THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

COMPUTER PREDICTION OF CUPOLA PERFORMANCE UTILIZING OXYGEN AND NATURAL GAS IN THE BLAST

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Considerable interest has recently been generated in the use of natural gas as a cupola blast injectant. As a potential replacement for part of the scarce high-quality metallurgical coke, natural gas injection could represent a considerable economic saving in cupola operations. Plant tests have been carried out to study the effect of natural gas injection in the cupola blast, but very few results have been reported in the technical literature. In contrast, however, the use of oxygen to enrich the cupola blast has been explored and reported quite extensively.[1-8] Independently, the use of a high temperature blast to effect coke savings and increase production rates has led to the development of the hot blast cupola. This is a particularly significant technological development in the cupola melting field, and has been studied in a number of investigations.[1,9-20] Cupola blast injection with oxygen and/or natural gas, simultaneous with higher blast temperatures, potentially offers a means by which a considerable increase in production and a substantial savings in coke consumption can be realized with current operating equipment.

A large number of studies have been implemented to evaluate the effects of blast enrichment, injection, and temperature changes on cupola performance. The difficulties in carrying out an experimental study on production-sized equipment are particularly troublesome in view of the fact that a considerable variation in most of the operating conditions is experienced throughout a trial period. It is possible to overcome some of this difficulty and provide a more consistent analysis of the experimental data when mass and energy balances on the experimental period are utilized in conjunction with the plant test results. To date, however, very few complete complete and detailed plant data have been published which permit accurate mass and energy balances to be made.

In an effort to stimulate interest among foundrymen in ultimately providing for a full study of any operating variable on the cupola furnace, and to execute a preliminary prediction of the coke savings and production increases possible with oxygen enrichment and natural gas injection, a computer study of these variables has been carried out utilizing a previously developed Thermochemical Model.[21]

THE THERMOCHEMICAL MODEL

The Thermochemical Model utilizes a mass and energy balance for the cupola melting furnace and a kinetic relationship based principally on the wind rate in order to provide a mathematical description of furnace operation. The Model utilizes prior furnace performance data to establish a base period of operation. Thermochemical equations employing a mass and energy balance are then applied to predict coke consumption and melting rate changes for different operating conditions. This Model has been previously discussed in some detail and its derivation outlined.[21]

The predictions made by this Thermochemical Model are dependent upon having the general operating conditions of the cupola furnace remain fairly constant. Both physical and chemical limitations exist which control cupola operations, and it is these conditions which must be satisfied for a meaningful prediction in terms of attainable operating conditions. Consequently, the Thermochemical Model must be used with discretion and with a careful consideration of the feasible operating conditions for a specific cupola operation. This approach should provide a reasonable basis for predicting the conditions under which optimum cupola performance can be realized.

COMPUTER PREDICTIONS

The use of the Thermochemical Model in predicting cupola performance has been discussed in some detail; and coke requirement and melting rate changes with oxygen enrichment, natural gas injection, and variable blast temperatures have been reviewed.[21] In the present discussion, however, these preliminary calculations have been considerably extended and the mutual effects of these three operating variables have been considered.

In executing these calculations, the reference period data are taken from the report of Sub-committee TS 52.[22] Qualitatively a change in operating condition should provide a similar effect regardless of the size of operation, but quantitative agreement may not be precise. The predictions recorded below should therefore be considered as pertaining only to the small cupola operation from which the reference data were taken; a similar result however, would be expected on larger operating units.

Prior to discussing the combined effect of oxygen enrichment, natural gas injection, and blast temperature, the individual contribution of each variable will be considered.

OXYGEN ENRICHMENT

Plant and laboratory tests of cupola operation with oxygen enrichment (see Table I) unanimously concur that oxygen enrichment will reduce coke rate and provide a higher melting rate. Calculations of predicted cupola performance with oxygen-enriched blasts were carried out using the Thermochemical Model. The results of these calculations are presented in Figures 1 and 2. Figure 1 demonstrates a marked decrease in coke rate with increasing oxygen enrichment, as indicated by the relative postions of the respective curves of 0%, 2%, and 4% oxygen enrichment. In Figure 2 the positions of the oxygen enrichment curves indicate that melting rate will increase with increasing oxygen enrichment.

NATURAL GAS INJECTION

The predicted coke and melting rates of 0%, 2% and 4% natural gas injection were evaluated for various blast temperatures. The results of these calculations are presented in Figures 3 and 4. In Figure 3 the coke rate is shown to decrease with increasing natural gas injection, as indicated by the respective positions of the curves. In Figure 4, the curves have the same relative positions that they held in Figure 3. This indicates that the production rate will slightly decrease, as shown by the proximity of the curves, with increasing levels of natural gas injection.

The reported plant trials (Table II) on natural gas injection indicated in two cases[23,24] that the use of natural gas (amount undisclosed) would markedly decrease the coke rate. In a more completely reported

