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AN EXPERIMENTAL STUDY OF THE BEHAVIOR OF SPHERES ABLATING UNDER CONSTANT AERODYNAMIC CONDITIONS

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SUMMARY

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Five spheres constructed of ablative material, with diameters of 0.6 inch to 2.0 inches, were subjected to aerodynamic heating to determine the physical behavior of such bodies as they are reduced toward zero volume by the ablation process. Three of the bodies were tested in hypersonic flow, one was tested in supersonic flow, and one was tested in subsonic flow. The stagnation-point heating rate for the tests varied between 52 and 565 Btu/(sq ft)(sec). The Reynolds number based on model diameter varied between 1.0×10^4 and 9.6×10^4.

For the range of test conditions covered in the experiment, results indicate that the recession rate of the stagnation point is essentially constant over the life span of such bodies, regardless of the magnitude and character of the convective heating imposed. There was an apparent tendency for the average radius of the ablating face to increase slightly with time at supersonic and hypersonic speeds and to decrease with time at the subsonic speed. In the supersonic tests, no noticeable loss of material occurred over the downstream surface of the bodies. In the subsonic test, however, loss on the downstream surface equaled that over the forward surface. A discussion of the measured recession rate of the stagnation point is presented.

INTRODUCTION

The ablation process has been shown to be a most efficient means of achieving thermal protection for vehicles reentering the earth's atmosphere. Post-reentry examinations have indicated that ballistic vehicles protected in this manner generally experience only small changes in basic shape and a relatively small loss of ablation material. Meteoroids, however, which enter the earth's atmosphere at higher velocities, are often completely destroyed. Any theory of meteoroid entry (ref. 1, for example) or spacecraft entry must necessarily include certain assumptions regarding the variation of the heating load on the reentering body and the resulting shape changes. Inasmuch as the ablation process for such bodies may not proceed in the manner assumed, it was considered appropriate to make a brief experimental study of the process.

Tests have been conducted at the Langley Research Center to determine experimentally the changes in shape and mass-loss rate with time experienced by spheres ablating under constant convective heating and loading. Three facilities, a subsonic arc-heated jet, a supersonic arc-heated jet, and a hypersonic combustion-heated tunnel, were used to provide a range of aerodynamic heating rates and flow conditions. The stagnation-point heating rate for the tests varied between 52 and 565 Btu/(sq ft)(sec) and the Reynolds number varied between 1.0×10^4 and 9.6×10^4.

A detailed description of these tests and a discussion of the pertinent results are presented herein.

SYMBOLS

c_p specific heat of ablative material (solid), Btu/(lb)($^\circ$R)

D_o initial diameter of sphere, ft

$H_e \equiv \frac{q}{\dot{m}} = c_p T_a + H_L + \eta(H_s - H_w)$, Btu/lb

H_L latent heat of vaporization, Btu/lb

H_s stream enthalpy at body stagnation point, Btu/lb

H_w enthalpy at body surface, Btu/lb

$\dot{m}$ mass loss rate due to ablation, lb/(sq ft)(sec)

q local heating rate to body, Btu/(sq ft)(sec)

q_s stagnation-point heat-transfer rate, Btu/(sq ft)(sec)

R test Reynolds number based on initial diameter of sphere

T_a temperature at which material ablates, $^\circ$R

t time, sec

V volume of body, cu ft

V_o initial volume of sphere, cu ft

x distance along streamwise axis of body (fig. 3)

x_f streamwise body-axis station where volume integral is closed (fig. 3) y radius of body normal to streamwise axis (fig. 3)

δ recession of stagnation point due to ablation of body, ft

η shielding coefficient

ρ density, lb/cu ft

Subscripts:

calc calculated

exp experimental

MODELS

All the bodies tested were initially spherical and were sized in accordance with the heating rate, running time, or test-section size of the facility to be used for testing. Table I presents the pertinent information for each sphere and

TABLE I.- DESCRIPTION OF SPHERES AND THERMAL PROPERTIES OF THE MATERIALS

Model	Sphere diam., D_o, in.	Material	Density (solid), ρ, lb/cu ft	Latent heat of vaporization, H_L, Btu/lb	Surface temp. at stagnation point (from ref. 4), °F	Shielding coeff., η	Specific heat (solid), c_p, Btu/(lb)(°F)	Effective heat of ablation,* H_e, Btu/lb
A	1.25	Ammonium chloride	88	1,340	990	0.5	0.38	1,890
B	.80	Teflon	137	700	1,380	.4	.30	1,267
C	.60	Teflon	137	700	1,410	.4	.30	1,332
D	2.00	Teflon	137	700	1,420	.4	.30	1,907
E	.60	Teflon	137	700	1,550	.4	.30	1,783

*Computed on basis of test conditions in table II.

indicates the model designations. Sketches of the models and their supports are presented in figure 1 and photographs of models A, D, and E are presented in figure 2. (Models A, B, and C differ only in material and sphere diameter.) It should be noted that the sphere support stings for the arc-heated (higher energy level) facilities were constructed of a phenolic-impregnated cloth. Experience has indicated that the high heating rate would cause failure of less bulky metal support stings in a time interval less than that needed to ablate the sphere to zero volume.

FACILITIES

Tests were conducted in three different facilities. Models A, B, and C were tested in the 7-inch Mach 7 pilot tunnel, which is a hypersonic blowdown tunnel that uses as its test medium the combustion products resulting from burning a

