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WADC TECHNICAL REPORT 53-192  
Part XV

48

**NATIONAL BUREAU OF STANDARDS REPORT**

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A

MECHANISM OF RAIN EROSION  
Part XV. Resistance of White Sapphire and  
Hot-Pressed Alumina to Collision with Liquid Drops

Olive G. Engel  
National Bureau of Standards

August 1959

Materials Laboratory  
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WADC TECHNICAL REPORT 53-192  
Part XV

MECHANISM OF RAIN EROSION  
Part XV. Resistance of White Sapphire and  
Hot-Pressed Alumina to Collision with Liquid Drops

OLIVE G. ENGEL  
NATIONAL BUREAU OF STANDARDS

AUGUST 1959

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## FOREWORD

This report was prepared by the National Bureau of Standards under USAF Contract No. AF 33(616)5912. The contract was initiated under Project No. 7340, "Non-Metallic and Composite Materials", Task No. 73400, "Organic and Inorganic Plastics". The project was administered under the direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center, with Mr. George P. Peterson acting as project engineer.

The experimental work that is reported was done at Convair, Division of General Dynamics Corporation, in San Diego, California. Other acknowledgements are made in the text.

This report covers the period of work from about September 1957 to September 1959.

## ABSTRACT

Data are presented that show the resistance of 0.318-cm (0.125-in.) thick plates of white sapphire and hot-pressed alumina to impingement with 0.2-cm-diameter water-drops and mercury drops. In collision with mercury drops, the velocity at which damage was first observed was  $3.514 \times 10^4$  cm/sec (1,153 ft/sec) for white sapphire and  $4.276 \times 10^4$  cm/sec (1,403 ft/sec) for hot-pressed alumina; the difference in the velocities found for the two ceramics is not considered to be significant. The velocity required to damage these ceramic materials on collision with a waterdrop was not reached experimentally. By means of a theoretical extrapolation, it is shown that plates of these ceramics of the indicated thickness can be expected to survive collision with 0.2-cm waterdrops without damage up to a velocity of  $33.7 \times 10^4$  cm/sec (11,100 ft/sec). For air at 0° C and 1 atm pressure, this is equivalent to a Mach Number of 10.

## PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

W. E. DIRKES  
Chief, Plastics Branch  
Non-Metallic Materials Division

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RESISTANCE OF WHITE SAPPHIRE AND HOT-PRESSED ALUMINA  
TO COLLISION WITH LIQUID DROPS

I. Introduction

The leading surfaces of objects that fly at high speed through rain are eroded as a result of collision with the raindrops. The erosion damage increases in severity as the relative impingement velocity is increased. It has become a major problem in the present era of high-speed flight.

1.1 Testing and Research

A search for materials that will resist this type of damage has been made for the past 10 years. Experimental testing of materials has been carried out at many laboratories of the aircraft industry. An effort to determine the cause of the damage and the mechanism by which it is produced has been in progress at the National Bureau of Standards.

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## 1.2 Rigid Materials or Rubbers

One of the questions asked, at the time that the research program on the mechanism of high-speed rain erosion was initiated, was whether a soft rubbery material or a hard rigid material should be sought as the solution to the rain-erosion problem. The answer to this question is now at hand. In practical terms, the answer is that there are rubbery coating materials that can withstand collision with waterdrops up to impingement velocities of roughly  $3 \times 10^4$  cm/sec (1,000 ft/sec) but that at higher impingement velocities the solution to the problem must be sought among the hard rigid materials of high strength.

Fused alumina has been reported to be one of the most promising materials for resistance to erosion due to high-speed collision with liquid drops. In this report some test results of the overall resistance and particular mode of failure of white sapphire and hot-pressed alumina, under high-speed liquid-drop impingement, are presented.

## II. Materials and Test Method

### 2.1 White Sapphire

White sapphire is a pure, single crystal alpha alumina made by dropping finely powdered alumina through a post-mixed oxyhydrogen flame onto the molten cap of a seed crystal supported in an insulating furnace. Crystallization occurs at the interface between the body of the crystal and the molten cap. Under proper operating conditions, the material that crystallizes has the same orientation as the seed crystal. The as-grown crystals are annealed at  $1,900^\circ$  C ( $3,452^\circ$  F) to remove strains.

Five disk-shaped target plates of white sapphire that were 1.59 cm (0.625 in.) in diameter and 0.318 cm (0.125 in.) thick were obtained from the Linde Air Products Company in New York City, New York, for use in the experiment. They were crystal clear and had the appearance of high quality glass. The face of the target plate that would strike the liquid drop was given a high polish by the manufacturer.

The physical properties of white sapphire, taken from data supplied by the manufacturer, are listed in Table 1.

## 2.2 Hot-Pressed Alumina

Hot-pressed alumina (gray) differs from the more common polycrystalline alumina (cream white) in that it is heated and pressed in one operation rather than in two. The heating and pressing is done in graphite dies and hot-pressed alumina is gray in color because it picks up a carbon impurity from the dies. The amount of carbon that diffuses into the alumina depends on the pressure, temperature, and time involved in the hot-pressing operation. Hot pressing produces an alumina having a density close to that of white sapphire; there is, however, a considerable amount of variability in the product from lot to lot.

H.P.Alundum is hot-pressed alumina of uniform density and hardness manufactured by sintering the pure aluminum oxide crystals. No bonding matrix is used. Five disk-shaped target plates of H.P.Alundum that were 1.59 cm (0.625 in.) in diameter and 0.318 cm (0.125 in.) thick were obtained from the Norton Company in Worcester, Massachusetts, for use in the experiment. They were opaque and light gray in color. The face of the target plate that would strike the liquid drop was given a high polish by the manufacturer by means of diamond grinding and lapping.

The physical properties of H.P.Alundum, taken from data supplied by the manufacturer, are listed in Table 1.

## 2.3 Liquid-Drop Collision Test

The target plates of white sapphire and hot-pressed alumina were sent to Convair, Division of General Dynamics Corporation, in San Diego, California, where the collision experiment was carried out. The ceramic target plates were fastened with adhesive to metal disks of the same size and were fired against mercury drops and waterdrops at velocities ranging from  $2.89 \times 10^4$  cm/sec (948 ft/sec) to  $11.88 \times 10^4$  cm/sec (3,898 ft/sec). The metal backing disks kept the ceramic target plates that were shattered by the liquid-drop collisions from falling into pieces.

The drop size specified for the collisions was 0.2-cm diameter. The mercury drops were weighed on an analytical balance and the diameter of each drop was calculated from its weight. The mercury drops that struck the target plates ranged from 5 percent above to 1 percent below the size that

Table 1.

## Physical Properties of White Sapphire and H.P. Alundum

Material	H.P. Alundum <sup>a/</sup>	White Sapphire <sup>b/</sup>
Density, g/cc	3.95	3.98
Modulus Elasticity, d/cm <sup>2</sup>	3.4 x 10 <sup>12</sup>	(3.4 - 3.8) x 10 <sup>12</sup>
psi	50 x 10 <sup>6</sup>	(50 - 55) x 10 <sup>6</sup>
		} depending on position of crystal C-axis
Modulus Rupture, d/cm <sup>2</sup>	2.4 x 10 <sup>9</sup>	(2.8 - 9.0) x 10 <sup>9</sup>
psi	35 x 10 <sup>3</sup>	(40 - 130) x 10 <sup>3</sup>
		} at 30° C
Compressive Strength, d/cm <sup>2</sup>	2.8 x 10 <sup>10</sup>	2.1 x 10 <sup>10</sup>
psi	400 x 10 <sup>3</sup>	300 x 10 <sup>3</sup>
		} at 25° C
Knoop Hardness (K 100)	2,000	1,525 - 2,000
Mohs Hardness	9 - 9.5	9
Melting Point, °C	2,000	2,040

<sup>a/</sup> Tabulated data supplied by Norton Company

<sup>b/</sup> Data supplied by Linde Air Products Company

was specified. It was estimated by the experimenters that the waterdrops were within  $\pm 10$  percent of the nominal size.

An attempt was made to distribute the velocities at which the target plates were fired. Closely similar velocities were sometimes unavoidably obtained, however, because the velocity produced by a given weight of powder is affected by temperature variation, amount of casing crimp, and the density of powder pack.

The velocities at which the white sapphire and hot-pressed alumina target plates were fired and the material of the drops with which they collided are listed in Table 2. These data were supplied by Convair.

### III. Observations

The target plates of white sapphire and of hot-pressed alumina that had collided with mercury drops and waterdrops at high speed were examined with use of a stereomicroscope. The failure that was observed to have occurred as a result of collisions with these liquid drops is described in the following sections. Observations of the result of collisions of the target plates with waterdrops are presented first. These are followed by a description of the damage that resulted from collisions of the target plates with mercury drops. The specific target plates are discussed in the order of the relative collision velocity at which they struck the liquid drops beginning with the lowest velocity at which a collision occurred.

