Sublimation of Flat-Nosed Cones with Various Axisymmetric Steps in Supersonic Flow

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A method of sintering powdered camphor and naphthalene after deaeration under vacuum which is well suited for making models for wind-tunnel experiments on the aerodynamics of subliming bodies is described. Exploratory tests on cones with flat and hemispherical noses and on several complex conical shapes, featuring downstream and upstream facing steps, rectangular grooves and shoulders are presented. The experiments were performed at a Mach number of 3, blowing parameters up to 0.35 and model Reynolds numbers up to 200,000. Emphasis is placed on the general evolution of the profiles, the history of the tips, and the occurrence of grooves, striations, and surface markings.

I. Introduction

PAST work on ablative heat shields was dominated by thermal and structural problems, and focused mainly on applications to blunt bodies. Recent experiments[1–5] have focused on fine details of the surface features left on the ablated skin after flight, which are of considerable fundamental interest. These include grooves associated with identifiable three-dimensional roughness elements, turbulence wedges, and even more surprising patterns, only recently identified, which look like crosshatching by grooves spiraling in both directions over the surface.

In these applications, a relatively thin shell of material ablates without substantially influencing the geometry or the aerodynamic characteristics of the vehicle. However, recent emphasis on low-fineness-ratio re-entry shapes has given prominence to changes in shape of the ablating surface, particularly in the neighborhood of the nose. These changes can seriously affect the drag, the aerodynamic stability parameters of the vehicle, and the amount and aerothermochemistry of observables left in the wake of the body. Some features of complex (composite) initial shapes with corners, steps, etc., are eroded smoothly and stably, whereas others tend to magnify and induce further self-perpetuating nonuniformities. There have been virtually no studies of such phenomena published and the possible uses of the coupling between the trajectory and the history of shape/drag/ablation thermochemistry of such composite shapes has not been considered.

The present report describes a method of sintering camphor and naphthalene which results in very satisfactory models for wind-tunnel investigations of the shape change of ablating bodies, and presents exploratory results on the surface recession history of cones, blunted cones, and composite shapes having expansion corners, upstream and downstream flow separations, and notches. The experiments were performed over a period of three years,[6,7] with limited resources. Only photographic records were collected which are not sufficient to allow a detailed and quantitative reduction of data and a comparison with theory. As an exploratory program, however, the tests were quite successful, and further exploitation of the technique seems quite worthwhile.

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II. Properties of Camphor and Naphthalene

There is a small number of readily available substances that sublimate at temperatures low enough to make wind-tunnel measurements convenient. Among them are dry ice, camphor, naphthalene, and also hexachloroethane, chloronil, and ammonium chloride. Camphor and naphthalene have been used most often in wind-tunnel testing.[8–10] A map of the aerothermal behavior of the camphor air system is shown, for example, in Ref. 6. Camphor is virtually always below the triple point. With stagnation temperatures up to 1000°F and stagnation pressures of the order of one atmosphere, one can obtain a wide range of blowing parameters with pure sublimation (solid/gas transition without a liquid phase change) in the supersonic range of Mach numbers. Naphthalene, for which the triple-point pressure is an order of magnitude below that of camphor, can be made to undergo melting ablation at very high blowing rates.

In most experiments reported in the literature, models were prepared either by mold-casting at atmospheric pressure or by layer casting (dipping) the ablator on a metal or plastic core. However, this technique is not entirely satisfactory, especially for making small models with a high fineness ratio. Castings are distinctly crystalline in nature. The bond between successive layers of models produced by dipping is weak, probably because of inert gases (air) adsorbed at the surface of the successive layers. The following technique was developed in the course of this study.[6,7]

Camphor or naphthalene are powdered and placed in a cylindrical mold which is placed under vacuum for about 15 min at room temperature to allow the material to deaerate. The mold is fitted with pistons at each end which are used to sinter the deaerated powder by compression to about 4000 psi. Two pistons were used to minimize piston-travel. The process produces a cylinder of material 2 in. long, 0.5 in. in diam, which is very homogeneous and translucent; within an hour after sintering the material cures at room temperature, and becomes completely transparent. A range of temperatures and times for deaeration and a range of pressures and rates of compression were tried. The homogeneity and clarity of the material does not depend on any of these but on how well the powder was deaerated. Professor Ginoux, von Kármán Institute for Fluid Dynamics, Rhode St., Genese, Belgium, (personal communication) has successfully produced cylinders up to 8 in. long and 3 in. in diam using deaeration at room temperature and compression to 8000 psi in a two-piston mold similar to ours. Williams[10] used the vacuum sintering technique to bond a 0.5-in.-thick layer of camphor to an aluminum core having dimensions of the order of a foot. In his case, finely powdered, deaerated camphor was placed in a plastic bag along with the core and compressed by an isostatic press with the aid of a conical female mold.