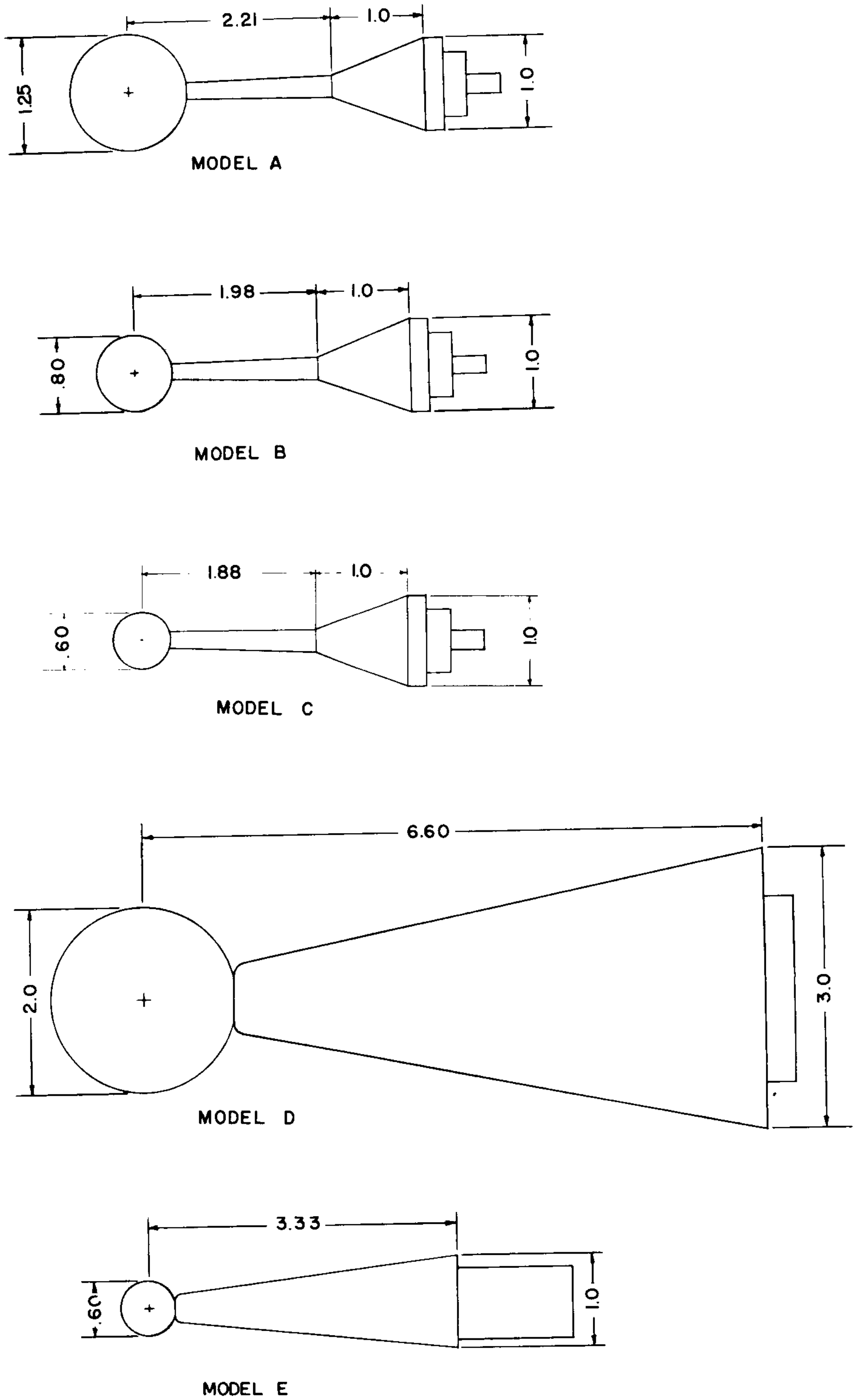


Figure 1.- Support arrangement and pertinent dimensions for the various spheres tested. All dimensions are in inches.

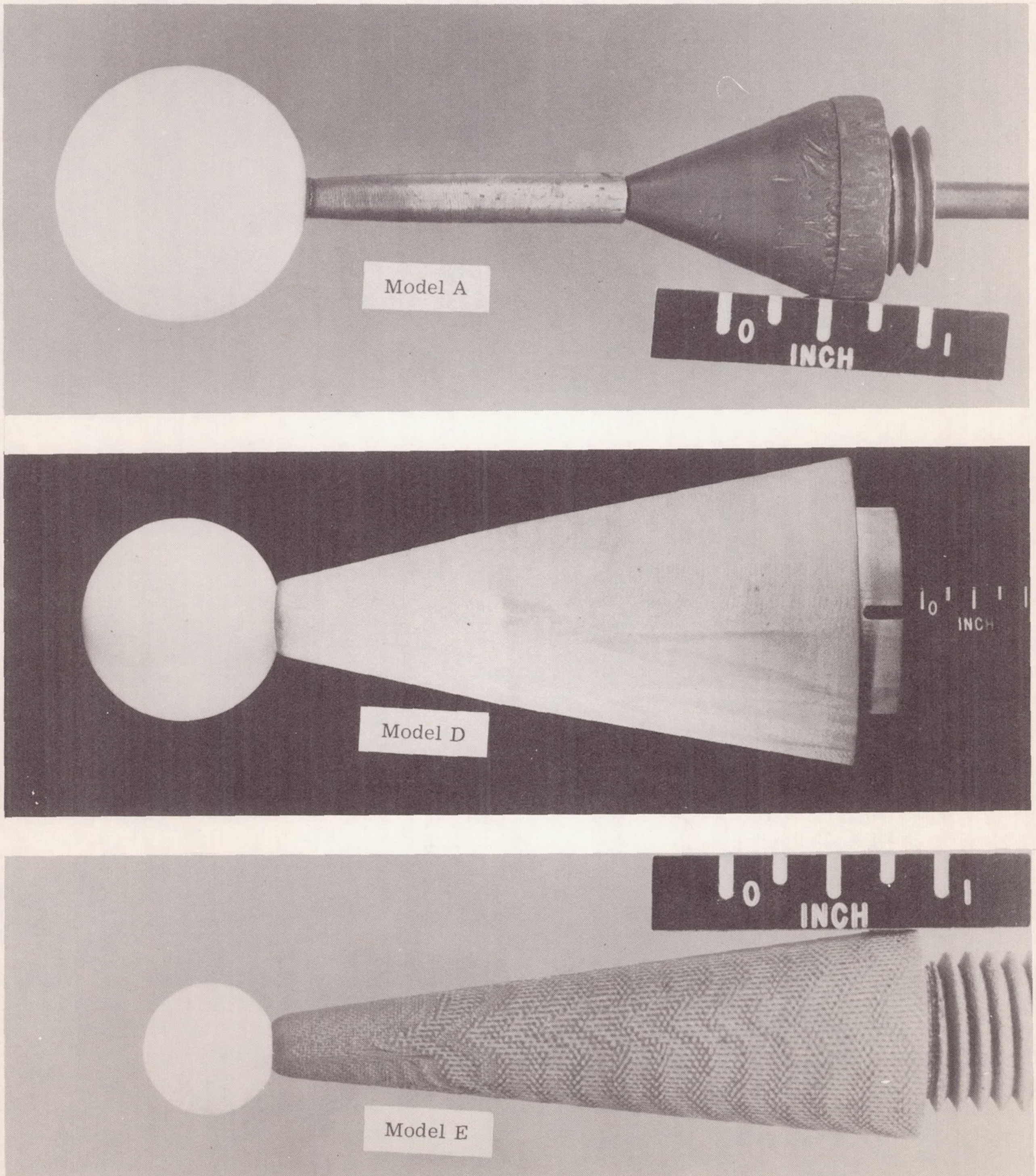


Figure 2.- Photographs of spheres prior to testing. L-63-23

mixture of ethylene (C_2H_4) and air under pressure. The flow developed by this facility simulates flight at a Mach number of 7.0 in that the gas is expanded to a static temperature near 0° F and correct velocity is simulated. The usable test core in this facility is approximately 3 inches in diameter.