#### 3.1 White Sapphire

Only one white sapphire target plate was used for collisions with waterdrops. This target plate was fired three times. In the first two firings, it collided with 0.2-cm waterdrops at velocities of  $4.779 \times 10^4$  cm/sec (1,568 ft/sec) and  $6.620 \times 10^4$  cm/sec (2,172 ft/sec) without sustaining any damage. It was then fired at a velocity of  $7.529 \times 10^4$  cm/sec (2,470 ft/sec). The 0.2-cm waterdrop was not hit, but the sapphire target plate cracked from firing shock. The maximum experimental evidence that resulted, therefore, for the resistance of white sapphire to a water-drop collision is that no damage is produced on a white

Table 2.  
 Data<sup>a/</sup> for Collision of Target Plates of White Sapphire and  
 Hot-Pressed Alumina with 0.2-cm-diam Drops

Target Plates of White Sapphire			
Specimen Number	Drop Liquid	Collision Velocity	
		$10^4$ cm/sec	ft/sec
1	mercury	4.420	1,450
2	mercury	4.584	1,504
3	water	4.779	1,568
3	water	6.620	2,172
3	water	7.529	2,470
4	mercury	3.581	1,175
5	mercury	2.890	948
5	mercury	3.197	1,049
5	mercury	3.216	1,055
5	mercury	3.514	1,153
Target Plates of Hot-Pressed Alumina			
Specimen Number	Drop Liquid	Collision Velocity	
		$10^4$ cm/sec	ft/sec
1	water	7.346	2,410
2	water	9.144	3,000
3	water	11.88	3,898
4	mercury	4.276	1,403
5	mercury	4.996	1,639
5	mercury	4.100	1,345

<sup>a/</sup> These data were obtained at Convair, Division of General Dynamics Corporation, San Diego, California.

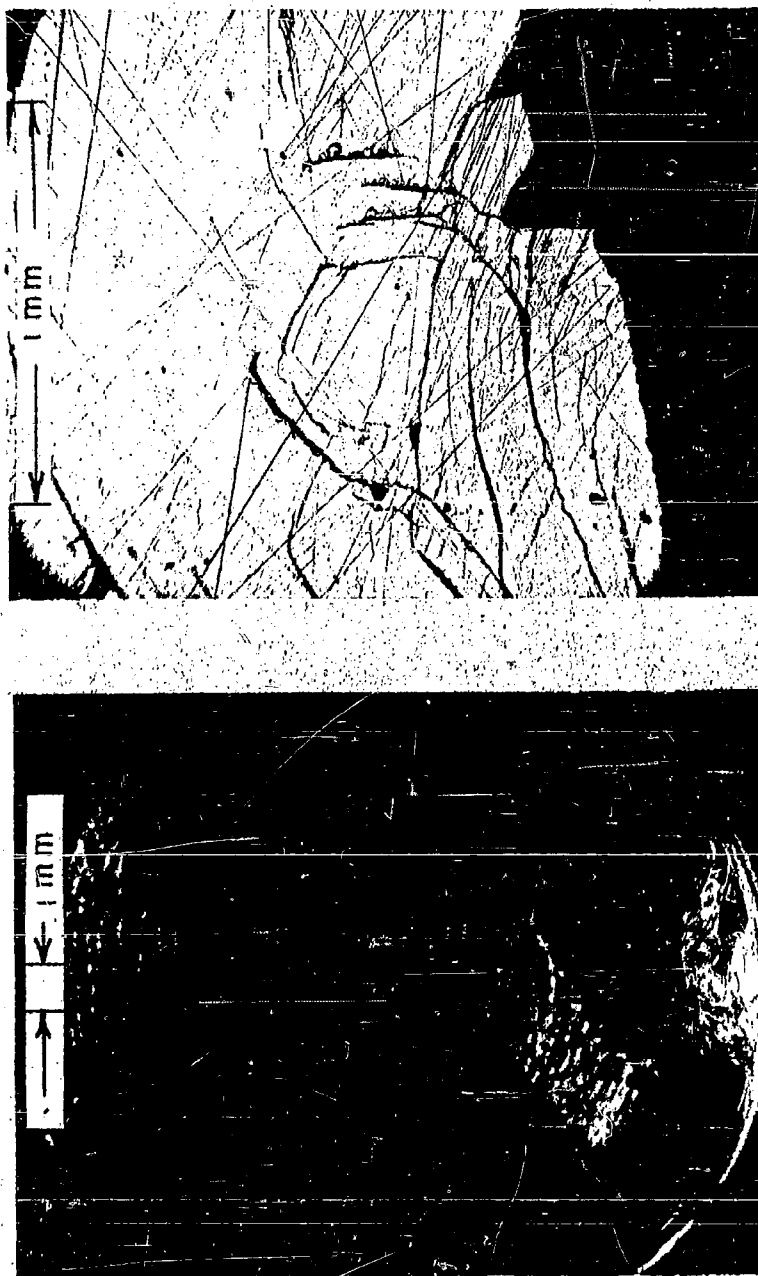
sapphire plate that is 0.318 cm (0.125 in.) thick on colliding with a 0.2-cm waterdrop up to a relative collision velocity of  $6.620 \times 10^4$  cm/sec (2,172 ft/sec).

The white sapphire target plate used for the lowest-velocity collisions with mercury drops was fired four times. In the first three firings, it collided with 0.2-cm mercury drops at velocities of  $2.890 \times 10^4$  cm/sec (948 ft/sec),  $3.197 \times 10^4$  cm/sec (1,049 ft/sec), and  $3.216 \times 10^4$  cm/sec (1,055 ft/sec) without sustaining any damage. In the fourth firing, it collided with a 0.2-cm mercury drop at a relative velocity of  $3.514 \times 10^4$  cm/sec (1,153 ft/sec). The white sapphire target plate was damaged by this collision.

An enlarged view of this target plate is shown in Figure 1a. The white sapphire is crystal clear; machining marks in the metal backing plate can be seen through the clear sapphire. Damage is restricted to the immediate site of the collision at the edge of the target plate; the remainder of the target plate is not affected.

A view of the central point, or eye of the collision, at higher magnification is shown in Figure 1b. It can be seen that the eye of the collision consists of an undamaged central area surrounded by an imperfectly developed polygon of short straight cracks that tend to form almost parallel to one another. Possible explanations of the existence of the undamaged center and of the formation of the characteristic polygonal crack structure are discussed in Sections 4.2.1 and 4.2.2. Evidence that these cracks extend down into the target plate in a conchoidal type of fracture is presented below. It can be seen that sapphire has been broken out of the surface along the polygonal cracks and on the side of the cracks away from the center of the collision, that is, in the direction of the radial flow of the liquid of the drop that impinged. A possible cause of the breaking away of material along the polygonal cracks is discussed in Section 4.2.3.

From the evidence provided by this target plate, it appears that the velocity at which a plate of white sapphire that is 0.318 cm (0.125 in.) thick is damaged, on collision with a 0.2-cm mercury drop, is  $3.514 \times 10^4$  cm/sec (1,153 ft/sec).



(a)

(b)

FIGURE 1. WHITE SAPPHIRE TARGET PLATE THAT COLLIDED WITH A 0.2-CM MERCURY DROPE

AT A VELOCITY OF  $3.514 \times 10^4$  cm/sec (1.153 ft/sec)

(a) View showing extent of damage to the target plate

(b) View of the central point of the collision

The next-highest-speed collision between a white sapphire target plate and a 0.2-cm mercury drop occurred at a velocity of  $3.581 \times 10^4$  cm/sec (1,175 ft/sec). This collision was also close to the edge of the target plate; it resulted in a piece of sapphire being chipped away. An enlarged view of this target plate is shown in Figure 2a where the machining marks in the metal backing plate and bubbles in the adhesive can be seen through the clear sapphire. A view of the eye of the collision at higher magnification is shown in Figure 2b. The imperfectly developed polygon of cracks around an undamaged center can again be seen. Sapphire is broken out of the surface along the cracks on the side away from the center of the collision, that is, in the direction of the radial flow of the liquid of the drop that impinged.

That the polygonal cracks extend below the surface in a conchoidal fracture can be seen in the views of the eye of this collision shown in Figure 3. These pictures were taken with a different mode of lighting, at lower magnification, and with greater depth of focus. In Figure 3a the structure of the subsurface fractures can be seen best but the polygonal cracks on the surface are dim. In Figure 3b it can be seen that the subsurface fractures extend from the surface cracks and that, with increasing depth, they diverge from a line taken through the central point of the collision.

Collision between a white sapphire target plate and a 0.2-cm mercury drop at a relative collision velocity of  $4.420 \times 10^4$  cm/sec (1,450 ft/sec) resulted in radial cracks that extended completely across the target plate. An enlarged view of the damaged target plate is shown in Figure 4a. The long radial cracks extend through the thickness of the sapphire plate. A possible explanation of the cause of the radial cracks is discussed in Section 4.2.4.

A view of the eye of this collision at higher magnification is shown in Figure 4b. It can be seen that sapphire has been broken out of the surface along the polygonal cracks and on the side of the crack away from the central point of the collision, that is, in the direction of the radial flow of the liquid of the drop that impinged. The large dark regions of Figure 4b are areas where sapphire has been chipped from the surface. It appears that this chipping out of the sapphire occurred between intersecting cracks.

