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THRESHOLD DAMAGE IN RADOME MATERIALS BY DISCRETE WATER IMPACT (BALLISTICS RANGE INVESTIGATION)

John L. Lankford, et al

Naval Ordnance Laboratory
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By
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Definite and repeatable thresholds of damage have been observed in slip-cast fuzed silica and other materials with variation in velocity of impact and drop size.

The results of this program indicate the continuing need for controlled discrete impact data of this type to supplement erosion data and to characterize damage in new materials. Results are presented for drop sizes of approximately 1mm and 2mm for a range of velocities from subsonic to 4,000 feet per second.

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NAVAL ORDNANCE LABORATORY
SILVER SPRING, MARYLAND

THRESHOLD DAMAGE IN RADOME MATERIALS BY DISCRETE WATER IMPACT (BALLISTICS RANGE INVESTIGATION)

The objective of this investigation was to demonstrate a valid technique for the study of threshold damage of materials by discrete impact and to present results on some representative materials. This report covers follow-on work during FY72-73. This work was conducted by the Missile Dynamics Division, Ballistics Department, of the Naval Ordnance Laboratory, Silver Spring, Maryland.

The program was supported by the Naval Ordnance Systems Command (ORD-035) under Task Area Number UF 32322503, Work Unit Number ORD 35A-002-201-32.

Ceramic and control materials have been supplied by the Engineering Experiment Station of Georgia Institute of Technology. The assistance of Professor J. D. Walton, Jr., Chief, High Temperature Materials Division, with materials characterization and evaluation is greatly appreciated.

NOTE: The mention of materials by brand names in this report is in no way to be considered as endorsement or criticism of them by the Government. The Government incurs no liability or obligation to any supplier of materials from the information included in this report.

ROBERT WILLIAMSON II
Captain, USN
Commander

A. E. Seigel
A. E. SEIGEL
By direction

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INTRODUCTION

The problem of high-velocity water impact damage has been under investigation for many years. As long ago as 1877, articles appeared in Proceedings of the Royal Society in England, discussing damage to low-pressure blades in steam turbines by water droplets in the wet steam.

Early investigations were carried out with water jet and wheel apparatus, cavitation "generators," and other means of providing damage environments.

In recent years, the problem has taken on additional importance because as flight speeds of missiles and aircraft increase, the damage to electronic windows, leading edges, and nose cone heat shields have become severe. The requirement for all weather capability in tactical aircraft and missiles dictates the need for solution of the problem of rain damage in critical components.

At very low impact velocities where the material is treated as a nondeforming solid and the fluid is treated as incompressible, results have been predicted successfully. Progress has also been made at very high velocities where the material can be evaluated by hydrodynamic methods, and relations between impacting energy and certain material properties can be made to correlate with material loss in some cases.

In the velocity range representing impacts from high subsonic velocities to about 3,000 feet per second, however, the material cannot be considered as a fluid nor can its deformation and interaction with the impacting drop be neglected or generally predicted. In this region, the need for controlled experimental data is particularly critical.

The Naval Ordnance Systems Command (ORD-035) has supported a joint effort at NOL and the High Temperature Materials Division at Georgia Institute of Technology to evaluate the effect of water drop impact in this critical range of velocities. Work has been completed on several control materials and on some characterized forms of slip-cast fuzed silica (SCFS), reference 1.

The present program was held to a modest effort by limitations of funding and available personnel. In order to properly attack the overall problem, a complete program appears to require the following phases.

1. Development and establishment of valid, controlled experimental techniques

2. Accumulation of basic data on control materials and new candidate materials

3. Development and improvement of simple but effective methods of damage evaluation

4. Correlation of damage characteristics with material properties for discrete impact

5. Comparison and correlation where possible with erosion and fatigue experiments

Reference 1 presents the results of preliminary efforts on phases one and two. The present report includes an extension of phases one and two and preliminary results on the phase three effort. Limitations on funding and temporary unavailability of personnel have precluded any appreciable effort on the last three phases.

This is unfortunate in the opinion of the authors and others working in this field (references 2 through 5), since many of the erosion and damage tests carried out on some materials are inconclusive or limited in value without complementary results on controlled discrete impact. A very large part of the effort expended on "erosion research" and testing has been spent to obtain empirical, relative numbers of merit that apply over limited ranges of parameters and fail to provide complete understanding of the "how" and "why" of developing rain resistant materials in the supersonic regime. The previous conclusion should not be treated as criticism of the satisfactory development of new coated and composite materials for subsonic applications.