Sintered camphor and naphtalene were found[7] to have densities of 63.4 and 73.5 lb per cubic foot, respectively. Their shear strength was measured to be about 100 and 160 psi, respectively, whereas casting yielded between 55 and 72 psi. A series of $7\frac{1}{2}°$ cones machined out of sintered cylinders were tested in the wind tunnel to determine the reproducibility of the sublimation history which was found to be very good, far better than when the models were cast. Camphor is slightly easier to sinter than naphthalene and yields a more nearly transparent stock.

Results

The tests described in this paper were performed using models machined out of sintered camphor and naphthalene. All models were initially 1.9 in. long and 0.5 in. in max diameter. The nominal wind-tunnel Mach number was 3 and the typical Reynolds number per inch was 100,000. Captions of the figures give the individual test conditions more precisely.

Figure 1 shows a sequence of schlieren photographs of a camphor cone with a flat nose initially. The blowing parameter is approximately 0.035;

$$B' = \dot{m}/(\rho_e u_e C_H)$$

A remarkable feature of these records is the sharpening of the nose to a point. Although the body becomes blunter in the sense that the over-all fineness ratio decreases as it sublimates, the tip becomes more pointed. The afterbody sublimates initially to a slightly concave profile immediately downstream of the shoulder, indicating a higher heat-transfer rate in that region. As the nose sharpens and stabilizes, the afterbody assumes a convex power-law profile. The same behavior was observed at higher stagnation temperatures corresponding to blowing parameters up to $B' = 0.15$ and on models having initially a hemispherical nose.

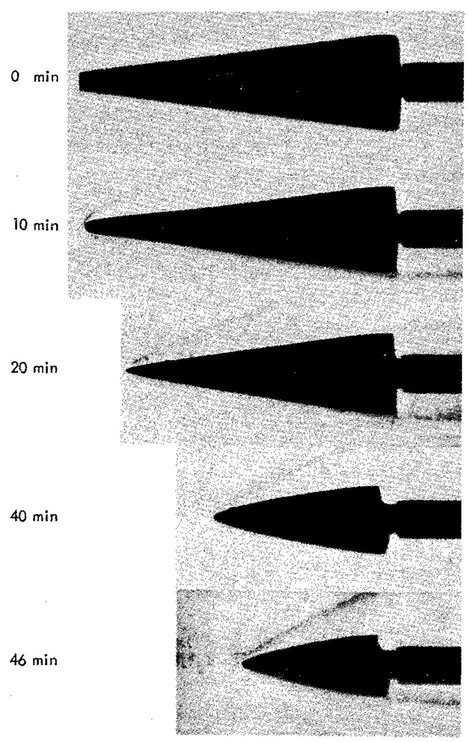


Fig. 1 Sublimation of a blunted camphor cone at $M = 2.78$ $P_0 = 1$ atm, $T_0 = 80°$F.

