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EMPIRICAL STAGNATION-POINT HEAT-TRANSFER RELATION IN SEVERAL GAS MIXTURES AT HIGH ENTHALPY LEVELS

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SUMMARY

A simple empirical method has been developed for computing stagnation-point heating rates in arbitrary gas mixtures. The method has been shown to be in good agreement with stagnation-point heating results in air, argon, carbon dioxide, hydrogen, nitrogen, and mixtures of argon, carbon dioxide, and nitrogen for enthalpy potentials up to 50 000 Btu/lbm $\left(1.17 \times 10^5 \frac{\text{joule}}{\text{g}}\right)$. One useful application of the method is for parametric stagnation-point heat-transfer studies. The method is in good agreement with the existing prediction methods and is in fair agreement with the existing experimental data.

INTRODUCTION

Methods for predicting stagnation-point heat-transfer rates in arbitrary gases are presented in references 1 to 5. These methods have been compared with experimental heat-transfer measurements in air and other gas mixtures in references 6 to 17. The results of the method of reference 1 have been shown to compare favorably with experimental heat-transfer measurements in air and carbon dioxide (refs. 6, 7, and 12), but the method is restricted to these two mixtures. In reference 17, the authors show that simple methods based on the free-stream molecular weight of the gas mixtures (for example, ref. 2) do not predict the measured heat-transfer rates for gas mixtures containing argon, which is a possible constituent of the Martian atmosphere (ref. 18). For the more general methods (refs. 3 to 5), the time required for computation can be prohibitive if several gas mixtures are considered. Also, the method of reference 5 is only applicable to a diatomic gas.

Because of the existing difficulties involved in predicting the stagnation-point heating rates for arbitrary gases, it is evident that a simple, accurate method is desirable. This paper presents a simple method for computing stagnation-point heating rates in air, argon, carbon dioxide, hydrogen, nitrogen, and mixtures of argon, carbon dioxide, and nitrogen. The empirical method was developed from the results of the existing methods and experimental data for enthalpy potentials up to 50 000 Btu/lbm $\left(1.17 \times 10^5 \frac{\text{joule}}{\text{g}}\right)$ in air, nitrogen, and carbon dioxide and up to 16 000 Btu/lbm $\left(0.376 \times 10^5 \frac{\text{joule}}{\text{g}}\right)$ in hydrogen and argon.

SYMBOLS

C_i	mass fraction of gas in undissociated stream
H	enthalpy
i	constituent of gas mixture
K_i	constant (eq. (1))
p	pressure
$\dot{q}$	heating rate
R_{eff}	effective nose radius

Subscripts:

s	stagnation-point conditions
w	wall conditions

EMPIRICAL EQUATIONS

In reference 1, stagnation-point heating rates have been predicted in air and carbon dioxide for enthalpies up to 50 000 Btu/lbm $\left(1.17 \times 10^5 \frac{\text{joule}}{\text{g}}\right)$ and in reference 2 for air, carbon dioxide, hydrogen, and nitrogen up to 12 000 Btu/lbm $\left(0.282 \times 10^5 \frac{\text{joule}}{\text{g}}\right)$. In reference 3, the stagnation-point heating rates have been predicted in air, carbon dioxide, and nitrogen for enthalpy potentials up to 50 000 Btu/lbm $\left(1.17 \times 10^5 \frac{\text{joule}}{\text{g}}\right)$ and in argon and hydrogen for enthalpy potentials up to 20 000 Btu/lbm $\left(0.468 \times 10^5 \frac{\text{joule}}{\text{g}}\right)$. Measured stagnation-point heating rates for air, argon, carbon dioxide, and nitrogen are given in references 6, 7, 9 to 13, and 16.

In this paper, a simple equation of the form

$$\dot{q}_s \sqrt{\frac{R_{eff}}{p_s}} = K_i\left(H_s - H_w\right) \tag{1}$$

where R_{eff} is the effective nose radius (ref. 19) and p_s is the stagnation-point pressure in atmospheres $\left(1 \text{ atmosphere} = 1.013 \times 10^5 \text{ N/m}^2\right)$, has been compared with the

experimental and predicted results. Equations similar to the form of equation (1) have been suggested in the literature (for example, refs. 1, 2, and 7). The constant is intended to account for the effect of the thermodynamic and transport properties of the gas at the wall and external to the boundary layer. The constant K_i in equation (1) was determined for air, argon, carbon dioxide, hydrogen, and nitrogen in this paper by fairing a straight line through the results of the prediction methods and the experimental measurements, which are shown in figure 1. The slope of the line K_i was then computed. Values of K_i for each of the previously mentioned gases are given in table I.

TABLE I.- HEAT-TRANSFER CONSTANTS FOR VARIOUS GASES

Gas	K_i	
	$\frac{\text{lbm}}{\text{ft}^{3/2}\text{-sec-atm}^{1/2}}$	$\frac{\text{g}}{\text{cm}^{3/2}\text{-sec-atm}^{1/2}}$
Air	0.0461	0.1235
Argon	.0651	.1744
Carbon dioxide	.0512	.1372
Hydrogen	.0152	.0407
Nitrogen	.0431	.1155

The approach used for determining the constant in a pure gas could be applied to gas mixtures, but this method would not provide the capability for computing heating rates in arbitrary gas mixtures. This restriction is due to the large number of possible combinations of gas mixtures. Since the constant K_i can be determined for a pure gas, it would be helpful if this result could be used in computing the stagnation-point heating rates for a mixture of pure gases.

Existing results of prediction methods and experimental measurements for mixtures of argon, carbon dioxide, and nitrogen (three of the pure gases investigated in this paper) from references 4, 7, 8, 14, and 15 are shown in figures 2 and 3. The equation

$$\dot{q}_s\sqrt{\frac{R_{eff}}{p_s}} = \left(\sum_i \frac{C_i}{K_i}\right)^{-1}\left(H_s - H_w\right) \tag{2}$$

where C_i is the mass fraction of the individual gases in the undissociated stream and K_i is the constant given in table I was found to predict the results shown in figures 2 and 3.

