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Reply by Author to W H Andersen

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IN the preceding comment, Andersen[1] surveys the published data in the linear pyrolysis (LP) field and comments on the author's recent paper The author appreciates Andersen's generally kind appraisal but wishes to comment on four specific criticisms: 1) that the conclusions might mislead persons unfamiliar with the history of the LP field; 2) that the theoretical results differ from those of Chaiken et al ; 3) that the predicted rate of pyrolysis depends on weight loading; and 4) that the experimental results on dry ice LP require too great a temperature correction

With regard to misleading conclusions, the author agrees with Andersen's statement that hypotheses, which are independent of absolute rate data, may be correctly deduced from existing LP data It is indeed possible to draw correct qualitative conclusions from inexact quantitative data! However, the author intended primarily to assert that the quantitative results of many LP experiments are subject to question because of the failure of most authors to consider gas-film effects Andersen acknowledges this point

The author[2] and Chaiken et al [3] have presented theoretical models by which the gas-film temperature correction to LP data may be calculated As Andersen notes, these theories give different corrections It is, therefore, appropriate to determine which model, if either, is suitable for calculation of the gas-film temperature correction of existing LP data The data of Chaiken et al [3] contain sufficient information to make numerical comparisons Before discussing these data, an important criterion for the validity of a theory must be noted Most theories (including those under discussion) contain explicit and implicit assumptions based on the magnitudes of various dimensionless parameters The ranges of the parameters involved must be consistent with the theoretical model chosen

As a numerical example, the following data point (in the notation of Ref 2) from Fig 4 and Table III of Chaiken et al [3] is examined†: $m = 1\ 6(10)^{-2}$ g/cm²-sec, $T_0 = 750°$K, $p_v = 6\ 03$ atm, and $p_\infty = 1$ atm From the theory of Chaiken et al ,[3] the calculated temperature correction and film thickness are $(T_1 - T_0) = 4\ 2°$K and $z_1 = 5\ 58(10)^{-5}$ cm For the calculated film, the reduced Reynolds number given by Schlichting[4] is‡ $R = mz_1/\mu = 2\ 26(10)^{-3}$ The magnitude of this parameter is inconsistent with the constant film pressure assumption of Chaiken et al ,[3] so that the applicability of their theorectical treatment to the present case is subject to objection The author's theory[2] is developed for a cylindrical specimen, and so, for purposes of comparison, an effective radius b is chosen Thus, the cylindrical cross sectional area $\pi b^2 = 0\ 5$ cm is identical to the rectangular area in the experiments of Chaiken et al The dimensionless weight $W = (p_{av} - p_\infty)/p_\infty = 5\ 03$, and the Sommerfeld number $S = 79\ 5$ With these additional parameters, the viscosity‡ $\mu = 3\ 95(10)^{-4}$ g/cm-sec, the calculated temperature correction and film thickness are $(T_0 - T_1) = 41°$K, and $z_1 = 5\ 54(10)^{-4}$ For these calculations, the magnitude of the Reynolds number is consistent with the assumption of a pressure gradient However, two inconsistencies with the assumptions of the author's theory do arise The calculated average radial velocity at $r = b$ is $3\ 28(10)^4$ cm/sec, which is almost the speed of sound [$5\ 40(10)^4$ cm/sec at average film temperature] The pressure at $r = b$ is, therefore, not p_∞ as assumed Also, the equilibrium pressure (p_{eq}) for the calculated surface temperature according to data extrapolated from Ref 5 is approximately 7 atm, so that $(p_{eq} - p_{av})/p_{eq} \approx \frac{1}{7}$, which would indicate that considerable condensation occurs Thus, the pyrolysis rate could not closely approximate the vacuum sublimation rate

The author's reply to Andersen's objections to the theoretical dependence on weight loading and to the large temperature correction for dry ice LP must reiterate portions of Ref 2, where it is stated that faster rates of evaporation result in channel formation on the evaporating surface (see Fig 11 of Ref 2) and where it is speculated that channel formation might result in the independence of pyrolysis rate on weight loading, as observed by Andersen and his associates Channel formation is clearly inconsistent with the assumptions of any current theory Andersen notes that Barsh and Schultz[6] report significantly larger dry ice LP rates than the author at comparable temperatures It is noteworthy that Barsh and Schultz use an external thermocouple that measures some temperature between plate temperature and ambient temperature in the solid If extrapolation of the author's data is permissible, evaporation rates of $20(10)^{-3}$ g/cm²-sec would occur at 249°K, which is not significantly greater than the calculated temperatures

In conclusion, at least two courses of action seem feasible for future interpretation of LP data on solid propellant materials: 1) perform additional experiments under suitable conditions (weight loading, ambient pressure pyrolysis rate, etc) such that the parameters are consistent with some existing theory; and 2) develop additional theory to include the necessary range of parameters, as the author noted might be

