

$$173 \times 3{,}210 = 555{,}000 \text{ B.T.U.}$$

The heat of decomposition of $Ca_3(PO_4)_2$ is given by:

$$4{,}325 \times \frac{310}{142} \times 926 = 8{,}750{,}000 \text{ B.T.U.}$$

The heat of decomposition of $CaCO_3$ is given by:

$$530 \times 812 = 430{,}000 \text{ B.T.U.}$$

The heat content of the gases leaving the furnace is given by:

$$\text{CO} \quad \frac{4{,}620}{28} \times 7.02 \times (430 - 65) = 422{,}300 \text{ B.T.U.}$$

$$CO_2 \quad \frac{196}{44} \times 9.67 \times (430 - 65) = 15{,}700 \text{ ``}$$

$$\text{Phosphorus} \quad 1{,}766 \times 307 = 542{,}000 \text{ ``}$$

$$SiF_4 \quad 130 \times 0.184 \times (430 - 65) = 8{,}600 \text{ ``}$$

$$H_2 \quad \frac{17 \times 7.00 \times (430 - 65)}{2} = 21{,}700 \text{ ``}$$

$$\text{HF} \quad \frac{39 \times 7.00 \times (430 - 65)}{20} = 4{,}980 \text{ ``}$$

Volatile matter (the composition is unknown).

The summation of the quantities (already calculated) is given in table No. III.

Condenser Heat Balance Run 1

Basis: 2,000 lbs. of phosphorus in the furnace charge.
Reference temperature 65 deg. F.

In: 420 deg. F.

The heat input is calculated above (heat in gases).
The heat evolved by the decomposition of SiF_4 in water is given by:

$$130 \times 74 = 9{,}600 \text{ B.T.U.}$$

Out: 120 deg. F.

The heat content of the gases leaving the condenser is given by:

$$\text{CO}: \frac{4{,}620 \times 6.96 \times (120 - 65)}{28} = 56{,}000 \text{ B.T.U.}$$

$$CO_2: \frac{196 \times 9.25 \times (120 - 65)}{44} = 2{,}270 \text{ ``}$$

$$\text{Phosphorus}: 198 \times 524 = 50{,}800 \text{ ``}$$

$$H_2: \frac{19}{2} \times 6.96 \times (120 - 65) = 3{,}630 \text{ ``}$$

$$H_2O: 400 \times ((120 - 65) + 1{,}025) = 431{,}000 \text{ ``}$$

Heat Out:

The heat content of the phosphorus (condensed) and the water leaving the condenser is given by:

$$\text{Condensed phosphorus } 1{,}582 \times 24 = 38{,}000 \text{ B.T.U.}$$

$$\text{Water } 5{,}340 \times (140 - 65) = 400{,}000 \text{ ``}$$

The summary of the quantities necessary to effect a balance is given in table No. IV.

Calculation of Factors

The factors for table No. VII may be calculated by either merely converting the given data in textbooks, journals, etc., into other units (specific heats, heat of vaporization, etc.) or by the usual methods of thermochemistry (heats of decomposition or reduction).

Example:

Heat of formation of $Ca_3(PO_4)_2$	1,765,000 B.T.U.
(65 deg. F.) 3 $CaCO_3$	820,100 "
P_2O_5	658,000 "

The heat of decomposition of $Ca_3(PO_4)_2$ into 3 CaO and P_2O_5 is given by:

$$\frac{1{,}765{,}000 - (820{,}000 + 658{,}000)}{310} = 926 \text{ B.T.U./lb.}$$

The dewpoint of the phosphorus in the furnace gases may be calculated from the relation:

$\log_{10}P = \frac{-3300}{T} + 9.65$ where P is the vapor pressure of phosphorus in mm. and T is the temperature in deg. Kelvin. There are $\frac{1{,}766}{31} = 56.8$ lb. moles of phosphorus in the furnace gases. The vapor pressure is given by $\frac{56.8 \times 760}{\text{lb. moles furnace gas} = 238} = 182$ mm. Substituting in the above relation and converting T to deg. F. it is found that the dewpoint is 346 deg. F.

The quantity of heat per lb. of phosphorus gas at 420 deg. F. may now be calculated as follows: (See table No. VII for data.)

$$0.202 \times (111 - 65) + 9 + 0.198(346 - 111) + 234 + 0.064 \times (420 - 346 = 308 \text{ B.T.U. per lb.}$$

The phosphorus in the condenser gases is at the dewpoint.