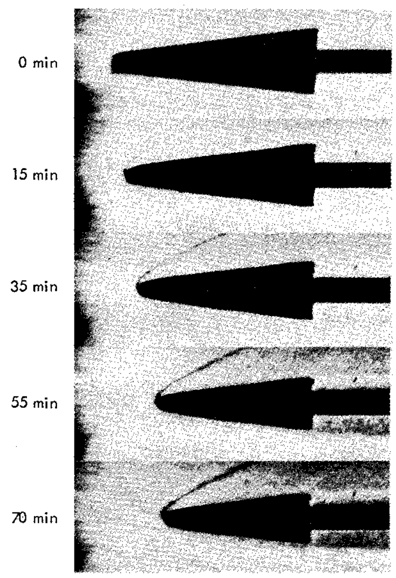


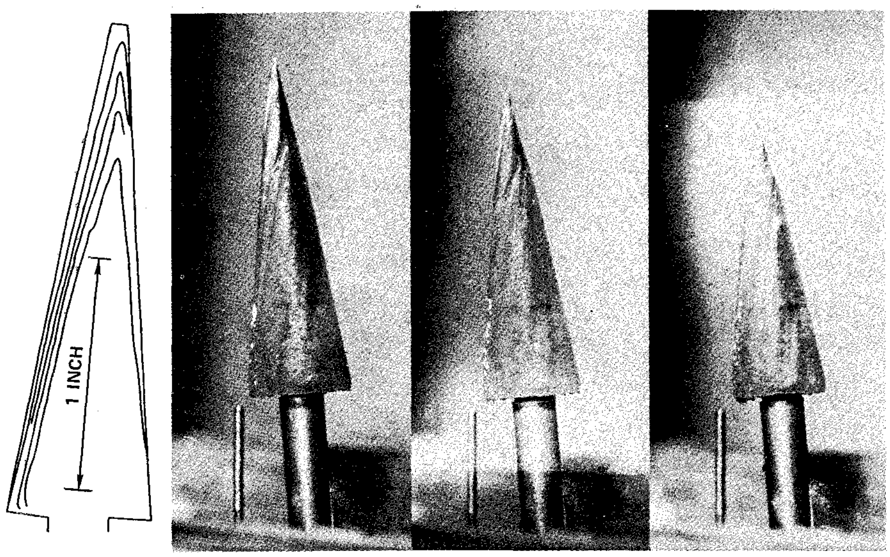
Fig. 2 Sublimation of a blunted naphthalene cone at $M = 2.78$ $P_0 = 1$ atm, $T_0 = 137°$F.

Figure 2 shows a study of a similar naphthalene cone. The stagnation temperature is higher, so that the blowing parameter for this material is in the same range as that for the camphor model of Fig. 1 ($B' = 0.035$). The recession history of the tip is nonetheless obviously different. The naphthalene model retains a definite hemispherical nose shape.

Existing analyses shed no light on this pronounced qualitative difference in the behavior of camphor vs naphthalene models. We know of one other laboratory study[11] which reported the sublimation of models, graphite cylinders, to needle-points as sharp as those we observed. Laminar/turbulent transition, which is sometimes identified as the cause of erosion that sharpens the shoulder of blunt nose, obviously cannot explain the phenomenon in this case. It may be due to: 1) the phase-change kinetic constraint on the process of sublimation in the region of the tip[12,13]; or 2) two-dimensional unsteady heat conduction in the ablating surface. It is worth noting that the bulk-temperature, room temperature, of the model is respectively lower and higher than the phase-change temperature at the static wind-tunnel pressure for camphor and naphthalene.

Figure 3 shows the evolution of the profile of an initially flat-nosed camphor cone at a 5° angle of attack traced from enlarged film records, together with still photographs of the same cone taken through the wind-tunnel wall. The tip of the model behaves the same way as at zero incidence. These photographs show grooves which originate at the tip, in one case somewhat downstream of the tip, and spiral from the windward to the lee side. Such grooves occur also in test shown on Figs. 1 and 2, but they are not visible on pictures taken through the Schlieren optics. With no incidence, the grooves are simply radial. The photographs also show traces of camphor powder recondensed both on the lee side of the body and in the base wake of the model. Experiments were conducted with 7.5° half-angle cones at angles of attack up to 15°. The structure of grooves extending from the windward to the leeward side remained qualitatively similar to that illustrated in Fig. 3. As expected, the recession rate of the windward ray increased with increasing angle of attack. The recession rate of the leeward ray at first decreased with angle of attack, but as the angle of attack exceeded the cone half-angle, a groove along the leeward ray was formed, as shown in Fig. 4.

The radial (no incidence) and spiral grooves (at incidence) described here seem to be associated with vortex-lines formed



PROFILES IN 1 MIN INTERVALS ~125 sec ~188 sec ~240 sec

Fig. 3 Sublimation of a flat nosed 15° camphor cone at 5° incidence; $M = 3.05$ $P_0 = 735$ mm Hg; $T_0 = 141$°F.

in regions of separation of the flow (as in the case of the leeward ray at incidence) or shed downstream of local disturbances caused by the breaking off of the pointed tip. It is remarkable that these grooves seem to reach an equilibrium depth.

Figure 5 shows a 25° cone with a cylindrical afterbody at zero incidence. This sequence exhibits an interesting regular pattern of streamwise grooves on the forebody; the grooves do not originate near the tip. The relatively pronounced concavity of the profile, see photograph at 125 sec, suggests that these forebody striations are associated with the formation of a Görtler vortex pattern. The order of magnitude of their spacing sustains this interpretation. Similar markings are discussed below in connection with the downstream-facing step, which also results in a slightly concave body profile.

