The limiting reaction is

$$2\mathrm{H} + \mathrm{O} \rightarrow \mathrm{H_2O}$$

$$h_c = 25{,}000 \text{ Btu/lb}$$

The large number of reactions that may simultaneously occur for different ablation conditions limits the usefulness of Eq. (3) to qualitative comparisons.

The restrictions on the theory (that the reactions occur at a sharp flame front, that the location of the flame front is determined by the dimensionless release rate and that the release rate must be low) cannot be used to account for disagreement between theory and experiments of this type. The theory presented by Lees[4] accounts for boundary-layer combustion by assuming thermochemical equilibrium at the decomposing surface; Lees also indicates that the results are independent of endothermic or exothermic reactions within the boundary layer and external to the surface. This author developed an analysis for ablative material behavior[3] from Ref. 4 and independently carried through the algebraic manipulations that showed that Eq. (3) predicted essentially identical combustion effects. The Lees theoretical approach of Ref. 4 is general and is certainly applicable for stagnation region investigations. It is doubtful that the laminar boundary-layer equations would be invalid in low-pressure experimental stagnation region investigations of ablative materials where there is significant surface thermal reradiation. The theoretical analyses are, of course, dependent upon unity Prandtl, Schmidt, and Lewis numbers. However, experimental results are subject to inaccuracies and empirical curve fits of mass-transfer effects.

This author is of the opinion that the experimental results presented in Ref. 1 are misleading. The discrepancy that is shown between using Eqs. (1) and (2) deserves an explanation or at least a clarification since the reported experimental results of Ref. 1 would tend to invalidate the theory of Refs. 2–4. This author concludes that experiments of this type may be considered conclusive only if Eqs. (1) and (2) give essentially identical results. However, the refinement of the experimental technique should permit satisfactory evaluation of combustion effects predicted by theory.

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Reply by Authors to C. L. Arne

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The preceding comments regarding Ref. 1 question the validity of the experiments and express concern over the lack of agreement between the results and existing theoretical predictions of combustion heating. Considering first the question of experimental techniques, it should be noted that the results obtained from the equation employed by the authors, i.e.,

$$\frac{\dot{q}_{\mathrm{comb},\,t}}{\psi_a \dot{q}_{hw,\,a}} = \frac{\psi_n \dot{q}_{hw,\,n}}{\psi_a \dot{q}_{hw,\,a}} - 1 \qquad (1)‡$$

should agree with the alternative approach suggested by Arne, namely,

$$\frac{\dot{q}_{\mathrm{comb},\,t}}{\psi_a \dot{q}_{hw,\,a}} \approx \frac{\epsilon\sigma T_w^4 + \dot{m}_v h_A}{\psi_a \dot{q}_{hw,\,a}} - 1 \qquad (2)$$

Indeed, the comparison presented in Fig. 1 indicates satisfactory agreement between the two methods for all but the highest temperature conditions (corresponding to $P_w = 4.9 \times 10^{-2}$ atm) where the differences can be attributed in part to the large uncertainty levels inherent in Eq. (2). That is, the results obtained by the authors from Eq. (1) do not depend explicitly upon either the surface temperature T_w or the intrinsic heat capacity of the material h_A, but depend only upon the measurements of heating rates and a definition of the heat-transfer parameter ψ. On the other hand, the results computed from Eq. (2) are highly dependent upon surface temperature, particularly at high values of T_w where the reradiated energy from the ablator surface becomes the predominant mode of heat rejection. One then would expect that the reliability of Eq. (2) would be very sensitive to uncertainties in the temperature. The uncertainty in each variable appearing in Eqs. (1) and (2) was estimated, and the extent to which these individual uncertainties propagate into the results was calculated using the methods outlined in Ref. 2. These calculations are represented in Fig. 1 as the bands associated with the circular symbols. It is to be noted that the magnitudes of $\dot{q}_{\mathrm{comb},\,t}/\psi\dot{q}_{hw,\,a}$ at $P_w = 4.9 \times 10^{-2}$ atm, as obtained by the authors from Eq. (2), are lower than the corresponding calculations of Arne which, as he has stated, are approximate. Although the total difference between the two techniques is not accounted for by uncertainty considerations alone, it is apparent that little, if any, significance may be attached to the differences cited by Arne at these conditions.