Thermal efficiency is equal to that fraction of the total power necessary to bring about the reactions in the furnace and to heat the outgoing products.

Run 1	
Electrical power	51,000,000 B.T.U.
Exothermic reactions	10,920,000 "
Endothermic reactions and heat in products	43,999,000 "

$$\text{Thermal efficiency} = \frac{43{,}999{,}000 - 10{,}920{,}000}{51{,}000{,}000} = 0.65 \text{ or } 65\%$$

Effective power consumption per ton of phosphorus volatilized:

$$\text{Run 1} \quad 0.344 \times 43{,}600 \times 0.65 \times \frac{2{,}000}{1{,}766} = 11{,}000 \text{ kw. hrs.}$$

% volatilization of phosphorus in the furnace:

$$\text{Run 1} \quad \frac{1{,}766}{2{,}000} \times 100 = 88.4\%$$

% recovery of phosphorus from the furnace gases:

$$\text{Run 1} \quad \frac{1{,}568}{1{,}766} \times 100 = 88.8\%$$

A.I.Ch.E. ANNUAL STUDENT CONTEST PROBLEM—1937

FOREWORD

The problem presented to the members of the Institute's student chapters for solution in the Sixth Annual Contest was one pertaining to a hypothetical chemical process requiring a certain amount of steam and a certain amount of electrical current. Basic cost data were furnished to make certain that the contestants used the same basic figures.

Council sponsors these contests annually through its Committee on Student Chapters. This year Dr. L. B. Hitchcock, Chairman, Mr. R. L. Murray and Mr. C. J. Henly acted as Sub-Committee on Awards of the Student Chapters Committee and handled this matter in its entirety. The Committee reports that generally the solutions submitted were of good quality and showed a sound fundamental grasp of the principles involved. There were fifty-five solutions submitted.

The prize winners were as follows:

1. Walter Bass, Cooper Union, First Prize—$100.00.
2. Earp F. Jennings, Jr., University of Illinois, Second Prize—$50.00.
3. Fred Planansky, Oregon State, Third Prize—$25.00.
4. Verne Loyd Simril, University of Illinois, Fourth Prize—$10.00,
5. Donald M. Wroughton, University of Illinois, Fifth Prize—$10.00.
6. T. R. Young, Princeton University, Sixth Prize—$10.00.

The problem and the solution receiving the first prize appear on the following pages.

STEPHEN L. TYLER,
Executive Secretary.

CONTEST PROBLEM

1937

Student Chapters—American Institute of Chemical Engineers

Open Only to Undergraduates or Those without a Degree in Chemical Engineering

STATEMENT

1. A certain large chemical company projects the erection of a branch plant for the manufacture of 100 tons per day of product "X." The new plant is in a remote location and is to be entirely independent and self-contained. It will operate 365 days per year. The process is one requiring 25,000 pounds of steam, dry and saturated, at 40 pounds per square inch absolute pressure and 2,000 KWH of electrical energy, per ton of "X."

2. As the chemical engineer assistant to the vice-president in charge of manufacture, you are asked by him to submit a report which he will include as a section in his recommendations to the Board of Directors. He asks you to cover the steam and power features of the new plant in such a way as to arrive at an estimate of cost for their optimum arrangement, concisely and effectively presented, with appended sample calculations and summarized calculations available for technical verification. Since the object of the vice-president's report at this time is simply to furnish preliminary figures which will indicate whether or not it is practicable to go further with the project, no details, drawings, specifications, or layouts are expected. Presumably the actual execution of this phase of the project, when and if undertaken, would be handled by the contracting engineers charged with design, construction, and installation of steam and power facilities.

3. The vice-president's memorandum to you sets forth certain general features which he considers advisable in establishing the basis for the desired preliminary estimates:

(a) The boiler plant is to be designed for operation at one of the following pressures: 400, 500, or 600 pounds per square inch absolute. Securing of quotations as well as the equipment itself is facilitated by the selection of one of these standard pressures:

(b) In the generating plant, consideration is to be given to the use of bleeder turbines as a source of part or all of the process steam requirements in connection with the generation of the stated electrical energy. The requisite number of 3000 KW. capacity A.C. turbo-generators (one to be in reserve) are to be installed, of a design permitting any amount of extraction from 0 to 100%. Should it be deemed uneconomical to operate turbines with sufficient bled steam to fill process needs, boiler steam may be reduced directly to process conditions if desired.