RESULTS AND DISCUSSION

As described in the section "Empirical Equations," a simple empirical method for computing stagnation-point heating rates in air, argon, carbon dioxide, hydrogen, nitrogen, and mixtures of argon, carbon dioxide, and nitrogen has been obtained from results of existing prediction methods and experimental results. A comparison of the results of the present method with the existing results for air, argon, carbon dioxide, hydrogen, and nitrogen is shown in figure 1 and for mixtures of carbon dioxide and nitrogen and of carbon dioxide, nitrogen, and argon in figures 2 and 3, respectively.

The method of reference 2 which is based on the free-stream molecular weight of the gas mixture is shown to underpredict the stagnation-point heating rates in argon as shown in figure 2. Since the method was obtained for dissociating gas mixtures, it is not surprising that the method does not predict the measured stagnation-point heating rates in a monatomic gas. The influence of a monatomic gas on the method of reference 2 probably accounts for the poor agreement which reference 17 noted when trying to apply the method to mixtures which contained significant amounts of argon.

In figures 2(a) and 2(b), the method of reference 4 is shown for a range of $\dot{q}_s\sqrt{\frac{R_{eff}}{p_s}}$ as a function of the enthalpy potential since the results of reference 4 indicated a pressure dependence. This result which is not explicitly shown by the other methods is relatively small. For the present results given in figures 2(a) to 3(c), the $\left(\sum_i \frac{C_i}{K_i}\right)^{-1}$ is 0.0506, 0.0441, 0.0442, 0.0519, and 0.0551 $\frac{\text{lbm}}{\text{ft}^{3/2}\text{-sec-atm}^{1/2}}$ $\left(0.1355, 0.1179, 0.1185, 0.1389, \text{and } 0.1475 \frac{\text{g}}{\text{cm}^{3/2}\text{-sec-atm}^{1/2}}\right)$, respectively. In figure 3(c), the method of reference 3 as well as the present method underpredicts the experimental data for enthalpy potentials from approximately 12 000 to 22 000 Btu/lbm $\left(0.281 \text{ to } 0.515 \times 10^5 \frac{\text{joule}}{\text{g}}\right)$. These same data have been investigated in references 7 and 14, and the data are reported to contain certain anomalies.

Based on the comparisons shown in figures 2(a) to 3(c), the present method should be applicable to arbitrary gas mixtures if the constants K_i for the pure gases are known. For the calculation of the stagnation-point heating rates in pure gases, a constant K_i which is given in table I for air, argon, carbon dioxide, hydrogen, and nitrogen and the stagnation-point pressure are required. For mixtures of the pure gases, the only additional quantity required in the present method for the computation of the stagnation-point heating is the mass fraction of the individual gases in the undissociated stream. The present method does, therefore, provide a simple technique for parametric stagnation-point heat-transfer studies especially in gas mixtures for which the K_i of the component gases is known.