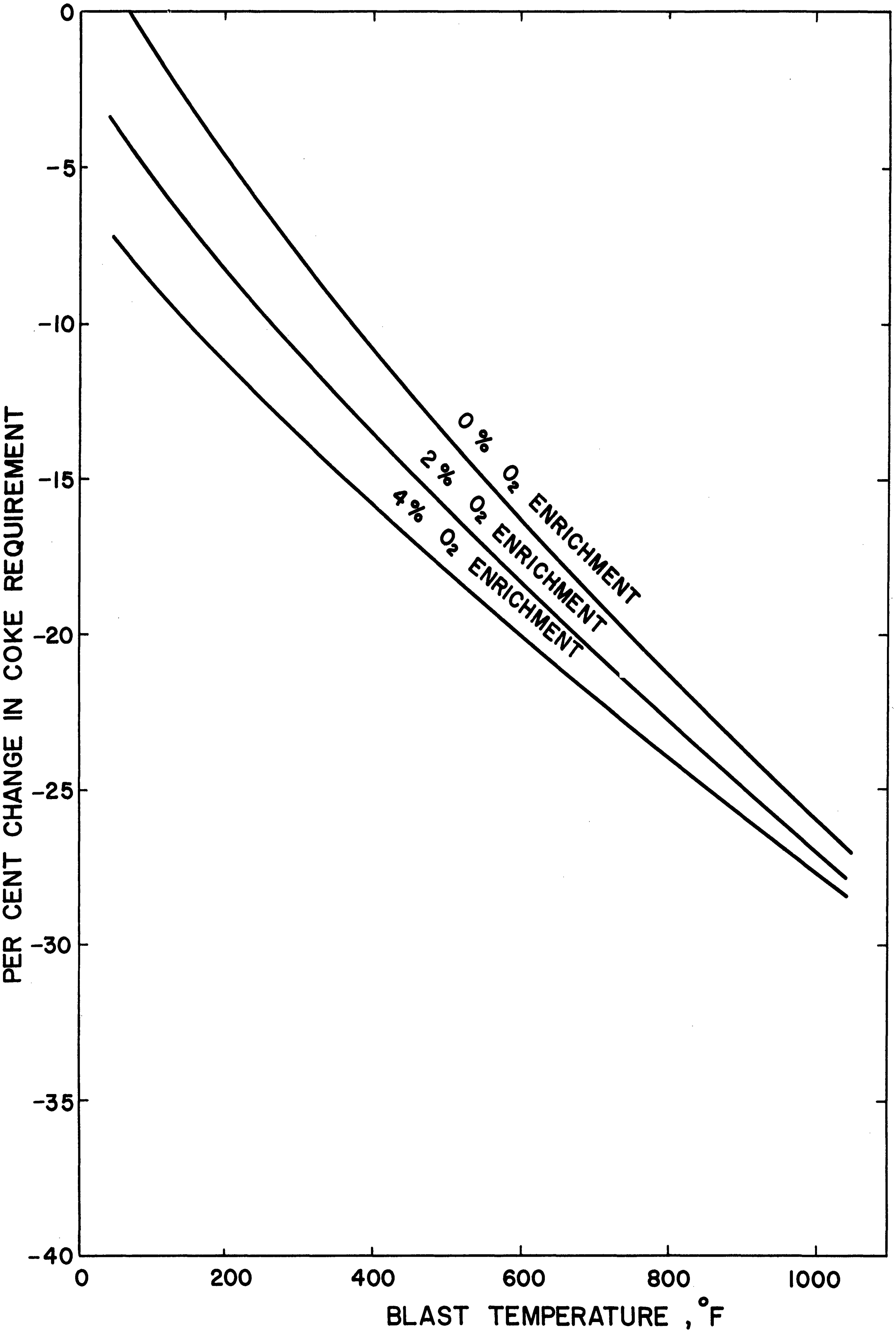

Figure 1. Calculated Effect of Oxygen Enrichment on Coke Requirement.

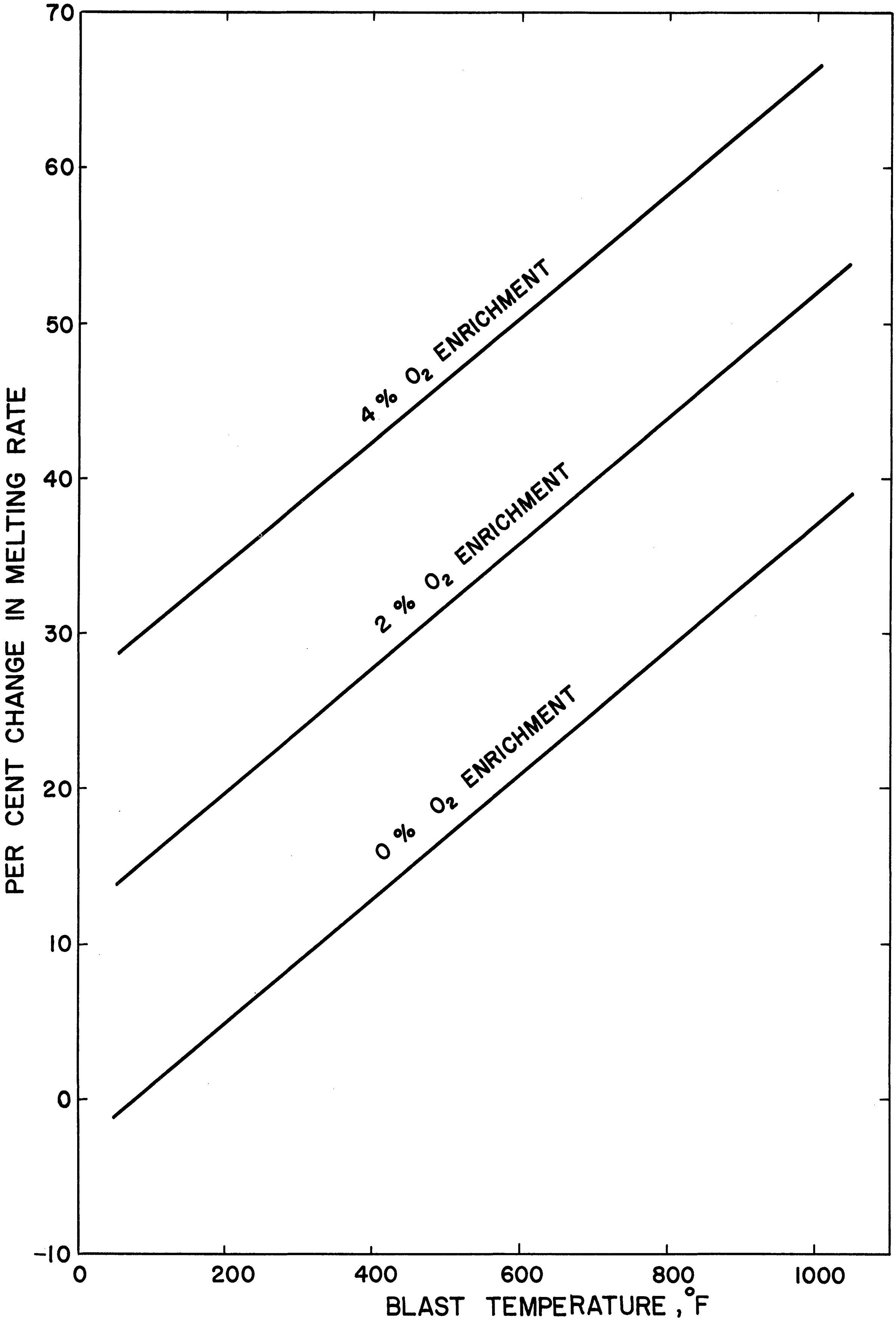

Figure 2. Calculated Effect of Oxygen Enrichment on Melting Rate.

