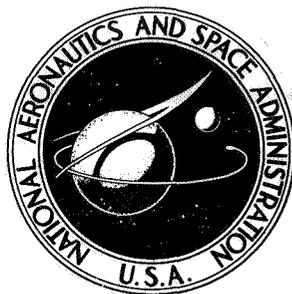


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EFFECTS OF MATERIAL COMPOSITION  
ON THE ABLATION PERFORMANCE OF  
LOW-DENSITY ELASTOMERIC ABLATORS

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SUMMARY

The ablation performance of materials composed of various concentrations of nylon, hollow silica spheres, hollow phenolic spheres, and four elastomeric resins was determined. Both blunt-body and flat-panel specimens were used, the cold-wall heating-rate ranges being 0.11 to 0.8 MW/m<sup>2</sup> and 0.11 to 0.18 MW/m<sup>2</sup>, respectively. The corresponding surface-pressure ranges for these tests were 0.017 to 0.037 atmosphere and 0.004 to 0.005 atmosphere. Some of the results show that (a) the addition of nylon significantly improved the ablation performance, but the nylon was not compatible with one resin system used in the study; (b) panel and blunt-body specimen data do not show the same effect of phenolic sphere content on ablation effectiveness; and (c) there appears to be an optimum concentration of hollow silica spheres for good ablation performance. The composition of an efficient, nonproprietary ablator for lifting body application is identified and the ablation performance of this ablator is compared with the performance of three commercially available materials.

INTRODUCTION

Ablative heat shields have been used to provide efficient thermal protection systems (TPS) for manned and unmanned space vehicles. If ablators are to be used on the space shuttle orbiter, then certain characteristics are required that were not required for previous flight vehicles. The orbiter is a large, reusable manned vehicle. Ablators therefore, must be low cost (since ablators may not be reusable), lightweight (because of the large vehicle area), and have high reliability. Because the orbiter is a high-lift vehicle, the aerodynamic shape of the vehicle must be maintained and, therefore, the ablator must have very little surface recession. Low-density, honeycomb-reinforced, elastomeric ablators have shown potential for meeting these requirements. Low-cost fabrication techniques, which reduce heat-shield costs by more than an order of magnitude below Apollo ablator costs, have been developed for these materials. (See refs. 1

to 5.) Materials made with these low-cost fabrication techniques show good ablation performance.

Previous investigations of low-density (160 to 320 kg/m<sup>3</sup>) elastomeric ablators are reported in references 6 and 7. In those studies, fiber reinforcement rather than honeycomb reinforcement was used. Only one silicone resin system was used with various percentages of hollow phenolic spheres and nylon.

The objective of the present investigation was to identify a low-density elastomeric ablator which meets the orbiter ablator requirements and is amenable to low-cost fabrication processes. To meet this objective, the ablator constituents and composition were systematically varied and a large number of ablators were made. The constituents which were varied were four silicone resin systems, two honeycomb reinforcement materials, hollow phenolic spheres, hollow silica spheres, and nylon. Specimens of each composition were tested in arc-jet facilities to evaluate their ablative performance. From these tests, a composition was selected which combined the best performance characteristics of the various ingredients. The ablation performance of this composite is discussed and compared with the performance of three well-characterized commercially available ablators.

#### SYMBOLS

E	ablative effectiveness, $q_{cw}t/m$
$\bar{E}$	relative ablative effectiveness
H	total enthalpy
L	model length
m	mass per unit area
p	pressure
q	convective heat-transfer rate
$r_b$	model body radius
s	distance from geometric center line along surface

t            time  
x            distance from front edge of panel specimen  
 $\bar{\rho}$           relative density

Subscripts:

cw          cold wall  
e            condition at edge of boundary layer  
mp          midpoint  
s            static condition  
stag        stagnation point  
t            total  
2            condition behind shock wave

## MATERIALS AND MATERIAL FABRICATION

### Materials

The materials evaluated in this investigation were low-density (200 to 300 kg/m<sup>3</sup>) elastomeric composites. Each composite consisted of an elastomeric resin, one to three filler materials, and a honeycomb reinforcement. These constituents, listed in table I, were selected because they are amenable to low-cost fabrication techniques. (See refs. 1 to 5.) The composition of each material tested in this investigation is given in table II.

### Material Fabrication

All the materials were manufactured in 30 cm by 30 cm by 3.8 cm billets. Manufacture of the billets was begun by bonding a honeycomb reinforcement to a 0.064-cm phenolic-fiberglass face sheet. This subassembly was vacuum bagged and oven cured at 408 K for 30 minutes. After this curing operation, the honeycomb was primed with a phenolic resin and placed in a mold on a vibrator table. The ablative fillers were sifted (a 20-mesh screen was used for the hollow phenolic spheres and a 32-mesh screen was

used with the hollow silica spheres and the nylon), mixed with a catalyzed silicone resin, and then spread by hand over the honeycomb as the honeycomb was being vibrated. The mold was vacuum bagged and placed in an autoclave. The material was vacuum molded into the honeycomb by lowering the vacuum bag internal pressure slowly to about 0.064 atmosphere and pressurizing the autoclave with nitrogen to about 3.0 atmospheres absolute. The autoclave temperature was held at 408 K during this molding process. The assembly was then transferred to an air-circulating oven for curing. The bag internal pressure was again lowered to about 0.064 atmosphere and the billets were cured at 355 K for 20 hours. After curing, the density of each billet was calculated and recorded.

The dryness of the low-density elastomer compositions created a problem in completely filling the honeycomb. Trial-and-error procedures indicated that a molding pressure of 3 atmospheres resulted in completely filled cells and this pressure was the maximum that could be used with a 24 kg/m<sup>3</sup> phenolic fiberglass honeycomb without crushing the honeycomb.

Several molding problems were encountered with the Sylgard 182 resin system, the reference resin system for this study. On several occasions, material compositions containing Sylgard 182 resin failed to cure completely in the normal cure cycle, but were eventually cured by extending the cure cycle. Some compositions never completely cured even after extending the cure cycle. The source of the curing problems is not understood.

Another problem encountered was that specimens with 20 percent Sylgard 182 resin and more than 10 percent nylon would not cure. In an attempt to identify the source of this problem, composite material samples were examined with a scanning electron microscope (SEM). Photographs of the specimens at several magnifications are shown in figures 1 and 2. Figure 1 shows SEM photographs of a material composed of 15 percent hollow silica spheres, 10 percent nylon, 50 percent hollow phenolic spheres, and 25 percent Sylgard 182 resin. Figure 2 shows a SEM photograph of a material with the same composition except that RTV-602 resin has been substituted for the Sylgard 182 resin. The broken pieces of hollow spheres on the nylon particle (fig. 2) indicate that the nylon was coated by the RTV-602 resin and was bonded to the hollow spheres. There is no evidence in figure 1 that the nylon was coated by the Sylgard 182 resin or that hollow spheres adhered to the nylon particle. The reason for this lack of coating is not understood.

## SPECIMEN CONFIGURATIONS

Test specimens of two different shapes (fig. 3) were fabricated from the billets of material. One configuration was a blunt body 6.3 cm in diameter and 1.3 cm thick and the other was a square panel 13 cm by 13 cm by 3.8 cm.

## Blunt-Body Specimens

Details of the blunt-body specimens are shown in figure 4(a). Specimens were fabricated from both the top and bottom sections of the billets. However, the material was not compacted well into the honeycomb cells near the bottom of the billet and, therefore, only data from specimens from the top section are included herein.

The front surface of each specimen was machined to a convex shape (fig. 4(a)) to give a nearly uniform heating rate across the surface. The specimen back surface was instrumented with a thermocouple soldered to a 1.3-cm-diameter by 0.08-cm-thick copper disk which was, in turn, bonded in place. Each specimen was bonded to a canvas-reinforced-phenolic holder which protected the thermocouple from the test environment and provided the means of attachment to the specimen inserter. A canvas-reinforced-phenolic disk was bonded in the center of the specimen holder to support the thermocouple lead wire.

## Square-Panel Specimens

Details of the square-panel specimens are shown in figure 4(b). Three copper disks, identical to those used on the blunt-body specimens, were bonded to the back surface of the panel. A groove was cut around each disk and these grooves were, in turn, encompassed by another groove. The grooves interrupt the lateral heat conduction path through the face sheet. The panels were mounted on a water-cooled wedge-shaped holder (fig. 4(c)), which supported the panel at an angle of attack of  $18^{\circ}$  to the test stream.

## TEST APPARATUS, ENVIRONMENT, AND PROCEDURE

### Test Apparatus

All the blunt-body specimens were tested in the supersonic arc-powered tunnel designated Apparatus B of the Langley entry structures facility. (See ref. 8.) A conical nozzle with a throat diameter of 7 cm and an exit diameter of 23 cm was used for these tests.

All tests on the square panels were made in the supersonic arc-powered tunnel designated Apparatus D of the Langley entry structures facility (ref. 8). A conical nozzle with a 2.5-cm throat and a 10-cm exit was used for the panel tests.

### Test Environment and Procedure

The nominal test environments are shown in table III, and the measured heating distributions over the specimens are shown in figure 5. A test stream of 3 percent (by mass) oxygen was used in the low-enthalpy blunt-body tests because it has been shown

(ref. 9) that to simulate high-enthalpy diffusion-controlled surface oxidation in a low-enthalpy test environment, it is necessary to reduce the oxygen concentration in the low-enthalpy environment. Cold-wall heating rates, heating-rate distributions, surface pressure, and pressure distributions were determined by using probes of the same size and shape as the specimens. Thin-skin calorimeters were used for the heating-rate measurements.

The test procedure for all tests was as follows: tunnel operating conditions were established and the test environment was allowed to stabilize; heating-rate and pressure measurements were made; the test specimen was inserted into the test stream and exposed to the test environment until the back surface temperature at the center of each specimen increased 167 K; and finally, the specimen was removed and post-test measurements of heating rate and pressure were made. Pretest and post-test conditions were essentially the same.

## RESULTS AND DISCUSSION

The materials were evaluated on the basis of the ablation effectiveness, recession, and char integrity. Ablation effectiveness was evaluated by using the ablation effectiveness parameter

$$E = \frac{q_{cw}t}{m} \quad (1)$$

where  $t$  is the time for the back surface temperature to increase 167 K. Material recession was determined by the difference between the initial and final total specimen thickness. The char integrity was evaluated by a qualitative assessment of the char-layer toughness.