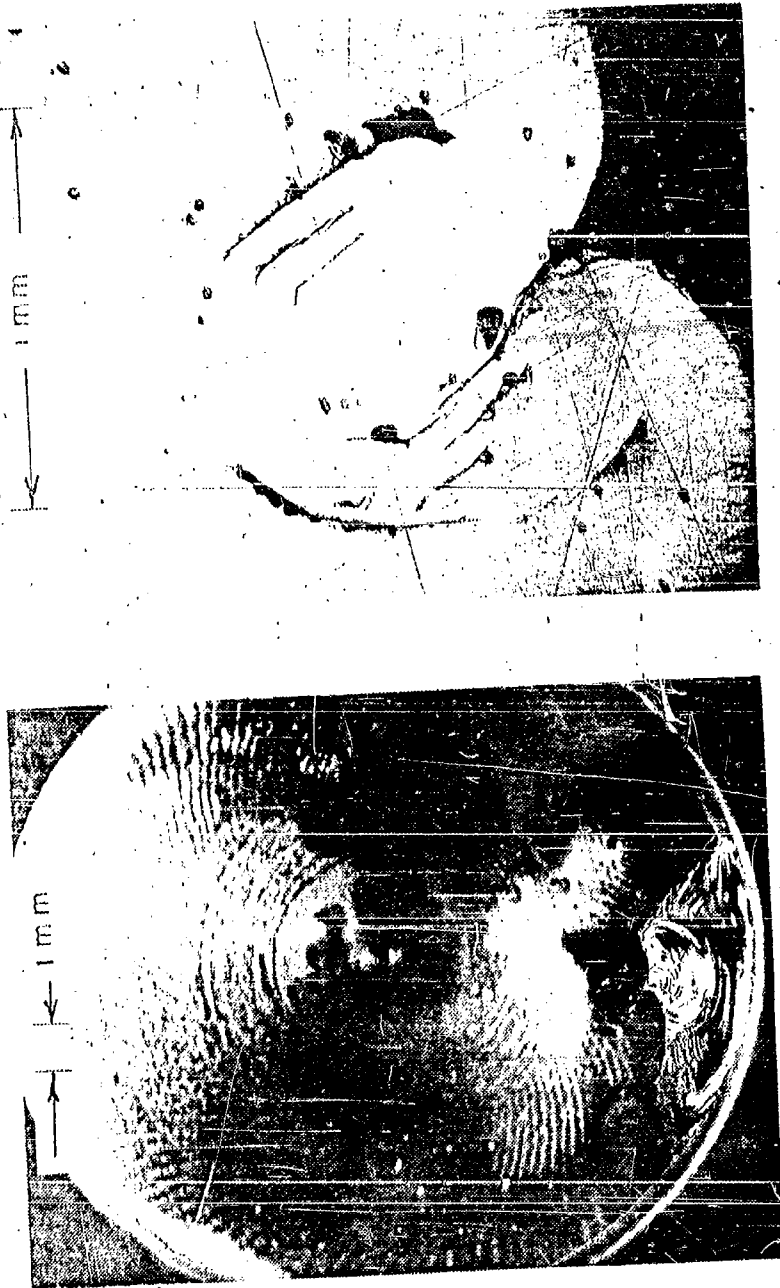


FIGURE 2. WHITE SAPPHIRE TARGET PLATE THAT COLLIDED WITH A 0.2-CM MERCURY DROP

AT A VELOCITY OF  $3.581 \times 10^4$  cm/sec ( $1.175 \text{ ft/sec}$ )

(a) View showing extent of damage to the target plate

(b) View of the central point of the collision



(a)

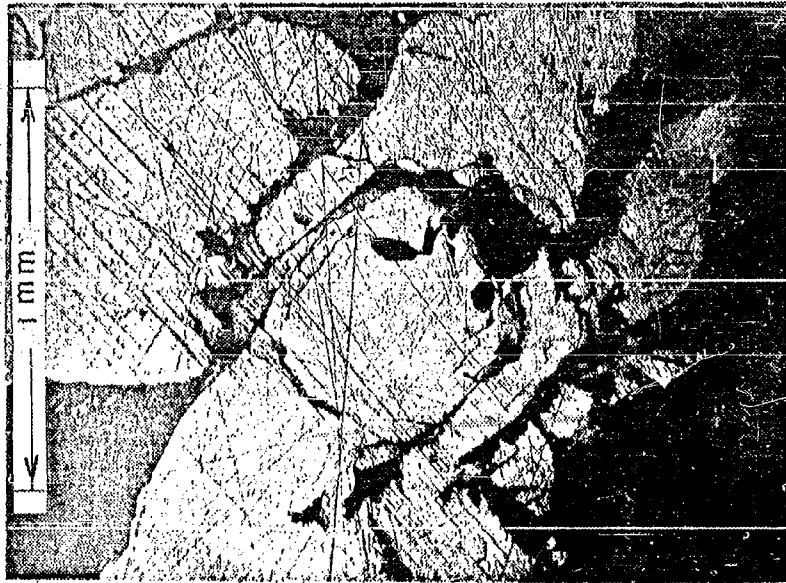


(b)

FIGURE 3. VIEWS OF THE SUBSURFACE FRACTURES EXTENDING FROM THE SURFACE CRACKS SHOWN IN FIGURE 2(b).



(a)



(b)

FIGURE 4. WHITE SAPPHIRE TARGET PLATE THAT COLLIDED WITH A 0.2-CM MERCURY DROP

AT A VELOCITY OF  $4.420 \times 10^4$  cm/sec (1,459 ft/sec)

(a) View showing extent of damage to the target plate

(b) View of the central point of the collision.

The highest velocity at which a white sapphire target plate collided with a 0.2-cm mercury drop was  $4.584 \times 10^4$  cm/sec (1,504 ft/sec). An enlarged view of the damaged sapphire target plate is shown in Figure 5a. A view of the eye of the collision at higher magnification is shown in Figure 5b. Extensive radial cracks run out from the central area of the collision where a considerable amount of sapphire has been chipped out of the surface. The chipping out of sapphire appears to have occurred between intersecting cracks.

Two semi-circular cracks are indicated with arrows in Figure 5a. These cracks appear to reflect the curved side of the target plate. A possible explanation of why these cracks formed is discussed in Section 4.2.5.

### 3.2 Hot-Pressed Alumina

Three target plates of hot-pressed alumina were used for collisions with 0.2-cm waterdrops. The lowest-velocity collision was at  $7.346 \times 10^4$  cm/sec (2,410 ft/sec). An enlarged view of this target plate is shown in Figure 6a. The circle and arrow were drawn on the target plate by the experimenters at Convair who reported observing an almost imperceptible damage mark. A view of the area enclosed by the circle at higher magnification is shown in Figure 6b. Careful inspection of the surface in this area failed to provide conclusive evidence that damage had occurred.

The second hot-pressed alumina target plate was fired at a velocity of  $9.144 \times 10^4$  cm/sec (3,000 ft/sec). It shattered due to firing shock.

The third hot-pressed alumina target plate was fired at a velocity of  $11.88 \times 10^4$  cm/sec (3,898 ft/sec) and it collided with two 0.2-cm waterdrops. The experimenters at Convair had coated this target plate with blue dye prior to firing it. An enlarged view of this target plate is shown in Figure 7a where it can be seen from flower-like traces in the dye that two waterdrops were struck. These traces were formed when the radial flow of the impinging waterdrops removed the dye from the surface. A view of the larger of these traces is shown in Figure 7b at higher magnification. After the pictures shown in Figure 7 were made, the dye was completely removed from the surface of the target plate with alcohol. The clean surface of the target plate was inspected under the microscope; no conclusive evidence of damage to the surface was seen.

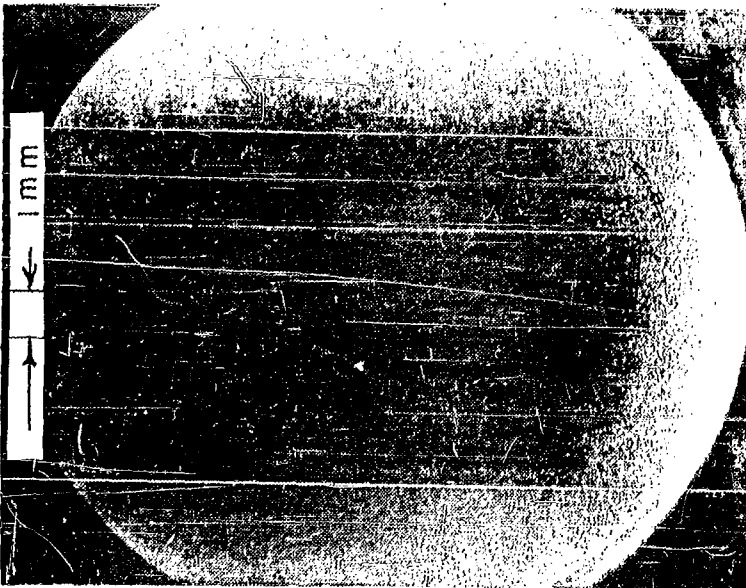


FIGURE 5. WHITE SAPPHIRE TARGET PLATE THAT COLLIDED WITH A 0.2-CM MERCURY DROP

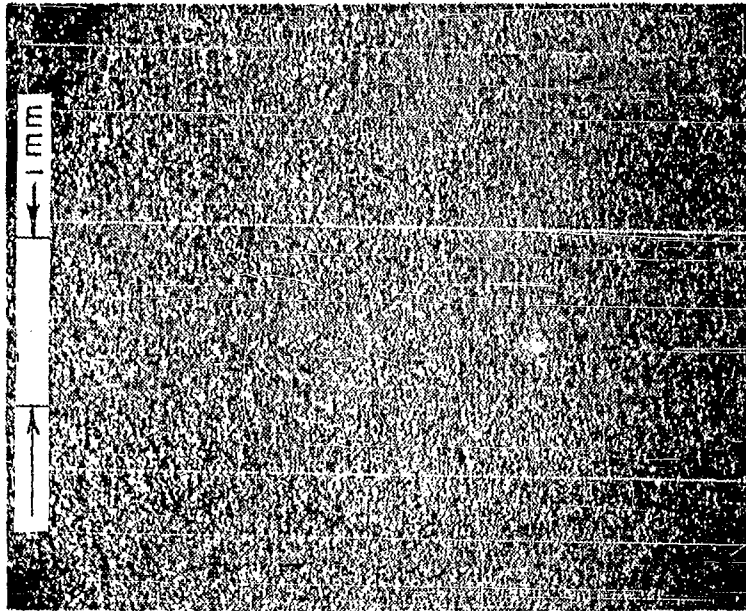
AT A VELOCITY OF  $4.584 \times 10^4$  cm/sec (1,504 ft/sec)

(a) View showing extent of damage to the target plate

(b) View of the central point of the collision



(a)