Model D was tested in a subsonic arc-heated air jet. The flow developed by this facility is a 4-inch-diameter jet of underexpanded high-temperature air discharging to the atmosphere at a velocity of approximately 900 ft/sec. The static temperature of the jet is about 6,800° R.

Model E was tested in a supersonic arc-heated air jet. The flow developed by this facility is an underexpanded free jet which discharges to a reduced pressure at a Mach number of 2.6. The static temperature of the jet is about 3,700° R and the velocity about 7,300 ft/sec. The jet diameter is 2 inches at the nozzle exit.

TESTS

Table II presents the pertinent test conditions to which each model was subjected. In each case the model was held out of the test region until the test conditions were established. The model was then inserted into the test region

TABLE II.- TEST CONDITIONS

Model	Stagnation-point temp., °R	Stagnation-point press., atm	Stagnation enthalpy, Btu/lb	Stagnation-point heating rate, q_s, Btu/(sq ft)(sec)	Test Mach number	Stream static temp., °R	Test Reynolds number, R
A	3,100	0.64	930	52.4	7.0	350	9.6×10^4
B	3,100	.64	930	65.6	7.0	350	6.1
C	3,200	.69	1,080	88.9	7.0	360	5.0
D	6,840	1.13	2,500	180.0	.24	6,804	1.4
E	5,850	.95	2,100	565.0	2.6	3,715	1.1

for the duration of the test and retracted prior to tunnel shutdown. In the case of models A, B, C, and E, reference measurements for the determination of stagnation pressure and temperature were recorded continuously during the test interval. These measurements were generally in the form of output from thermocouples and pressure transducers and were recorded on oscillographs. For the test of model D, a calibrated calorimeter was inserted into the jet just prior to insertion of the model. The output from this calorimeter was calibrated in terms of stagnation-point heating rate. With this rate and the known pressure in the arc chamber, the stagnation conditions on the model were computed.

The degree of uncertainty of the body stagnation-point conditions quoted in table II varies for the different test facilities used. For example, for models A, B, and C the stagnation-point heating rate is believed to be quite accurately known (to within ±3 percent) as a result of accurate measurements of the tunnel stagnation temperature and pressure. For model D the stagnation-point heating rate indicated by the calorimeter is believed to be accurate to within about ±10 percent. For model E the stagnation heating rate was deduced from a knowledge of the flow rate of air through the tunnel, the tunnel stagnation pressure, and the power input to the arc. The resulting heating rate quoted for model E is believed to be accurate to within ±10 percent.

The basic data obtained from the tests were shadowgraph pictures taken every 3 seconds during the test interval for models A, B, C, and D. For model E the pictures were taken every 1.5 seconds. In addition to these shadowgraph pictures, black and white or colored motion pictures were taken to provide pictorial data for each test.

RESULTS AND DISCUSSION

The shadowgraph pictures taken at discrete time intervals during the tests were enlarged and traced for each of the models. A composite drawing of these tracings for four of the models is presented in figure 3. (For ease in making comparisons between models, the scale of the spheres has been adjusted in figure 3 so that all models appear the same size.) Models B and E were ablated to zero volume. In order to accomplish this result for model B, two runs were required. Although transient conditions were encountered at the beginning of each test run, they did not seriously alter the progression of the ablation, as will be shown later in the discussion. Model E was reduced to zero volume during one test run.

The bodies tested in hypersonic and supersonic flows experienced similar variations in forward-surface profile. In general there was a tendency for the radius of the forward surface to increase slightly with time. It should be noted here that the shape changes experienced by the bodies in these tests are due entirely to convective heating. If radiative heating were large, as it would be for hyperbolic reentry into the earth's atmosphere, further increases in forward-surface radius could probably be expected. No significant loss of material occurred on the downstream surface of the bodies tested in supersonic flows.

The irregularity of the contours of model E (fig. 3) at 11.1 and 14.1 seconds was indicated by motion pictures to be due to the interference with the body by the compression wave originating at the jet exit. The model moved off the jet center line as the test progressed because of unsymmetrical heating of the metal support, and thus encountered the effects of the compression wave during the final half of the tests. The stagnation point shifted on the body as a result of the angle of attack and caused a rounding of the shoulder opposite the one affected by the shock wave.

Models A, C, and D were not ablated to zero volume. Two runs were made of model A without completing its ablation. A photograph of the remaining portion of the body is presented as figure 4. The appearance of the body in this photograph is typical of the bodies in their final stages of existence in supersonic flow.