CONCLUSIONS

A simple method has been developed for computing stagnation-point heating rates in air, argon, carbon dioxide, hydrogen, nitrogen, and mixtures of argon, carbon dioxide, and nitrogen. The method was developed from the results of existing prediction methods and experimental data. For the evaluation of the stagnation-point heating rates of the pure gas, a predetermined constant and the stagnation-point pressure for each gas are required. For mixtures of the pure gases, only the predetermined constant for each pure gas, the stagnation-point pressure for the gas mixture, and the mass fraction of the individual gases in the undissociated stream are required to compute the stagnation-point heating rate. Since the method requires the knowledge of only a few simple parameters, one useful application of the method is for parametric stagnation-point heating studies. The method is in good agreement with existing prediction methods and is in fair agreement with the existing experimental data.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 24, 1968,
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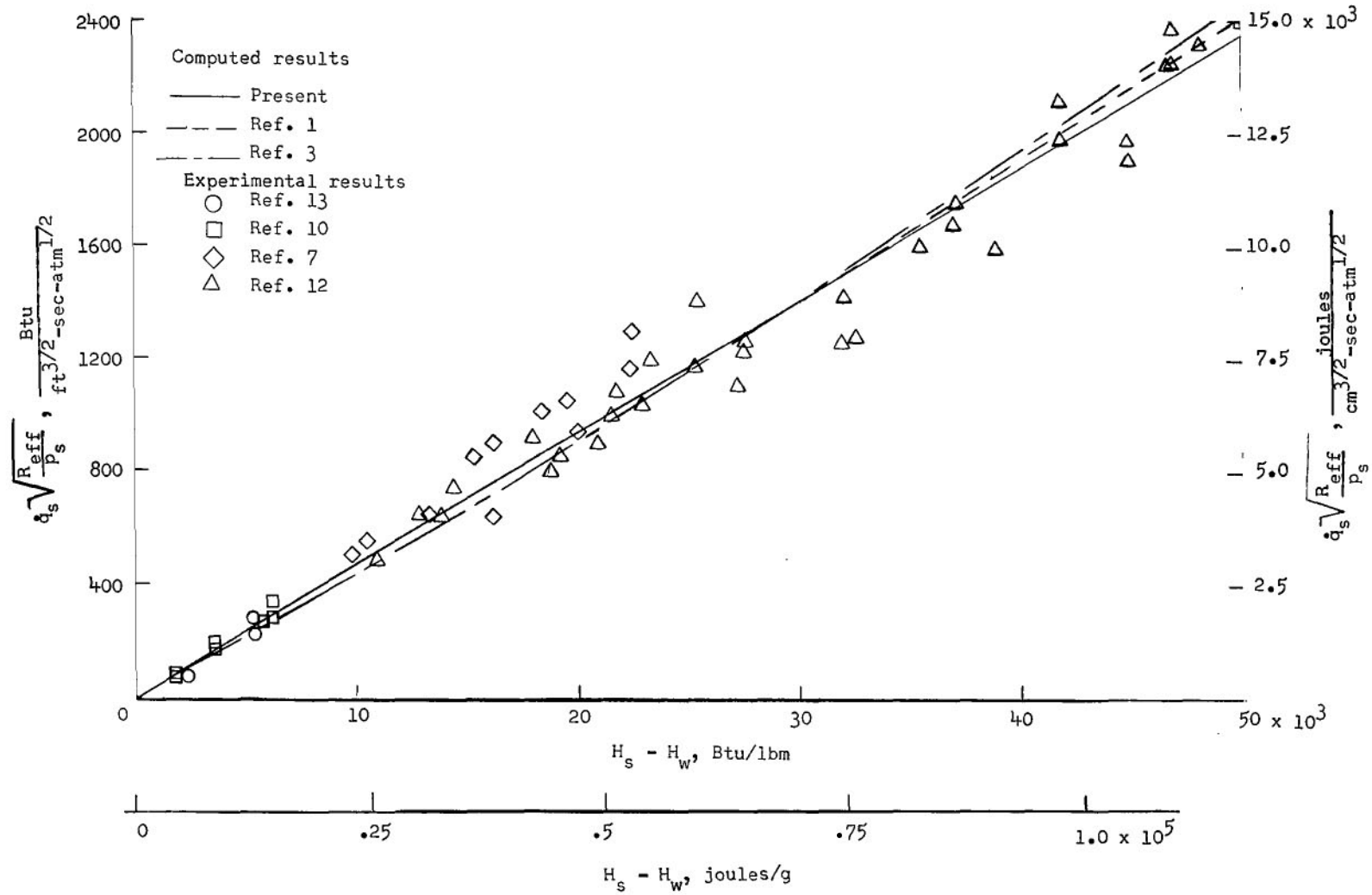
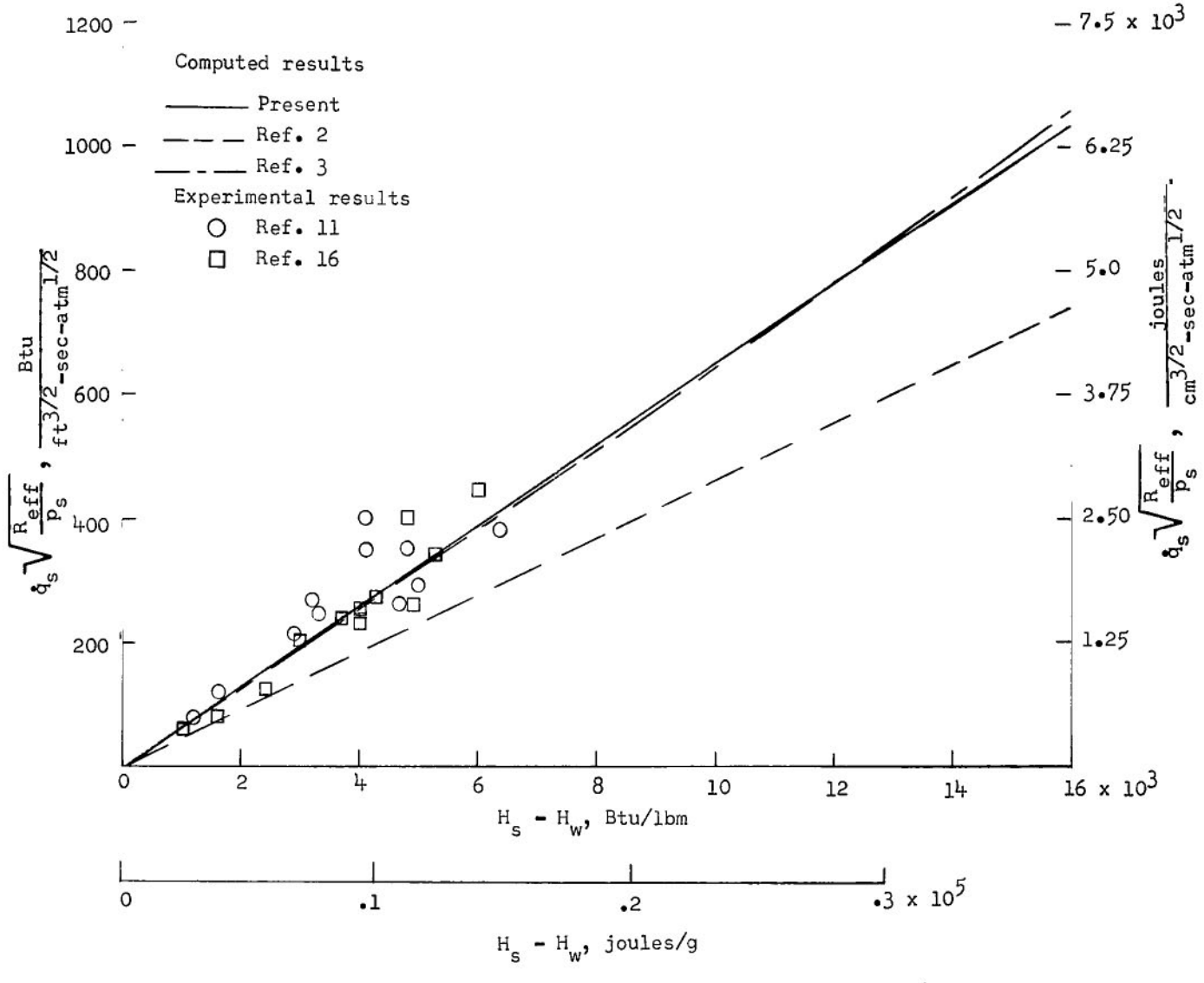