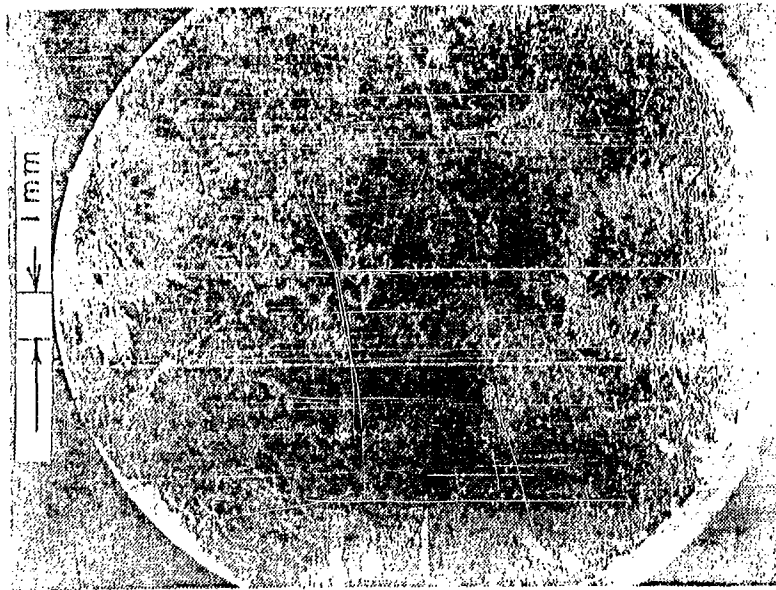


(b)

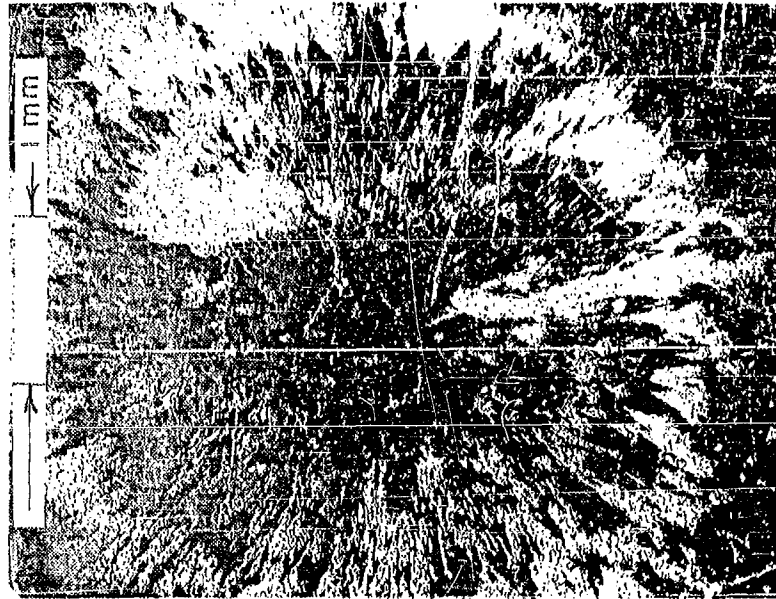
FIGURE 6. H.P. ALUMINA TARGET PLATE THAT COLLIDED WITH A 0.2-CM WATERDROP AT A VELOCITY OF  $7.346 \times 10^4$  cm/sec (2,410 ft/sec)

(a) View showing extent of damage to the target plate

(b) View of the encircled area



(a)



(b)

FIGURE 7. H.P. ALUMINA TARGET PLATE THAT COLLIDED WITH A 0.2-CM WATERDROP AT A VELOCITY OF  $11.88 \times 10^4$  CM/SEC (3,898 FT/SEC)

(a) View showing extent of damage to the target plate

(b) View of one of the two collision sites

On the basis of these observations it appears that hot-pressed alumina plates that are 0.318 cm (0.125 in.) thick will not be damaged by collision with 0.2-cm waterdrops up to a collision velocity of  $11.88 \times 10^4$  cm/sec (3,898 ft/sec).

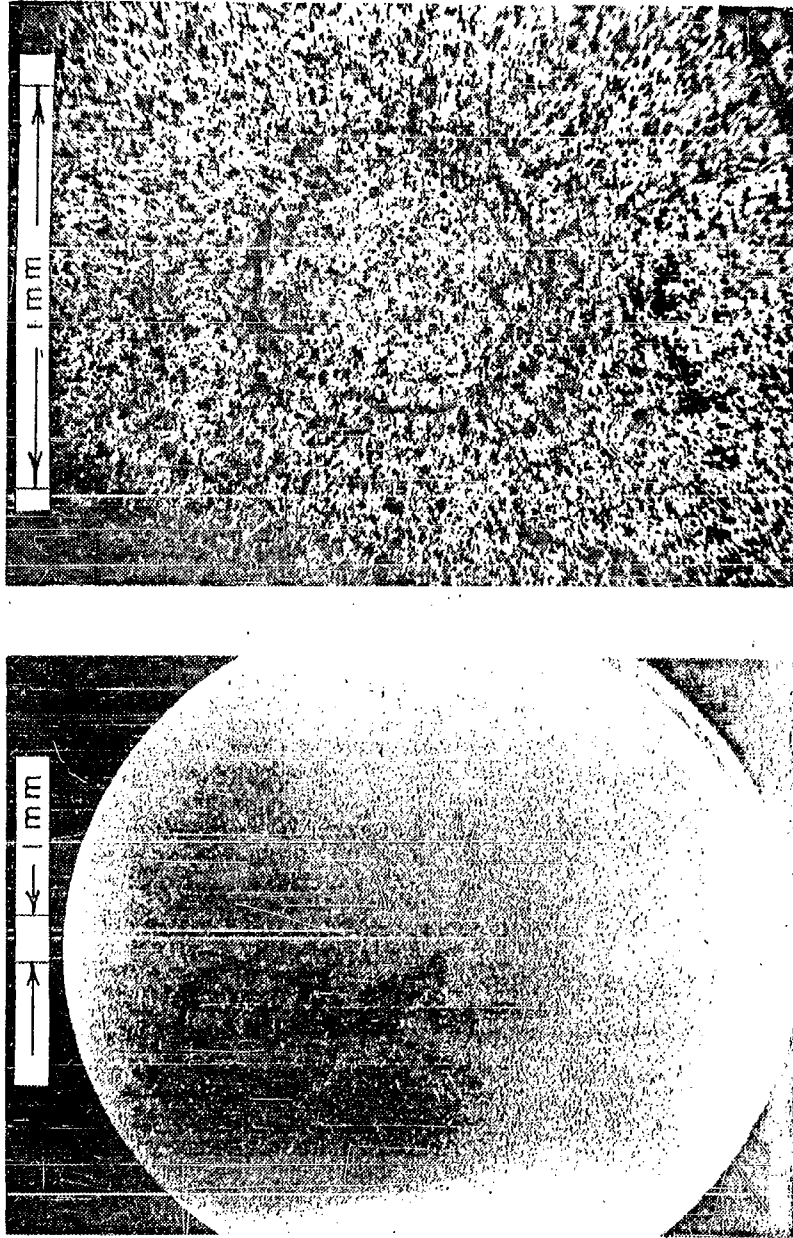
The fourth hot-pressed alumina target plate collided with a 0.2-cm mercury drop at a velocity of  $4.276 \times 10^4$  cm/sec (1,403 ft/sec). The target plate was damaged by the collision. An enlarged view of the damaged target plate is shown in Figure 8a. The experimenters at Convair drew a circle around the damage mark which they reported was 0.0005 cm (0.0002 in.) deep and 0.071 cm (0.028 in.) in diameter.

A view of the eye of this collision at higher magnification is shown in Figure 8b. It can be seen that the eye of the collision consists of an undamaged central area surrounded by circles of short cracks. Because the hot-pressed alumina is opaque, the amount of damage that exists below the surface cannot be assessed.

From the evidence provided by this target plate, it appears that the velocity at which a plate of hot-pressed alumina that is 0.318 cm (0.125 in.) thick is damaged, on collision with a 0.2-cm mercury drop, is  $4.276 \times 10^4$  cm/sec (1,403 ft/sec). Because this is the lowest velocity at which collision between a hot-pressed alumina target plate and a mercury drop occurred, it is not known if this is the very lowest velocity at which observable damage would be produced.

The fifth hot-pressed alumina target plate was fired twice. It was chipped by an edge collision with a 0.2-cm mercury drop at a velocity of  $4.996 \times 10^4$  cm/sec (1,639 ft/sec) and was then shattered by collision with a 0.2-cm mercury drop at a velocity of  $4.100 \times 10^4$  cm/sec (1,345 ft/sec). An enlarged view of the target plate is shown in Figure 9a; a view of the eye of the lower-velocity collision is shown at higher magnification in Figure 9b; a view of what remains of the eye of the higher-velocity edge collision is shown in Figure 9c.