Tests indicated that the orientation of the honeycomb ribbon direction with respect to the test stream direction did not influence the material performance over the range of test environments considered here; therefore, no special orientation was used.

The blunt-body specimen test times varied from 55 to 400 seconds. The panel specimen test times varied from 550 to 2200 seconds. The longer test time and resulting heat loads for the panel specimens are characteristic of the space shuttle entry.

### Ablative Performance

Hollow phenolic spheres.- Data in figures 6 and 7 show the effects of the amount of hollow phenolic spheres on ablation effectiveness for both blunt-body and panel specimens. The mass fractions of the hollow phenolic spheres and the resin were varied

simultaneously. The blunt-body test data show that ablation effectiveness increases with increased amounts of phenolic spheres (this result is consistent with the results of ref. 6), whereas the panel test data show the opposite trend. This decrease in effectiveness of the panel test specimens is due to increased surface recession and a reduction in char integrity as the resin content decreases. (See fig. 7.)

The difference between the trends of the blunt-body and panel test data was unexpected. The major differences between the blunt-body and panel specimens, other than geometry, are the ablator mass per unit area and the orientation of the specimen surface with respect to the test stream. Reference 10 shows that ablator mass per unit area has no effect on effectiveness trends and only a small effect on the magnitude of the effectiveness parameter. Therefore, the difference between the trends of the data is attributed to the specimen test orientation. A more accurate simulation of material performance in flight should be obtained when the test-specimen orientation with respect to the stream is similar to the corresponding vehicle surface orientation with respect to the stream.

Nylon.- Powdered nylon was found to be one of the most beneficial fillers used in this study for the systems with which it was compatible. Replacing 10 percent of the phenolic spheres with nylon increased the thermal efficiency by about 35 percent. (See fig. 6.) Other studies (ref. 6) have also noted significant improvements in thermal efficiency with the addition of nylon. A test specimen is shown in figure 8.

Resin.- The effect of the silicone resin systems on the ablative effectiveness of both blunt-body and square-panel specimens is shown in figures 9 and 10 for four resins, Sylgard 182, RTV-602, RTV-655, and a General Electric experimental resin 541-111. All these materials were composed of 20 percent resin and 80 percent hollow phenolic spheres. The material made with the General Electric experimental resin had high ablation effectiveness but it also had high surface recession and poor char integrity. (See figs. 9 and 10(b).) The materials made with RTV-602 and Sylgard 182 resins had the best overall performance (figs. 7(b), 9, and 10(a)). The RTV-602 and Sylgard 182 resins resulted in effectiveness values as high or higher than those for the RTV-655 resin. (See fig. 9.) The RTV-602 resin materials had the highest ablation effectiveness in the panel tests.

Hollow silica spheres.- Figure 11 shows the variation of ablation effectiveness as the amount of hollow silica spheres was varied from 0 to 40 percent and the amount of hollow phenolic spheres was varied from 80 to 40 percent. All these materials contained 20 percent Sylgard 182 resin. At lower heating rates the effectiveness increased with higher concentrations of silica spheres up to 15 to 20 percent. This increase may be due to better material compaction which reduced permeability. Also, the increased amounts of silica reduced surface recession by oxidation. The lower effectiveness with higher

silica sphere concentration is attributed to higher thermal conductivity. Both the blunt-body and the square-panel specimen showed the same trend but to a different extent. Tested panel specimens are shown in figure 12.

Reinforcement.- Two types of honeycomb reinforcements were used in this study: a phenolic fiberglass honeycomb and a phenolic-nylon-paper honeycomb. The phenolic fiberglass honeycomb resulted in the best ablation performance. The phenolic-nylon-paper honeycomb shrank, ablated, and resulted in increased char recession.

#### Material Recession

The surface recession of the blunt-body specimens and square-panel specimens is shown in figure 13. Recession was measured at the blunt-body specimen stagnation point and over the center thermocouple for the panel specimen. The data show that the recession increased with decreasing amounts of resin. Increasing the hollow silica sphere content reduced the recession. The data show that the recession is not sensitive to changes in heating rate over the range of test conditions considered.

#### Ablator Selection

The test data shown in figures 6 to 13 imply that high ablation effectiveness might be obtained with a material whose composition is 15 to 25 percent hollow silica spheres, 10 percent nylon, and the remaining 65 to 75 percent of the material a mixture of RTV-602 resin and hollow phenolic spheres. Based on these data, the composition of an ablator, designated 41, for space shuttle application was chosen to be 15 percent hollow silica spheres, 10 percent nylon, 50 percent hollow phenolic spheres, and 25 percent RTV-602 silicone resin.

Comparisons of the ablation performance of the selected ablator and the other material compositions tested are shown in figures 13 and 14. Ablator 41, in all cases, retained a smooth char surface (fig. 15) with little recession (fig. 13). The effectiveness of ablator 41 blunt-body specimens (fig. 14(a)) was comparable with the other materials tested. The data (fig. 14(b)) show that the effectiveness of ablator 41 panel specimens was about 45 percent higher than any of the other materials tested in this study.

The test data (fig. 9) indicate that the RTV-602 resin system resulted in the best ablation performance of all those resin systems considered. However, other properties of the ablation material, which influence overall performance, may be deciding factors in the resin system selection. For example, the low-temperature strain capability of the ablator, which is dependent on the resin system, will be important for the space shuttle because the heat-shield surface temperature could drop to 172 K during orbit. Therefore, it may be desirable to choose a resin system with a very low glass transition

temperature (temperature when an elastomer changes from a low-modulus rubbery-type behavior to a high-modulus glassy-type behavior) to maintain satisfactory strain capability and reduce the probability of mechanical failure. The glass transition temperature for the RTV-655 and Sylgard 182 resins is lower than that for the RTV-602 resin.

#### Comparison of Ablator 41 With Commercially Available Ablators

Table IV shows the ablation performance of ablator 41 and three proprietary ablators. Panel specimens of the materials were tested with a cold-wall heat-transfer rate and static pressure, at the panel midpoint, of  $0.17 \text{ MW/m}^2$  and 0.005 atmosphere, respectively. The effectiveness and density have been normalized with respect to ablator 41. These data show the selected material has the highest effectiveness of those materials tested. The two materials with the high volatile fraction, ablator 41 and SLA-561, had higher ablative effectivenesses than the two materials with the low volatile fraction. These results were expected because it has long been known that the production of gases which block convective heating is an important ablative heat protection mechanism, particularly at high-enthalpy levels.

#### CONCLUSIONS

An experimental study has been made of the effectiveness of resin systems and fillers on ablation performance and fabrication of low density ( $200$  to  $300 \text{ kg/m}^3$ ) charring elastomeric ablators. Both blunt-body and flat-panel specimens were used, the cold-wall heating-rate ranges being  $0.11$  to  $0.8 \text{ MW/m}^2$  and  $0.11$  to  $0.18 \text{ MW/m}^2$ , respectively. The corresponding stagnation and static pressure ranges for these tests were  $0.017$  to  $0.037$  atmosphere and  $0.004$  to  $0.005$  atmosphere. The following conclusions were reached from this study:

1. The data showed that there is a difference in ablation performance with specimen orientation with respect to the test stream which is not accounted for by other factors.
2. The optimum percentage of hollow silica spheres for best ablation performance was 15 to 25 percent.
3. Ablation performance of panel test specimens decreased as the concentration of hollow phenolic spheres was increased from 75 percent to 85 percent.
4. Ablation performance was significantly better for materials that contain nylon. However, ablation material with 20 percent Sylgard 182 resin, hollow phenolic spheres, and more than 10 percent nylon would not cure.
5. Composites with RTV-602 resin had better ablation performance than materials of the same compositions and other resin systems.

6. Composites with phenolic fiberglass honeycomb reinforcement had better ablation performance than the same composites with nylon paper honeycomb reinforcement.

Based on these conclusions, an ablator composition was determined which shows good ablation performance in simulated lifting entry vehicle environments. This material (50 percent hollow phenolic spheres, 25 percent RTV-602 resin, 10 percent nylon, and 15 percent hollow silica spheres) is amenable to low-cost fabrication techniques.

Langley Research Center,  
National Aeronautics and Space Administration,  
Hampton, Va., April 6, 1973.

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TABLE I.- ABLATION MATERIAL CONSTITUENTS

	Manufacturer
<b>Resins:</b>	
Sylgard 182 . . . . .	Dow Corning Corporation
RTV-602 . . . . .	General Electric Company
RTV-655 . . . . .	General Electric Company
G.E. 541-111 (experimental resin) . . . . .	General Electric Company
<b>Fillers:</b>	
Hollow phenolic spheres (B40-0930) . . . . .	Union Carbide Corp.
Hollow silica spheres . . . . .	Emerson and Cuming, Inc.
Nylon 66D . . . . .	Polymer Corp.
<b>Reinforcement:</b>	
0.95-cm-diameter hexagonal-cell phenolic fiberglass honeycomb core . . . . .	Hexcel Products Co.
0.95-cm-diameter hexagonal-cell nylon paper honeycomb core . . . . .	Hexcel Products Co.