(c) Fuel at the proposed new site will be natural gas having a lower heating value of 1000 BTU per cubic foot at 60° F. and one atmosphere pressure, at a cost of 15 cents per 1000 cubic feet at the same conditions.

4. For simplicity in preliminary estimates you decide to make these assumptions:

(a) The steam and power installation is to be sufficient to provide 5% excess capacity exclusive of the reserve turbine; *e.g.*, the load factor is 0.95.

THE BOILER PLANT

(b) The boiler efficiency based on lower heating value of the fuel is 90%.

(c) To avoid the need for special materials of construction, steam temperatures must not exceed 750° F.

(d) Boiler make-up feed water will be at 60° F. Its cost is included in the operating charges given by Table III.

(e) Any hot water obtainable from the turbo-generating station will be used as feed water.

(f) Condensate from process will not be returned to the boiler plant.

THE TURBO-GENERATING STATION

(g) The turbine efficiency is 70% independent of load or fraction bled; turbine efficiency is defined as the ratio of the work actually produced per pound of steam fed, to that which would be produced per pound in an isentropic expansion to the same final pressure as reached in the actual expansion. Heat losses from turbines may be neglected.

(h) Since these turbines are all built to order, their final design will depend on the result of these calculations; the unit cost is the same per KW. regardless of the per cent condensed, and each turbine will deliver 3000 kw. when installed under the given conditions.

(i) The pressure drop in all piping may be neglected.

(j) Process steam must be available which is at least dry and saturated; superheat is an advantage though no credit will accrue for present purposes. If wet steam is bled from the turbines for process use, it will be passed through a moisture separator before going to process. Separated water will be returned for use as boiler feed.

(k) Condenser water is available under conditions such that condenser pressure may be assumed uniform the year around at 0.5 pounds per square inch absolute pressure.

5. Cost Data:

The engineering department have certain cost data, chiefly on the basis of past experience, relating to a standard type of construction. You obtain the following figures from them:

TABLE I. UNIT COST OF INSTALLED BOILER CAPACITY INCLUDING BOILER, BUILDING, AND AUXILIARIES COMPLETE

	Pressure Pounds per Sq. In. Abs.		
Pounds Steam per Hour Installed Capacity	400	500	600
		Dollars per Lb.Hr.	
50,000	$4.75	$6.56	$7.84
100,000	3.85	5.42	6.54
150,000	3.30	4.95	5.95

TABLE 2. UNIT COST OF INSTALLED POWER GENERATING CAPACITY INCLUDING TURBO-GENERATORS, BUILDING, AND AUXILIARIES COMPLETE

	Boiler Pressure Pounds per Sq. In. Abs.		
KW Installed Station Capacity	400	500	600
		Dollars per KW	
3,000	$109.00	$121.00	$134.00
5,000	89.50	99.50	109.00
7,500	72.00	79.00	85.50
10,000	61.50	66.50	70.50
12,000	56.50	60.00	63.00

TABLE 3. OPERATING CHARGES—COST OF OPERATING LABOR, MAINTENANCE, AND SUPPLIES EXCLUSIVE OF FUEL

$$R = \frac{\text{oper. labor} + \text{maintenance} + \text{supplies}}{\text{fixed charges}} \times 100$$

subscript "S" = Steam plant; "T" = turbo-generator plant

	Pressure Pounds per Sq. In. Abs.		
Pounds Steam per Hour Installed Capacity	400	500	600
		R_S	
70,000	76.0	69.0	61.5
100,000	72.5	66.0	59.0
130,000	69.0	63.0	56.5
KW Installed Station Capacity		R_T	
4,000	69.0	88.0	100.0
6,000	56.5	75.0	86.0
8,000	44.0	62.0	72.0

Condensers

Total annual charges, including condenser water, may be estimated at a flat figure of $1.45 per pound hour of installed condensing capacity.

Fixed Charges

Fixed charges of 15% will be assumed uniformly on all capital investment.

Auxiliaries, Accessories, etc.