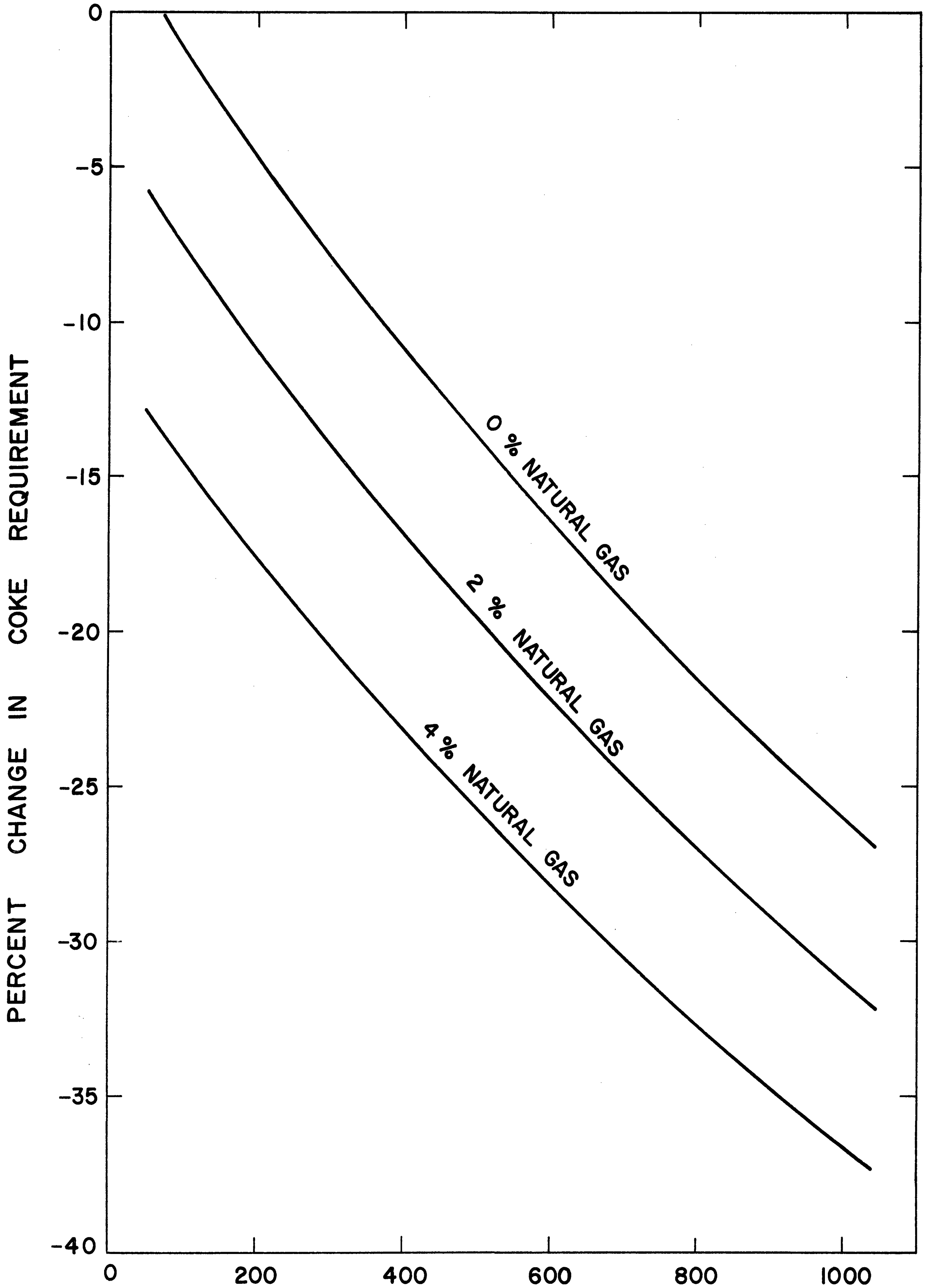

Figure 3. Calculated Effect of Natural Gas Injection on Coke Requirement.

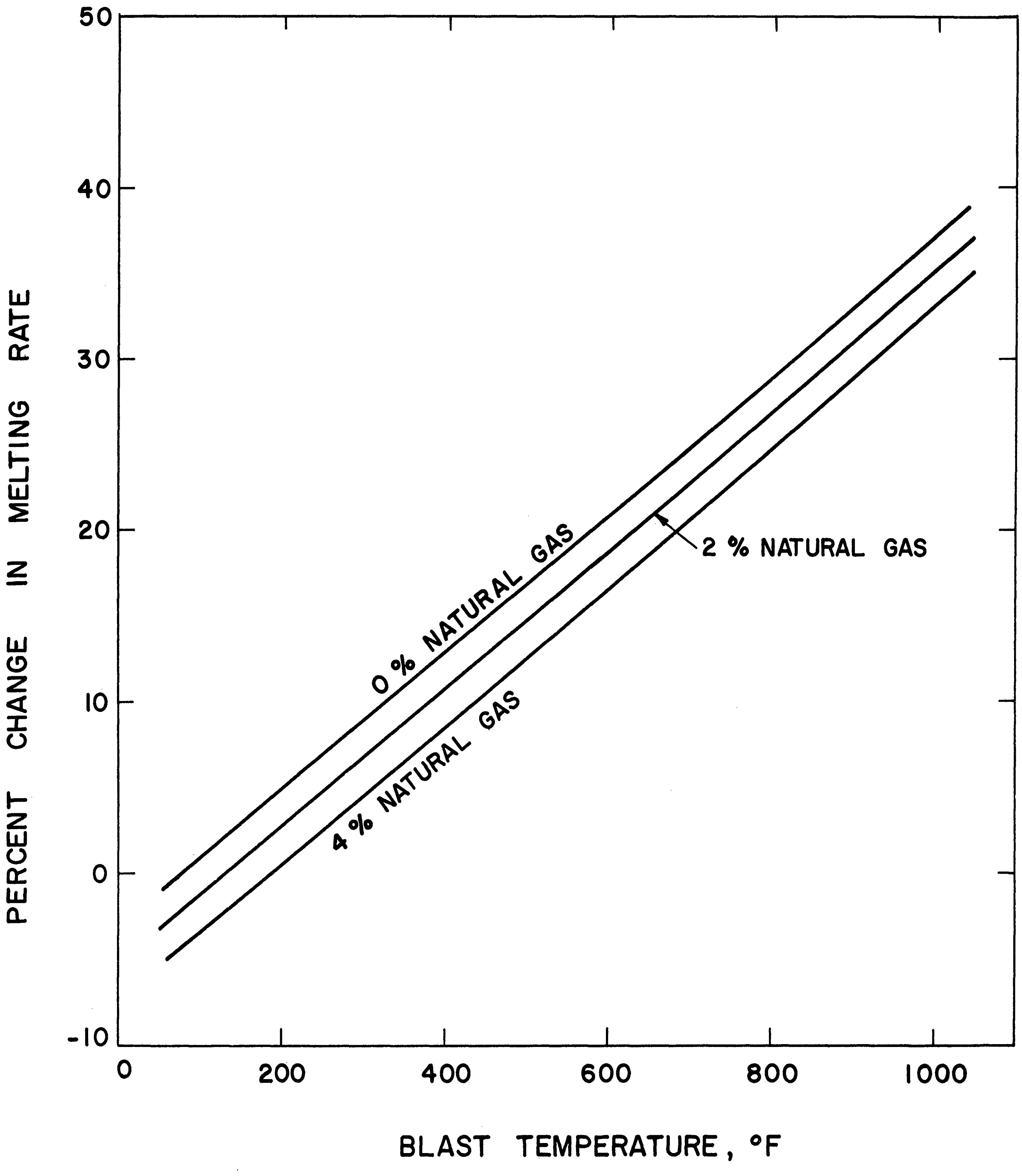

Figure 4. Calculated Effect of Natural Gas Injection on Melting Rate.