TABLE II. - MATERIAL COMPOSITIONS  
 [All materials are phenolic fiberglass honeycomb reinforced]

Material	Resin type	Resin, mass fraction	Hollow phenolic spheres, mass fraction	Hollow silica spheres, mass fraction	Nylon, mass fraction	Average specimen density, kg/m <sup>3</sup>
1	Sylgard 182	0.25	0.75	0	0	239
2	↓	.20	.80	↓	↓	231
3		.15	.85			199
10	↓	.20	.70		.10	262
20	RTV-602	↓	.80	↓	0	255
21	G.E. experimental 541-111		.80	↓	↓	213
22	RTV-655		.80			247
30	Sylgard 182		.70	.10		223
31	↓		.60	.20		244
32			.50	.30		265
33			.40	.40		262
41	RTV-602	↓	.50	.15	.10	297

TABLE III.- NOMINAL TEST ENVIRONMENTS

(a) Apparatus B (blunt-body stagnation point)

$q_{cw}$ , MW/m <sup>2</sup>	$p_{t,2}$ , atm	H, MJ/kg
0.11	0.017	2.6
.23	.022	4.2
.45	.028	7.0
.57	.031	7.4
.79	.037	9.7
Test stream . . . . . 3% oxygen, 97% nitrogen		

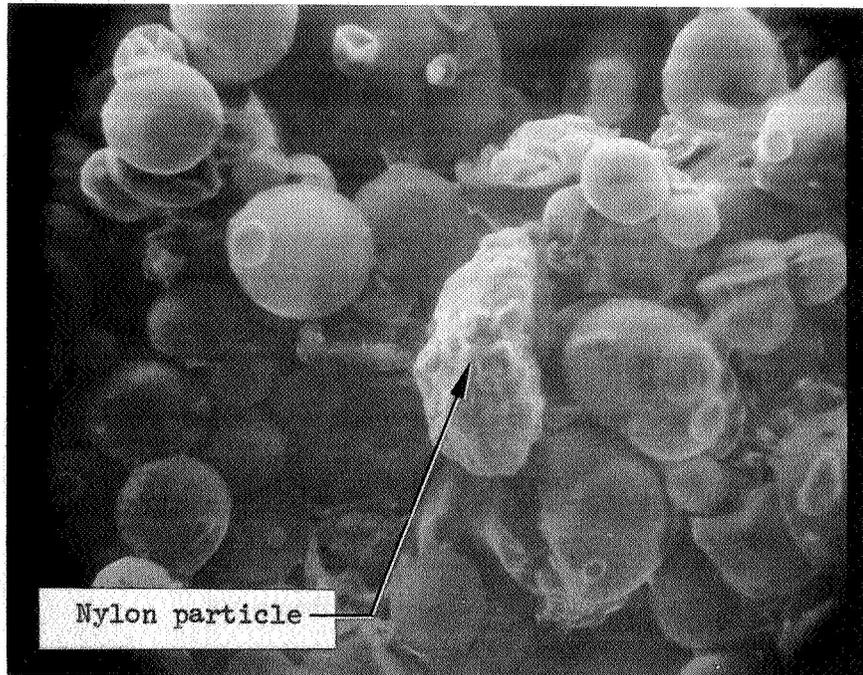
(b) Apparatus D (midpoint of panel)

$q_{cw}$ , MW/m <sup>2</sup>	p, atm	H, MJ/kg
0.11	0.004	14
.18	.005	23
Test stream . . . . . 23% oxygen, 77% nitrogen		

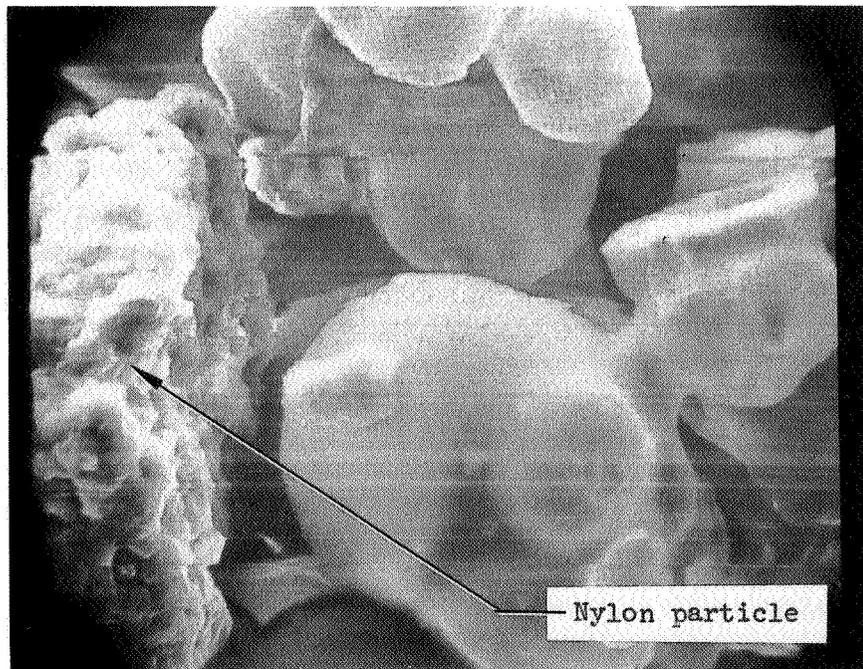
TABLE IV.- ABLATION PERFORMANCE OF SELECTED COMPOSITE  
AND COMMERCIAL COMPOSITES

$[q_{cw} \approx 0.17 \text{ MW/m}^2, H \approx 23 \text{ MJ/kg}, p_{mp} = 0.005 \text{ atm}, 13 \text{ by } 13 \text{ cm panel}]$

Ablator designation	$\bar{p}$	$\bar{E}$	Remarks
41	1.00	1.00	Smooth, tough char surface; material in honeycomb reinforcement; selected ablator
SLA-561	.93	.88	Smooth, tough char surface; supplied by Martin-Marietta Corporation, Denver Division, Denver, Colorado
480-1M	1.00	.58	Surface cracks, tough char surface; supplied by AVCO Corporation, Space Systems Division, Lowell, Massachusetts
ULD100-4	1.28	.45	Rough surface, extremely tough char layer; supplied by McDonnell Douglas Astronautics Company, East, St. Louis, Missouri



(a) Magnification  $\times 245$ .

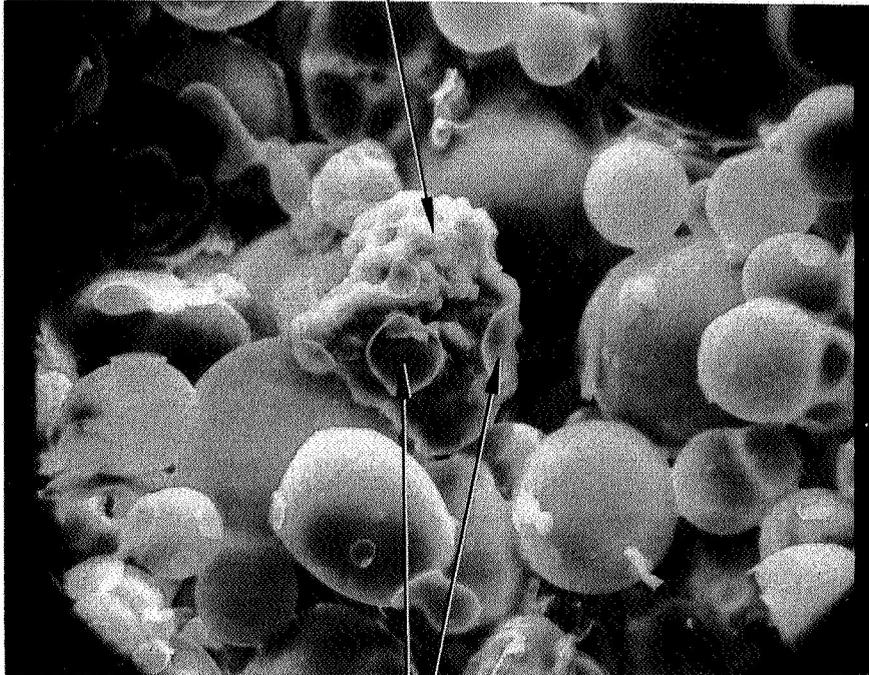


(b) Magnification  $\times 620$ .

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Figure 1.- SEM photographs of material composed of 15 percent silica spheres, 10 percent nylon, 50 percent phenolic spheres, and 25 percent Sylgard 182 resin.

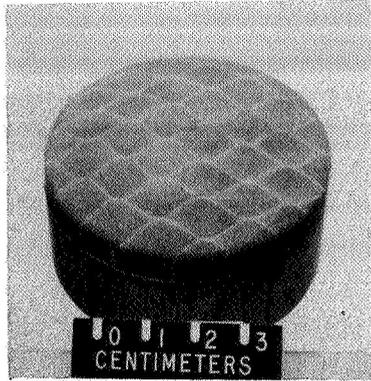
Nylon particle



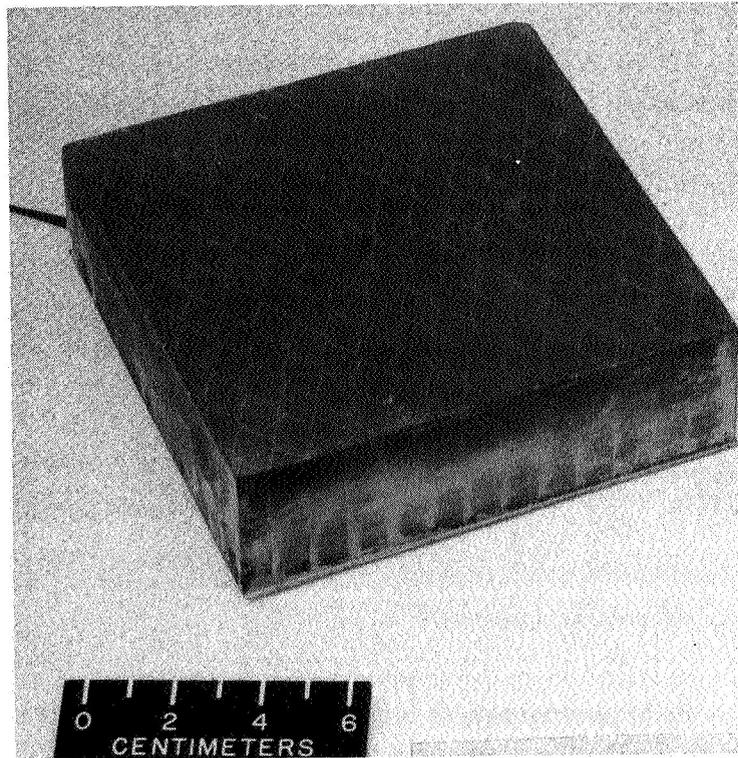
Sections of hollow spheres

L-73-3023

Figure 2.- SEM photograph of material composed of 15 percent silica spheres, 10 percent nylon, 50 percent phenolic spheres, and 25 percent RTV-602 resin (magnification  $\times 280$ ).