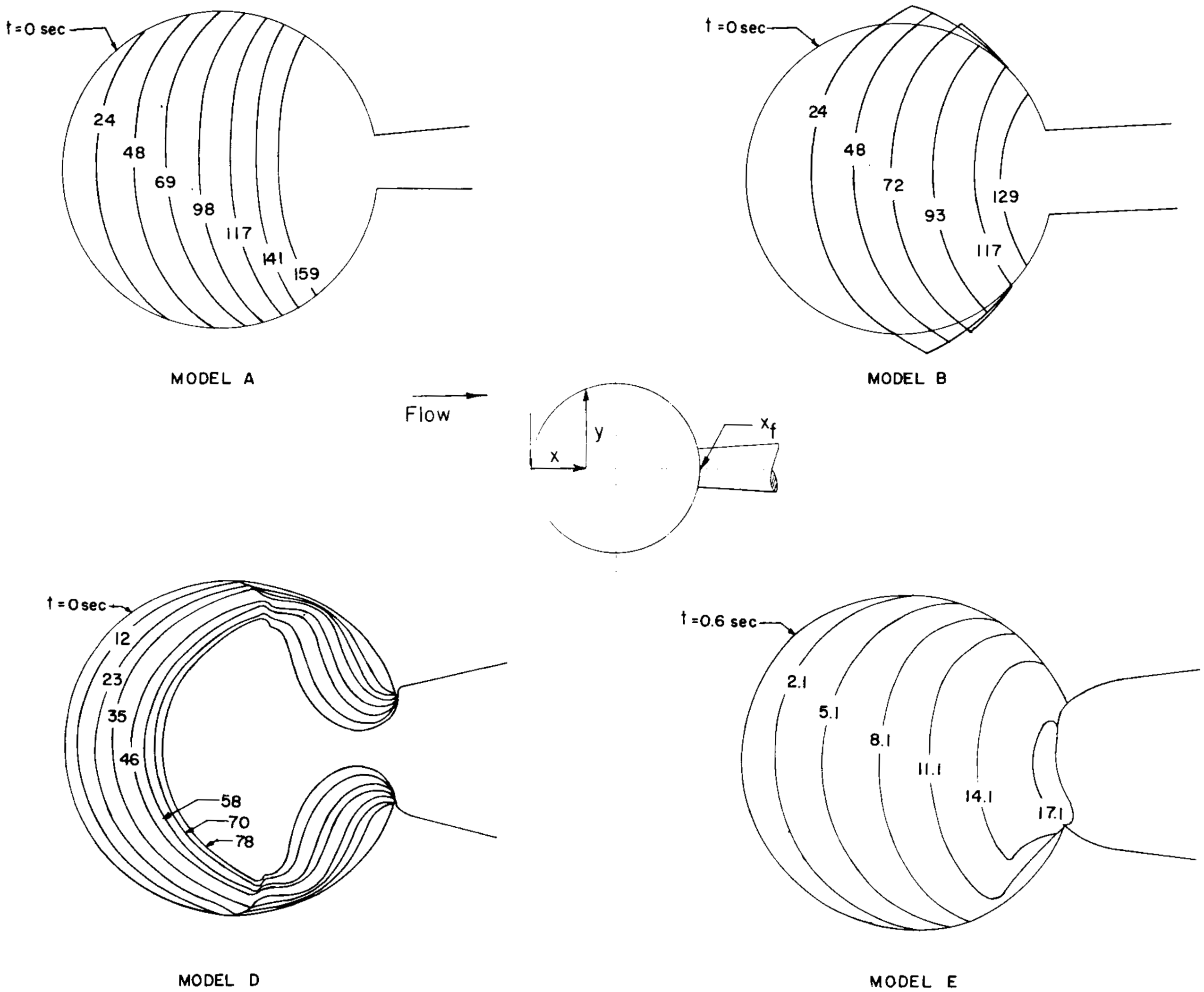


Figure 3.- Composite drawings showing the profiles of the bodies at specific times during the ablation process.

Model D, which was tested in subsonic flow, experienced mass loss over the downstream surface of the body in an amount about equal to that over the forward face (fig. 3). After 82 seconds the ablation on the rear portion of the body caused the body to part from the sting. A photograph of the remains is presented as figure 5. The downstream ablation experienced by the body in the subsonic jet is believed to be due to the relatively high static pressure and temperature of the jet and the turbulent action of the wake downstream of the point of separation on the body. It should be noted that the forward half of this model maintained more of a spherical shape than the models in the supersonic and hypersonic tests. (Compare models A, B, and E with D in fig. 3.)