TABLE I

INFLUENCE OF OXYGEN INJECTION ON COKE AND MELTING RATES

Reference	Change in Coke Rate	Change in Melting Rate	% O_2 Injection
1	0	4%	2%*
1	0	20 to 25%	2%**
1	-3	0	2%*
1	-22	0	2%**
1	--	25%	2.5-3.0
2	-1.3%	25%	1.4-4.5
3	0	9.0	4.5
4,5	0	19.4	8.6
4,5	0	40.2	13.8
4,5	-11.5 to 12.5%	nil	1.0
6	-8.3 to 15.4%	+16.7%	1.7
	nil	+20.0%	2.8
7,8	-4%	+100%	5%

* Direct oxygen enrichment

** Oxygen injected in cupola well

TABLE II

INFLUENCE OF NATURAL GAS INJECTION ON COKE AND MELTING RATES

Reference	Change in Coke Rate	Change in Melting Rate	% Natural Gas
23	-50%	--	--
24	-50%	--	--
25	-27.5	5*	4.7
	-46.5	16*	4.52
	-46.5	18.2*	4.34
	-40 to 50**	15 to 20**	4.5**

* Corrected to reference blast rate

** Average values

series of tests,[25] the coke rate was observed to decrease on the order of 40-50%, whereas the melting rate increased by 15-20%, at the 4 1/2% natural gas level. The results predicted by the Thermochemical Model are much more conservative than these reported plant results and are based on unchanged operating conditions. There is, however, some indication that improved combustion efficiency and top gas temperatures may be achieved with changes in blast conditions. The conclusion that can be reached from the computer prediction combined with plant tests is that a coke saving can be realized with natural gas injection, but that the improvement in melting rate is less than the corresponding improvement in coke rate; moreover, in the limiting case there may even be a slight decrease in the melting rate.

BLAST TEMPERATURE

The curves of Figures 1 and 3 indicate that the coke rate sharply decreases with increasing blast temperature whereas in Figures 2 and 4 the melting rate is shown to increase markedly with increasing blast temperature. These results are in good agreement with numerous plant investigations on the hot-blast cupola. Table III summarizes the results of various plant and laboratory investigations of the influence of blast temperature on coke and melting rates. These studies are almost unanimous in their agreement that increasing blast temperature decreases coke rate and increases melting rate.

A statistical average of the results reported in Table III reveals that a blast temperature on the order of 500°C (930°F) should decrease the coke rate by 25% and increase the melting rate by approximately 30%.

TABLE III

INFLUENCE OF BLAST TEMPERATURE ON COKE AND MELTING RATES

Reference	Change in Coke Rate	Change in Melting Rate	Hot Blast Temperature
1	0	+13.5%	520°C
1	33%	0	520°C
9	-30%	0	450-500°C
9	0	+30 to 50%	450-500°C
10	-8%	--	600°C
11	-35 to 50%	--	---
12	--	+4%	500°C
13	-22 to 30%	--	500°C
14	-55%	+50%	600°C
15	--	15 to 20%	---
16	-33%	33%	---
17	-27%	*	500-550°C
17	-28%	*	430°C
18	nil	20	400°C
18	-14.4	17	470°C
18	-19.0	22	470°C
18	-27.0	25	550°C
18	-28.7	33	450°C
18	-33.0	20	450°C
18	-6.0	nil	500°C
18	-25.5	50	390°C
18	-14.2	17	390°C
18	-28.7	49	500°C
18	-29.5	21	500-600°C
19	+33%	-12.5	400-500°C
19	-33%	+33	500°C
19	-23	nil	500°C
19	-12	nil	520°C
19	-20	+12.5	520°C
19	-29	nil	525°C
20	-28	+25%	320°C

* Increased corresponding to decrease in coke rate.

A comparison of these average results with the zero injection level curves of Figures 1 and 2 indicates that there is a good correspondence between the computer prediction and the average results obtained in practice.

SIMULTANEOUS ENRICHMENT, INJECTION, AND BLAST PREHEAT

The simultaneous effects of oxygen enrichment, natural gas injection, and blast preheat are not directly calculable by summation of the individual effects of each blast modification. However, this technique of totalling the individual effects will provide a reasonable estimate of the combined influence of various injections on cupola coke requirement and melting rate. Calculations were made of the simultaneous effect of oxygen enrichment and natural gas injection; in Figures 5 and 6 the results at the 2% and 4% levels of each constituent are presented as a function of blast temperature.

The simultaneous employment of oxygen and natural gas offers considerable opportunity for increasing the melting rate and decreasing the coke requirement. A further advantage in the control of the cupola melting process could be realized through injection rate, which would provide a control technique to which the process would rapidly respond. Of even greater importance may be the necessity for simultaneously using oxygen and natural gas to obtain optimum performance with practicable operating conditions as discussed in the following section.