The scope of the program results included in this paper is limited to normal impacts on disc-shaped specimens 1/2 inch in diameter and 1/2 inch thick. These were held in polyethylene sabots and fired into controlled water drop patterns. Details of the technique and the apparatus for 1.2mm drops will be found in reference 1. Impact was monitored photographically, and the specimen and sabot were nondestructively captured after impact. A schematic of the apparatus for normal impact at atmospheric pressure is shown in Figure 1.

The 1.2mm drops were highly spherical before the encounter with the shock wave, and distortions of the drop were observed when possible and predicted analytically. This evaluation is discussed in some detail in reference 1. Two typical phases of distortion and impact are indicated in the photographs of Figure 2.

The 2mm drops were more difficult to control, and initially, some of the drops were nonspherical. Distortion and stripping through the shock were less for this drop size, however, and no measurable effect on damage was observed due to the variation in original drop shape.

Effort is continuing on stabilization and definition of drop condition at impact with 2mm and larger drop sizes.

The use of other techniques for introduction of the drop (reference 4) can be substituted if necessary. Very well controlled and definitive experiments of discrete impact have been carried out on many materials by A. A. Fyall, et al, of R. A. E. (references 3, 4, and 5). That work has been limited in velocity for several reasons, and catching damage in some materials had begun to appear at upper velocities with that technique.

The technique presented here was developed to obtain information through a closely spaced range of velocities from subsonic up to the order of 3,000 feet per second in order to supply much-needed experimental data on several materials in that velocity range. Preliminary effort was directed toward establishing the effect of discrete impact under controlled conditions of drop size and velocity with the object of defining and presenting damage "thresholds" or characteristic damage patterns if such were found to exist. Preliminary work indicated that distinct patterns do exist and that initially these patterns and thresholds can be semi-quantitatively evaluated by simple low-magnification photographs. Preliminary observation was made of the material after impact with several lighting techniques. An example of this type of damage classification is shown in Figure 3 for impact of untreated SCFS by 1.2mm drops. More exact quantitative definition of the damage areas was investigated as indicated in Figure 4. The studies to establish simple, but effective means of quantitative damage measurement, were discontinued on this program due to program restrictions. These preliminary results are discussed later.

Typical results for untreated SCFS are presented in Figures 3, 4, and 5. This material was developed and characterized by Georgia Institute of Technology, references 1, 6, and 7. Three distinct thresholds were apparent. Early damage appeared as very small pits appearing at random locations within the impact area. This damage characteristic appeared to be somewhat dependent upon smoothness of original surface and variation in individual specimens (see Figure 4). The general data were well ordered and consistent, however, when consideration of experimental scatter and repeatability was taken into account. The results can be summarized in a plot such as Figure 5. Here the damage characteristics or regimes are indicated as influenced by velocity and drop size, while the thresholds as influenced by individual specimen and experimental scatter are shown as bands between areas of different damage characteristics. The trends indicated in Figure 5 were repeated for several series of specimens and included samples from three lots of material. The total number of specimens fired at each condition is not sufficient for meaningful statistical evaluation, however, and additional firings would be necessary to provide statistical data for this material. The data repeat well enough, however, within the limits shown in Figure 5, to be considered significant and representative. In one or two cases at each drop size, a ringed crater formation did appear at lower velocities than indicated in Figure 5. The infrequency of this result and the fact that it was not repeated when additional shots were made under the same conditions led to the preliminary conclusion that a particularly weak spot in the material was the reason for such inconsistency.

SUMMARY, UNTREATED SCFS

The 1.2mm drop size in untreated SCFS indicated no visible damage below approximately 1,300 feet per second while some pitting always appeared above 1,500 feet per second. As velocity was increased with the 1.2mm drops, pitting became heavier and more general over the impact area. Above approximately 2,100 feet per second, definite craters appeared over the extent of the impact area (~1mm in diameter). The floors of these craters were irregular or generally flat in contour. With the exceptions noted, above approximately 2,600 feet per second, the craters always showed a ringed depression around their periphery with a hump or raised section in the center. The general nature of these damaged characteristics is indicated in Figures 3, 4, and 5.