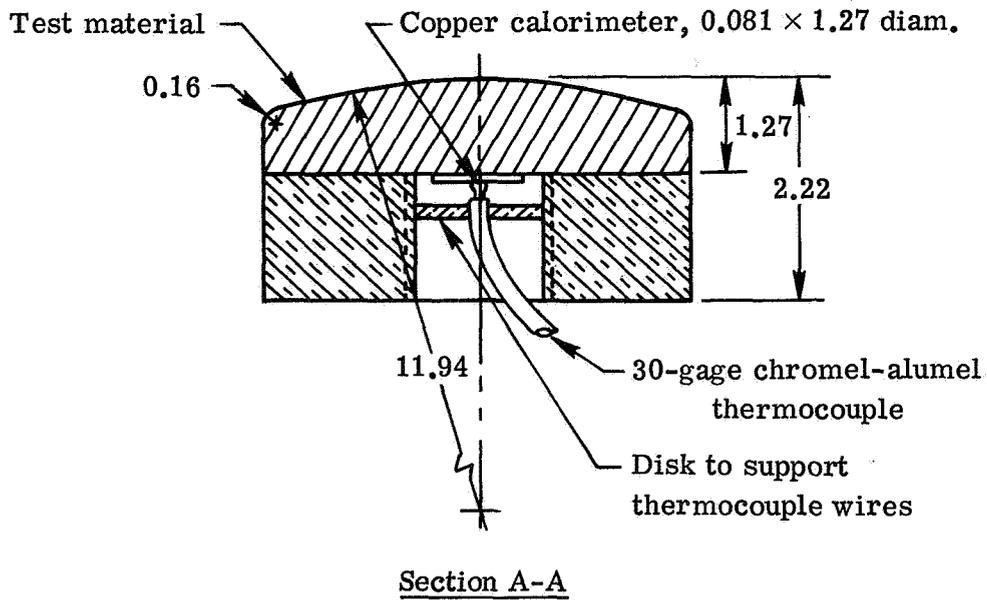
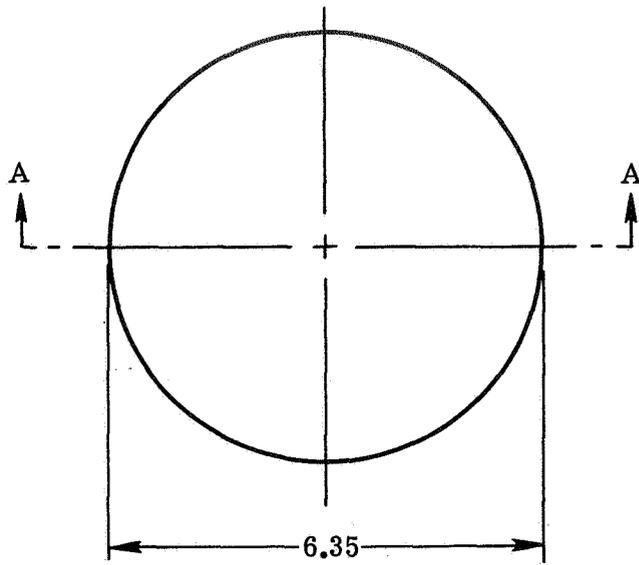
(a) Blunt-body specimen.



L-73-3024

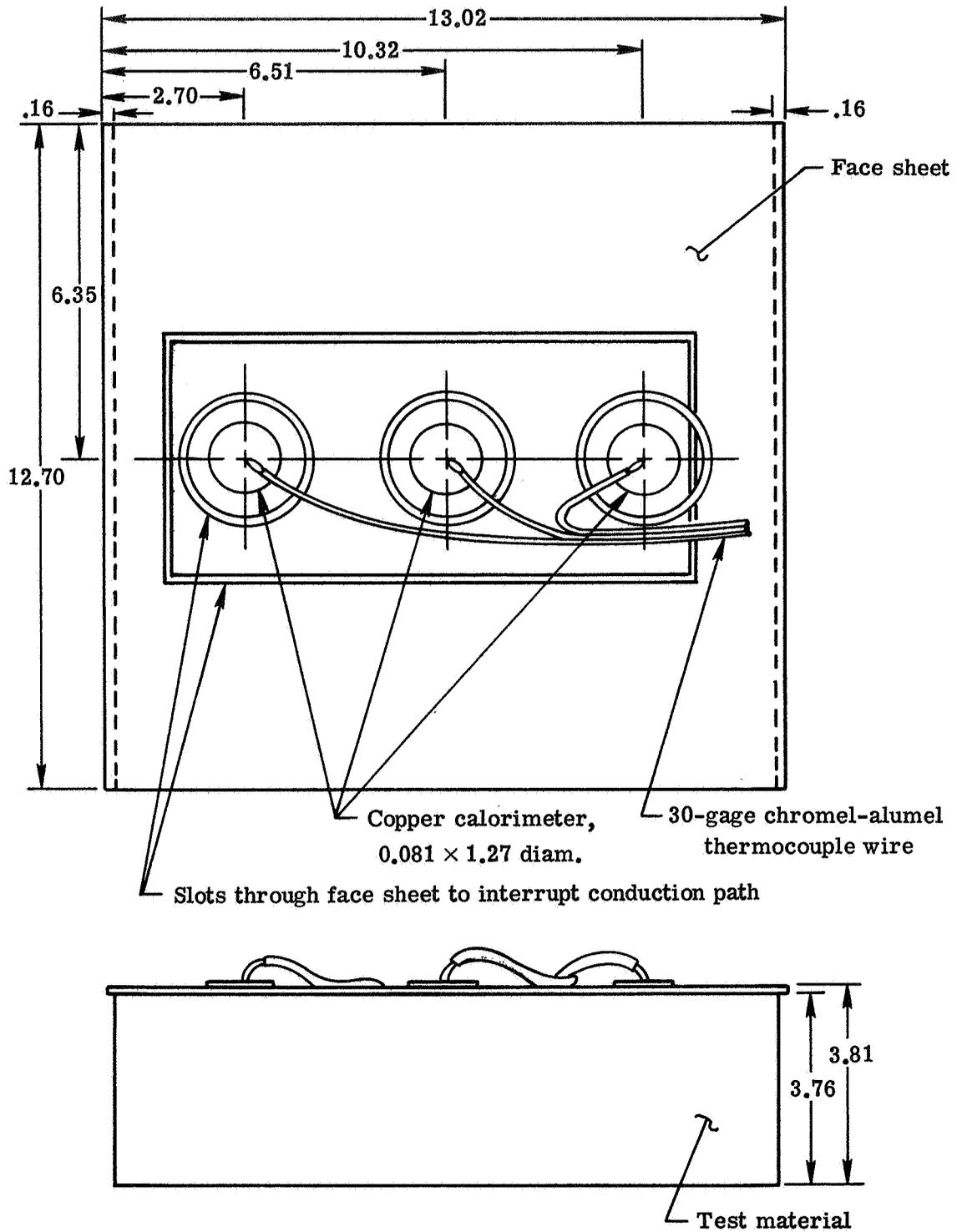
(b) Square-panel specimen.

Figure 3.- Typical blunt-body and square-panel specimens before testing.



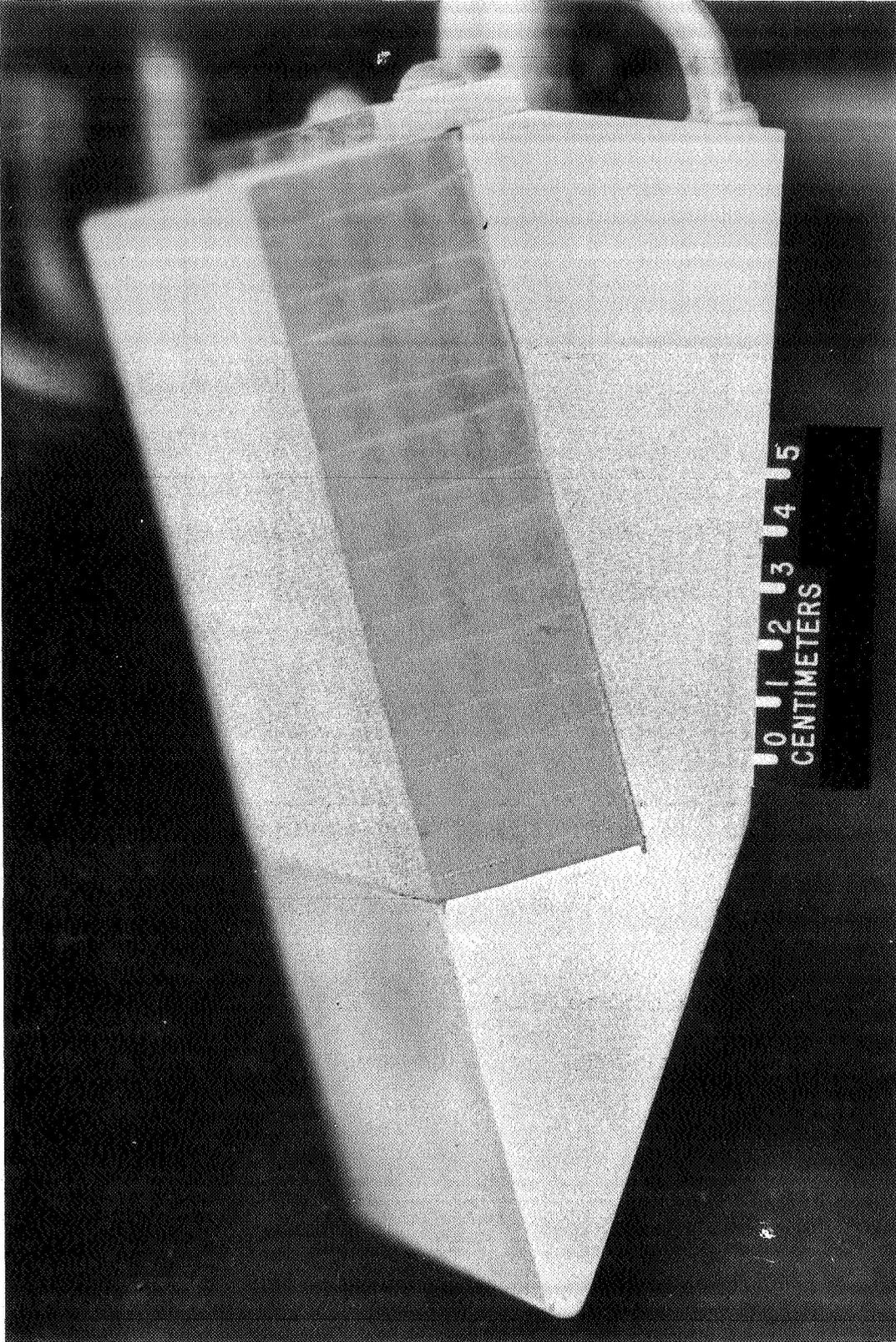
(a) Blunt-body specimen.