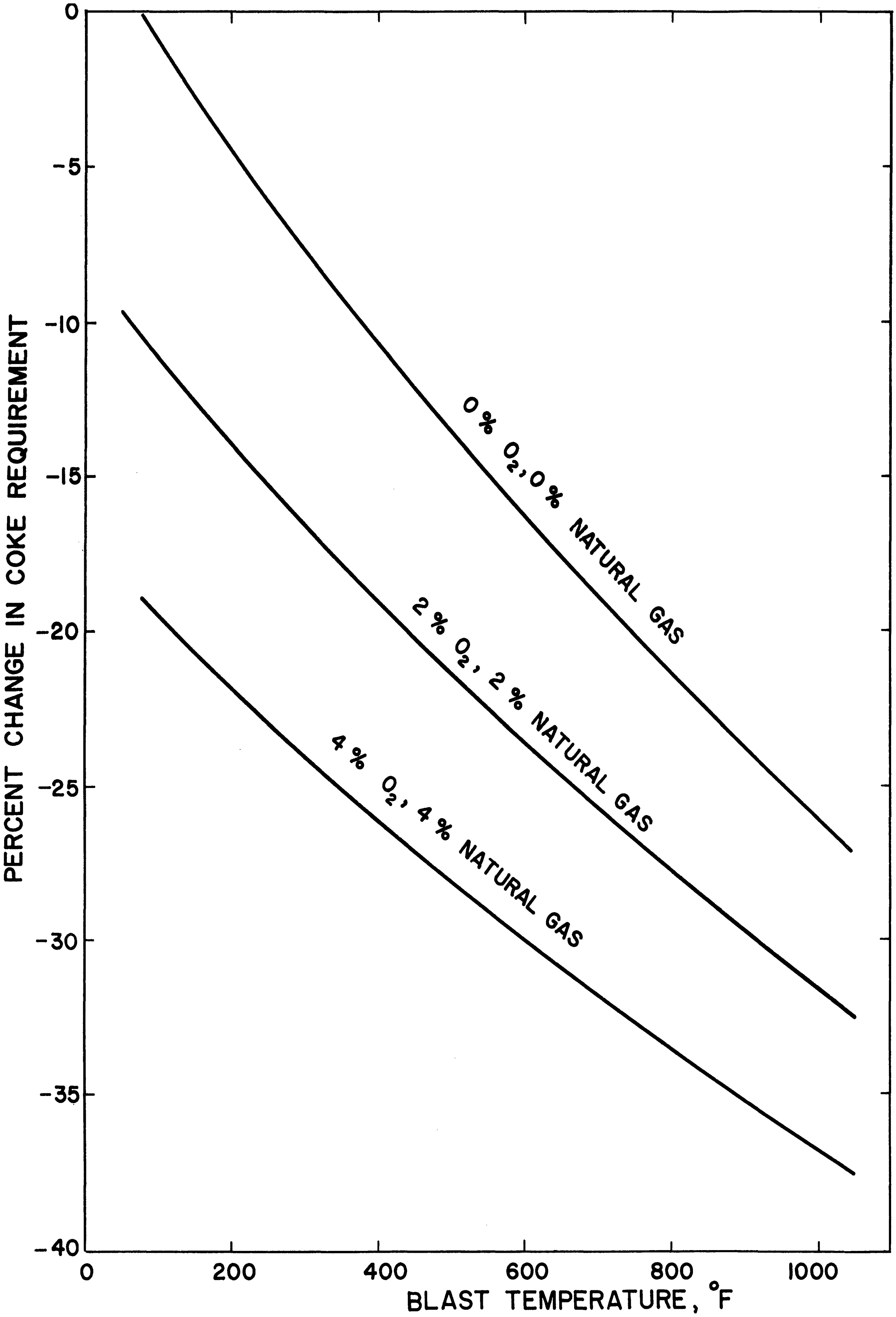

Figure 5. Calculated Effect of Simultaneous Oxygen Enrichment and Natural Gas Injection on Coke Requirement.

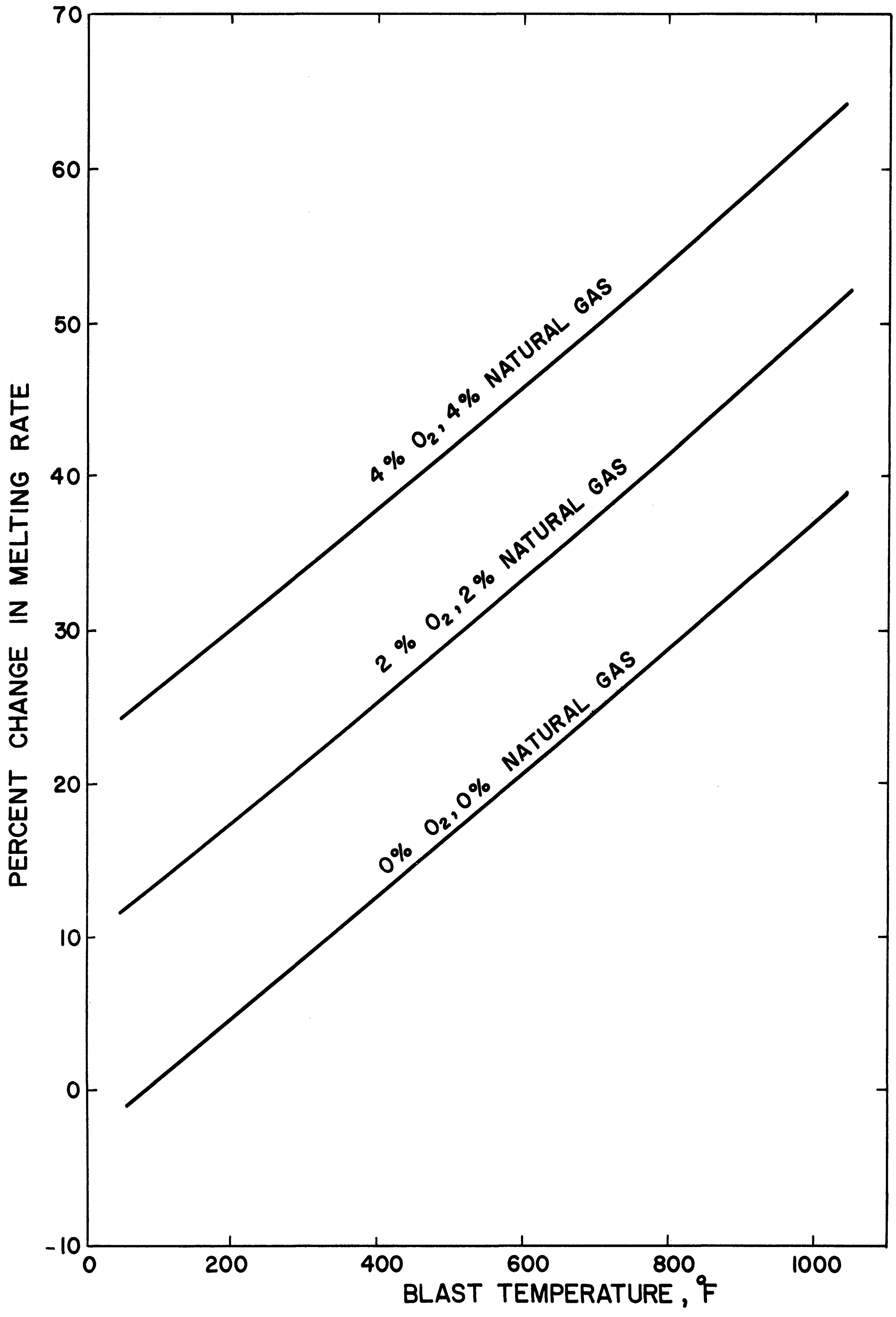

Figure 6. Calculated Effect of Simultaneous Oxygen Enrichment and Natural Gas Injection on Melting Rate.