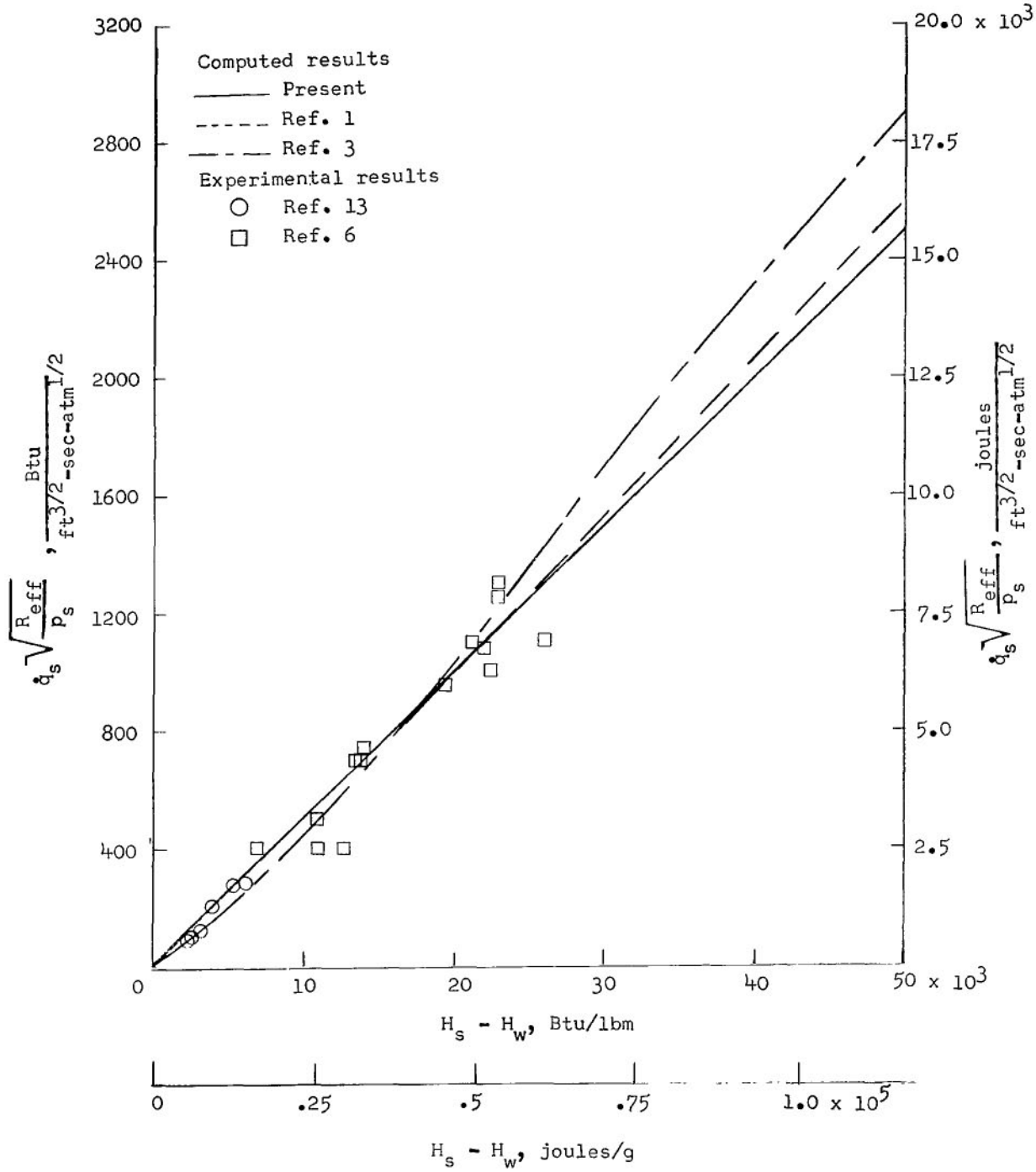
(a) Air.

Figure 1.- Comparison of computed and experimental stagnation-point heating rates with present results.



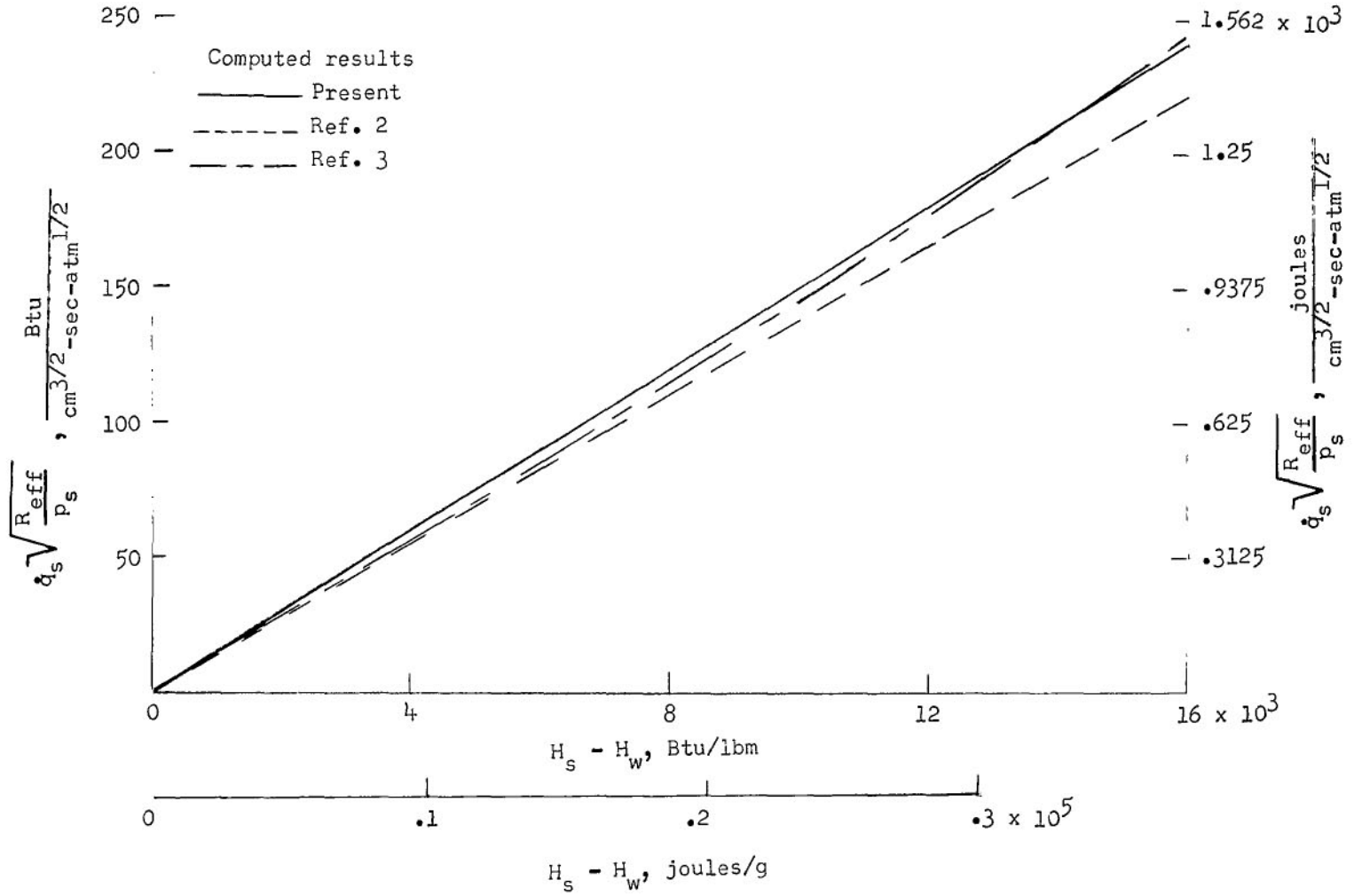
(b) Argon.