Figure 4.- Test specimen configurations. All dimensions are in centimeters.



(b) Square-panel specimen.

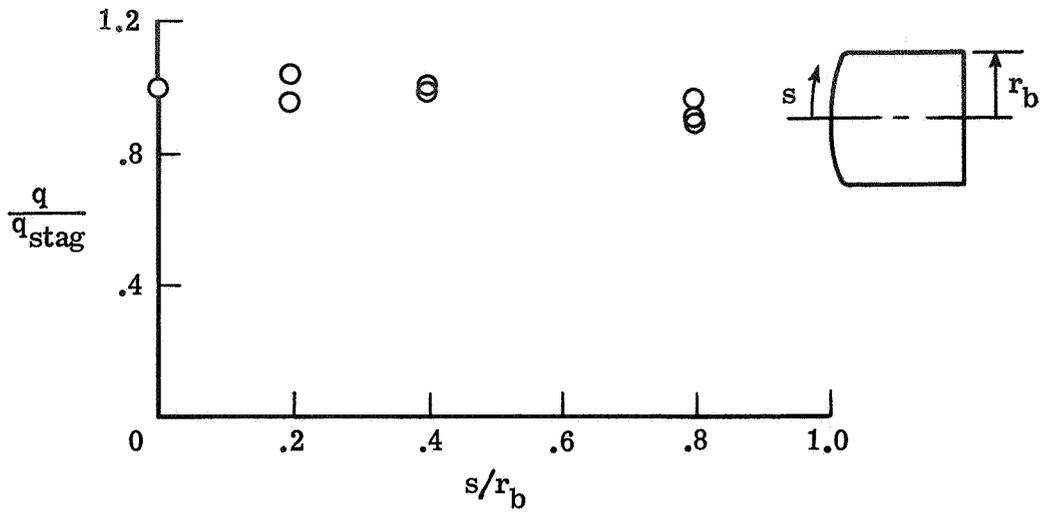
Figure 4.- Continued.



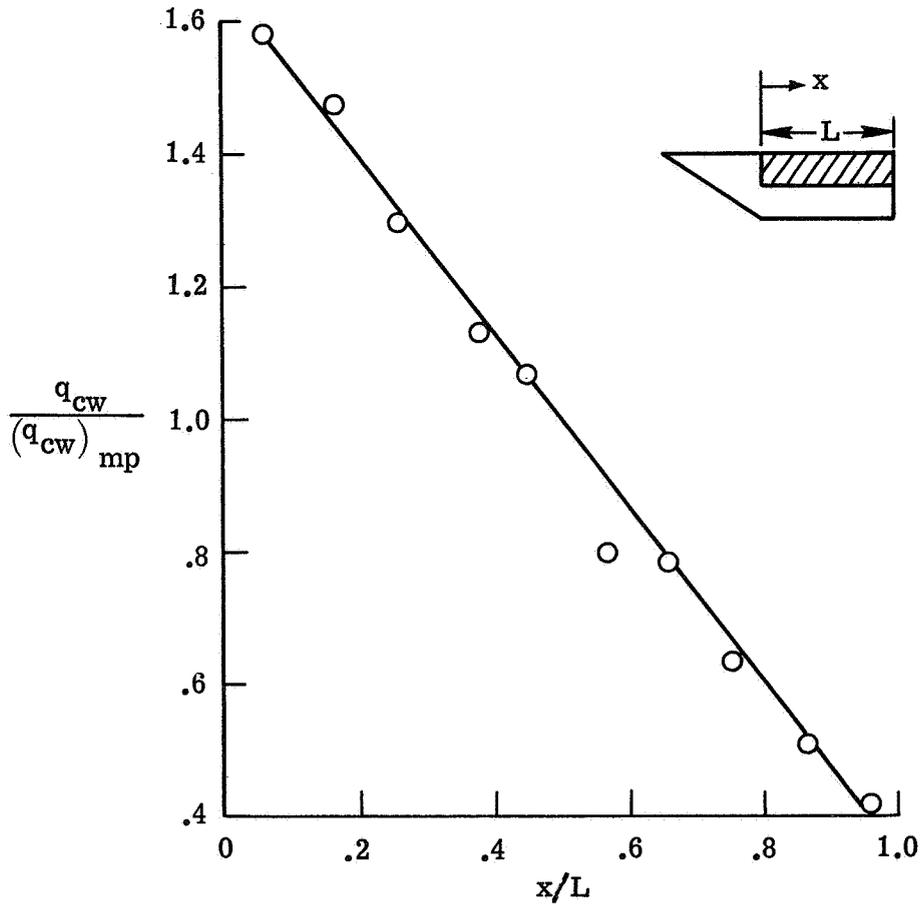
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(c) Square panel mounted on water-cooled wedge holder.

Figure 4.- Concluded.



(a) Distribution over blunt-body models.



(b) Streamwise distribution over panel specimen.

Figure 5.- Heating-rate distribution over models.

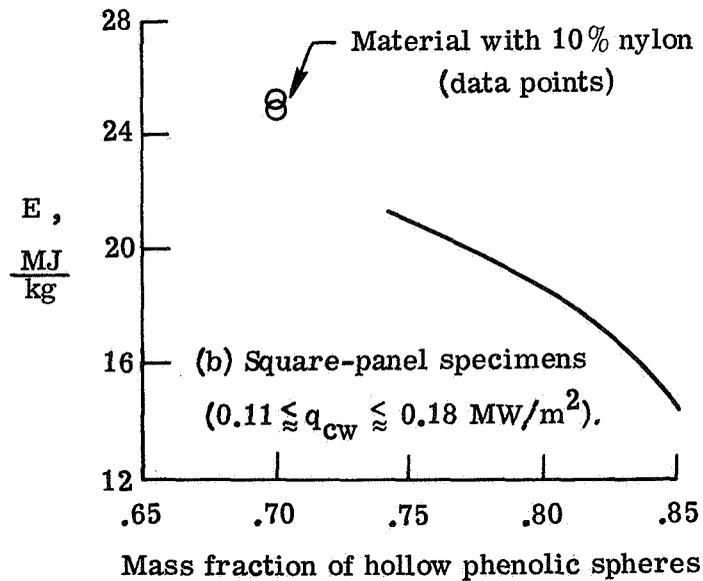
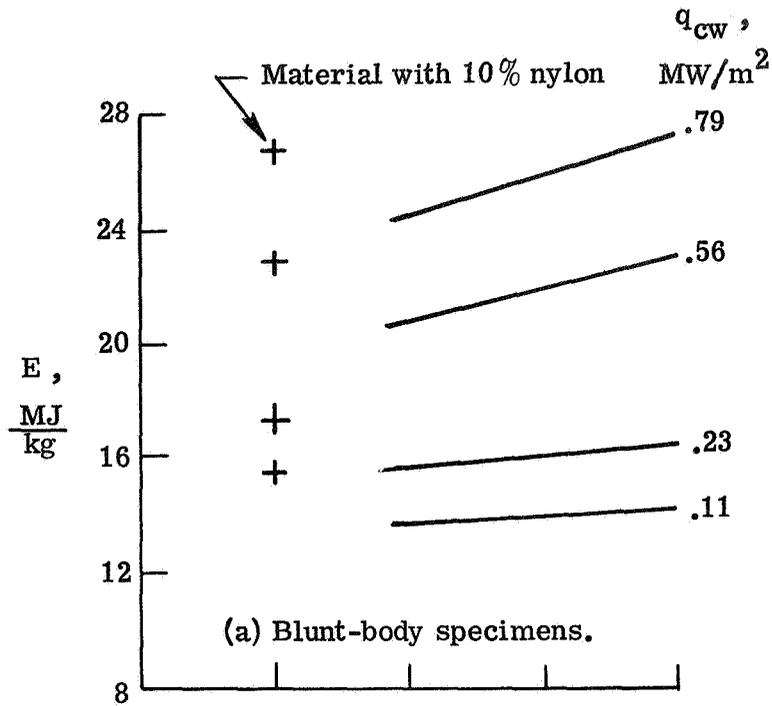
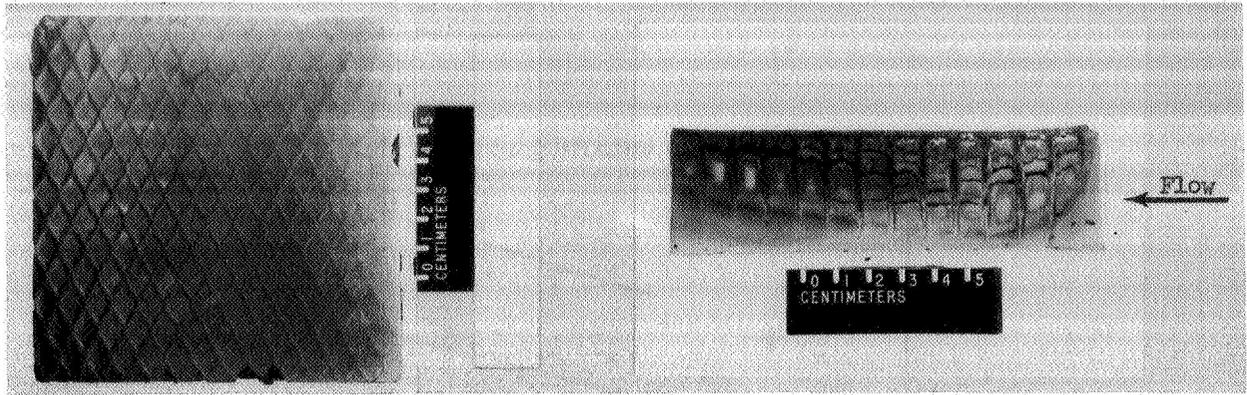
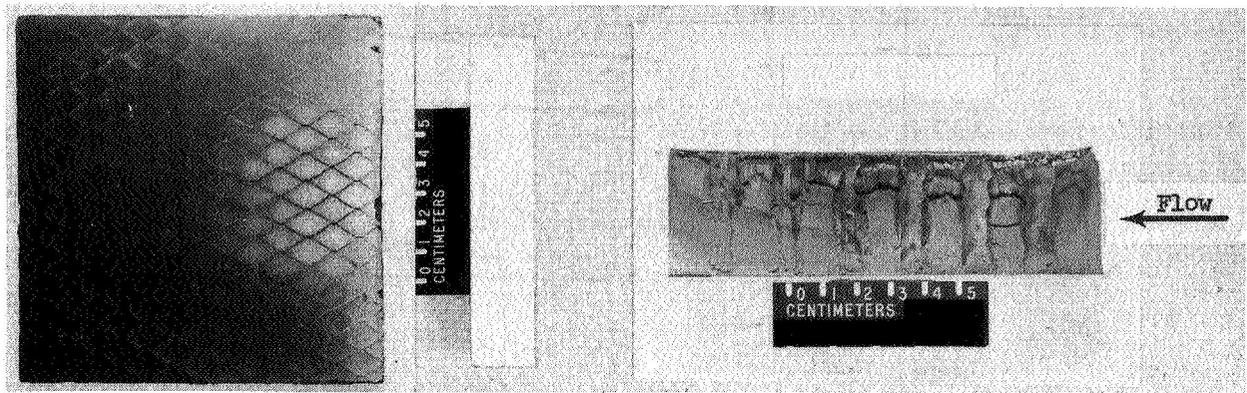