ADIABATIC FLAME TEMPERATURE CONCEPT

The operating conditions attainable with oxygen and natural gas injection are not well established. However, one of the physical limitations which is placed on the coke-fueled shaft furnace (such as the cupola or blast furnace) is the necessity for a specific temperature distribution to exist in the melting zone just above the tuyeres. As oxygen or natural gas is injected into the blast, the temperature distribution in the melting zone will change. To enable the furnace to accommodate these changes in blast composition and maintain the desired temperature distribution above the tuyere zone, the concept of adiabatic flame temperature can be adopted.

The adiabatic flame temperature is assumed to relate to the combustion of the blast with the downwardly moving coke in the zone just in front of and above the tuyeres. If the furnace has been satisfactorily operating with a given burden and blast composition and temperature, the adiabatic flame temperature can be computed for these conditions, assuming an incoming temperature for the downwardly moving coke and neglecting temperature changes of the metal and slag components as they move through this zone. The combustion products at the flame temperatures encountered in normal plant operations can be assumed to be carbon monoxide and hydrogen along with the unchanged nitrogen.

If a suitable flame temperature for a particular furnace has been determined, it is also possible to compute the adjustments in blast composition and temperature to maintain this flame temperature. Several possiblilties exist. For example, the blast could be enriched with oxygen and a compensation made for the increased flame temperature by adding moisture or natural gas. Alternatively, the blast temperature could be increased, which would increase the flame temperature, and a compensation made by adding moisture or natural gas. This concept has been very useful as a guide in estimating the ranges of potential blast conditions for the iron blast furnace.[26,27] Futhermore, cupola refractory life could be extended by controlling the temperature distribution at the tuyeres, and in addition some of the initial difficulties encountered with injection in the cupola could be better controlled.[7]

The injection of cold natural gas at the tuyeres decreases the temperature in the melting zone because of the decomposition of the gas (approximately 90% methane) to carbon and hydrogen. Since the ensuing combustion in the presence of hot coke does not proceed beyond carbon monoxide and hydrogen, the overall result is that less energy is developed within the melting zone with injection. Consequently, natural gas injection should be accompanied by oxygen enrichment or an increased blast temperature to maintain a given melting zone temperature. Figure 7 presents the effect of natural gas injection and oxygen enrichment on the adiabatic flame temperature at the tuyeres. These calculations are based on a constant moisture level in the entering air of 5.5 grains/ft^3 and a coke temperature of 2800°F. The curves should prove useful for comparative purposes, although the actual accuracy

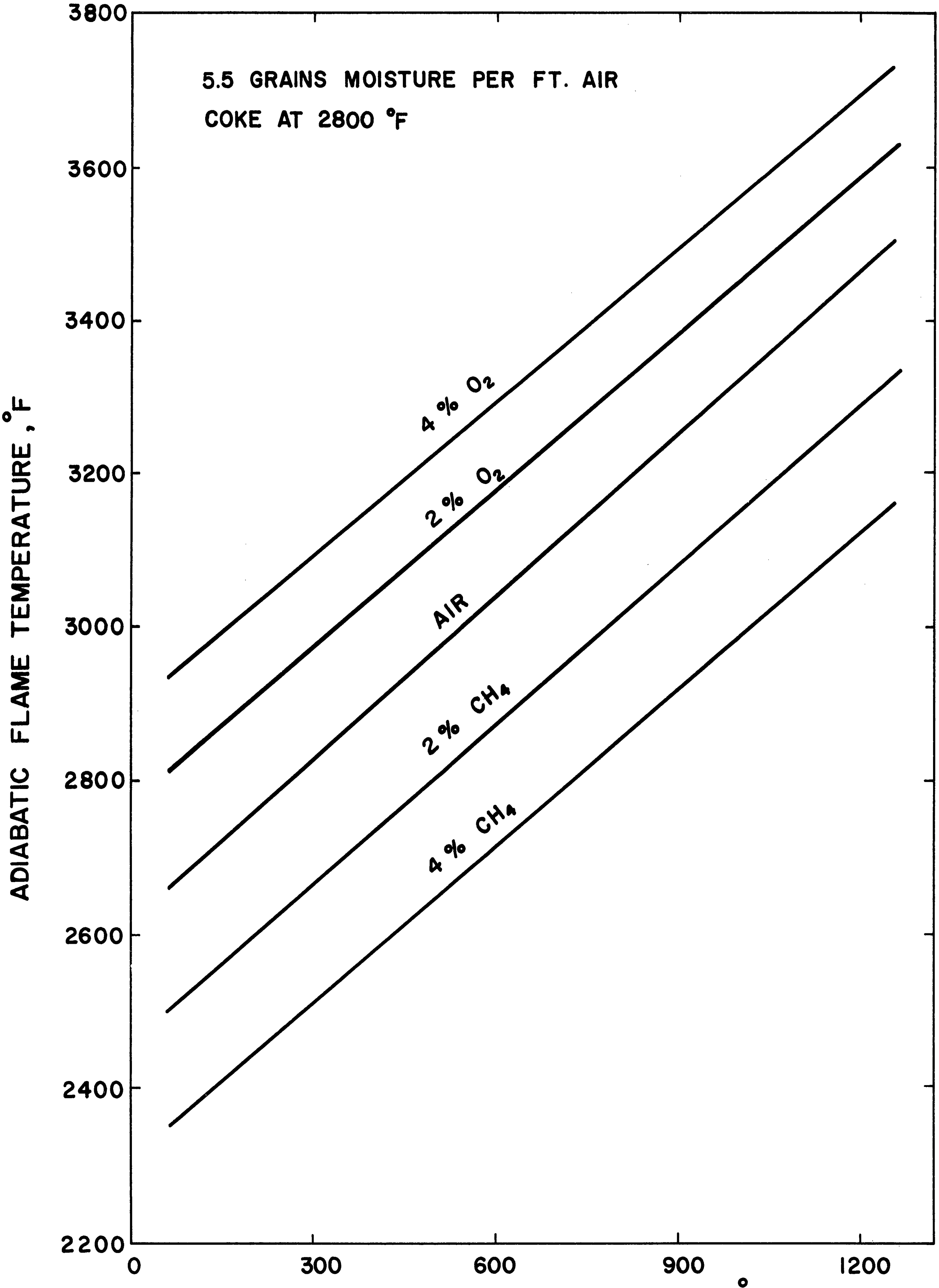

Figure 7. Calculated Adiabatic Flame Temperature in Tuyere Zone for Various Levels of Blast Enrichment.

of the calculated flame temperatures is limited by the accuracy of the assumptions on which they are based. It is reasonable, however, to assume that blast conditions which produce an adiabatic flame temperature in the same range as those which are already achieved with good operating conditions would provide a smooth cupola practice.