From Figure 9a it can be seen that a crack runs across the target plate between the two points of collision. If this crack existed even partially before the second (lower-velocity) collision occurred, the extent of damage caused



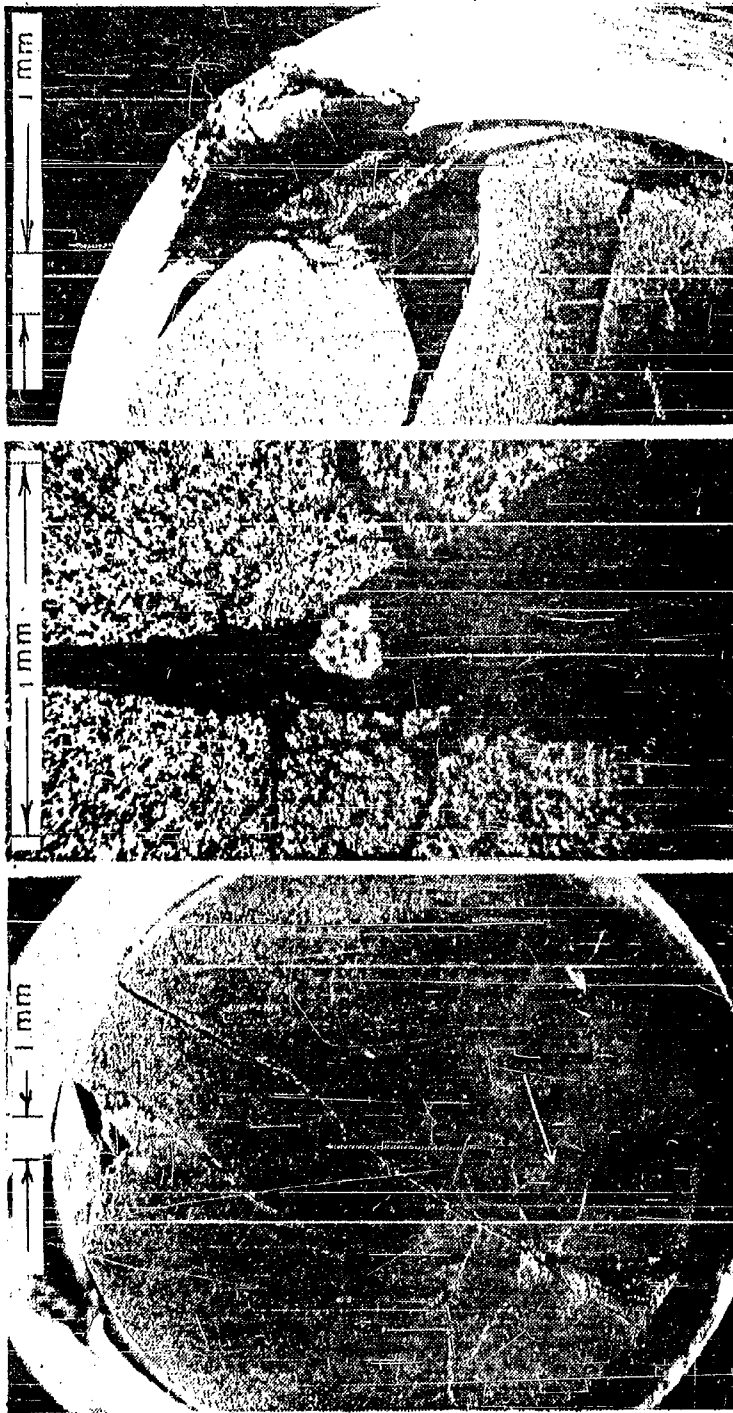
(a)

(b)

FIGURE 8. H.P. ALUMINA TARGET PLATE THAT COLLIDED WITH A 0.2-CM MERCURY DROP AT A VELOCITY OF  $4.276 \times 10^4$  cm/sec (1,403 ft/sec)

(a) View showing extent of damage to the target plate

(b) View of the central point of the collision



(a) (b) (c)

FIGURE 9. H.P. ADMINA TARGET PLATE THAT COLLIDED WITH 0.2-CM MERCURY DROPS AT VELOCITIES OF

$4.100 \times 10^4$  cm/sec (1,345 ft/sec) and  $4.996 \times 10^4$  cm/sec (1,639 ft/sec)

(a) View showing extent of damage to the target plate

(b) View of the central point of the lower-velocity collision

(c) View of the higher-velocity collision site

by the collision at  $4.100 \times 10^4$  cm/sec (1,345 ft/sec) may not be representative. In this connection, it should be pointed out that the degree of damage seen in Figure 9 was not produced in the collision of the hot-pressed alumina target plate with a 0.2-cm mercury drop at  $4.276 \times 10^4$  cm/sec (1,403 ft/sec). See Figure 8a.

From Figures 9b and 9c it can be seen that the eye of the collision is again bounded by a circle of short cracks. Less than half of the eye of the collision that occurred at a velocity of  $4.996 \times 10^4$  cm/sec (1,639 ft/sec) can be seen in Figure 9c; the remaining part of this area was apparently lost when a chip from the edge of the specimen broke away. Because the eye of this collision was broken in half, the crack structure below the surface of the opaque hot-pressed alumina can be observed. Microscopic inspection of this damaged area with the target plate turned at an angle revealed that the short and more or less parallel cracks that bound the eye of the collision run deep into the ceramic; they may extend through the target plate. The innermost cracks of the ring may have formed nearly perpendicular to the surface, but the outermost cracks formed at an angle that was estimated roughly to be close to  $45^\circ$  to the surface.

From Figure 9a it can be seen that seven radial cracks formed around the eye of the lower-velocity collision; the longer of these cracks are characterized by dichotomous branching. From a comparison of the damage produced on this hot-pressed alumina target plate and that produced on the hot-pressed alumina target plate that collided with a mercury drop of the same size at a velocity of  $4.276 \times 10^4$  cm/sec (1,403 ft/sec), it might be concluded that the circular cracks that bound the eye of the collision form either with or without the formation of the long radial cracks. On the other hand, the damage produced by the collision with a 0.2-cm mercury drop at a velocity of  $4.100 \times 10^4$  cm/sec (1,345 ft/sec) may be misleading, as was pointed out above. Cracks that were almost invisible may have been produced in this target plate as a result of the edge collision with a mercury drop that it had already suffered.

An interesting crack that appears to reflect the contour of the edge of the target plate is indicated with an arrow in Figure 9a. This crack intersects five of the seven radial cracks that run out from the eye of the lower-velocity collision. The possible origin of this crack is discussed in Section 4.2.5.

### 3.3 Summary of Observations

For the 0.318-cm (0.125-in.)-thick plates of white sapphire and hot-pressed alumina that were used, no damage was done to either ceramic by collision with a 0.2-cm-diam waterdrop at the highest collision velocities that were used, namely,  $6.620 \times 10^4$  cm/sec (2,172 ft/sec) for white sapphire and  $11.88 \times 10^4$  cm/sec (3,898 ft/sec) for hot-pressed alumina. In collision with 0.2-cm-diam mercury drops, the velocity at which damage was first observed was  $3.514 \times 10^4$  cm/sec (1,153 ft/sec) for white sapphire and  $4.276 \times 10^4$  cm/sec (1,403 ft/sec) for hot-pressed alumina; the difference in the velocities found for the two ceramics is not significant because the velocity given for hot-pressed alumina is the lowest velocity at which collision between a mercury drop and this ceramic occurred.

The first evidence of failure of high-strength white sapphire and hot-pressed alumina under high-speed mercury-drop impingement was the formation of cracks that bound a more or less circular undamaged area around the central point or eye of the collision. In white sapphire these cracks were polygonal; in hot-pressed alumina they were circular. These cracks ran deep into the ceramic material. The cracks nearest to the central point of the collision were nearly perpendicular to the surface of the target plate but the outer-lying cracks were inclined at an angle to the surface of the target plate.

The material of the target plate was broken out of the surface along these cracks and on the side of the cracks away from the central point of the collision, that is, in the direction of the radial flow of the liquid of the drop that impinged. The erosion damage was more severe the higher the velocity at which the collision occurred.

At high impingement velocities radial cracks formed. The radial cracks ran out from the center of the collision and extended completely across and through the target plate.

Curved cracks that appear to reflect the curved edge of the target plates also formed when the impingement velocity was high. Cracks of this kind observed in white sapphire were below the surface of the target plate; the curved crack observed in hot-pressed alumina extended to the surface of the target plate.

#### IV. Failure

In order to understand how the damage that has been observed was produced, it is necessary to review the stresses that are imposed by an impinging liquid drop.

##### 4.1 Liquid Drops as Damage Tools

When a liquid drop collides with the planar surface of a solid, (a) it exerts a localized pressure and (b) it flows out radially around the central point of impingement.

##### 4.1.1 Localized Pressure

During the early stages of the collision between a liquid drop and the planar surface of a solid, maximum pressure exists in a ring around the central point of the collision. At the first instant of the collision, when the maximum pressure is higher than at any later time, this ring may be regarded as a point circle. The radius of the ring of maximum pressure increases and the value of the maximum pressure in the ring decreases with time until the radius of the circle of contact between the drop and the solid is about 0.6 of the original radius of the drop. When this stage of the collision is reached, the ring of maximum pressure vanishes.

Savic and Boulton [1]<sup>1/</sup> have given a hydrodynamic treatment of the collision of a drop of incompressible liquid with a completely unyielding solid. They found that the pressure is infinite at the first instant of the collision when the ring of maximum pressure may be regarded as a point circle. They state that this infinity is prevented physically by the fact that the high initial pressure is absorbed in the bulk compressibility of the liquid, giving rise to an emitted compression wave.

According to the treatment of Savic and Boulton [1], very high pressure maxima are developed during the early stages of the collision when the pressure maximum exists in a ring around the central point of the collision. Approximate values of the pressure maxima found by them for various values of the radius of the circle of contact

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<sup>1/</sup> Numbers in brackets refer to literature references at the end of this paper.

between the drop and solid surface are given in Table 3. In Table 3,  $R$  is the original radius of the drop,  $\rho$  is the density of the liquid of which the drop is composed, and  $U$  is the impingement velocity. They found that when the radius of the circle of contact is  $0.6 R$ , the ring of maximum pressure vanishes, maximum pressure then exists at the center of the drop, and the pressure profile across the contact area decreases from the center to the periphery of the circle of contact.