III. Albation of Bodies with Regions of Separated Flow

Figure 6 shows the erosion of a cross-stream notch. Notches having a smaller initial length-to-depth ratio were also tested and found to behave in a way similar to the case shown. Such notches disappear relatively rapidly, beginning in the high-heat-transfer region of the recompression step. The floor of the cavity, where heat transfer is low, is hardly eroded until the entire notch is erased. The behavior of such transverse grooves is in sharp contrast to that of streamwise grooves, which do not erode away.

Figure 7 shows the history of a conical forebody terminating in an upstream-facing step. A region of high-mass transfer upstream of the step can be immediately identified downstream of the point of separation of the boundary layer on the cone. The existence of this region is inconsistent with theoretical models in which it is assumed that the internal, recirculating cavity flow is nearly dead. The face of the step, and in particular, the recompression corner, appear to erode remarkably slowly, which is surprising. Note also the spots of recondensed material are visible not only at the base of the model, as noted on other models, but also on the surface of the cylindrical afterbody downstream of the step. This indicates that the boundary layer never truly reattaches, or at least that it is very much thickened by the reattachment process.

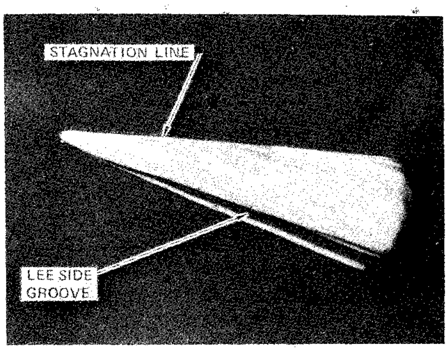


Fig. 4 Photo of a cone model with a streamwise groove along the leeward ray.

These photographs also display the results of an interaction between a tip-generated groove propagating downstream and the cavity, which leads to an asymmetrical distortion of the flowfield. The termination point of the groove on the first two photographs indicates the point at which the boundary layer separates upstream of the step. The model is irregularly scarred with streamwise striations on the afterbody; however, these do not exhibit the homogeneity and uniformity of striations occurring when the basic profile is convex.

In contrast with the upstream-facing separation, the downstream facing step shown in Fig. 8, is eroded in a smooth and stable fashion. High heat transfer in the region of recompression causes the afterbody to become slightly convex, see first photograph, whereupon the regular pattern of streamwise grooves appears immediately. The grooves are spaced more widely here than in Fig. 5; which may be due to the fact that the boundary layer is thicker after recompression than that on the cone forebody of Fig. 5. This observation is compatible with the suggested explanation that the forebody striations are due to a Görtler type of secondary flow.

Note that in the same period of time and under the same freestream conditions the over-all fineness ratio of a cone changed from 0.3 to 0.35, whereas that of the cone with a downstream facing step (Fig. 8) changed from 0.3 to 0.285. For the upstream-facing step (Fig. 7) the fineness ratio changed only slightly, from 0.28 to 0.295. Associated with these changes is a significant change in the drag coefficient—an increase in the case of the cone and a decrease in the case of the cone-step-cone model.

Discussion

In observing the sublimation of models in the tunnel, one can at all times follow and qualitatively interpret what is happening. The development of nonuniformities and stream-

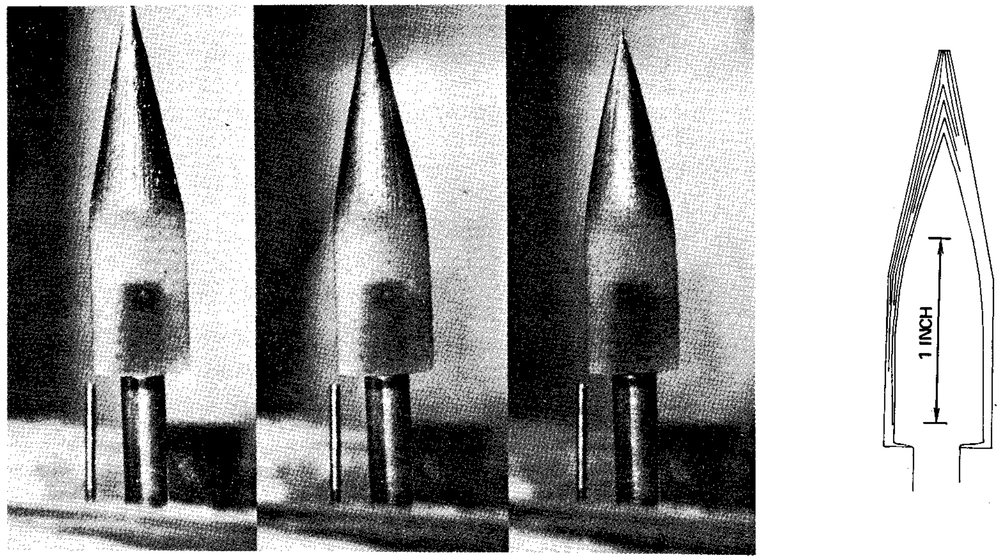


Fig. 5 Sublimation of a 25° blunted camphor cone with cylindrical afterbody. M = 3.05, P_0 = 735 mm Hg, T_0 = 138°F.