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† Since the data are partially determined from a graph, they may not agree exactly with the original data However, they are well within the experimental scatter

‡ In the calculations, a viscosity of $3\ 95(10)^{-4}$ g/cm sec is used This value is arbitrarily chosen so that the Prandtl number $(c_p\mu/\lambda)$ is 0 75 when the thermal conductivity ($2\ 0 \times 10^{-4}$ cal/cm-sec-°K) of Chaiken et al is used and where the specific heat (c_p) of the gas is identical to the specific heat of the solid

necessary in the final section of Ref 2 Incidentally, theoretical models for LP of some substances should differ considerably from either of those discussed in this note The evaporation process might not be confined to a layer several molecules thick, which is implicit in the models considered Also, the pyrolysis might even be time-dependent, as exemplified by the chuffing pyrolysis of ammonium perchlorate discussed by Andersen It is hoped that the present note will aid future LP workers in properly matching experimental conditions and theoretical models

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Comment on "Effects of Controlled Roughness on Boundary-Layer Transition at a Mach Number of 6 0"

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Nomenclature

k = height of roughness element
Re_{t0} = Reynolds number of transition with no roughness applied
$R_{k\,c}$ = value of Reynolds number sufficient to cause $x_t \approx x_k$, based on k and computed flow conditions at height of roughness element in undisturbed laminar boundary layer
T_w = wall temperature
T_{aw} = adiabatic (insulated) wall temperature
x_t = station of transition
x_k = station where roughness is located
δ = boundary-layer thickness at location where roughness is applied, computed for undisturbed laminar flow
ω = exponent in relation between viscosity and temperature

SUBJECT note[1] reports additional evidence that neither k/δ nor R_k are adequate parameters for assessing the influence of surface roughness on transition of boundary layers Conclusive demonstrations of this result have been published previously [2–4] The conclusion in Ref 1 relative to influence of increasing Mach number on values of k/δ required to effect transition with constant T_w/T_{aw} also supports earlier published work [2 4]

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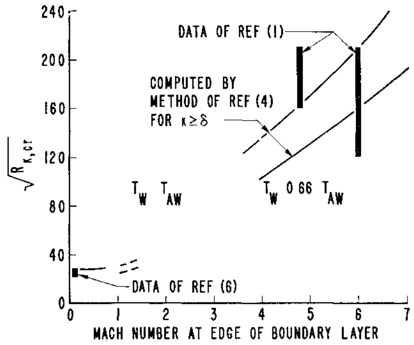

Fig 1 Effective roughness required to cause transition at the roughness

The purpose of this comment is to direct attention to relevant earlier work, possibly overlooked by the authors of Ref 1 Using the method proposed in Ref 4, both the influence of Mach number and wall temperature are predicted in relatively good agreement with published experimental data, considering that significantly varying test conditions are represented in the experiments compared

Because of the inconsistency in values of Re_{t0} given in Figs 1 and 2 of Ref 1, no attempt is made to estimate x_t when $x_t > x_k$ by the method of Ref 4, which requires knowledge of Re_{t0} for that purpose If, as implied in Ref 1, entire leading-edge sections were interchanged and all were supposed to have nominal thicknesses of 0 002 in, at least a partial explanation of the apparent inconsistency may be suggested For example, if a dimensional tolerance of $\pm$0 0005 in is assumed, on the order of $\pm$10% variation in Re_{t0} is estimated from Refs 2 or 4

The conditions necessary for three-dimensional roughness elements to cause transition from laminar to turbulent flow near the roughness have been calculated according to Ref 4, thereby yielding $(R_k\ )^{1/2}$ as used in Ref 1 (The result is dependent on ω, and ω = 0 88 has been selected in view of the temperatures of concern in Ref 1) In accord with the conditions of Ref 1, $k \geq \delta$ has been assumed This often is the situation at higher Mach numbers but is not generally the case at lower Mach numbers (The possible side effects of using such large roughness are apparent) Thus, the computed curves in Fig 1 are shown as broken lines in the region of lower supersonic Mach numbers The method of Ref 4 permits estimates for $k < \delta$ as well, but present purposes are served by the examples shown here

Figure 1 shows that the rapid increase with Mach number of relative roughness size required to establish transition at or near the roughness has been predicted A large amount of data confirming the computed curves to the extent reasonable to expect for transition data may be found in Refs 2 and 4 The data of Ref 5 (Ref 2 in Ref 1, Fig 3) are not shown in Fig 1 because it is the present authors' understanding that they refer to the roughness just adequate to initiate movement of transition, rather than the roughness needed to move transition forward to very near the location of roughness To confirm the subsonic portion of Fig 1, the experimental data of Ref 6 are shown When Mach number approaches zero, the curves representing Ref 4 are not affected by k/δ

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