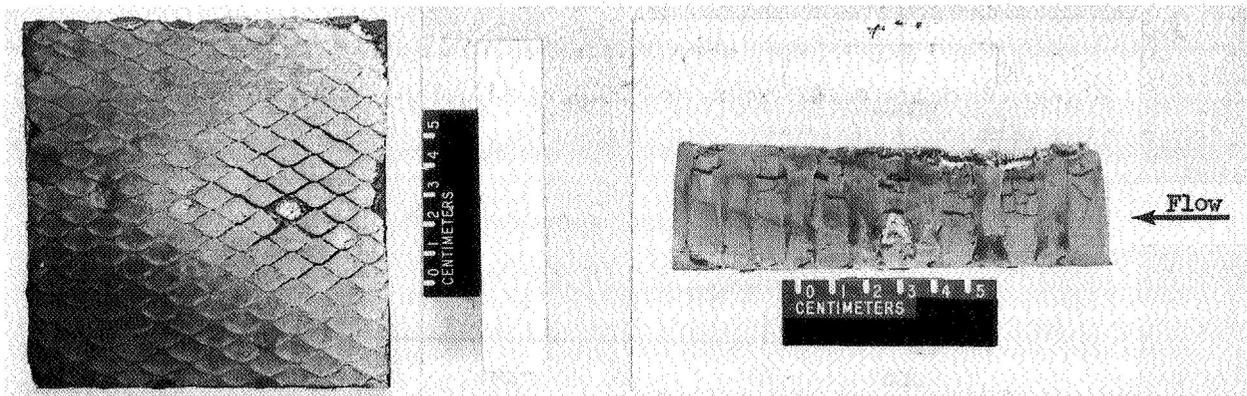
Figure 6.- Least-squares fit to data to show effect of hollow phenolic sphere content and nylon content on ablation effectiveness.



(a) Material 1: 25 percent Sylgard 182 resin and 75 percent hollow phenolic spheres.



(b) Material 2: 20 percent Sylgard 182 resin and 80 percent hollow phenolic spheres.

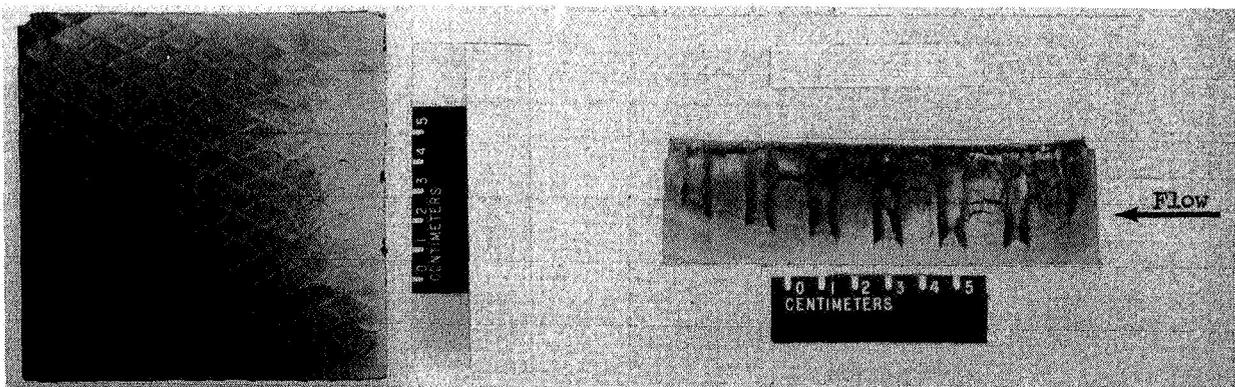


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(c) Material 3: 15 percent Sylgard 182 resin and 85 percent hollow phenolic spheres.

Figure 7.- Effect of hollow phenolic sphere content on ablation performance.

Flow is from right to left.



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Figure 8.- Panel specimen of ablator material 10 with 10 percent nylon, 20 percent Sylgard 182 resin, and 70 percent hollow phenolic spheres. Flow is from right to left.

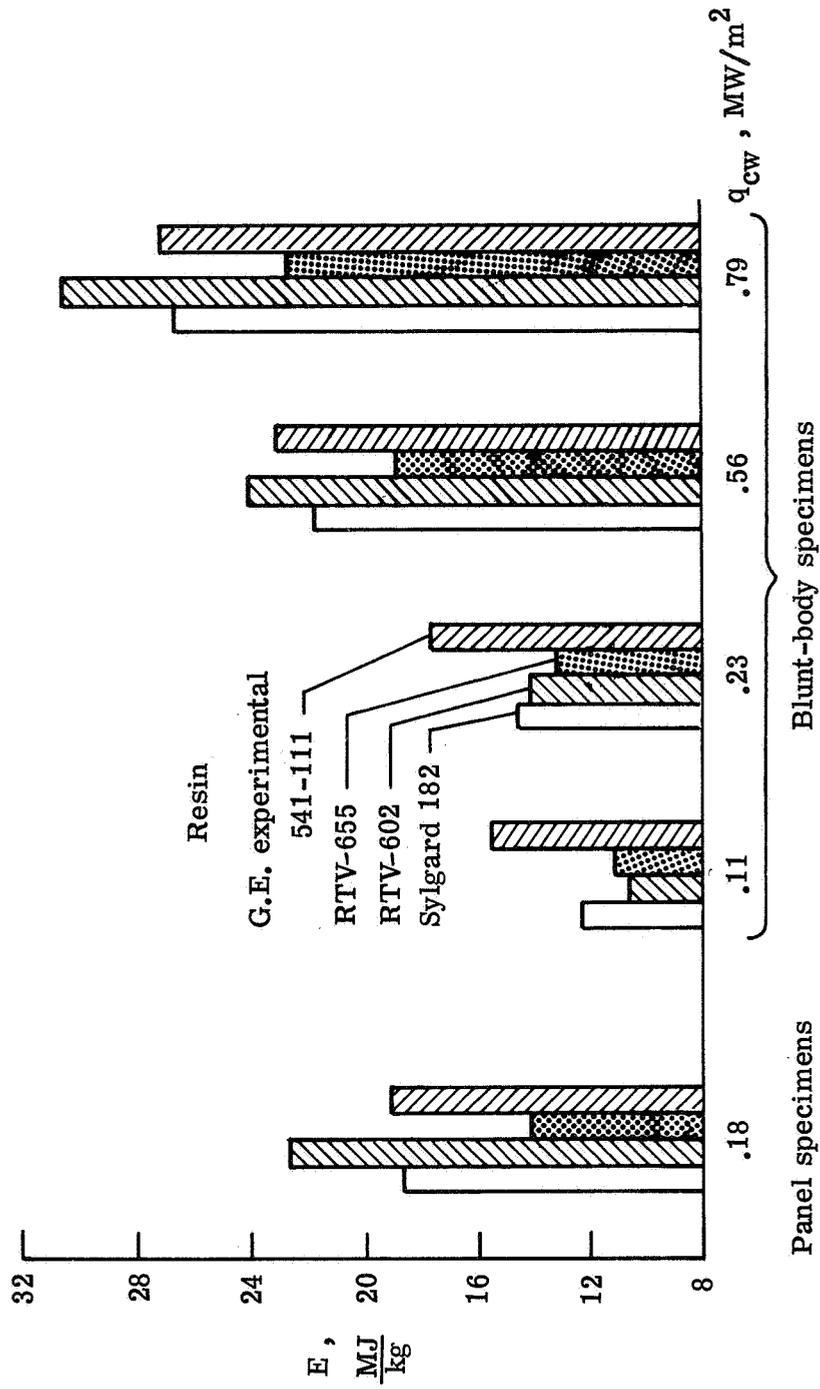
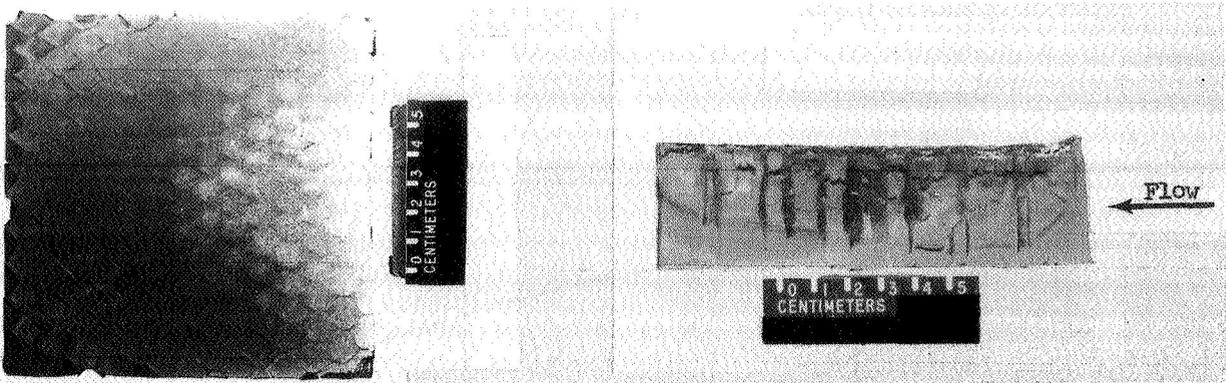
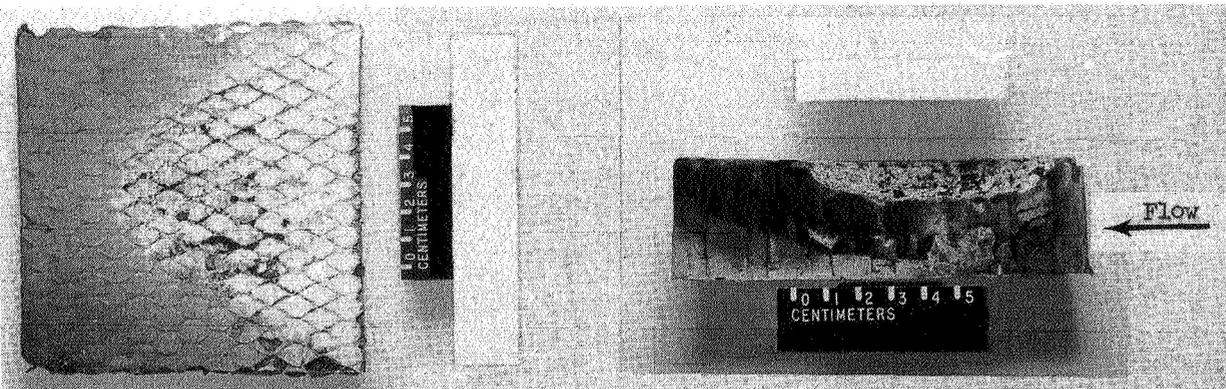