wise scars can be observed and related to identifiable causes, such as, the way in which the needle tip erodes and shears off. The vacuum-sintered material behaves very satisfactorily, even when sharp corners and steps are machined in it.

However, the over-all profile of the model at any instant, which depends on the time integral of its previous history, exhibits variations which cannot be foreseen a priori. The most notable nonuniformities occur when the tip of the model recedes into the streamwise scars (grooves) that originated near the tip at any earlier time.

One of the most striking anomalies was recorded during tests with one 15° flat-nosed cone (Fig. 1) and with the flat-nosed 25° cone-cylinder (Fig. 5). Immediately after the start of the test and for a period of about 15 sec, camphor powder accumulated on the face of the flat nose, causing an apparent increase of 0.2 in. in the total length of the 15° cone! The 25° model evidenced less accumulation, and the material was not uniformly distributed over the face of the nose. The material accumulated has the appearance of a fairly loose and porous powder. The observation is accurate, but cannot be explained at this time. In any case, about 30 to 45 sec after start, the deposit disappeared and the shoulder gradually eroded to a rounded shape and finally to a sharp point.

In general, a blunt-nosed cone becomes slightly concave downstream of the nose/afterbody junction, apparently as the result of the separation of the boundary layer at the corner and its subsequent re-establishment on the afterbody.‡ The subsequent evolution of the profile is intimately related to the history of the tip. The shoulder erodes, forms a sharp tip which recedes, and then catches up with the concave surface rather rapidly, forming a biconvex, ogival final shape. In Fig. 5, on the other hand, the erosion of the shoulder leaves a needle tip of remarkable length, see the photograph taken at 125 sec, and a distinctly convex forebody profile. Ultimately, this body also relaxes to the more stable ogival shape like the others.

With camphor, the tip always tends to form a needle point under the present test conditions. Typically, the needle has a 0.01 in. diam at the base and a 0.10 in. length. The needle erodes by crumbling more or less randomly, and an observer often has the impression of seeing the body escape upstream into the needle. How the needle behaves is critically important; it is stronger (and longer) on cones with a larger divergence angle. One would expect there to be, for each specific ablator, a critical divergence angle beyond which the phenomenon would not occur; naphthalene, for example, did not behave in this way.

On a slightly coarser scale, the sublimation of these simple and composite cones is quite reproducible. A characteristic velocity of the over-all process can be identified as the streamwise recession rate of the tip, at least during the period after it becomes pointed. Figure 9 gives examples of tip-recession rate data for camphor cones at one stagnation temperature. Data corresponding to a lower-stagnation temperature are presented in Ref. 7. After an initial period of adjustment, the recession of the tip becomes remarkably linear. There is some scatter in the results, possibly due to an insufficiently close control over the stagnation temperature, which varied in some of the tests by 10°, the persistence of the influence of the initial period and the effect of streamwise scars formed in that time. Neither the divergence angle of the conical afterbody nor the incidence of the model to the flow seems to affect the recession rate.

The constancy of the tip-recession velocity and its independence of the geometry of the body suggest a thermochemical limit phenomenon which is independent of the local transfer properties of the boundary layer. Such a phenomenon was considered in Ref. 12 where it was shown that downstream of a sharp tip (the origin of the boundary layer) there is a zone characterized by a length, δ, which is defined by physical constants of the sublimating material and freestream parameters only, and within which the sublimation process is controlled by the kinetics of phase change and not by the boundary-layer diffusion mechanism. The blowing parameter tends to zero at the tip, the surface temperature tends to the adiabtic recovery temperature of the freestream, and the ablation rate tends to a maximum which, provided the cone-angle remains approximately constant, would result in a tip recession rate of

$$\dot{x}_{\max} = \epsilon P_s/[\rho 2\pi(R/M)T_{aw}]^{1/2}$$

where P_s is the equilibrium phase-change pressure of the sublimating material evaluated at the adiabatic wall temperature T_{aw}, ρ, and M are density and molecular weight of the sublimator, respectively, R is the universal gas constant, and ϵ is an empirical vaporization coefficient. The value of ϵ is not well established. For solid sublimators, it probably does not exceed 0.1[13] and can be less than that by two orders of magnitude. Using data for camphor, one obtains the values shown in Table 1.