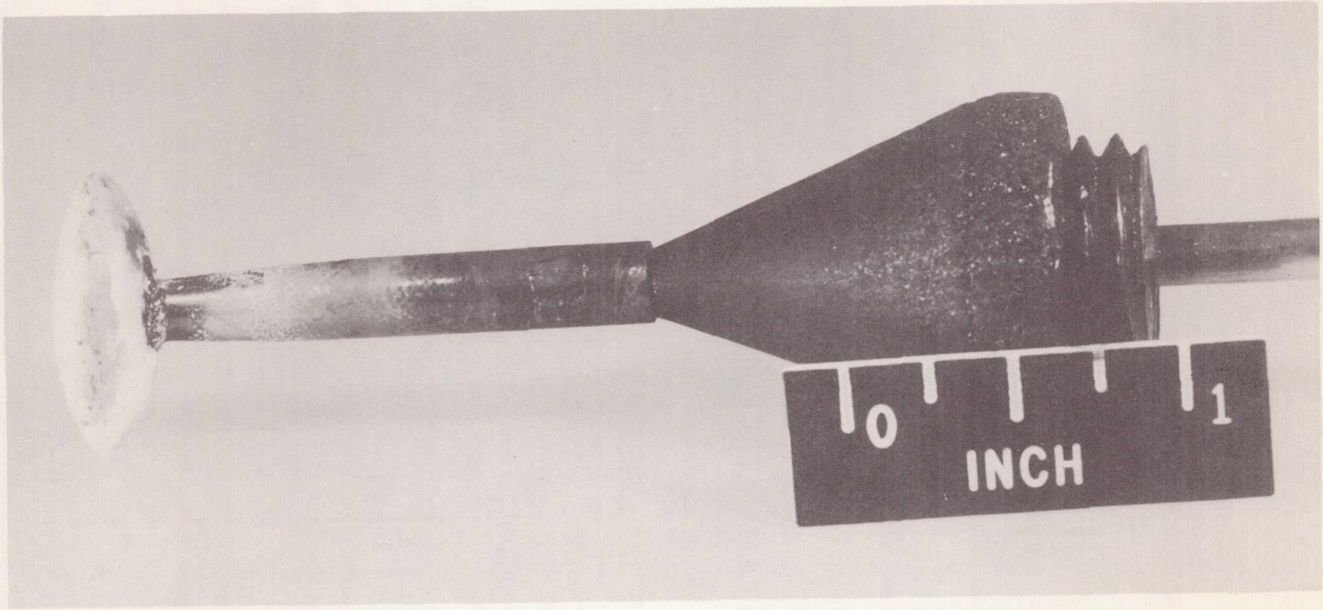


Figure 4.- Remaining portion of model A after tests. L-62-2464

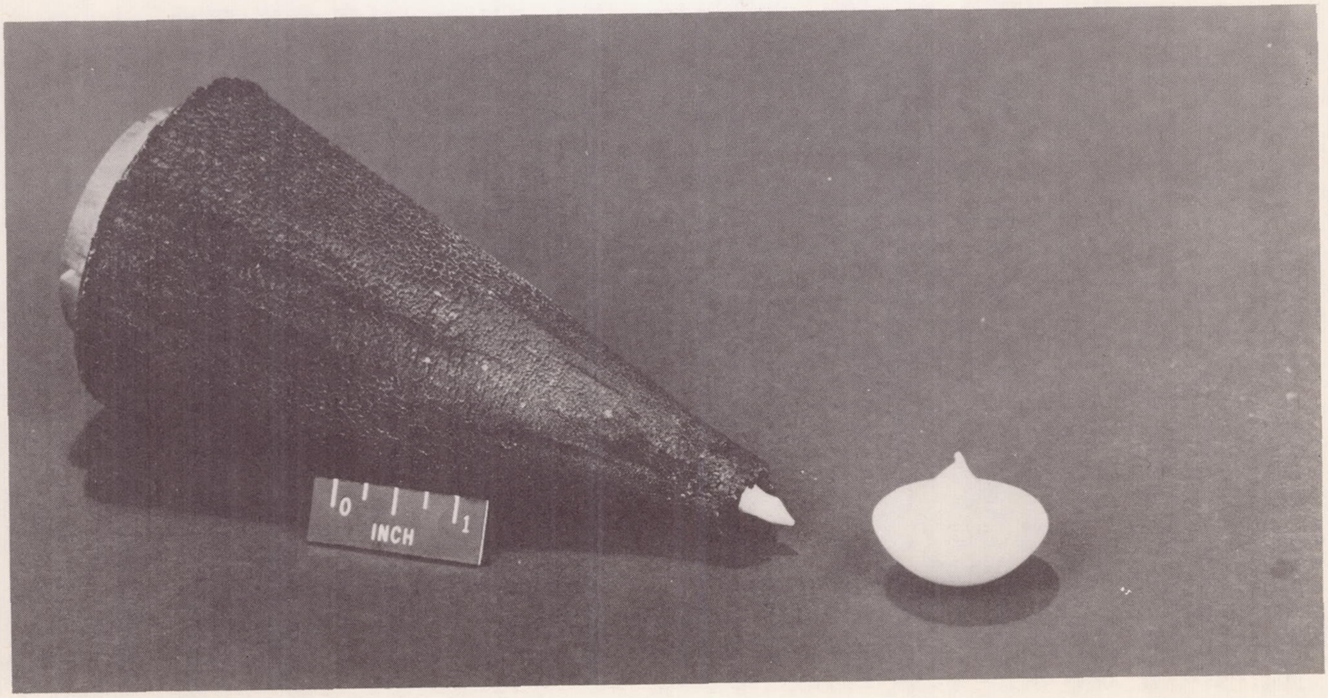


Figure 5.- Remaining portions of model D and support after tests. L-62-1356

The volume of the body corresponding to any shadowgraph picture was computed by mechanical integration of the equation

$$V = \pi \int_0^{x_f} y^2 dx$$

where values of y and x were obtained from measurements made on the tracing of the enlarged shadowgraph. The enlargement for all bodies was sufficient to make small inaccuracies of measurement result in insignificant changes of computed volume. The ratios of the computed volume V to the initial volume V_o for each model are presented as a function of time in figure 6.

The density of the materials from which the models were constructed was found to vary somewhat during the test run. Thermal expansion of Teflon was very noticeable during the long runs at low heating rates (see fig. 3, model B). Also, for both the ammonium chloride body (model A) and the Teflon body (model B) there was a discontinuity of volume between the test runs (see figs. 6(a) and 6(b)) that indicated thermal expansion. The apparent density changes of the ammonium chloride were less than those exhibited by the Teflon. During the initial 10 seconds of the tests that were made at low heating rates (models B and C) the expansion of the Teflon offset the volume lost due to ablation (see figs. 6(b) and 6(c)). In the tests at high heating rates (models D and E) the expansion was not noticed. In all cases, as the body temperature approached equilibrium the apparent rate of volume loss became reasonably regular over the length of the test run.

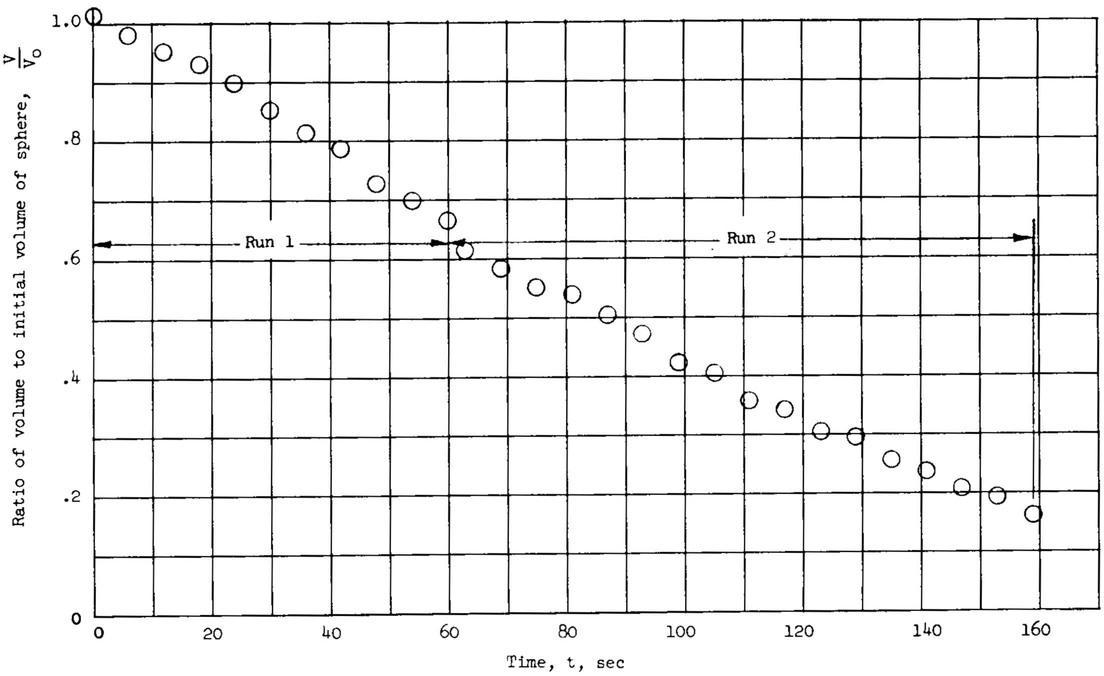
The measured recession of the stagnation point due to ablation, as obtained from measurements of shadowgraph pictures, is expressed as $1 - \frac{\delta}{D_o}$ and presented in figure 7 as a function of time. All the bodies experienced a nearly linear recession of the stagnation point with time. It should be noted here, also, that the recession of the stagnation point for models A and B was not significantly altered by the fact that the ablation took place during two separate test runs.

