A.I.Ch.E. ANNUAL STUDENT COMPETITION—1936

Foreword

The problem presented to the members of the Institute's student chapters for solution in the Fifth Annual Contest was the interpretation of three runs obtained in the pilot plant operation of an electric furnace manufacturing elemental phosphorus from phosphate rock. Complete heat and material balances were required. The solution was to be submitted in the form of a monthly progress report.

Council sponsors these contests annually through its Committee on Student Chapters. The committee this year appointed Raymond L. Copson, Chairman; and R. H. Newton and C. E. Hartford members of the Sub-Committee on Awards. These members are all with the T.V.A., and are located at Wilson Dam, Alabama.

Reports that reached the committee indicated that a larger number of students attempt a solution of the problem each year. In several of the schools solution of the problem is made a regular part of the class work. Only the three best solutions from each chapter are submitted to the Sub-Committee on Awards. This selection is made by the chapter counsellor. This year forty-eight solutions were submitted from twenty-six colleges.

To Henry G. Staaterman of Cooper Union went the first prize of $100; to Paul A. Mills of Ohio State University, second prize, $50; to John H. Johnsen, Armour Institute of Technology, third prize, $25. Three honorable mention prizes were awarded for the first time in 1936. These went to Walter J. Ewbank, Purdue University; F. J. McAdam, Columbia University, and Charles J. Leyes, Cooper Union.

The first prize solution of the problem follows.

Frederic J. LeMaistre, *Secretary.*

CONTEST PROBLEM

1936

National Student Competition Sponsored by the American Institute of Chemical Engineers Under the Direction of the Committee on Student Chapters

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

Statement

An experimental pilot plant for the production of phosphorus from phosphate rock consists of an electric furnace, a phosphorus condenser, and the accompanying accessory equipment.

Phosphate rock, silica, and coke are crushed to the proper size, weighed, mixed, and charged into the furnace. The furnace is a single-phase unit, has two carbon electrodes, and is lined with carbon below the slag line and with refractory brick above. It has a rated capacity of 200 kw. Slag and metal (ferrophosphorus) are tapped from the furnace at intervals of a few hours, and are weighed when cool.

The gas from the furnace passes directly into the bottom of the condenser, which consists essentially of a vertical, cylindrical chamber. Water sprays are located in the upper half of the condenser. The condensed, molten phosphorus and the unevaporated water are removed from the bottom of the condenser through a water seal. The phosphorus is collected and weighed under water.

The cooled gas leaving the top of the condenser passes through an exhauster and is discharged through a vertical pipe line, at the top of which it is burned. The exhauster is operated so as to maintain a slight suction throughout the system; this tends to prevent leakage of phosphorus vapor and carbon monoxide from the electric furnace.

During the period with which we are concerned, this pilot plant was operated continuously for thirty days. After three days of preliminary operation, three test runs of nine days duration each were made successively. The object of these runs was to study the effect of variations in the composition of the furnace charge upon the recovery of phosphorus, and upon the electrical power used. The runs were designated as No. 1, No. 2, and No. 3, respectively. The following experimental data were obtained:

	No. 1	No. 2	No. 3
Power input to furnace, total kw. hrs.	43,600	39,500	39,100
Phosphate rock charged to furnace, total pounds	43,000	41,000	27,000
Composition of phosphate rock, average,			
P_2O_5, %	31.0	25.4	33.3
CaO, %	44.0	35.3	46.9
SiO_2, %	14.0	16.8	5.0
Fe_2O_3, %	2.0	5.5	3.3
Al_2O_3, %	1.5	5.3	1.8
CO_2, %	1.4	4.0	2.6
F, %	3.6	2.9	3.7
H_2O, %	1.0	2.2	1.5
Silica charged to furnace, total pounds.	7,750	4,500	12,400
Composition of silica, average,			
SiO_2, %	96.3	92.0	95.5
Fe_2O_3, %	0.8	2.6	1.5
Al_2O_3, %	0.5	1.7	1.2
CaO, %	1.3	1.9	0.9
CO_2, %	1.0	1.5	0.7
H_2O, %	0.1	0.1	0.1
Coke charged to furnace, total pounds..	6,900	5,750	4,900
Composition of coke, dry basis, average,			
Fixed carbon, %	85.8	82.5	84.6
Volatile combustible matter, %	2.3	1.8	2.0
SiO_2, %	6.1	7.2	6.5
Fe_2O_3, %	1.8	2.9	1.8
Al_2O_3, %	4.0	5.4	5.0
Moisture in coke, %	0.5	0.3	0.5
Slag tapped from furnace, total pounds.	36,200	30,500	28,400
Composition of slag, average,			
CaO, %	51.9	47.0	42.9
SiO_2, %	37.6	36.4	50.5
Al_2O_3, %	2.0	7.6	2.6
Fe_2O_3, %	0.1	0.3	0.2
P_2O_5, %	2.2	2.1	0.4
F, %	3.2	3.0	1.2
Ferrophosphorus tapped from furnace, total pounds	1,270	2,300	1,570
Composition of ferrophosphorus, average,			
P, %	26.1	25.9	25.7
Si, %	0.2	0.1	0.1
Temperature of slag and ferrophosphorus tapped from furnace, average, °F.	2,720	2,610	2,650
Temperature of gas between furnace and condenser, average, °F.	430	390	420
Phosphorus recovered from condenser, total pounds	4,600	3,280	3,180
Composition of phosphorus, average, Phosphorus, %	99.1	99.3	98.8
Temperature of phosphorus and water from condenser, average, °F.	140	130	135
Temperature of gas leaving condenser, average, °F.	120	100	110
Temperature of water sprayed into condenser, average, °F.	65	65	65
Quantity of water sprayed into condenser, total gallons	2,000	3,940	2,810
Orsat analysis of gas leaving condenser, average,			
CO, %	92.8	86.8	88.0
CO_2, %	2.5	7.9	4.1
Phosphorus in gas leaving condenser, average, grams per cu. ft. (S.T.P.)..	0.108	0.055	0.077