‡ This type of behavior has been observed before and interpreted in terms of laminar/turbulent transition. Although transition does not seem to be the cause here, it would have a similar effect.

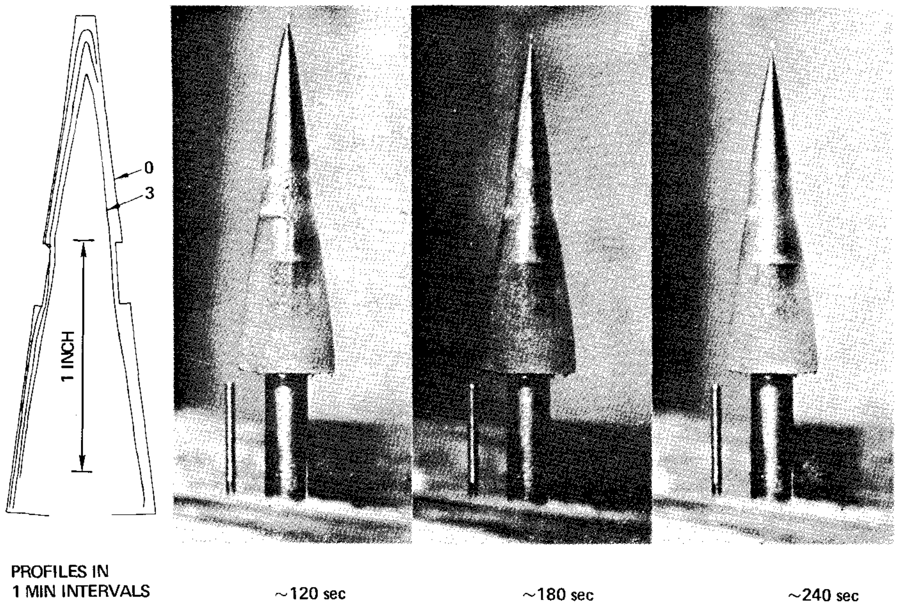


Fig. 6 Sublimation of a 15° blunted camphor cone with a transverse notch (initially 0.050 in. deep; 0.250 in. long), $M = 3.05$, $P_0 = 735$ mm Hg, $T_0 = 146°F$.

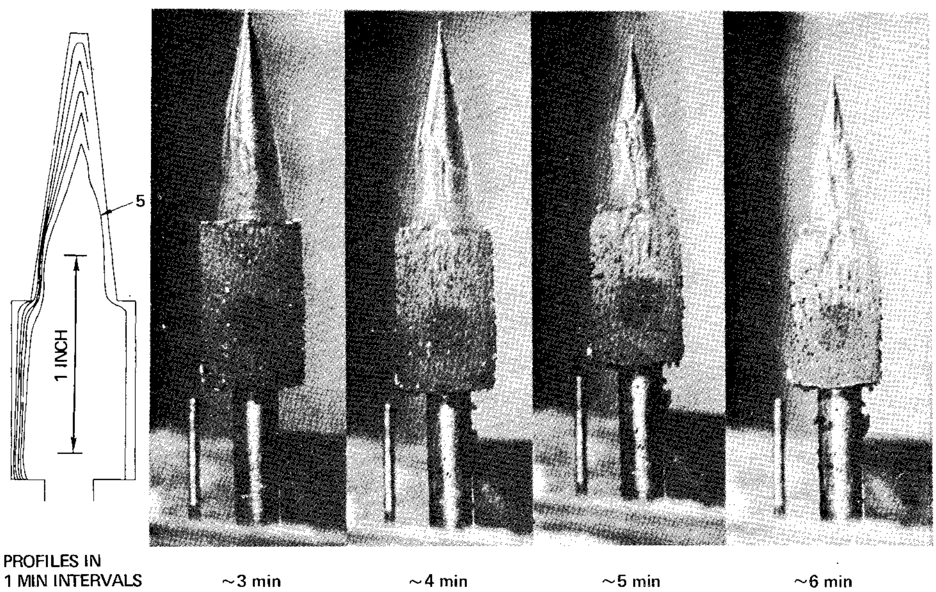


Fig. 7 Sublimation of a 15° blunted camphor cone with an upstream facing step (initially 0.0625 in. high) $M = 3.05$, $P_0 = 735$ mm Hg, $T_0 = 140°F$.