Recognizing that the foregoing analysis is presented only as a useful guide, another possibility might be considered upon which satisfactory operating conditions could be estimated. This prediction of operating conditions could be based on the oxidation level, or oxygen potential, of the blast to provide a consistent metalloid recovery to the iron. Oxidation loss at higher levels of oxygen enrichment may represent a limit to the extent of economical oxygen utilization in cupola melting.[28] Consequently, an analysis of the oxygen potential of the blast could possibly be based on a mass balance and a dynamic model for combustion at the tuyeres. This model might be developed to provide a basis for predicting levels of blast injection which are acceptable in terms of temperature and chemistry of the slag, metal, and gas phases in the tuyere zone.

VARIATION IN OPERATING CONDITIONS

The predicted results when utilizing oxygen and natural gas in the blast are based on an assumed set of operating conditions. The normal range of conditions realized with a present cupola operation may be markedly changed when the blast conditions are altered. Changes in metal temperature, metal compositions, CO/CO_2 ratio, metalloid recovery, and top gas temperature can result when blast modifications are made.[1,4,8,17-20,22,29-33] Furthermore, the technique employed in making a blast modification is very important in controlling changes in operating conditions. For example, marked differences in metal temperature and metal carbon and silicon contents were noted when 2% oxygen was injected into the cupola well, as compared to enriching the blast by 2%.[2]

In order to provide a means for considering these changes in predicting cupola performance, computer calculations were carried out over a range of operating conditions in order to determine the influence of each operating variable on the coke requirement and melting rate. Table IV summarizes the results of these calculations in the form of linear coefficients, which may be used to estimate the changes in coke and melting rates brought about by assumed changes in operating variables. Hence, if the cupola operator has a reasonable estimate of changes which may result in operating variables with a given set of blast modifications, the predicted cupola performance can be modified to account for these accompanying changes in furnace operation. The coefficients of Table IV were found to be nearly linear over a wide range of operating conditions. Calculations involving simultaneous changes in several variables showed the effects to be additive. Consequently, the coefficients can be utilized to make a reasonable estimate of corrections for changes in operating variables over the entire range of conditions encountered in standard commercial operations.

One other variable which becomes particularly significant as the level of natural gas injection is increased is the H_2/H_2O ratio in the stack gases. In normal operation, this change in stack gas composition is of secondary influence, important only as the moisture level in the

TABLE IV

EFFECT OF OPERATING VARIABLES ON CUPOLA COKE REQUIREMENT AND MELTING RATE AS CALCULATED BY THERMOCHEMICAL MODEL

CHANGE IN VARIABLE	PERCENT CHANGE IN COKE REQUIREMENT*	PERCENT CHANGE IN MELTING RATE*
Decrease in slag volume of 10 lb/NT Metal	-1.1	+1.0
Increase in Steel scrap in charge (substituted for pig iron) of 100 lb/NT Metal	+4.1	-1.8
Decrease in blast moisture from 5.5 to 4.5 gr/ft^3	-1.0	+0.5
Decrease of 0.1 in CO.CO$_2$ ratio in Stack Gas (1.17 to 1.07)	-3.2	+1.8
Increase of 1% in carbon content of coke	-1.4	+0.2
Decrease in Stack Gas Temperature of 100°F	-4.3	+4.5
Increase in slag temperature of 100°F	+.3	-0.3
Increase in metal temperature of 100°F	+3.2	-3.2
Increase of 0.2% in carbon content of metal	+2.4	-0.7
Increase of 0.2% in silicon content of metal	+1.8	-1.0
Increase of 0.1% in manganese content of metal	+0.5	-0.4
Increase of 0.05% in phosphorous content of metal	+1.0	-0.7

* Based on reference period of operation
Coke rate - 265 lb/NT Ton Metal
Melting rate - 6.425 Net Tone Metal/hr.
Slag Volume - 136 lb/Net Ton Metal

blast changes. In operations with natural gas injection, however, the amount of hydrogen in the stack gases as moisture or as hydrogen gas is increased. Figures 8 and 9 present the influence of variations in the stack gas H_2/H_2O ratio on cupola coke requirement and melting rate. At lower H_2/H_2O ratios, the coke rate is found to decrease whereas the melting rate increases. A lower ratio indicates a higher H_2O content in the stack gas and hence an increase in the thermal energy released in the furnace.