Table 3.  
Maximum Pressure in an Impinging Liquid Drop

Radius of Circle of Contact in Terms of the Original Drop Radius $R$	Approximate Value of Maximum Pressure
0.1 $R$	$3 \rho U^2$
0.2 $R$	$3/2 \rho U^2$
0.3 $R$	$\rho U^2$
-----	-----
0.6 $R$	$1/2 \rho U^2$

Structural materials do not usually fail when a uniform pressure is applied to them. However, when a localized pressure is applied, tensile and shear stresses, which may cause failure, appear in the solid material. A circular compressed area in a thin plate has radial symmetry. The traces of the principal planes of stress are the radii of the circular area and tangents to any circle drawn around the central point of the compressed area. The principal stresses act at an angle of  $90^\circ$  to the principal planes of stress<sup>2/</sup>.

The stresses that are introduced into an elastic plate by a spherical indenter were studied with use of small foam rubber pads and spherical indenters of glass and steel.

<sup>2/</sup> Helpful conversations with Dr. J. M. Frankland of NBS Engineering Mechanics Section with regard to the principal stresses are gratefully acknowledged.

The kinds of stresses that were acting and the directions in which they were acting were deduced from the behavior of blemishes (holes and scratches) in the rubber as observed under low power magnification.

By pressing a steel sphere into the rubber it could be seen that, at the periphery of the compressed area, the principal stresses are tensile stresses acting at an angle of  $90^\circ$  to the tangent planes of principal stress and compressive stresses acting at an angle of  $90^\circ$  to the radial principal planes of stress. See Figure 10. The principal stresses below the indenter were studied with use of a spherical glass indenter that was flattened on one side. The behavior of the rubber under the indenter as it was pressed into the pad was observed through the flat area on the sphere. It could be seen that, near the center of the compressed area, the principal stresses are all compressive. See Figure 10. The principal stresses at the convexity on the opposite side of the plate were studied by pressing the rubber pad over a steel sphere. It could be seen that, at the convexity, the principal stresses are all tensile stresses. See Figure 10.

A cavity may form in a solid to which a local pressure is applied if the strength of the solid is low or if the pressure that is exerted is high.

An impinging liquid drop acts like an impinging solid sphere in exerting a localized pressure. However, for any given impingement velocity, the localized pressure exerted by an impinging liquid drop is never as great as that exerted by an impinging solid sphere. This is because part of the collision energy of an impinging drop is transformed into radial flow of the liquid of which it is composed. An impinging solid sphere can inflict damage only by exerting a localized pressure; an impinging liquid drop can inflict damage both by the localized pressure that it exerts and by its radial flow.

#### 4.1.2 Radial Flow

The impact pressure that is produced by the collision of a liquid drop with the planar surface of a solid drives the liquid that is close to the solid surface radially outward around a central stagnation point. The flow velocity

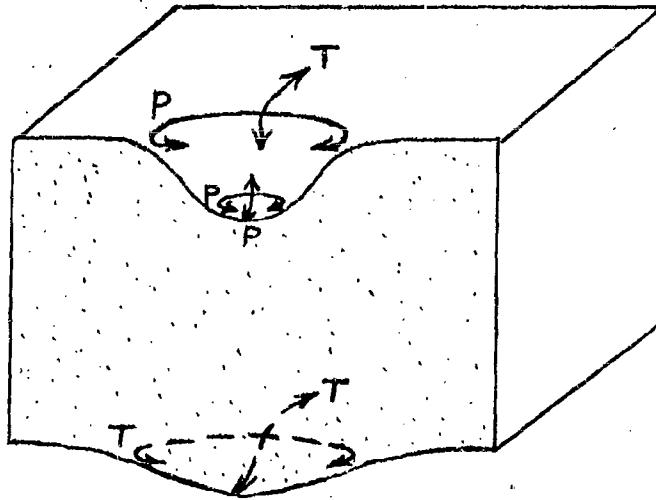


FIGURE 10. PRINCIPAL STRESSES (P, PRESSURE; T, TENSION) AT THE CONCAVITY  
AND CONVEXITY PRODUCED BY A SPHERICAL INDENTER PRESSING  
AGAINST AN ELASTIC SOLID PLATE

can become very high. In the case of a waterdrop colliding with a glass plate, it may approach ten times the value of the impingement velocity for short times after the collision incident [2].

The radially flowing liquid of an impinging drop exerts a shear stress on the surface of the solid over which it is running. The shear stress  $\tau$  between layers of liquid in laminar flow is given by  $\mu (\partial v / \partial z)$  where  $\mu$  is the viscosity of the liquid,  $v$  is the velocity at which the liquid is moving, and  $z$  is the direction through the thickness of the liquid sheet. The layer of liquid molecules in direct contact with the surface of the solid has zero velocity but the velocity gradient is not zero and the shear stress is applied to the solid.

If the radial flow of an impinging liquid drop runs over a surface protrusion, it exerts forces against the protrusion that act in opposition to the cohesion of the protrusion to the underlying layers of material. Pressure exerted against the protrusion by the flowing liquid tends to move the protrusion along the planar surface of the solid and results in a shear stress at the base of the protrusion. The pressure exerted by the liquid also results in a turning moment that tends to bend the protrusion over. The turning moment is the integrated cross product of the compressive force exerted by the liquid and the distance above the planar surface of the solid of the point where the force is applied. If the forces exerted by the rapid flow of liquid are large enough, or if the protrusion has a notable elevation above the planar surface, failure may occur. The protrusion may be bent over, it may be broken off, or part of the solid material below the surface may be torn out with it.

#### 4.2 Correlation

A logical explanation of the observations on the failure of white sapphire and hot-pressed alumina under mercury-drop impingement, which were summarized at the end of Section 3, must be based on the stresses that an impinging liquid drop exerts. These have been reviewed in Section 4.1. In this section the observed damage will be considered in the light of the stresses that were produced in the ceramic materials.

#### 4.2.1 Undamaged Center

The first characteristic of the damage mark produced on white sapphire and hot-pressed alumina by mercury-drop impingement that was cited was an undamaged center surrounded by a polygon of cracks in the case of sapphire and by a circle of cracks in the case of hot-pressed alumina. The undamaged center is the part of the damage mark that was under high pressure during the collision incident. If a cavity formed during the collision, the undamaged center was the highly compressed material at the bottom of the cavity where the principal stresses are all compressive (see Figure 10). Brittle materials, such as glass, fail in tension [3], and it can be surmised that white sapphire and hot-pressed alumina will fail in tension. Because no tensile stresses form in the compressed solid material near the center of the collision, failure would not be expected here, and the existence of an undamaged area at the center of the collision is to be anticipated.

#### 4.2.2 Polygonal or Circular Cracks

In the first damage marks produced on white sapphire and hot-pressed alumina the undamaged central area was surrounded with polygonal cracks and circular cracks, respectively. These cracks formed in the region of tensile stress around the central compressed area. See Figure 10. It seems reasonable to suppose that these cracks are the result of a tensile failure.

The expression for the radial tensile stresses that form at the periphery of the compressed area is known for the case that the maximum compressive stress exists at the central point of the compressed area and that the pressure decreases regularly to the periphery of this area [3]. It is

$$\sigma_r = (1 - 2\nu)/3 q_0$$

where  $\nu$  is Poisson's ratio and  $q_0$  is the maximum pressure at the center of the compressed area. The type of pressure distribution for which this equation applies exists under an impinging liquid drop only after the circular pressure peaks that develop during the earliest stages of the collision have vanished. This occurs when the radius of the circle of contact is about 0.6 of the original radius of the drop.

See Section 4.1. The maximum pressure at this time, according to the hydrodynamic treatment of Savic and Boulton [1] for a drop of incompressible liquid impinging against the planar surface of an unyielding solid, is  $9.3 \times 10^9 \text{ d/cm}^2$  (135,000 psi) for the case that the liquid of the drop is mercury and the collision velocity is  $3.581 \times 10^4 \text{ cm/sec}$  (1,175 ft/sec). The damage mark made on a white sapphire target plate on collision with a 0.2-cm mercury drop at this velocity is shown in Figure 2b. Using this value for the maximum pressure,  $q_0$ , and 0.26 for an average value<sup>3/</sup> of Poisson's ratio,  $\nu$ , gives a value of  $1.5 \times 10^9 \text{ d/cm}^2$  (22,000 psi) for the radial tensile stress,  $\sigma_r$ . This is only about half of the tensile strength of white sapphire. See Table 1. From Figure 2b it can be seen that the radius of the area enclosed by the outermost polygonal cracks is about 0.05 cm or half the original radius of the 0.2-cm-diam mercury drop, whereas the calculated value of  $\sigma_r$  is for a radius of 0.06 cm.

Furthermore, polygonal cracks have formed at distances from the central point of the collision that range from about 0.025 cm to about 0.05 cm. From the treatment of Savic and Boulton [1], the maximum pressure would be increased by a factor of 2 for the case that the radius of the circle of contact is 0.3 of the radius of the original drop (0.03 cm) and would be increased by very close to a factor of 3 for the case that the radius of the circle of contact is 0.2 of the radius of the original drop (0.02 cm). See Table 3. Hence it can be surmised that the radial tensile stresses are from 2 to 3 times higher than  $1.5 \times 10^9 \text{ d/cm}^2$  (22,000 psi) at the distances from the central point of the collision where polygonal cracks are observed to have formed, and are in excess of the tensile strength of white sapphire. However, because the equation given for the radial tensile stress,  $\sigma_r$ , is based on a different pressure distribution from that which exists in a liquid drop when the radius of the circle of contact is less than 0.6 of the original radius of the drop, this equation cannot validly be used to compute them.