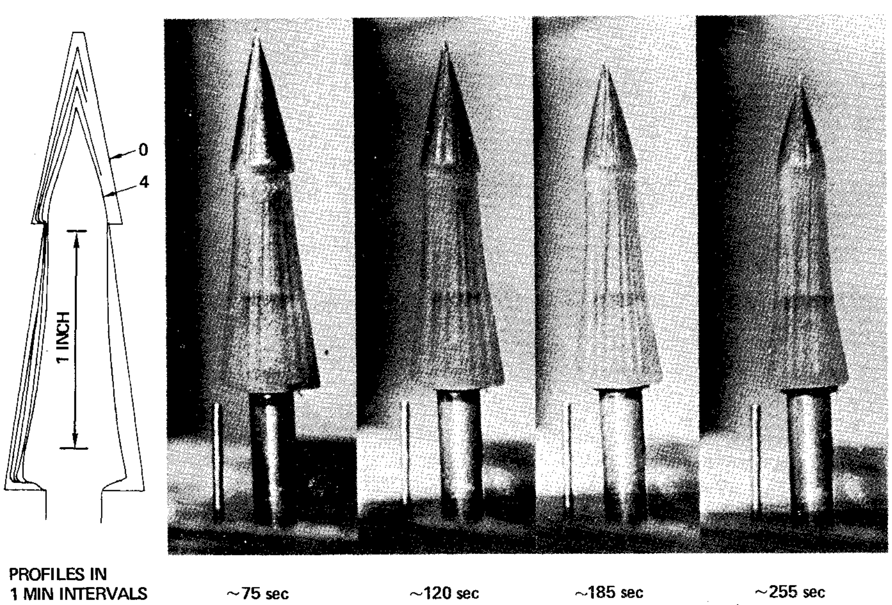


Fig. 8 Sublimation of a 15° blunted camphor cone with a downstream facing step (initially 0.625 in. high), $M = 3.05$, $P_0 = 735$ mm Hg, $T_0 = 141°F$.

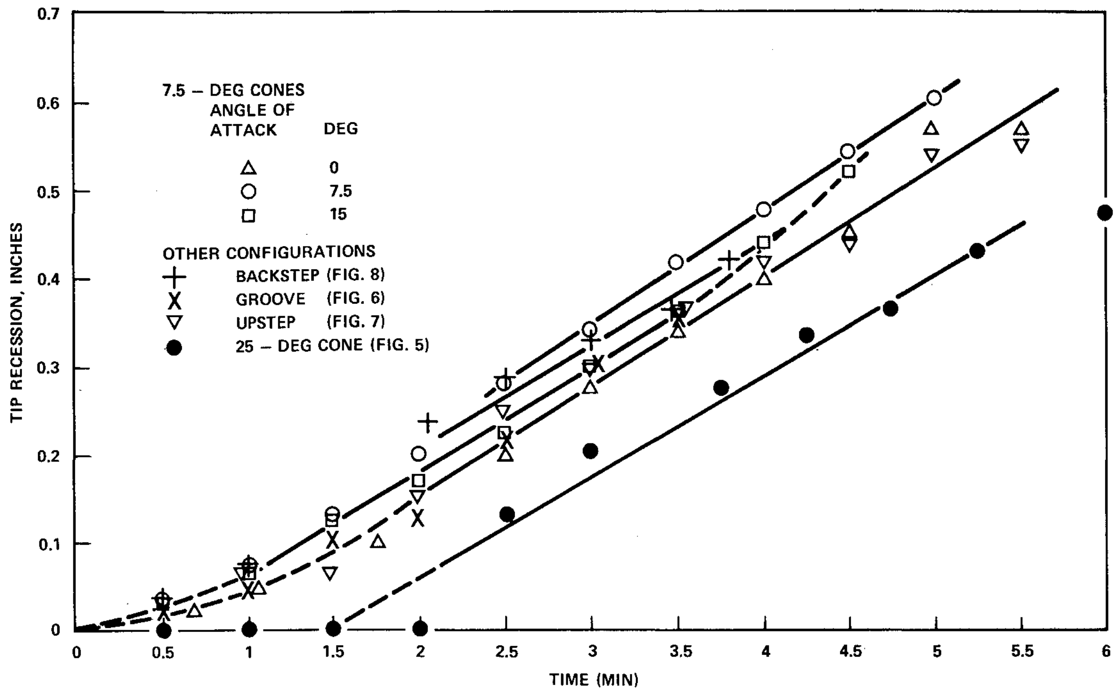


Fig. 9 Tip recession rates of flat-nosed camphor cones and conical bodies; $M = 3.05$, $P_0 = 1$ atm, $T_0 =$ approx 140°F.