The effective heat of ablation for the different bodies has been determined by use of the equation

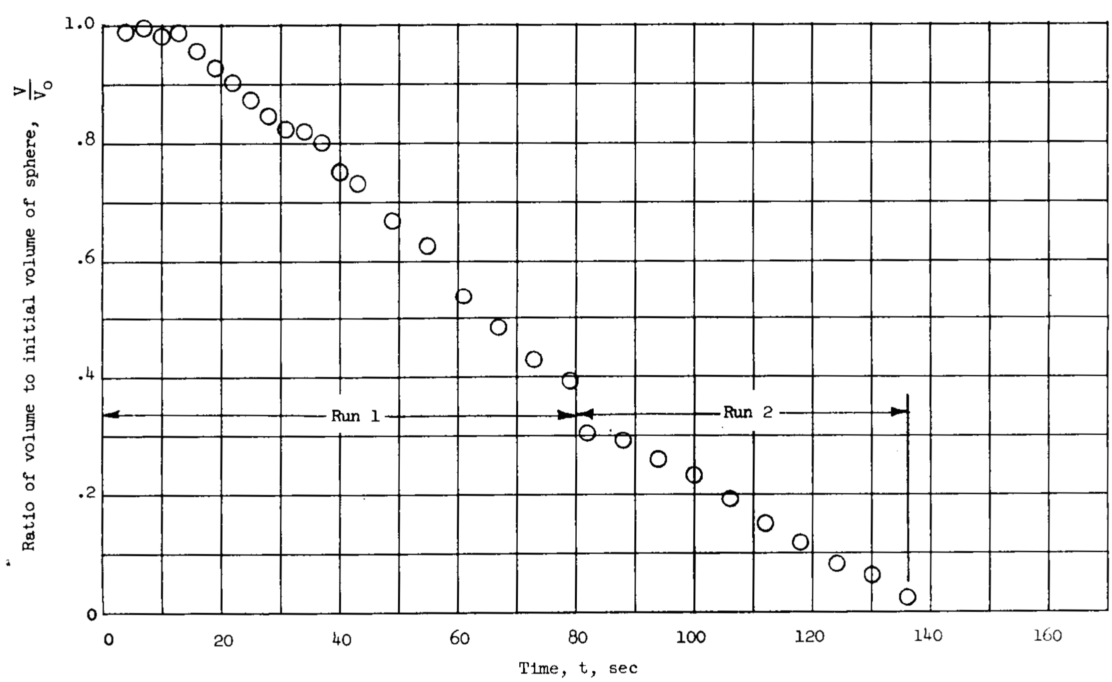
$$H_e = \frac{q_s}{\rho \frac{d\delta}{dt}}$$

where the values of stagnation-point heating rate and material density are those presented in tables I and II and the recession rate $d\delta/dt$ was determined from figure 7. These experimentally determined effective heats of ablation are compared with the values computed according to the equation

$$H_e = C_p T_a + H_L + \eta\left(H_s - H_w\right)$$

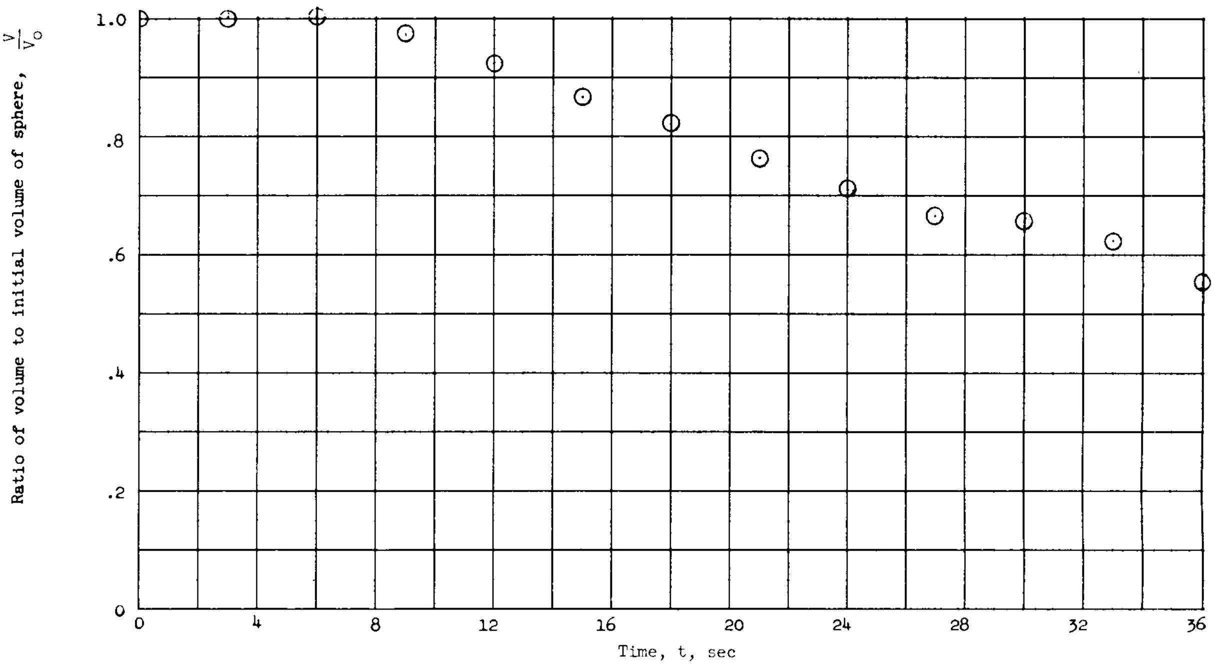


(a) Model A (ammonium chloride).