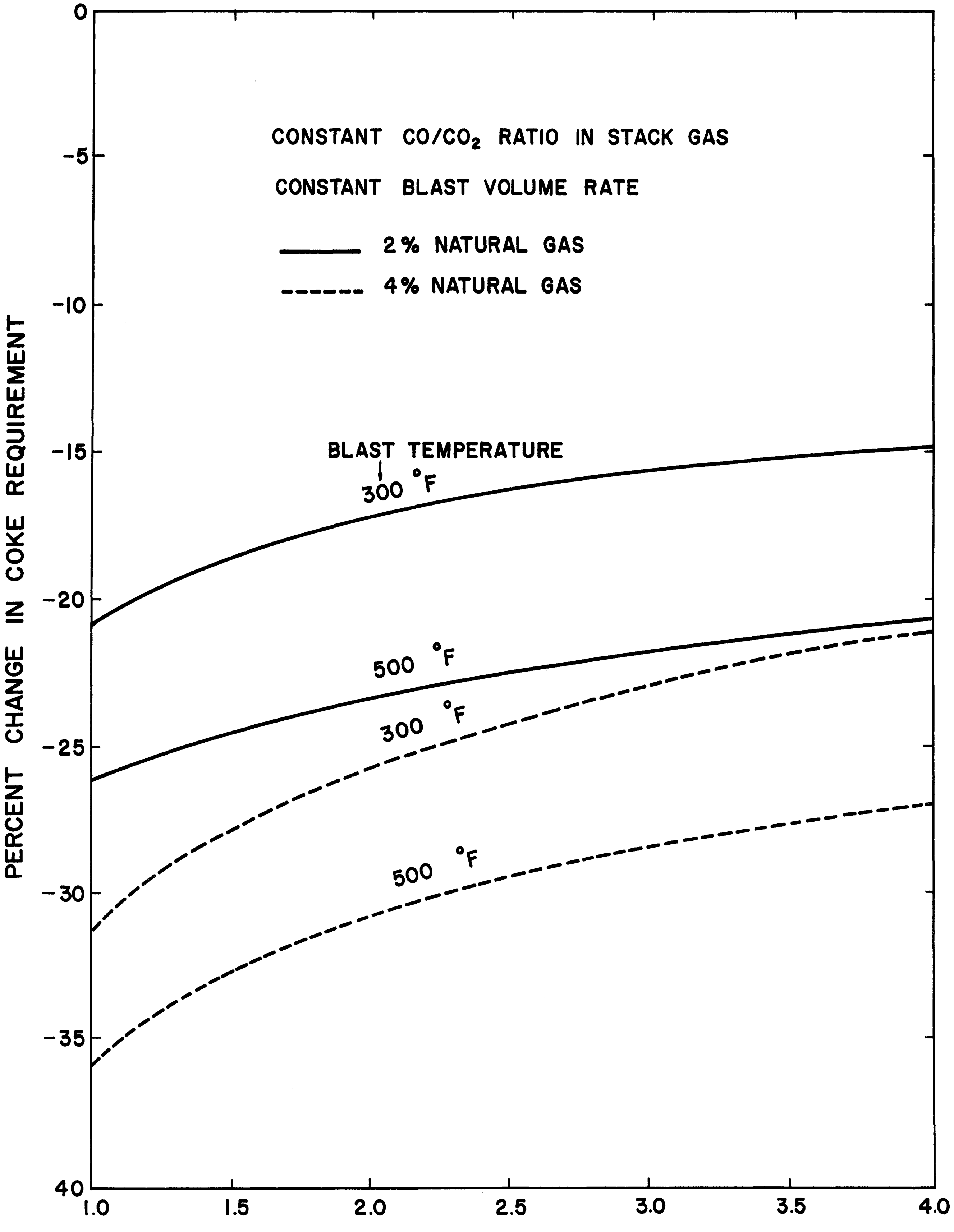

Figure 8. Effect of H_2/H_2O Ratio in Stack Gas on Coke Requirement with Natural Gas Injection.

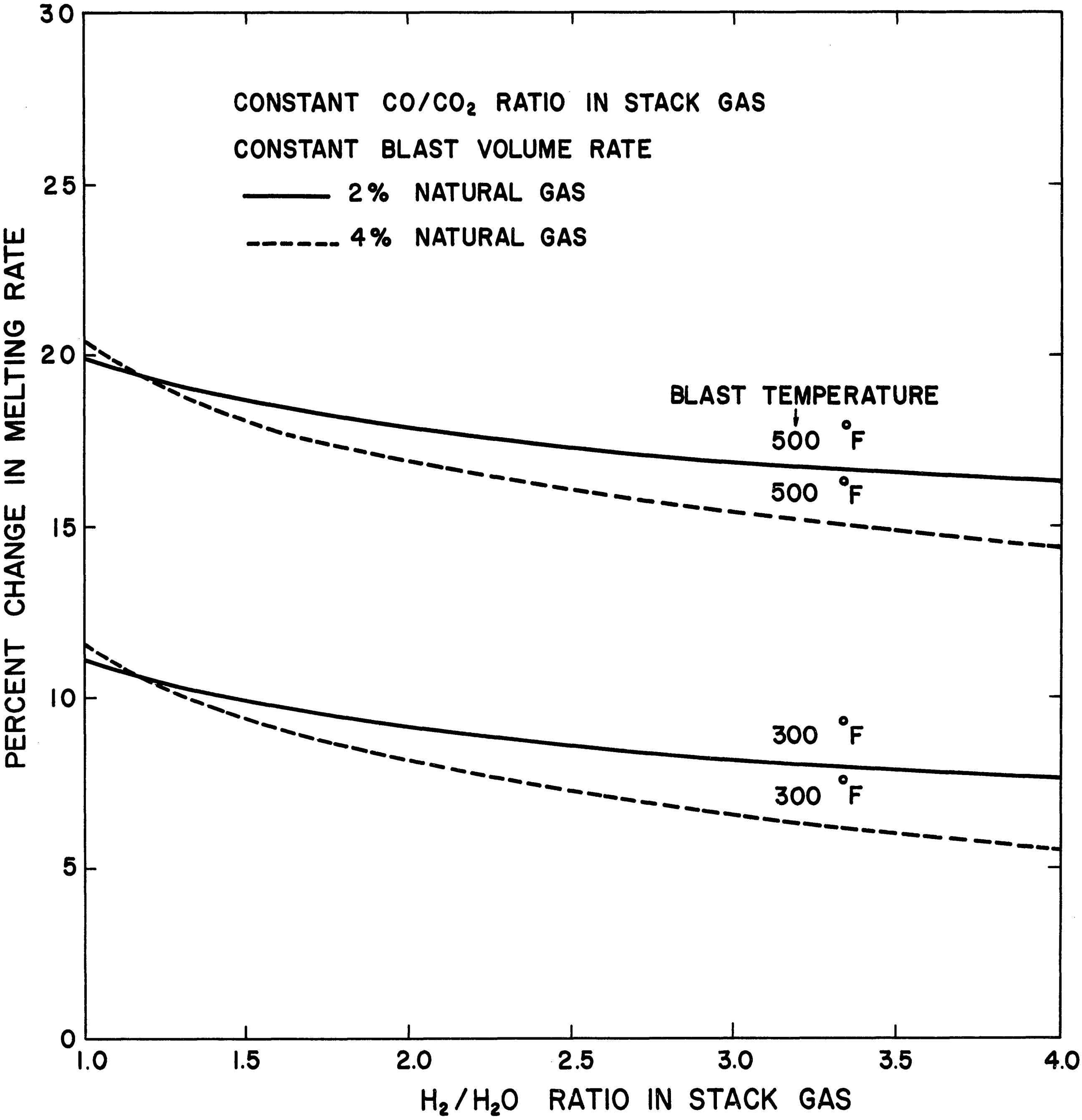

Figure 9. Effect of H_2/H_2O Ratio in Stack Gas on Melting Rate with Natural Gas Injection.

CONCLUSION

The use of the Thermochemical Model has been shown to provide a means for testing plant data for consistency and general accuracy, and is a particularly powerful means for searching out general areas in which optimization of cupola operations should be studied using plant trials.

The use of adiabatic flame temperature of the blast as a guide in choosing realistic operating conditions has been discussed. The combined utilization of this concept with a thermochemical model of the cupola furnace presents a new horizon for exploration in the continued development of the cupola process.

The thermochemical study of cupola operation utilizing oxygen enrichment, natural gas injection, and blast preheat has shown that oxygen enrichment and blast preheat both provide substantial coke savings and production increases. The use of natural gas in the blast is an effective means for saving coke, but alone provides a slight decrease, if anything, in metal production rate. However, the combined effects of enrichment, injection, and increased blast temperature offer a multitude of operating conditions under which the maximum economic potential of the cupola can be realized.

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