The temperature dependence of $\dot{x}$ is in reasonable agreement with the predicted trend. In addition, line d of Table 1 indicates that the observed recession rates are of the order of the maximum allowed by the phase-change kinetics (note that line d may be interpreted as experimental values of ϵ). The general accord of these exploratory experimental trends with predictions of the theory suggests that further study may prove to be fruitful.

Trends in tip recession data for naphthalene models are the same as for the camphor model, however, one cannot expect a quantitative comparison with the theory, which applies only to pointed bodies, and the naphthalene models never formed a sharp tip.

We did not observe the crosshatching pattern mentioned in the Introduction. This accords with the experience of other investigators. This pattern has not been noticed except in regions of transition or turbulence.

Towards the end of the tests, we did observe on some models, irregular, streamwise striations, together with cross-stream (irregular) wavelets,[1] on the downstream third of the model's surface. However, this occurred only after the model had ablated quite a distance, exposing the material around the sting imbedded in the camphor. This stub is screwed into the piston during the compression process, and the powder often does not sinter around it as well as it does in the bulk of the material. Thus the surface markings may well be due to the different properties of this portion of the model (e.g., lower shear strength or inhomogeneous structure).

The deep streamwise grooves, most often originated at the very tip and formed all along the length of the model at once. This indicates that rather than being eaten out of the downstream edge of the disturbance, the grooves result from a disturbance in the boundary layer, such as a vortex with its axis parallel to the flow, which is attached at the disturbance and convected downstream with a velocity of the order of the freestream velocity.

There appears to be a minimum depth of a streamwise groove. Shallow grooves disappear when the disturbances causing them are removed. Deeper grooves persist, apparently sustaining a disturbance in the boundary layer. One can observe many weak striations that appear at the tip as it erodes and disappear if the tip changes shape (the typical time associated with this process is estimated to be 15 sec for the camphor models at 140°F). If the disturbnce persists long enough to scar the surface critically, the groove remains.

An example of this process is seen in Fig. 5. The pattern of striations visible on the forebody was associated in the foregoing discussion with a Görtler instability of the flow over a concave surface. The grooves are not deep, and as the surface becomes convex (~220 sec) are totally erased.

The sensitivity of sublimation to vortical disturbaces in the boundary layer is remarkable. A subliming surface may indeed be used to detect such phenomena, which would otherwise be virtually unmeasurable. Finally, the erosion of the notched models indicates that transverse grooves or cracks are unstable in the sense that they cause a disturbance which erases them, contrary to stable streamwise grooves.

Conclusions

The method of sintering a deaerated powder described herein provided a far stronger and more homogeneous block of camphor or naphthalene from which one can machine wind-tunnel models for the study of sublimation in high-speed flow than casting.

A series of models fabricated by this method, comprising blunt-nosed cones and composite models with downstream-and-upstream-facing steps, notches and corners, was subjected to an exploratory study. The erosion of these shapes follows a logical pattern, reproducible in its gross features but subject to local, random variations associated with the history of the erosion of the tip. It seems feasible and useful to consider further the use of certain of these features, for instance, downstream-facing steps in connection with prescribing a drag-ablation profile for a re-entry trajectory.

Table 1 Tip recession characteristics

a)	Stagnation temperature	70°F	140°F
b)	Measured mean tip recession rate, $\dot{x}$	0.0018	0.125
c)	Calculated: $\dot{x}_{max}/\epsilon$, in./min	0.161	2.08
d)	Ratio $\dot{x}/(\dot{x}_{max}\epsilon)$	0.073	0.060

It was demonstrated that there are consistently reproducible conditions in which the blunt nose of a body becomes pointed in the absence of laminar turbulent transition and tends to form a sharp needle. The recession of a pointed tip appears to be linear with time, and tentatively verifies the predictions derived from a theory exploring the kinetic-rate-limit on the sublimation rate. Further study is indicated to achieve a thorough understanding of these phenomena.

It was shown that cross-stream grooves tend to be erased, whereas streamwise grooves couple with the boundary layer in such a way as to be perpetuated. There seems to be a critical depth at which such grooves persist; this is also a promising subject for further quantitative study using the present experimental technique. A regular pattern of striations was consistently observed on concave surfacs. It is suggested that this is evidence of a Görtler instability.

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