You are a member of the group engaged in the operation of this pilot plant. You are to prepare a progress report for the month under consideration. In preceding progress reports, the pilot plant, method of operation, and previous experimental runs have been described. The report to be prepared should be confined to a discussion of the above three runs.

The report should include heat and material balanaces, both on the furnace and on the condenser. Quantities not measured should be calculated where possible. To conform to the practice in previous reports, the heat and material balances should be set up on the basis of one ton (2,000 lbs.) of phosphorus in the furnace charge, employing the units tons and B.T.U.

The material balances should indicate clearly the distribution of phosphorus, fluorine, and silica in the products. Both the percentage volatilization of phosphorus in the furnace, and the percentage recovery of phosphorus from the furnace gases, should be calculated.

From the heat balances, the thermal efficiency of the furnace should be calculated as that fraction of the total power which is effective in bringing about the reactions in the furnace and in heating the products leaving the furnace. There should also be calculated the effective power consumption per ton (2,000 lbs.) of phosphorus volatilized.

In interpreting the results, there should be discussed in particular the effect of composition of the phosphate rock and of the furnace charge upon the recovery of phosphorus, and upon the power consumption. It is also required to predict the performance of an electric furnace of commercial size, upon the assumption that the percentage recovery of phosphorus will be the same as in the pilot plant, but that the large furnace will have a thermal efficiency of 90 per cent. In addition, the discussion should be extended to include other items in so far as is justified by the data, in order to derive the maximum amount of information from the experimental results.

In making the calculations, the heat of formation of slag from CaO and SiO_2 should be taken as 270 B.T.U. per pound. Other data required to supplement that given above should be obtained from the literature, or should be approximated by suitable assumptions.

Method of Presentation

Assume that the progress report is to be submitted to the director of research. The report should be in such form that this executive can ascertain in a few minutes exactly what was done, the results obtained, and the conclusions drawn. He also will require that any assumptions be clearly indicated, and the calculations given in sufficient detail so that they may be checked readily by his technical assistant.

It is to be assumed that the above statement of the problem contains all the experimental data available. It will be necessary to obtain supplemental data or information by the use of textbooks, reference books, journal articles, or lecture notes. The source of such data should be indicated. A survey of literature sources pertinent to the problem may well precede the solution, but a written survey should not be included in the report.

The exact arrangement of the report as to form and context is left to your judgment of how you best can meet the above requirements. In grading the reports consideration will be given, first, to the appearance, form, and grammatical correctness of the report; second, to the accuracy and completeness of the calculations; and, finally, to the ability demonstrated in deriving the maximum information from the data, in discussing the results, and in drawing correct conclusions.

Your instructor is not to be consulted in regard to doubtful points. The problem is not to be discussed with anyone. The solution is understood to represent the work of the individual contestant, and submittal of a report for the competition implies adherence to the above conditions.

Solutions must be received by local Chapter Counsellor three weeks after statement of problems are issued at that chapter.

Each solution should be accompanied by a letter of transmittal giving only the contestant's name, school address, home address, and student chapter. This letter will be retained for identification by the Chairman of the Committee on Student Chapters. The solution itself must contain no reference to the student's name or institution by which it might be identified. Each Counsellor should select the best solutions from his chapter, not more than three in number, and mail these to A. McLaren White, University of North Carolina, Chapel Hill, North Carolina, *to arrive* not later than March 15, 1936.

FIRST PRIZE WINNING SOLUTION

CONTEST PROBLEM

1936

Student Chapters

American Institute of Chemical Engineers

By

HENRY G. STAATERMAN

Cooper Union

Awarded first prize. This is, in general, an excellent example of report writing. It is concise, and the results are conveniently summarized. The calculations are accurate, complete, and clearly indicated. The sources of data are particularly well shown. The author assumes that the data on the composition of the gas leaving the condenser are in error, and that the water in the furnace charge is reduced. These assumptions are not defended or explained. The discussion of the effect of changes in the composition of the furnace charge is inadequate.—Sub-Committee on Awards.