Foundations, piping, fuel handling, feedwater equipment, land, engineering, and miscellaneous charges, are included in the figures already given under the appropriate heading of boiler plant or power generating plant.

METHOD OF PRESENTATION

The solution should be presented as a report in the form best suited in the contestant's judgment for inclusion in the vice-president's report to the Board of Directors. Among other things, these specific answers are required:

(1) Total annual cost of steam and power

(2) Cost of power, mils per KWH, if process steam charged at 30 cents per 1000 pounds

(3) Installed capacity of boiler plant, pounds of steam per hour

(4) Pressure and superheat at which boiler plant is to operate

(5) Per cent of steam generated which is bled from turbines due to process steam requirement

(6) Condition (pressure, temperature, quality if wet) of steam bled from turbines due to process steam requirement

These data should be numbered and listed to correspond with the above list. Required results should be accompanied by sufficient explanation of the methods employed and important assumptions made to assure the executives of their validity. Not more than five minutes should be required for consideration of this section of the main report. Specimen calculations, together with a summary of other calculations, should be presented in the appendix in such a way that the results may be readily verified by another engineer.

Reports will be graded on (a) conclusions reached (b) accuracy of computations and (c) form of presentation.

It is to be assumed that the above statement of the problem contains all the data available and your instructor is not to be consulted in regard to doubtful points. The problem is not to be discussed with any person whatever until after March 15, 1937. This is particularly important in cases where neighboring institutions may not begin the problem until after its completion by another chapter. The use of text books, handbooks, journal articles, steam tables, and lecture notes is permitted. Submittal of a report for the competition implies adherence to the above conditions.

A period of not more than 21 consecutive days is allowed for completion of the solution. This period may be selected at the discretion of the individual counsellor, but a solution must be postmarked not later than midnight March 15, 1937, in order to be eligible. Each solution should be accompanied by a letter of transmittal giving only the contestant's name, school address, home address, and student chapter, lightly attached to the report. This letter will be retained for identification by the Chairman of the Committee on Student Chapters. The solution itself must bear no reference to the student's name or institution by which it might be identified. Each counsellor should select the best solution, or solutions, from his chapter, not to exceed three in number, and send these registered mail to Professor Joseph C. Elgin, Princeton University, Princeton, New Jersey.

FIRST PRIZE WINNING SOLUTION

Contest Problem, 1937, Student Chapters, A.I.Ch.E.

ESTIMATION OF STEAM AND POWER PLANT COSTS

By WALTER BASS,[1] Cooper Union Chapter
Cooper Union, New York, N. Y.

INTRODUCTION

The object of this report is to cover the steam and power features of a proposed plant which is to manufacture 100 tons per day of product. The plant is to be entirely self-contained; the installed power plant must be sufficient to meet all process steam and electrical requirements. These are estimated to be 25,000 lbs. per hr. of dry and saturated steam (superheat not objectionable) at 40 #/in.^{2} and 2000 KWH per ton of product, at a load factor of 0.95.

Consideration is to be given to the use of bleeder turbines of 3000 KW capacity (one in reserve), permitting any desired degree of steam extraction, as a source of process steam in connection with the generation of the necessary electrical energy. The boiler is to use natural gas as a fuel and is to operate at 400, 500 or 600 #/in.^{2} Abs. at a temperature not exceeding 750° F.

Various cost data obtained from past experiences with similar equipment are to be used as the basis for the selection of the most economical arrangement and for the calculation of preliminary cost estimates.

SUMMARY OF REPORT

The hourly process steam and electrical requirements (including auxiliary power) were computed, and the required number of turbo-generators determined. Various arrangements of the turbines with respect to the individual power and steam loads were investigated and the optimum arrangement determined (See Appendix II).

Calculations were made to determine the boiler and condenser capacities and fuel consumption necessary for the generation of the required amounts of process steam and electrical energy, for boiler pressures of 400, 500 and 600 #/in.^{2} at various boiler temperatures up to 750° F. This was done for a Rankine Cycle (bleeding steam to process at 40 #/in.^{2}) and also for a two-stage regenerative feed water heating cycle.

Unit costs and operating percentages for the steam plant and turbo-generator plant were determined for the computed boiler and turbine capacities, and from these the corresponding fixed and operating charges were calculated. Fuel costs and condenser charges were calculated and the total annual charges for each case determined (See Table I). On the basis of these figures the most economical arrangement was selected.