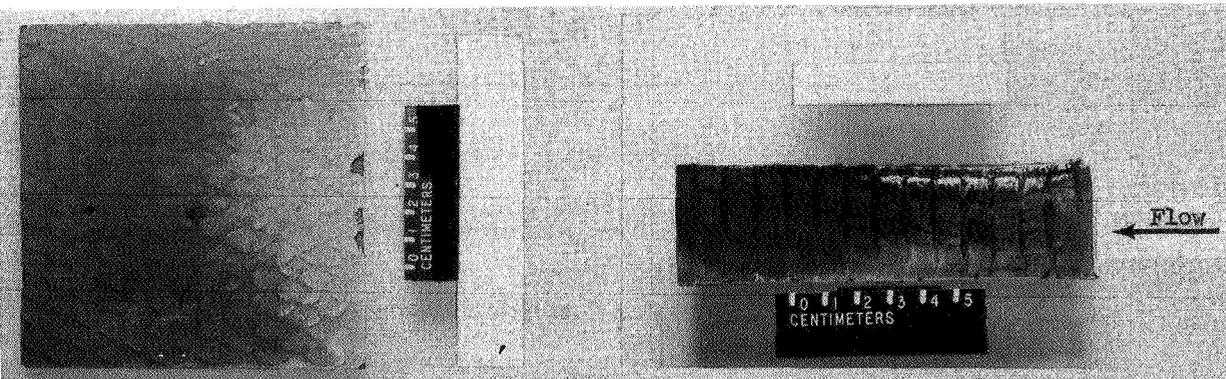
Figure 9.- Effect of resin on ablation effectiveness. Pressure about 0.02 atm.



(a) Material 20: 20 percent of RTV-602 resin.



(b) Material 21: 20 percent of G.E. experimental 541-111 resin.



(c) Material 22: 20 percent of RTV-655 resin.

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Figure 10.- Effect of resin system on ablation performance. All materials contain 80 percent hollow phenolic spheres. Flow is from right to left.

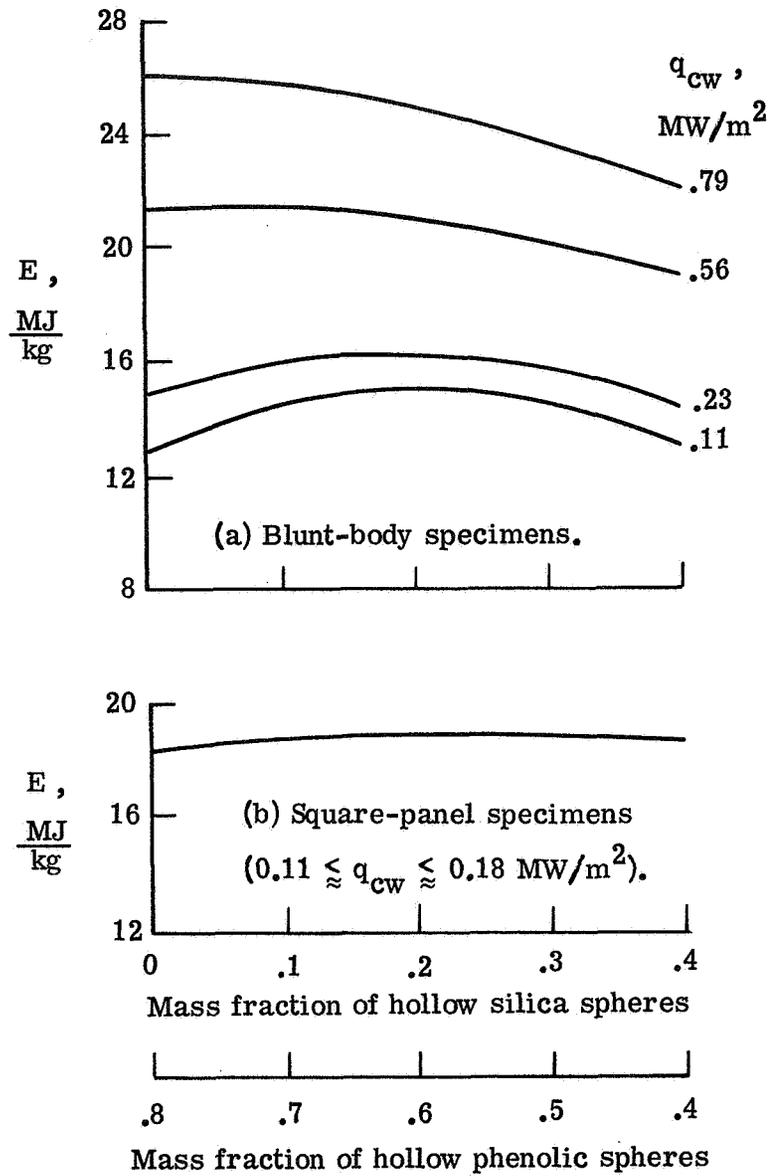
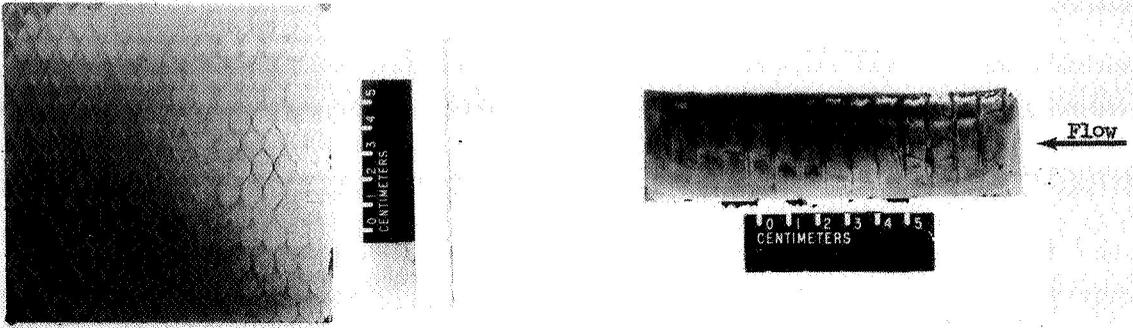
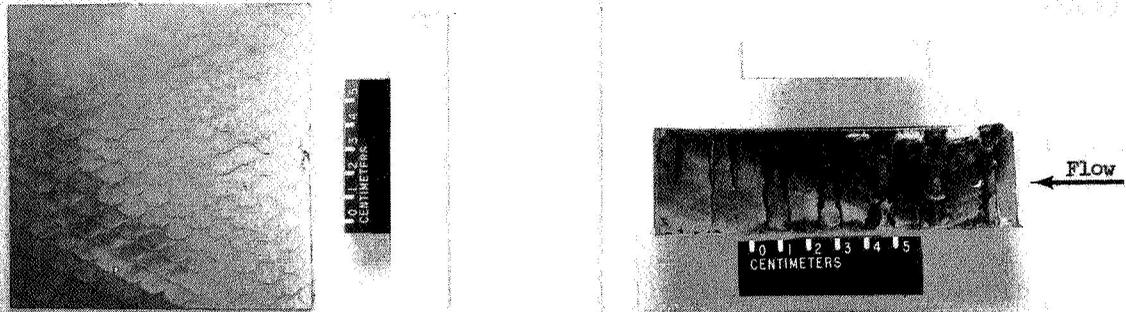


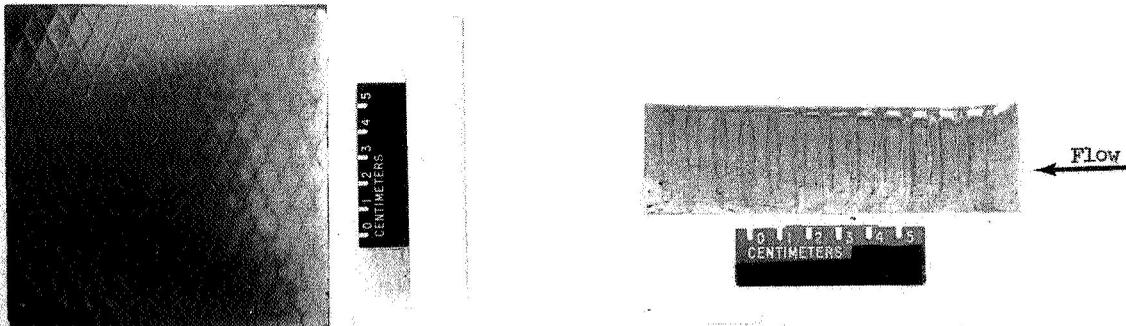
Figure 11.- Least-squares fit to data to show the effect of hollow silica sphere content on ablation effectiveness. Resin mass fraction is 0.2.