Figure 1.- Continued.



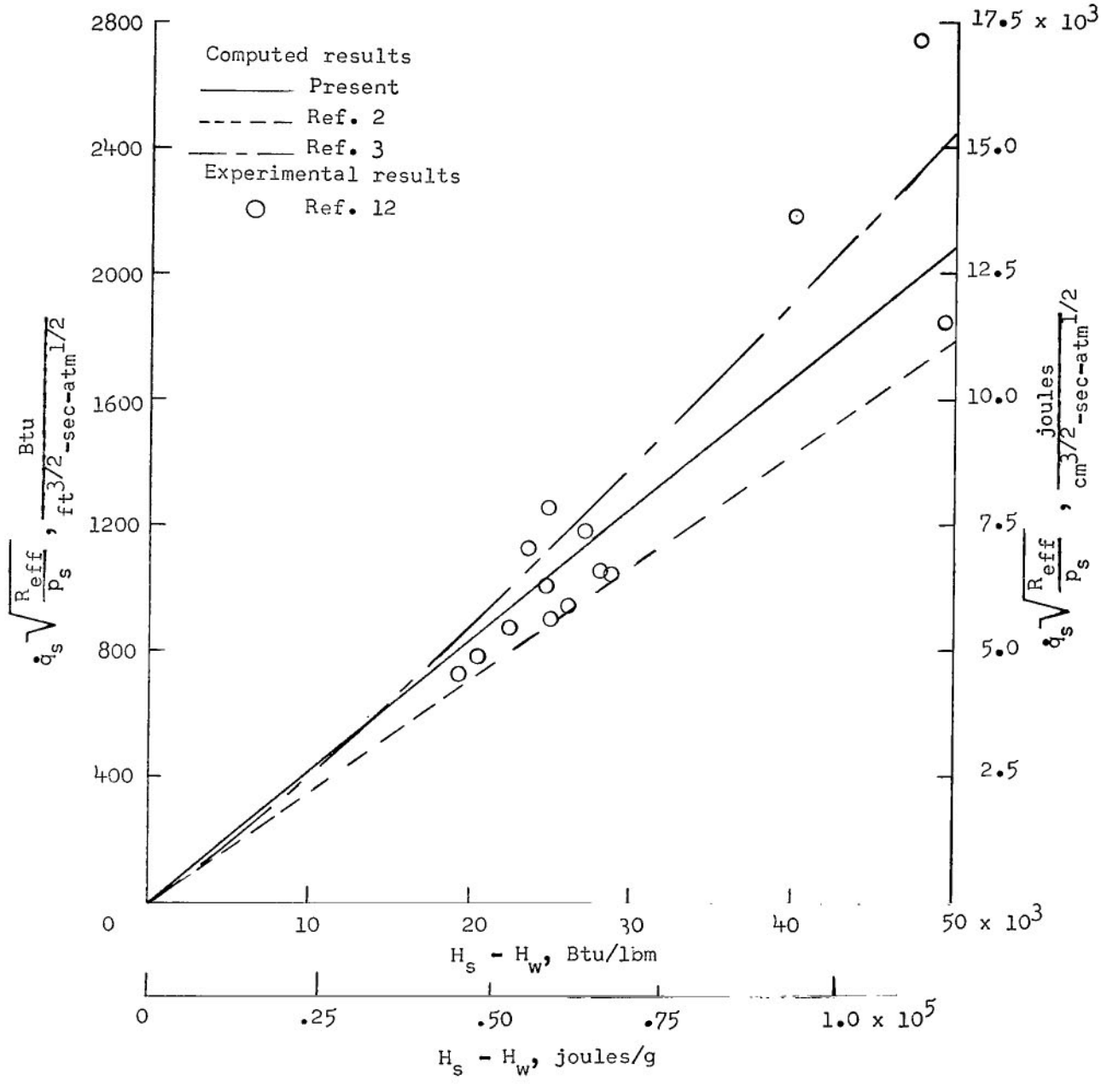
(c) Carbon dioxide.

Figure 1.- Continued.