PROGRESS REPORT

Test Operations of an Experimental Pilot Plant for the Electrothermal Production of Phosphorus

TABLE OF CONTENTS

Sample Calculations, Run 1

INTRODUCTION

The object of the test operations on the experimental pilot plant (described in previous reports) for the electrothermal production of phosphorus is to study the effect of variations in the composition of the furnace charge upon the recovery of phosphorus and upon the electrical power consumed.

Briefly described, the plant consists of an electric furnace, a phosphorus condenser (water spray type), and the accompanying accessory equipment. The furnace is a single-phase unit, has two carbon electrodes, and is lined with carbon below the slag line and with refractory brick above. It has a rated capacity of 200 kw. Furnace gases pass directly from the furnace to the bottom of the condenser, which consists essentially of a vertical, cylindrical chamber.

In preceding reports the pilot plant, method of operation, and previous experimental runs have been described.

SUMMARY OF THE REPORT

Phosphate rock, silica, and coke are crushed to the proper size, weighed, mixed, and charged to the furnace in varying proportions. For each test a different phosphate rock is employed. Slag and ferrophosphorus are tapped from the furnace at intervals of a few hours and are weighed when cool. The condensed, molten phosphorus and the unevaporated water are removed from the bottom of the condenser through a water seal; the phosphorus is collected and weighed under water. An Orsat analysis of the condenser gases is made. The gases are also analyzed for phosphorus. Chemical analyses of the charge, slag, and ferrophosphorus are made. The plant is operated continuously for thirty days, three days for preliminary operations, and nine days for each of three test runs. Various data essential in preparing material and heat balances on the furnace and the condenser are recorded. Quantities not measured are obtained from the literature or calculated where possible or approximated by suitable assumptions. Material and heat balances have been made on the furnace and the condenser. The distribution of phosphorus, silica, and fluorine in the products is calculated. The percentage volatilization of phosphorus in the furnace and the percentage recovery of phosphorus from the furnace gases are calculated. From the heat balances, the thermal efficiency of the furnace is calculated, which is that fraction of the total power which is effective in bringing about the reactions in the furnace and in heating the products leaving the furnace. The effective power consumption per ton (2,000 lbs.) of phosphorus volatilized is also calculated. See tables No. 1, 2, 3, 4.

CONCLUSIONS

Phosphorus is most economically produced in run 1, as compared with run 2 and run 3. Therefore, the percentages by weight of $Ca_3(PO_4)_2$,SiO_2, and carbon in the charge of run 1 are those to be employed for the best operating conditions.

If the percentage of silica is greatly increased, a large decrease in the thermal efficiency of the furnace results. The effective power consumption per ton of phosphorus volatilized is not appreciably affected. (Compare run 1 with run 3.) In run 3 there is a large unaccounted for heat loss from the furnace; the furnace is probably operating at a higher temperature than those of the other runs. The silica balance for this run indicates that the refractory lining of the furnace is deteriorating.

When a low grade ore, such as in run 2, is used, the effective power consumption per ton of phosphorus volatilized increases due to the greater amount of oxides of iron, silicon, aluminum, etc., which enter with one ton of phosphorus. An increase in the percentage of carbon in this charge does not evolve enough heat in smelting to take care of the amount required to reduce some of the above oxides.

From the condenser material balances it is seen that over twice the amount of spray water must be pumped into the condenser in run 3 as in run 1 with 42 lbs. extra condensation of phosphorus in run 3.

The analysis of the condensed phosphorus indicates in each run that no marked fuming occurs.

The percentage of volatilization of phosphorus and the percentage recovery of phosphorus increase with the "richness of the ore."

When the furnace charge is made up as in run 1, considerably less material must be handled (mixed, weighed, etc.) for one ton of phosphorus charged.

RECOMMENDATIONS

A commercial size furnace will operate with less power-input per ton of phosphorus charged (assuming that all other conditions remain the same). The thermal efficiency of a commercial furnace is assumed to be 90%. Assume that this furnace is charged as in run 1. Then, according to the basis chosen here, 33,079,000 B.T.U. are required to bring about the reactions in the furnace and heat the outgoing products. The power input is given by:

$$\frac{33{,}079{,}000}{0.2930 \times 1000 \times 0.9} = 12{,}800 \text{ kw.hr./ton phosphorus charged.}$$

The power input for the pilot plant furnace is given by:

$$0.344 \times 43600 = 15{,}000 \text{ kw.hr./ton phosphorus charged.}$$

It is then evident that the same will be true if the charge is that of run 2 or run 3. The power input to the commercial furnace, when the charge is that of run 2, is given by:

$$\frac{36{,}844{,}000}{0.2930 \times 0.9 \times 1000} = 14{,}000 \text{ kw.hr./ton phosphorus charged.}$$