For the latter case, the fraction of the total steam generated which is bled from the turbine for process purposes and the condition of this steam is calculated. The cost of power for a predetermined process steam charge of 30 cents per 1000 lbs. was calculated.

CONCLUSIONS

The electrical requirements necessitate the installation of four 3000 KW turbo-generators (one of which is in reserve). The use of bleeder turbines as a source of all process steam is indicated; reduction of high pressure boiler steam to process conditions is not feasible.

The most favorable operating cycle is the two-stage regenerative feed water heating cycle operating at boiler pressure of 400 #/in.^{2} and temperature of 750° F. This arrangement gives the lowest annual cost (Table I), and shows an annual saving of 7.1% over the Rankine Cycle operated at the same conditions.

Increasing the boiler pressure to 600 #/in.^{2} at 750° for the Rankine Cycle increases the annual costs 16% over that at 400 #/in.^{2} although the fuel cost has diminished by 6% and the condenser charges by 20%. Similarly, changing to 500 #/in.^{2} increases the total charges by 11%, although fuel cost has decreased 3% and condenser costs decreased 12%.

The total annual charges for the different cases considered are summarized in Table I, while the component costs are found in Tables IV and V.

TABLE I.—SUMMARY OF TOTAL ANNUAL CHARGES $/YR.

Boiler Press. #/in.^{2}		Boiler Temp. °F. 750	740	720	700	680
400	Rankine	583,600	584,300	586,000	589,400	593,300
	Regen.[a]	542,100*	543,000	545,700	547,900	550,900
500	Rankine	645,800	646,800	648,600	654,300	656,600
	Regen.	612,700	614,100	616,600	620,000	623,400
600	Rankine	675,700	677,800	681,700	685,500	687,500

a—Regenerative feed water heating cycle consisting of two stage heaters using steam bled from turbine at 90 and 14.7 #/in.^{2}

* Most economical arrangement.

RECOMMENDATIONS

It is recommended that the installed system consist of 171,000 #/hr. boiler (or boilers) to be operated at 400 #/in.^{2} Abs. and 750° F., and four 3000 KW capacity A.C. bleeder turbo-generators (one of which is in reserve), the latter to operate on a two-stage regenerative feed water heating cycle, permitting steam extraction at 90 and 14.7 #/in.^{2} for heater purposes and at 40 #/in.^{2} for process purposes. An adjustment of not over $1,200,000 is required. The pertinent data relative to this proposed arrangement is given below:

TABLE IA.—ESTIMATED DATA, 2-STAGE REGENERATIVE CYCLE PROPOSED

(1)	Total annual cost of steam and power	$542,100/yr.
(2)	Cost of power if process is charged at 30 cents per 1000 # steam:	
	Cost of power *	3.61 mils/KWH
(3)	Installed capacity of boiler plant	171,000 #stm/hr.
(4)	Operating boiler pressure	400 #/in.^{2} Abs.
	Operating boiler temperature	750° F.
	Superheat	305° F.
(5)	64.1% of steam generated bled at 40 #/in.^{2} for process. 12.6% of steam generated bled at 14.7 #/in.^{2} to Heater 2. 10.5% of steam generated bled at 90 #/in.^{2} to Heater 1.	
(6)	Steam bled for process is at 40 #/in.^{2} pressure and 400° F. It is superheated 133° F.	

* Process is charged with cost of auxiliary power.

DISCUSSION

In order to calculate the necessary output of the turbine, the generator efficiency and auxiliary power requirements must be determined. A generator efficiency of 0.96 is assumed, as an average of the values given by Pender [1*] and Perry.[2] It is further assumed the auxiliaries are electrically driven since this is common practice in modern plants [3] and the power required to operate the auxiliaries is 2% of the net electrical output. The latter figure is averaged from the literature; [4] calculations show it to be substantially correct.

It is evidently much more economical where both steam and power are required for process in constant amounts to generate steam at a higher pressure than needed for process and use in a prime mover as much heat as possible before sending to process, than to throttle the high pressure steam directly to process conditions. The high irreversibility of the throttling process introduces serious thermal losses. The economy of using bleeder turbines rather than direct throttling for steam requirements is discussed in Appendix II.

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* Literature references on page 268.