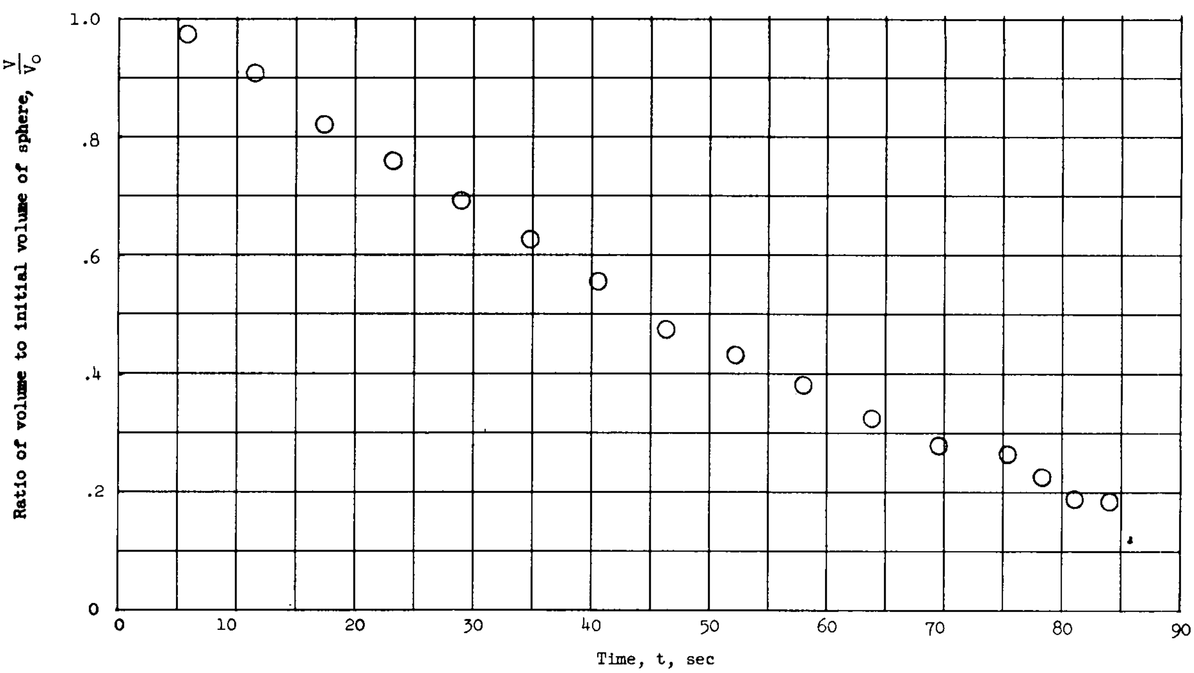


(b) Model B (Teflon).

Figure 6.- Variation of body volume with time for each of the spheres tested.

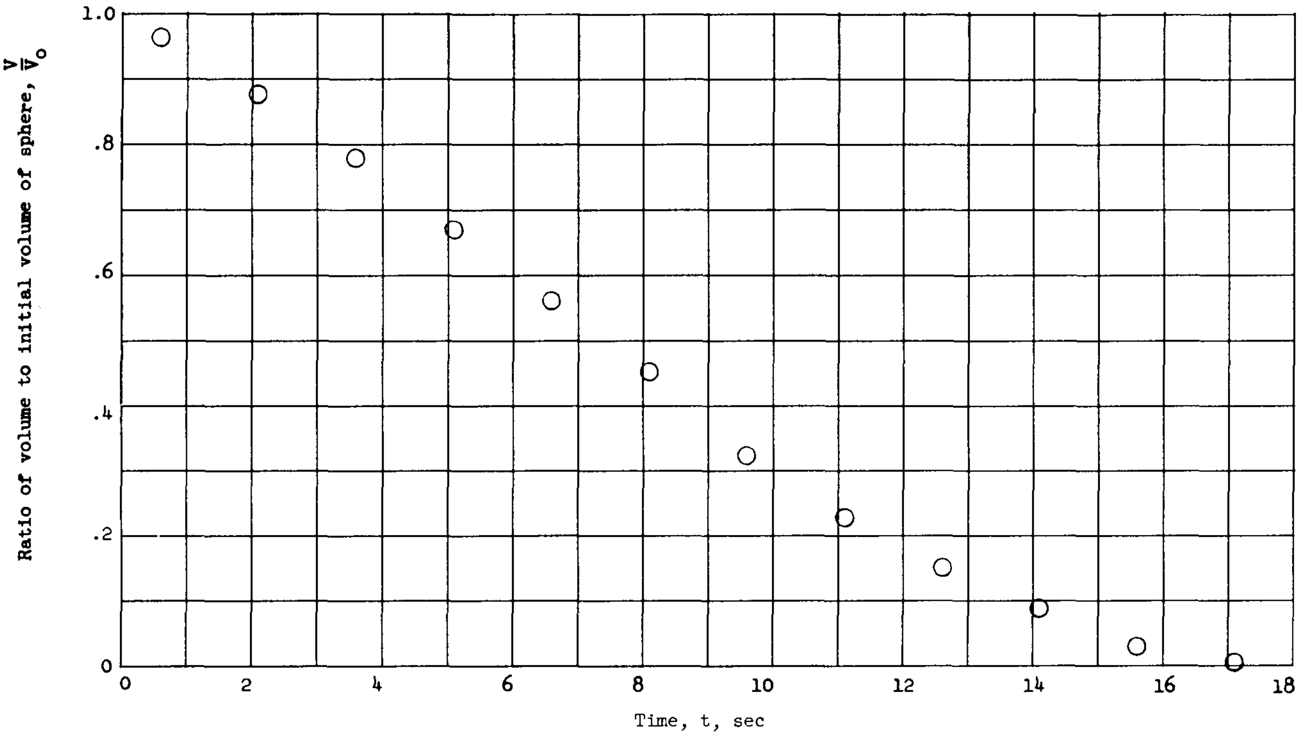


(c) Model C (Teflon).



(d) Model D (Teflon).

Figure 6.- Continued.



(e) Model E (Teflon).

Figure 6.- Concluded.