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3/ This average value of Poisson's ratio for white sapphire and polycrystalline alumina was kindly supplied by J. B. Wachtman, Jr., of NBS Engineering Ceramics Section.

It was observed that the cracks that form in white sapphire as a result of the radial tensile stresses are polygonal whereas those that form in hot-pressed alumina are circular. The difference in the type of cracks appears to result from the degree of anisotropy of the two ceramics. The single-crystal white sapphire is characterized by cleavage planes on which failure occurs first whereas polycrystalline hot-pressed alumina is isotropic.

#### 4.2.3 Breaking Out of Material

White sapphire is eroded away along the polygonal cracks that formed in it. This damage appears to be the result of the radial flow of the mercury drops that impinged. If the broken edges of the cracks were raised above the planar surface of the target plate by plastic flow, they may have provided protrusions against which the radially flowing mercury exerted pressure. The pressure would result in a shear stress below the protrusion and a turning moment exerted against it that may have caused the loss of material.

The reasoning just given is supported by the observation that the loss of sapphire material occurred on the side of the crack away from the central point of the collision. If the raised broken edge of the crack provided a protrusion against which the radial flow of the mercury of the drop could exert a pressure, this is the side of the crack against which the pressure would be exerted.

There are two other observations that support the reasoning given. One of these is that the outermost of the polygonal cracks are more eroded than the innermost. This may be explained in terms of the magnitude of the velocity of the radial flow at different distances from the stagnation point (zero flow velocity) at the center of the collision. On the other hand, there may have been an increase in the magnitude of the radial tensile stress with increase in distance from the center of the collision and the outermost cracks may, therefore, have developed higher raised edges due to plastic flow. The other is the observation that the erosion damage increased in severity as the impingement velocity was increased. This could be in agreement with the fact that the velocity of the radial flow is increased as the impingement velocity is increased. However, the magnitude of the radial tensile stresses introduced is also

increased as the impingement velocity is increased and this could explain the observation in terms of higher raised edges along the cracks.

#### 4.2.4 Radial Cracks

Radial cracks formed at the highest impingement velocities at which mercury drops struck the target plates of white sapphire and hot-pressed alumina. They ran out from the center of the collision and extended completely across and through the target plates.

These cracks are probably also the result of a tensile failure. Tensile stresses perpendicular to the radial principal planes of stress are required to account for them. The stresses perpendicular to the radial principal planes of stress around the periphery of the area of the target plate that was compressed by the colliding drop are compressive (see Section 4.1 and Figure 10).

It is possible that these cracks may originate on the reverse face of the target plate when the compressional wave initiated by the collision reflects as a tension wave. The principal stresses in the convexity that should form on the reverse face of the plate when this reflection occurs are all tensile stresses (see Figure 10). Hence radial cracks could be expected to form on the reverse face of the plate as a result of a tensile failure. It is possible that the radial cracks originate on the reverse face of the target plate and progress through it to the collision surface.

#### 4.2.5 Curved Cracks

Cracks that reflect the curvature of the bounding edge of the target plates formed in both white sapphire and hot-pressed alumina as a result of high-speed collision with mercury drops. A wave of compression is initiated in the target plate as a result of the collision. When this wave reaches the curved edges of the target plate, it reflects as a tension wave. It seems very likely that the curved cracks, which have been observed in white sapphire and hot-pressed alumina, formed when the level of stress in the reflected tension wave exceeded the tensile strength of the ceramic material.

From Figures 5a and 9a it can be seen that the distance from the edge of the hot-pressed alumina target plate to the curved crack is about the same as the distance from the edge of the white sapphire target plate to the curved crack that formed furthest from the edge of it. On the basis of the observation that no second crack formed in hot-pressed alumina, and of the information that the tensile strength of the ceramics and the size and velocity of the impinging drops were closely similar, it can be deduced that the crack furthest from the edge of the white sapphire target plate formed first. This deduction is in agreement with the observation that the curvature of the two cracks is in the same direction. If the crack nearest the edge of the sapphire target plate had formed first, the compressional wave initiated by the collision would have begun to reflect from the curved surface of this crack, and it would be expected that, if the level of tensile stress in the tension wave reflected from this crack again exceeded the tensile strength of the ceramic, the second crack to form would curve in the opposite direction.

The curved edges of the target plates focus the reflected tension waves in the same way that a curved mirror focuses reflected light waves. This is in agreement with the observation that the curved cracks are isolated; they do not extend from edge to edge of the target plate. The curved cracks formed in white sapphire are below the surface. This may be ascribed to the effect of the bevelled edge of the target plate on the reflected wave. In hot-pressed alumina, however, the curved crack extends to the surface.

If the curved crack furthest from the edge of the white sapphire target plate formed first, as seems to be the case from the evidence at hand, the mechanism by means of which the crack nearest the edge of the target plate then formed needs to be explained.

At the time that the curved crack furthest from the edge of the target plate forms, a tension wave superposed on a pressure wave is trapped between this curved crack and the curved edge of the target plate. The curvature of both bounding surfaces between which the trapped wave must travel is such as to focus the wave further. This is in agreement with the observation that the crack that eventually

forms closest to the edge of the target plate is shorter than the crack that appeared first and that formed furthest from the edge of the target plate. If the boundaries between which the trapped wave must reflect were straight, the level of tensile stress in the tension wave would never again exceed the tensile strength of the ceramic. In the case of reflection between concave curved boundaries, the focusing effect of the boundaries may make the formation of the second fracture possible.

#### V. Resistance to Waterdrop Impingement

The information of greatest interest from a practical standpoint is the resistance of white sapphire and of hot-pressed alumina to waterdrop impingement. This information was not obtained in the tests that were made because impingement velocities high enough to fracture these ceramics on colliding with a waterdrop were not reached. In this section an equation is developed from which an estimate of the resistance of these ceramics to waterdrop impingement can be obtained by extrapolation of their resistance to mercury drop impingement.

To develop this equation the following assumptions are made: 1) a concavity (no matter how small) forms in a thin ceramic plate, whose reverse face is a free surface, as a result of high-speed liquid-drop impingement, 2) elastic recovery without fracture occurs when the impingement velocities are low and the depth of the concavity is small, and 3) corresponding velocities to produce equal depth of concavity in a given edge-supported ceramic plate by impingement with drops of a liquid A and drops of a liquid B are corresponding velocities for fracture when the concavity reaches the depth at which the tensile stresses that develop around it (either by themselves or when they are reinforced by the tension wave reflected from the reverse face of the plate) are sufficient to produce fracture.

Assumptions 1) and 2) are reasonable because, although microscopic plastic deformation at stress concentrations has been found to take place in white sapphire and ruby [4], in macroscopic terms these ceramics may be said to yield elastically until fracture occurs. The validity of assumption 3) is open to question. It depends on similarity considerations and, therefore, on the implication that concavities of equal depth produced by impingement of drops of different liquids are of similar shape. However, it may be sufficiently reliable for a rough estimate if the diameters of the drops and the viscosity and surface tension of the liquids that are used are not too widely different. Within the validity of the assumptions made, an equation from which extrapolated corresponding velocities for equal fracture of thin edge-supported ceramic plates by liquid-drop impingement can be calculated, has been developed as follows.

When a fast-moving target plate collides with a stationary liquid drop, a core of material through the target plate under the collision area is slowed down with respect to the remainder of the target plate as a result of the collision. As in a previous treatment [5], the situation is idealized in two ways. First, the core is regarded as a true cylinder that is free to move in the direction of the collision blow but is restrained laterally. A similar cylinder exists in the liquid of which the drop is composed. Secondly, the compressional waves that move through the cylinder in the target plate and through the cylinder in the drop are regarded as plane waves.

The depth,  $\zeta'$ , of the concavity that forms elastically in a ceramic target plate as a result of high-speed collision with a liquid drop is proportional both to the particle velocity,  $v'$ , produced in the core of target material under the contact area as a result of the collision, and to the time,  $t$ , that this particle velocity exists. Then,

$$\zeta' = k v' t \quad (1)$$

where  $k$  is a constant. It has been shown [6] that, for the case that the target plate collides with a liquid drop rather than with a solid sphere,

$$v' = \frac{\alpha z V}{z' + \alpha z} \quad (2)$$

where  $\alpha$  is a coefficient having a value less than one,  $V$  is the impingement velocity, and  $z = c/\rho$  where  $\rho$  is the density and  $c$  is the speed of irrotational waves in infinite medium. Primed quantities refer to the material of the solid target plate; unprimed quantities refer to the liquid of which the drop is composed. All quantities are in cgs units. It has also been shown [6] that

$$\alpha = 0.41/[1 + (0.59 z/z')]. \quad (3)$$

As before [5], the time  $t$  is the time required for the compressional wave initiated in the liquid of the drop to move through the drop, reflect as a tension wave from the free liquid-to-air interface, and return to the contact area between the drop and the target plate. Then,

$$t = 2 d/c \quad (4)$$

where  $d$  is the diameter of the drop.

By substituting eqs (2) and (4) into eq (1), the depth of concavity produced by collision of the target plate with a drop of liquid A is

$$\delta'_A = k \left( \frac{\alpha_A z_A V_A}{z' + \alpha_A z_A} \right) \left( \frac{2 d_A}{c_A} \right). \quad (5)$$

Similarly, for a drop of a liquid B,

$$\delta'_B = k \left( \frac{\alpha_B z_B V_B}{z' + \alpha_B z_B} \right) \left( \frac{2 d_B}{c_B} \right). \quad (6)$$

By equating eqs (5) and (6), it is found that

$$V_A = \left( \frac{\alpha_B z_B}{\alpha_A z_A} \right) \left( \frac{z' + \alpha_A z_A}{z' + \alpha_B z_B} \right) \left( \frac{c_A}{c_B} \right) \left( \frac{d_B}{d_A} \right) V_B \quad (7)$$

If the stresses that appear in the ceramic are proportional to the depth of the concavity that forms, then, by substituting into eq (7) the velocity known to produce any arbitrary amount of fracture on a brittle elastic solid by impingement of drops of a liquid B, the velocity required to produce the same amount of fracture on the same solid by impingement of drops of a liquid A can be calculated.