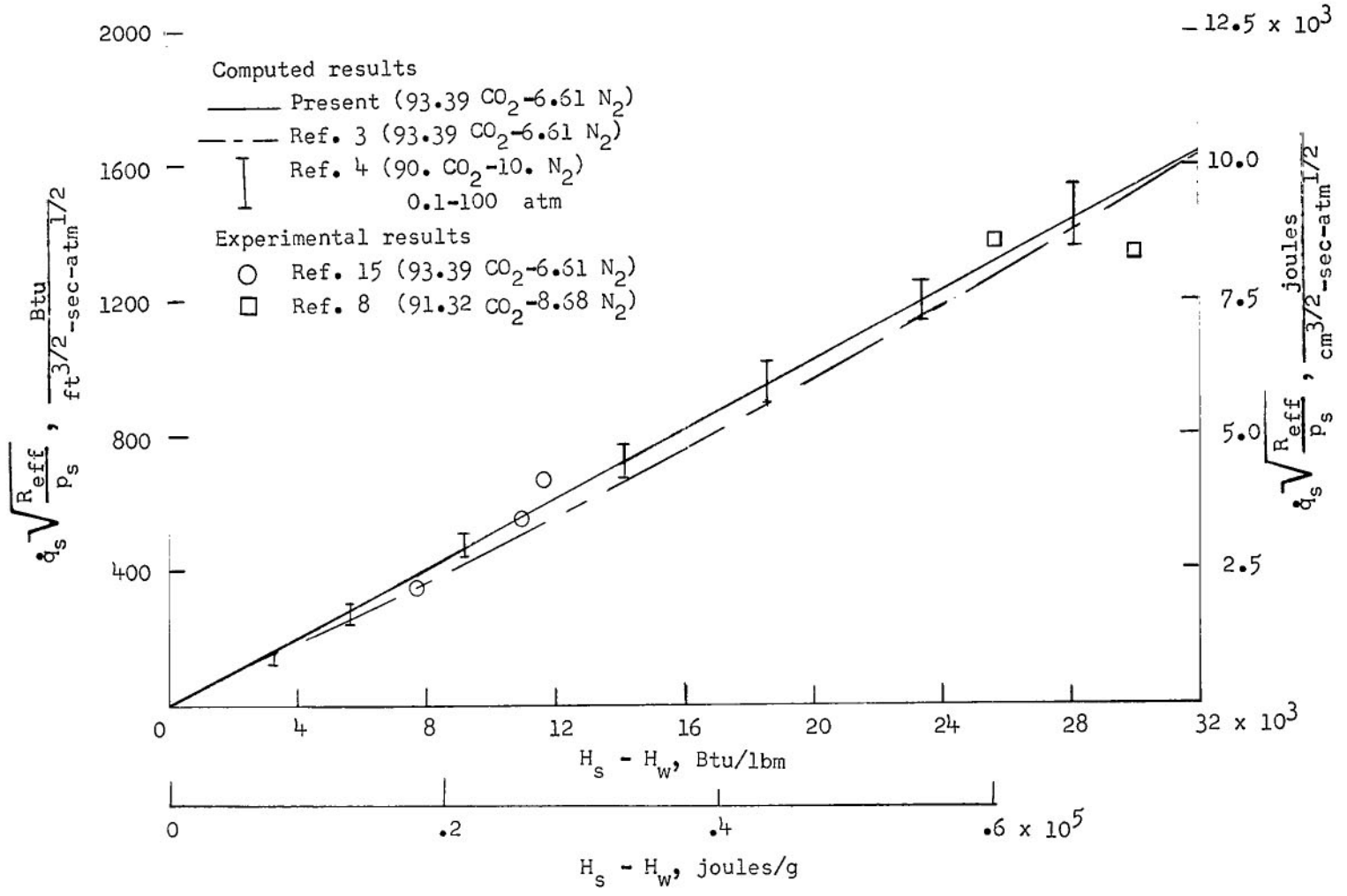
(d) Hydrogen.

Figure 1.- Continued.



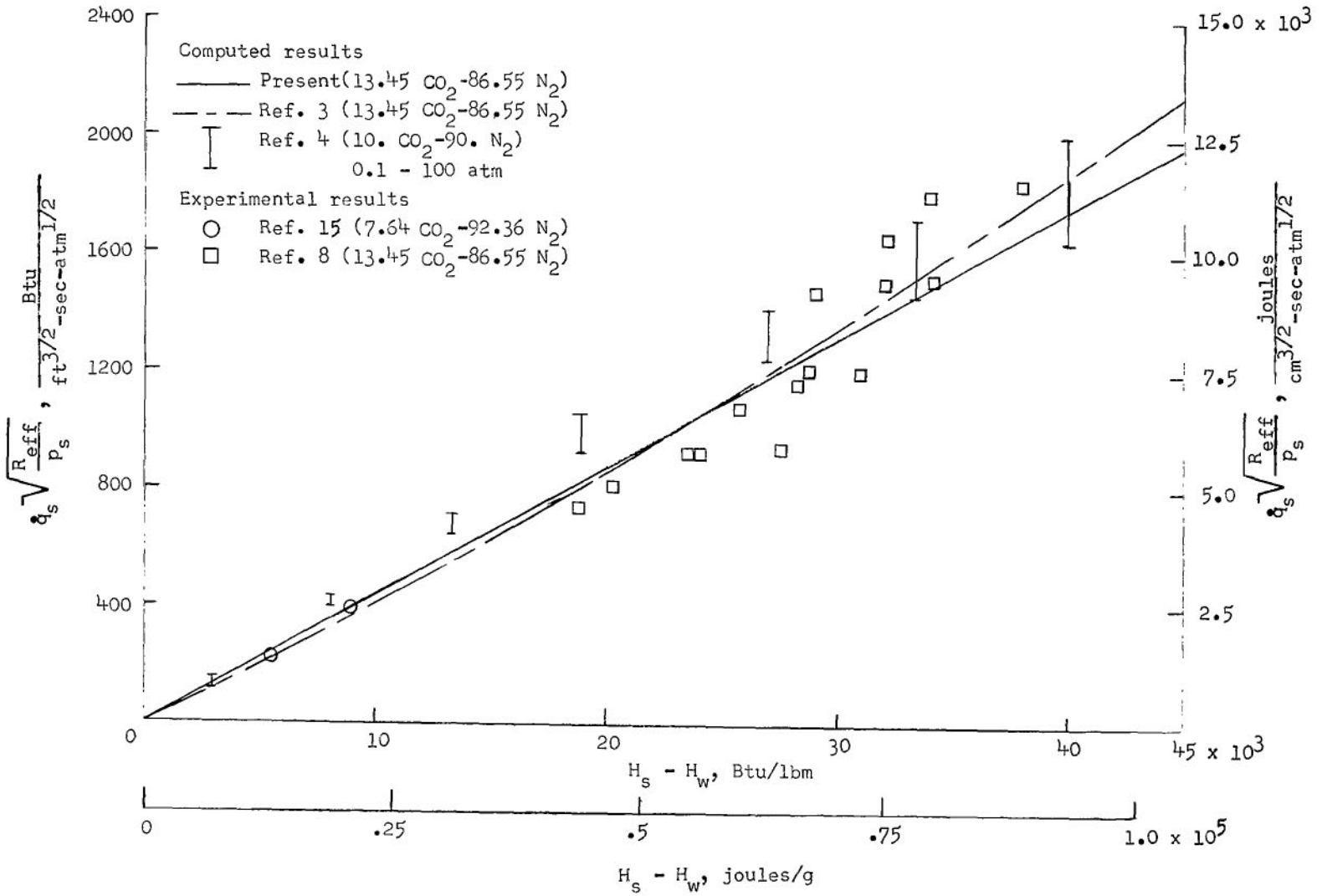
(e) Nitrogen.