The results are presented in the following table:

Model	$(H_e)_{exp}$	$(H_e)_{calc}$	$\frac{(H_e)_{exp}}{(H_e)_{calc}}$
A	1,316	1,890	0.695
B	1,153	1,267	.910
C	1,230	1,332	.924
D	2,062	1,907	1.082
E	1,720	1,783	.965

The variation of the experimental value of H_e from the calculated is less than ±10 percent for the Teflon bodies (models B, C, D, and E), indicating that the certainty of the test conditions and the knowledge of the ablating characteristics of this material (Teflon) are very good. The prediction of the stagnation-point recession rate based on the calculated value of H_e would also have been within ±10 percent if it were assumed that the bodies had a constant stagnation-point heating rate.

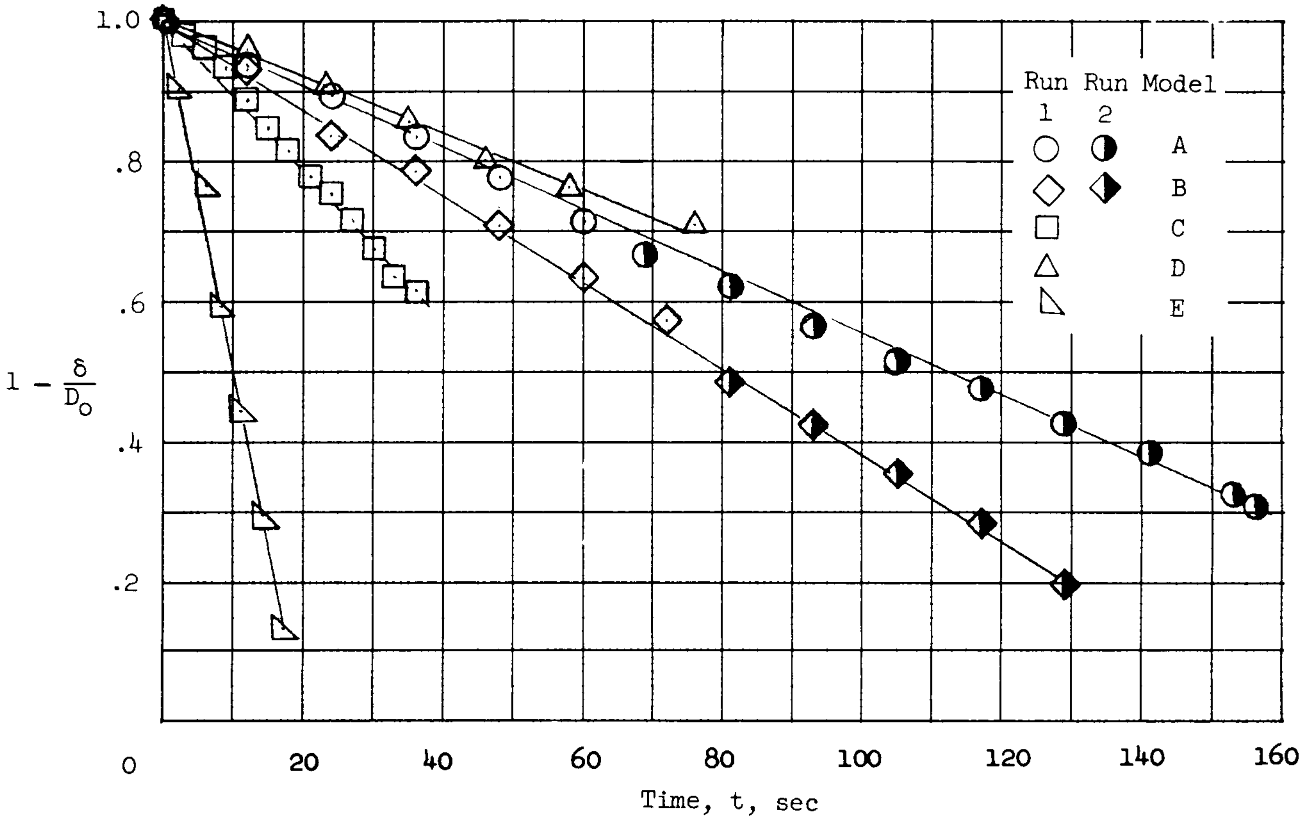


Figure 7.- Variation of stagnation-point location with time for the various spheres tested.

For model A (the ammonium chloride body) the agreement between experimental and calculated values of H_e was poor. This discrepancy is believed to result from a lack of knowledge of the ablation characteristics of the material. The heat of vaporization used to compute H_e for the ammonium chloride model was 1,340 Btu/lb (taken from ref. 2). Handbooks give the heat of vaporization as 142 Btu/lb (see, for example, ref. 3). The heat actually absorbed in the ablation of the material is dependent upon the extent to which the sublimated material is dissociated and, hence, is a function of the stream stagnation temperature and the heating conditions. Agreement between theory and experiment could have been achieved for the ammonium chloride body if a heat of vaporization of approximately 700 Btu/lb had been used. This value is between the two values quoted from the literature and indicates that for the present results there is either a partial dissociation, a loss of material due to processes other than ablation, or a chemical process occurring in the combustion-products test medium of this particular facility that reduces the effective heat of ablation of ammonium chloride from what it would be in air under similar conditions.

CONCLUDING REMARKS

Five spheres constructed of ablative material, with diameters of 0.6 inch to 2.0 inches, have been subjected to aerodynamic heating to determine the physical behavior of such bodies as they are reduced toward zero volume by the ablation process. Three of the bodies were tested in hypersonic flow, one was tested in supersonic flow, and one was tested in subsonic flow. The results indicate that the recession rate of the stagnation point is essentially constant over the life span of such bodies. There was an apparent tendency for the average radius of the ablating face to increase slightly with time at supersonic and hypersonic speeds and to decrease with time at subsonic speeds. In the supersonic tests, no noticeable loss of material occurred over the downstream surface of the bodies, whereas in the subsonic test the loss over the downstream surface equaled that over the forward surface, apparently because of turbulent wake action at the high static temperature.

The effective heats of ablation computed by using the experimental stagnation-point recession rate, material density, and body stagnation-point heating rate were in good agreement with the calculated values for the Teflon bodies. The inability to achieve similar agreement for the ammonium chloride body is believed to be due primarily to lack of knowledge of the ablation characteristic of this material.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 21, 1963.

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