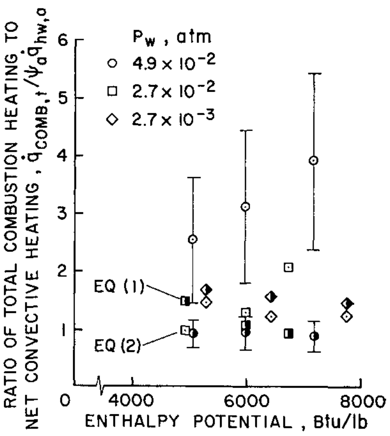

Fig. 1 Variation of total combustion heating rate with enthalpy: a comparison of Eq. (1) and (2).

With regard to the discussion of the thermochemical analysis and role of the intrinsic heat capacity h_A in influencing the calculations, it is interesting to note that the adequate agreement of the two methods at low temperatures, mentioned previously, would no longer hold if the calculated values of h_A proposed by Arne in Fig. 2 were used in place of 1000 Btu/lb. Furthermore, recent measurements of h_A have been performed at Ames,[5] and in contrast to the calculations, indicate only a slight variation of h_A with temperature.

Received September 23, 1964.

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‡ Nomenclature is that of Ref. 1.

The difference in ψ for tests conducted in nitrogen and air, resulting from the influence of chemical reactions on the molecular weight of injection products and subsequent effects on the mass transfer factor β, is shown in Fig. 3 of the preceding comments. Careful inspection of this figure reveals that, at a value of normalized mass transfer $B = \dot{m}_t\Delta H/\dot{q}_{hw} = 0.6$, β for the two gases differs by less than 10% and, in addition, the curves appear to coalesce at higher values of B. Since the measured values of the normalized mass-transfer parameter exceeded 0.6 for all test conditions reported in Ref. 1, it is highly doubtful that this suggested refinement in the technique would significantly improve the accuracy of the calculations.

In answer to the questions raised concerning the determination of the vapor injection rate, it must be pointed out that:

1) Vapor injection rates calculated from Eq. (A10) of Ref. 1 suffer the same high uncertainty level described earlier, because the equation also contains the reradiation term.

2) Energy stored within the char layer will, indeed, increase the magnitude of Δm_v, but this will be the same for the various time duration runs at a given stream condition, and thus the derivative $\Delta m_v/\Delta t$ will be unaffected. This multiple run technique, as discussed in Ref. 1, minimized transient effects that occur during the initiation of ablation.

The authors recognize the need for additional experiments as well as an extension and refinement of existing analyses in order to understand more fully the complicated physical and chemical interactions taking place in boundary-layer flows with ablation species present. Only then will the observed differences between experiment and theory be resolved. In this regard, additional tests of phenolic nylon for both radiative and convective heating in air and nitrogen have been recently completed at Ames,[5] and the results of these experiments are in substantial agreement with the data presented in Ref. 1.

The disagreement between existing theory and the results presented in Ref. 1 will now be re-examined. There is no reason to expect that the theory[3, 4] would agree with experiment in view of the simplifying assumptions employed in the derivation and solution of the differential equations. Specifically, analyses of the boundary-layer heat-transfer problem on the basis of the conservation equations presented in Ref. 3 may be questioned for very high mass transfer rates where the thermal boundary layer may be blown off. Another important factor, which also limits the applicability of the results contained in Ref. 3, even at low mass transfer rates, is the assumption that the Lewis (Le) and Prandtl (Pr) numbers are unity with the result that the total enthalpy and mass fractions of the individual chemical elements satisfy identical differential equations. This approach is regarded as proper only when the molecular weight (and hence transport properties) of the injected gases and boundary-layer species are comparable. However, for the case under consideration, the phenolic nylon vapors produced during ablation contain a large fraction of low molecular weight species (e.g., H and H_2) and the solutions of the conservation equations based on this coupling assumption are no longer valid. In fact, Lees has devoted an entire section of Ref. 4 (pp. 467–478) to the discussion of mixtures containing light gas components and concludes that " . . . clearly the approximation of constant average values of Pr and Sc across the boundary layer may be inadequate in this case and a more careful study is required . . . " Moreover, the experiments performed by Barber for hydrogen injection as pointed out previously in Ref. 1 also serve to illustrate the limitations of the similarity approach. In the comparison of the experiment with theory, the nature of the reacting species (that is whether atomic or molecular oxygen is combining with the ablative vapors) plays a strong role in determining the extent of combustion heating. This choice influences the "upper limit" quoted in Ref. 1, and the discussion of Arne regarding this point is certainly pertinent to the interpretation of the results.

In view of the comments contained in this reply, the authors feel that the experimental results presented in Ref. 1 are valid and are not misleading. They further agree wholeheartedly with the opinion of Arne regarding the applicability of the theory, namely, its usefulness is limited to qualitative comparison.

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