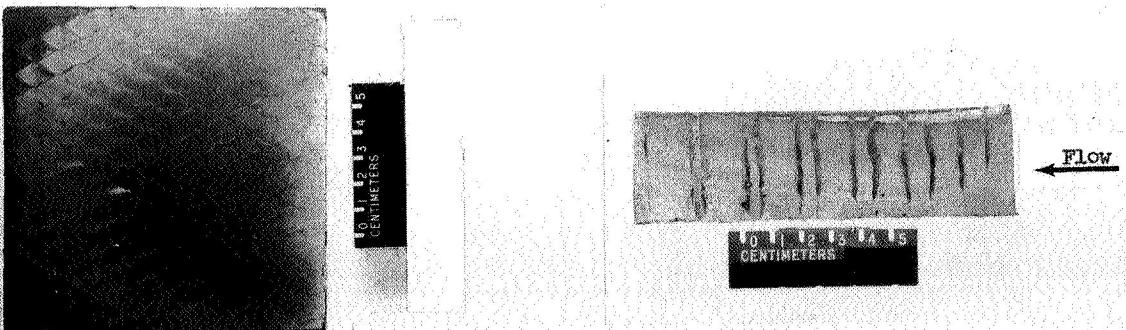
(a) Material 30: 70 percent hollow phenolic spheres and 10 percent hollow silica spheres.



(b) Material 31: 60 percent hollow phenolic spheres and 20 percent hollow silica spheres.



(c) Material 32: 50 percent hollow phenolic spheres and 30 percent hollow silica spheres.



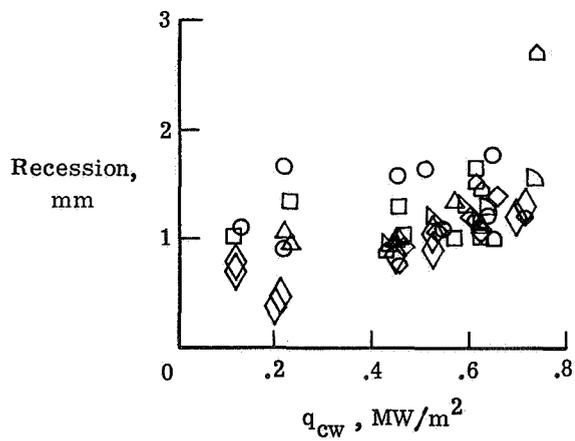
(d) Material 33: 40 percent hollow phenolic spheres and 40 percent hollow silica spheres.

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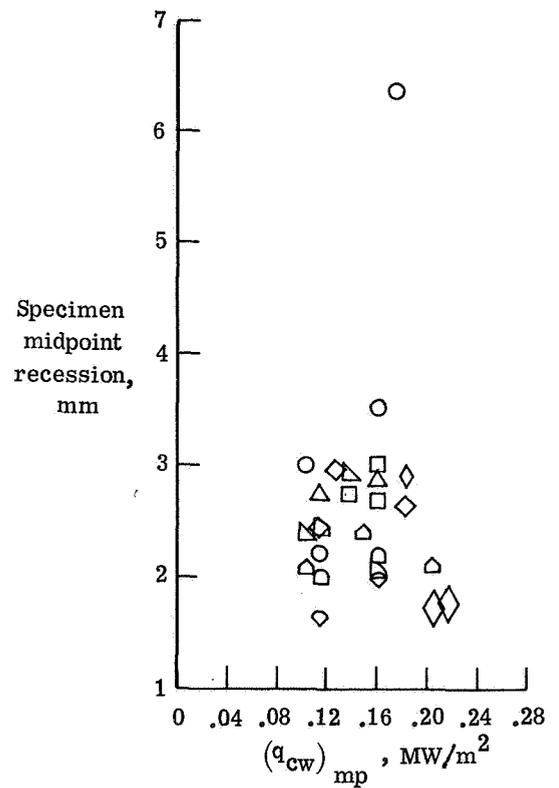
Figure 12.- Effect of hollow silica sphere content on ablation performance. (All materials contain 20 percent Sylgard 182 resin.) Flow is from right to left.

Composition by Mass Fraction

Symbol	Resin	Hollow phenolic spheres	Hollow silica spheres	Nylon	Material number
○	0.15	0.85	0	0	3
□	.20	.80	0	0	2
◇	.25	.75	0	0	1
△	.20	.70	0	.10	10
◊	.20	.80	0	0	20
▴	.20	.80	0	0	22
▵	.20	.70	.10	0	30
▷	.20	.60	.20	0	31
◁	.20	.50	.30	0	32
◊	.20	.40	.40	0	33
◊	.25	.50	.15	.10	41



(a) Blunt-body specimens.

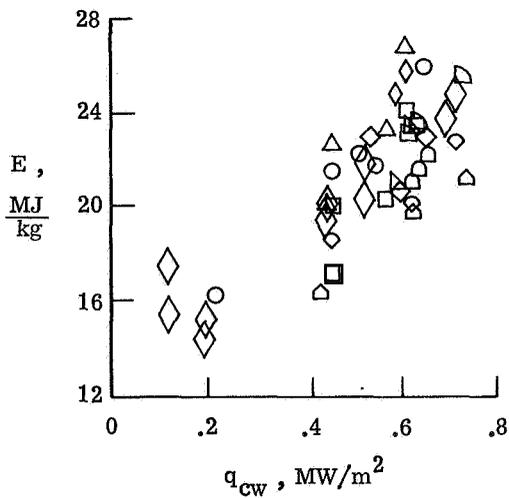


(b) Panel specimens.

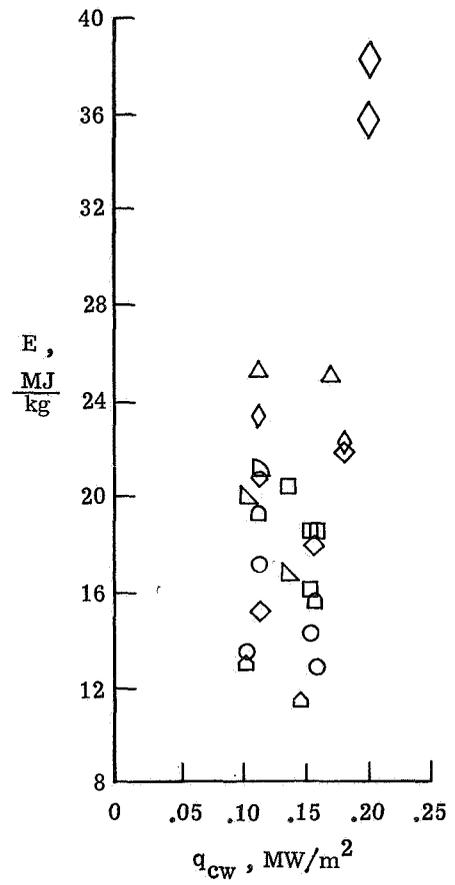
Figure 13.- Effects of cold-wall heating rate and material composition on surface recession.

Composition by Mass Fraction

Symbol	Resin	Hollow phenolic spheres	Hollow silica spheres	Nylon	Material number
○	0.15	0.85	0	0	3
□	.20	.80	0	0	2
◇	.25	.75	0	0	1
△	.20	.70	0	.10	10
◇	.20	.80	0	0	20
△	.20	.80	0	0	22
▽	.20	.70	.10	0	30
▷	.20	.60	.20	0	31
◁	.20	.50	.30	0	32
◇	.20	.40	.40	0	33
◇	.25	.50	.15	.10	41

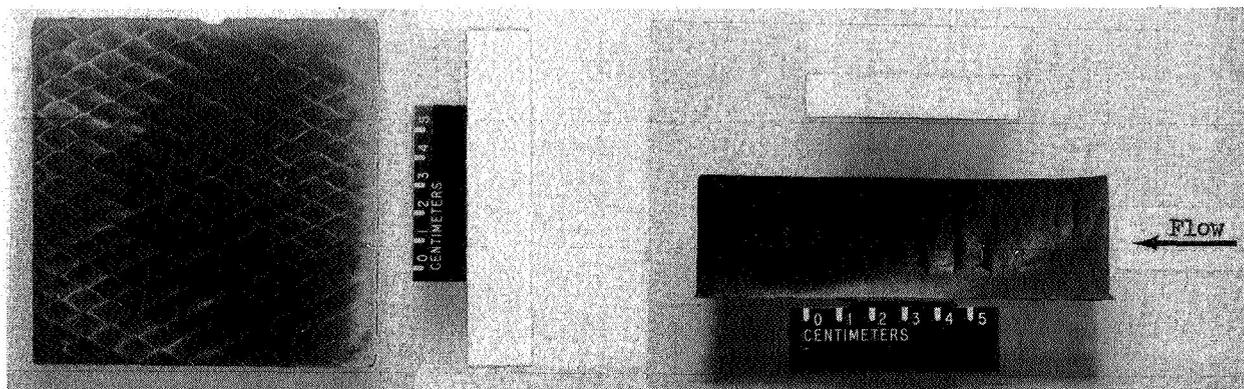


(a) Blunt-body specimens.



(b) Panel specimens.

Figure 14.- Effect of material composition and heating rate on ablation effectiveness.



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Figure 15.- Panel specimen of selected composition 41, 25 percent RTV-602 resin, 50 percent hollow phenolic spheres, 15 percent hollow silica spheres, and 10 percent nylon. Flow is from right to left.



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