Let liquid A be water, liquid B be mercury, and the target plate be of white sapphire. From eq (3), and the data of Table 4, the coefficient  $\alpha$  for waterdrops impinging against white sapphire is 0.40, and the coefficient  $\alpha$  for mercury drops impinging against white sapphire is 0.32. Then, from eq (7) and the data of Table 4,

$$V_W = 9.6 \frac{d_M}{d_W} V_M, \quad (8)$$

where sub-W indicates water and sub-M indicates mercury. For the condition that the waterdrop and mercury drop have the same diameter,  $V_W = 9.6 V_M$ . It required an impingement velocity of  $3.514 \times 10^4$  cm/sec (1,153 ft/sec) to produce the damage seen in Figure 1 on a white sapphire target plate that was 0.318 cm (0.125 in.) thick by collision with a 0.2-cm mercury drop. From eq (8), a 0.2-cm waterdrop would have to collide with the same target plate at a velocity of

33.7 x 10<sup>4</sup> cm/sec (11,100 ft/sec) in order to produce the same amount of damage. Taking the speed of sound in air at 0° C and 1 atm pressure to be 3.317 x 10<sup>4</sup> cm/sec (1,088 ft/sec), the Mach Number equivalent is 10.

Table 4.  
Acoustic Impedance

Material	Density g/cm <sup>3</sup>	Sound Speed cm/sec	Acoustic Impedance g/(cm <sup>2</sup> , sec)
water	a/0.99707	b/1.497 x 10 <sup>5</sup>	0.1493 x 10 <sup>6</sup>
mercury	a/13.546	b/1.451 x 10 <sup>5</sup>	1.966 x 10 <sup>6</sup>
polyethylene	a/0.92	c/1.95 x 10 <sup>5</sup>	0.1794 x 10 <sup>6</sup>
white sapphire	d/3.98	f/11.00 x 10 <sup>5</sup>	4.378 x 10 <sup>6</sup>
hot-pressed alumina	e/3.95	f/11.00 x 10 <sup>5</sup>	4.345 x 10 <sup>6</sup>

a/ Data from Handbook of Chemistry and Physics

b/ Data from L. Bergmann, Der Ultraschall, S. Hirzel, Stuttgart, 1954

c/ Data from American Institute of Physics Handbook, 1958

d/ Data supplied by Linde Air Products Company

e/ Data supplied for H.P. Alundum by Norton Company

f/ Approximate average value supplied by Mr. John B. Wachtman, Jr., of NBS Engineering Ceramics Section

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Experimental verification of eq (7) is needed before corresponding velocities calculated by use of it can be relied upon. The only experimental data that are available to check eq (7) are those being obtained in a study currently in progress on the fracture of an unidentified polycrystalline

alumina by impingement of polyethylene pellets [7]. In this study, 12.7-cm (5-in.) square plates of 99+ percent pure polycrystalline alumina that are 0.635 cm (0.25 in.) thick are being used as targets for impingement of 0.5-cm polyethylene pellets that are fired at a constant velocity of  $23.5 \times 10^4$  cm/sec (7,700 ft/sec). The ceramic plates are maintained at a temperature of 1371° C (2500° F) during the firings. The angle at which the polyethylene pellets strike the target plates is increased until erosion, and finally breakage failure, occurs. The data available at present are that two plates have been tested to complete failure. Significant erosion was not noted until the impact angle was in each case 40°. One of the plates failed to the point of breakage at an impact angle of 40° and the other plate failed to the same extent at an impact angle of 60°. These impact angles were reported to correspond to normal velocities of  $14.9 \times 10^4$  cm/sec (4,900 ft/sec) and  $20.4 \times 10^4$  cm/sec (6,700 ft/sec), respectively [7].

Because the resistance of white sapphire and of hot-pressed alumina to mercury-drop impingement was found to be nearly the same, and because the more common, cream-white polycrystalline alumina is a ceramic of comparable strength properties, the reliability of eq (7) can be tested roughly by calculating the velocity required to damage white sapphire to the point of radial crack formation by impingement of a 0.5-cm polyethylene pellet.

By use of eq (3) and the data of Table 4, it is found that the coefficient  $\alpha$  for collision of a polyethylene pellet with a white sapphire plate is 0.40. By use of eq (7) and the data of Table 4, it is found that

$$V_P = 10.5 \frac{d_M}{d_P} V_M \quad (9)$$

where the sub-P notation indicates polyethylene. From Figure 4 it can be seen that radial fracture of a white sapphire target plate occurred as a result of impingement of a 0.2-cm mercury drop at a velocity of  $4.420 \times 10^4$  cm/sec (1,450 ft/sec). Using this velocity for  $V_M$ , 0.2 cm for  $d_M$ , and 0.5 cm for  $d_P$ , eq (9) predicts that an impingement velocity of  $18.6 \times 10^4$  cm/sec (6,090 ft/sec) would be required to produce the extent of fracture seen in Figure 4 with use of a 0.5-cm polyethylene pellet.

The velocity calculated by use of eq (9) is between the two values that have been found experimentally. However, the fact that the ceramic target plates were held at a temperature of 1371° C (2500° F) during the test firings, which may have affected their resistance, and the fact that the polyethylene pellets impinged at an angle, which should result in an unsymmetrical distribution of stress, raise questions that reduce the significance of this good agreement.

Jackman and Roberts [8] have found that the strength of polycrystalline alumina is not changed by an increase in temperature until the temperature reaches 700° C (1292° F). If the temperature is increased further there is a gradual decrease of strength with increase of temperature [8]. At 1300° C (2372° F) the strength is roughly one third of its room-temperature value [8]. The strength of white sapphire has a very different temperature dependence [4] [8]. It decreases with increase of temperature to a minimum in the range of 300 - 600° C (572 - 1112° F) and then increases with further increase in temperature until, at about 1000 - 1200° C (1832 - 2192° F), it is very close to its room-temperature value.

It is possible that, at the high rates of loading involved in the impingement tests, the temperature of the ceramic plates may not have an important effect on the velocity that an impinging pellet must have to break them<sup>4/</sup>. Both this effect and the effect of the angle at which the collision occurs need to be determined.

Until eq (7) is verified more conclusively with experimental evidence, corresponding velocities calculated by use of it should not be regarded as more than estimates.

## VI. Ultimate Failure

In order to extrapolate from the observed liquid-drop-impingement failure of white sapphire and hot-pressed alumina to what may be expected at higher collision velocities, it is useful to consider the failure of low-strength brittle solids, such as (poly)methylmethacrylate and (poly)styrene, under imposed stresses of the same kind.

Polygonal cracks have been observed in (poly)methylmethacrylate as a result of waterdrop impingement at a velocity of  $2.234 \times 10^4$  cm/sec (733 ft/sec) [9]. The

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<sup>4/</sup> I am indebted to Mr. J. B. Wachtman, Jr., of NBS Engineering Ceramics Section for this suggestion.  
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cracks were widened by breaking out of the surface material along them in a direction away from the central point of impact as a result of the radial flow of the water [9]. With respect to these features, the damage marks produced on low-strength (poly)methylmethacrylate by waterdrops impinging at a velocity of  $2.234 \times 10^4$  cm/sec (733 ft/sec) are similar to the damage marks produced on high-strength white sapphire by mercury drops impinging at a velocity of  $3.514 \times 10^4$  cm/sec (1,153 ft/sec).

The ultimate kind of failure that white sapphire will undergo may be predicted from the observed damage done to a 0.318-cm (0.125 in.)-thick plate of (poly)styrene that collided with a waterdrop at a velocity of  $7.666 \times 10^4$  cm/sec (2,515 ft/sec). A circular plug of (poly)styrene was cut out of the plate as a result of the collision. See Figure 11. It can be expected that similar damage will be done to white sapphire and to hot-pressed alumina as a result of collision with a waterdrop. The only difference will be that the collision velocity required to produce this degree of damage will be much higher for the high-strength ceramics than for the relatively weak (poly)styrene. Indeed, it has already been reported informally [7] that a plug has been cut out of a plate of polycrystalline alumina as a result of collision with a polyethylene pellet.

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FIGURE 11. (POLY)STYRENE TARGET PLATE THAT STRUCK WAX-BUDS AT A VELOCITY OF  $7.666 \times 10^4$  cm/sec (2.515 ft/sec)

The plug of (poly)styrene that was cut out of the target plate is also shown.

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1. Raindrops - Physical effects
2. Sapphire - Erosion
3. Alumina - Erosion
4. Ceramic materials - Erosion
5. High-speed impact - Erosion

Unclassified report  
 In collision with 0.2-cm mercury drops, the velocity at which damage was first observed was 1,153 ft/sec for 0.125-in.-thick plates of white sapphire and 1,403 ft/sec for 0.125-in.-thick

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AD- plates of hot-pressed alumina. The difference in the velocities found necessary to damage the two ceramics is not considered to be significant. The velocity required to damage these ceramics on collision with a waterdrop was not reached experimentally, but a theoretical extrapolation indicates that plates of these ceramics of the nominal thickness can be expected to survive collision with a 0.2-cm waterdrop without damage up to a velocity of 11,100 ft/sec. For air at 0°C and 1 atm pressure, this is equivalent to a Mach Number of 10.

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- I. Engel, Olive G.
- II. Wright Air Development Center
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