Figure 1.- Concluded.



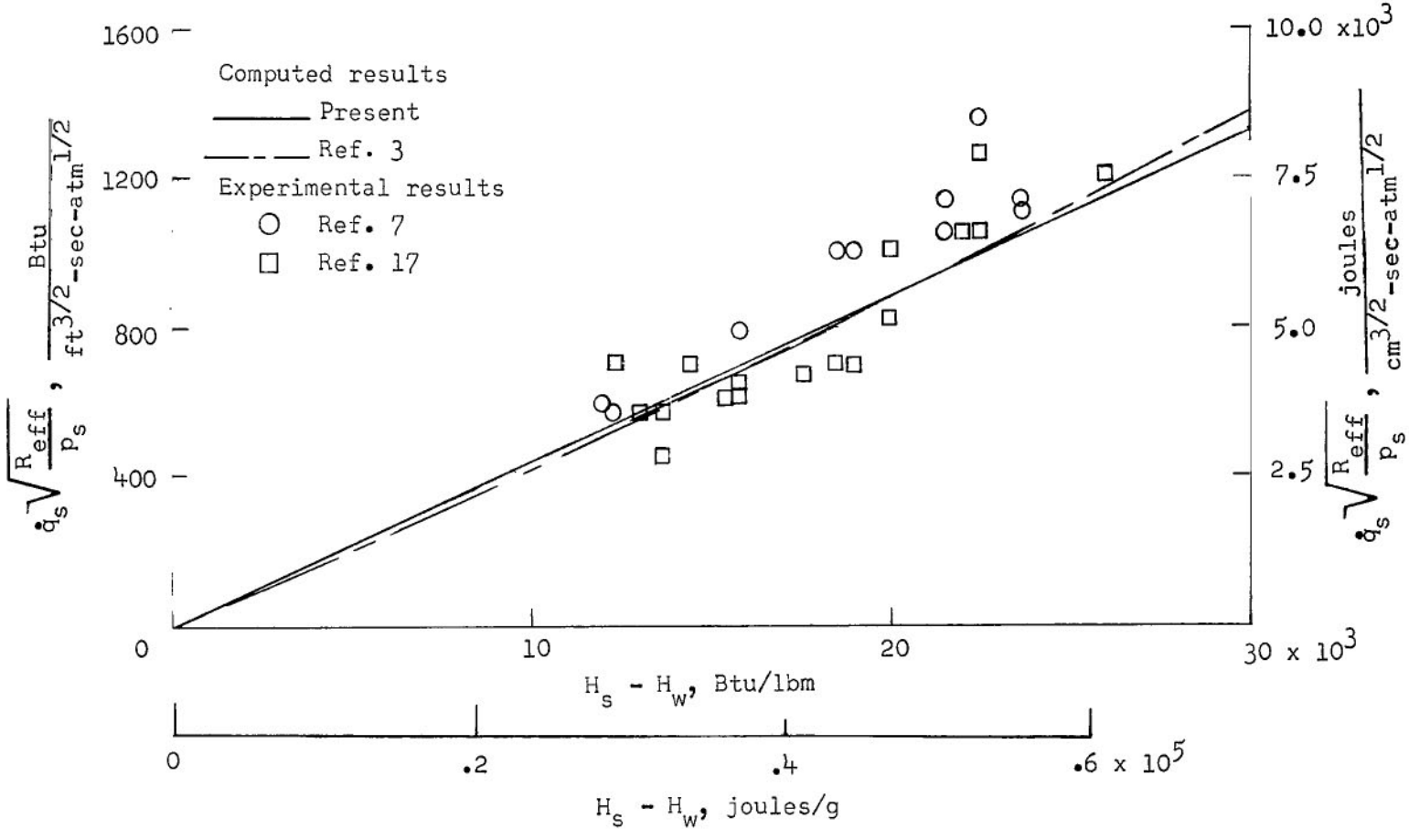
(a) CO_2 predominance.

Figure 2.- Comparison of predicted and experimental stagnation-point heating rates in mixtures of carbon dioxide and nitrogen with present results.



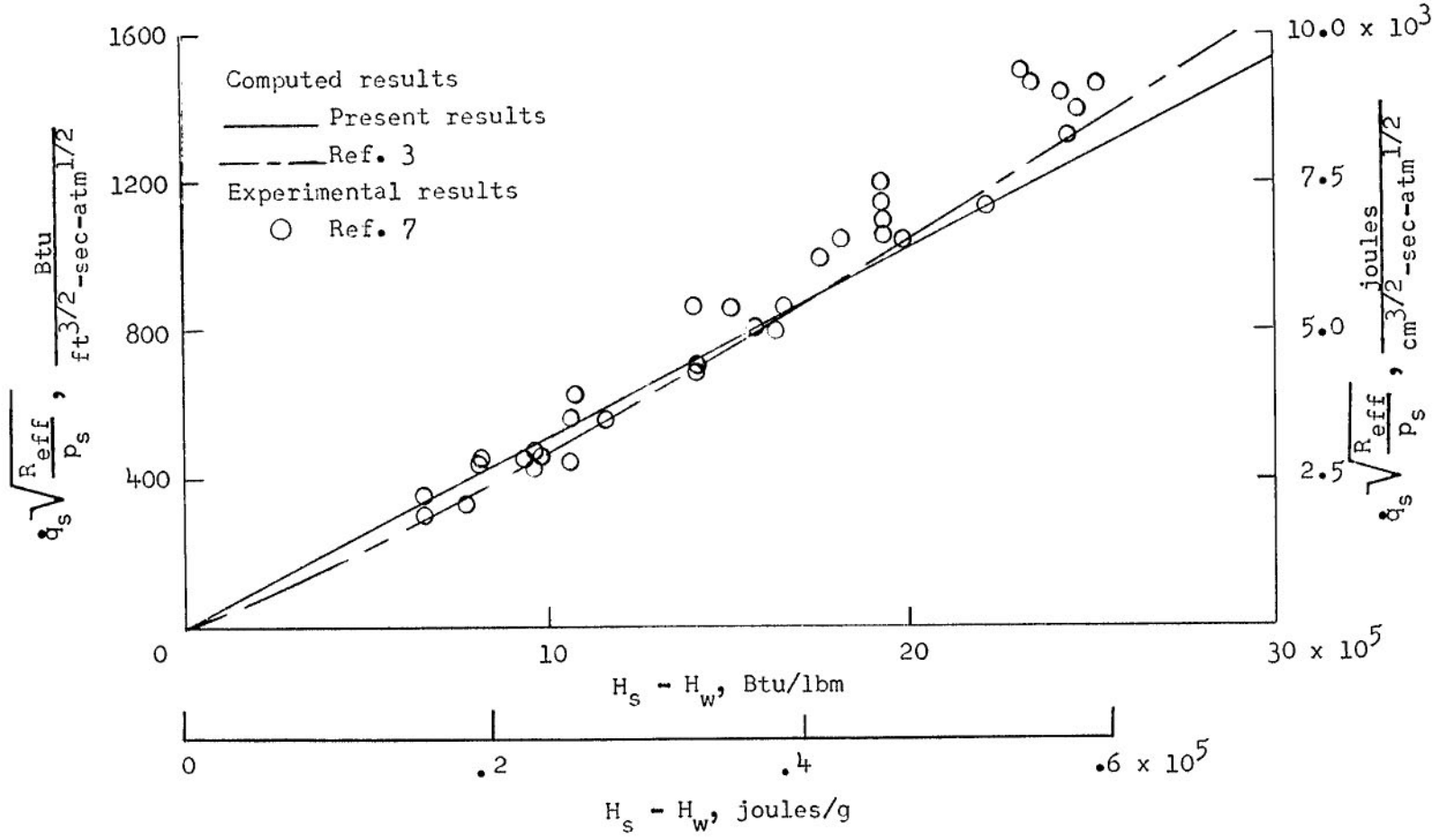
(b) N_2 predominance.

Figure 2.- Concluded.



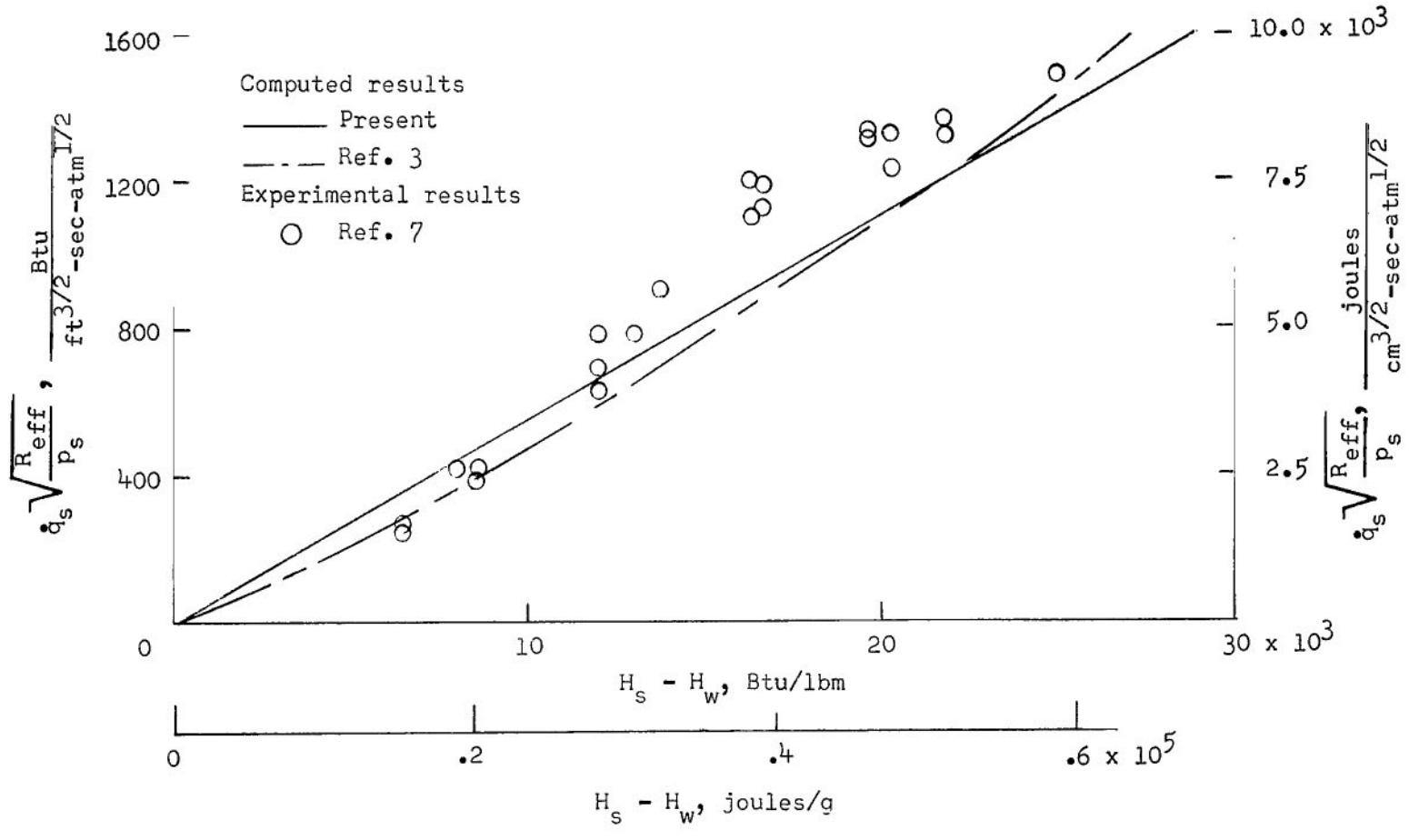
(a) 13.39 CO_2 - 85.25 N_2 - 1.36 Ar.

Figure 3.- Comparison of computed and experimental stagnation-point heating rates in mixtures of argon, carbon dioxide, and nitrogen with present results.



(b) 36.26 CO_2 - 30.77 N_2 - 32.97 Ar.

Figure 3.- Continued.



(c) 67.14 CO_2 - 32.86 Ar.

Figure 3.- Concluded.

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