The preliminary results with 2mm drops were similar to those for the smaller drops in that the same sequence and type of damage patterns appeared. A definite effect of drop size is apparent, however, since all thresholds appeared at lower velocities with the larger drops. This support results from several experiments, indicating that damage increases with drop diameter at a given velocity beyond the simple increase in impact area.

More thorough and detailed quantitative measurements in the damage areas should provide valuable data for correlation and analysis. The visual damage thresholds and characteristics defined by preliminary results already indicate that data of the type indicated in Figure 5 should precede and complement erosion testing and evaluation of brittle materials in the velocity range covered by this investigation. Variations in velocity and nonuniformity in simulated rain fields could exceed thresholds in ceramic materials and cause failure or damage by discrete impact that cannot be readily understood or explained in terms of "average" or mean erosion rate. The need for experimental data on discrete impact under controlled conditions is also apparent even for some materials that will also be studied in an erosion or fatigue environment.

TREATED SCFS

The results to be discussed for slip-cast fuzed silica, soak impregnated with a silicon varnish (SR80), are interesting enough to warrant mention. Characterization of major materials is listed in Appendix A. The caution is made, however, that these results are for a very limited number of shots with one lot of material and should be treated as tentative. The purpose of soak impregnating the SCFS was to improve resistance to moisture absorption, but preliminary results indicate that impact resistance is also affected.

The number of specimens was limited in the FY72 program, and only a few firings with 1.2mm drops for preliminary data and trial shots with 2mm drops were conducted.

Figure 6 indicates the lower threshold or pitting damage in the treated or impregnated material. Comparison with Figure 4 indicates that the incipient damage threshold appears to be raised of the order of 500 to 1,000 feet per second by the treatment. The material lots were different in these cases and the possibility of differences in material strength cannot be discounted until more firings are completed on the same material lot. There does seem to be an increase in impact resistance in the treated specimens, however. It is important to mention that the material did not appear to accept or retain the impregnant uniformly over its entire surface. The areas of deeper or more dense impregnation appeared more resistant than those more lightly impregnated. This resulted in a wider threshold "belt" or more scatter in defining damage characteristics. All of the few specimens fired at both drop sizes did show the increased resistance to damage, however.

SILICON NITRIDE

Preliminary results were also obtained on silicon nitride specimens (see Appendix A for characterization data). The number of specimens was again limited for the FY72 investigation, and results should be treated as tentative.

The catching technique was extended to higher velocities to handle the silicon nitride investigation. The improvements in the catcher are discussed later in this report.

In brief, for the few specimens investigated, no apparent damage was experienced until velocities of the order of 2,000 feet per second with 2.2mm drops were encountered.

Above 2,000 feet per second, pitting began to appear near the outer edges of the impact area. The depth, rather than the number of pits, seems to increase most rapidly with increase in velocity. The impact appears to remove the softer or less resistant material, leaving the harder sections until they are insufficiently supported or are loosened in catching.

Impressive velocities are reached with 2.2mm drops (above 3,500 feet per second) before appreciable cratering and gross material loss are encountered.

Catching tests with no water impact at velocities as high as 4,000 feet per second indicated no apparent effect of catching on the undamaged specimen.

CGW CODE #7940

A few samples of Corning Vitreous Silica, designated as "CGW Code #7940," materials were investigated with water drops of approximately 2.2mm diameter. The limited number of samples investigated were supplied by the Raytheon Corporation (Appendix A) through the Georgia Institute of Technology. The results discussed are preliminary and tentative, based upon the small sampling.

No apparent damage was observed up to approximately 1,000 feet per second. In this range of velocities and above, brittle fracture and some evidence of subsurface cracking appear. At approximately 1,500 feet per second, additional fracture outside the impact area is noted. As velocities are increased beyond 1,500 feet per second, the material starts to shatter and large-scale failure upon catching results.

RAYCERAM III

Another material supplied by Raytheon Corporation through Georgia Institute of Technology was Rayceram III (Appendix A). The same limitations apply to the preliminary results as on the other investigations with limited samples.

The Rayceram, another glass-like material, was more resistant to impact with drops of approximately 2.35mm than the code #7940 material. At approximately 2,500 feet per second, however, light annular cracks appeared. Increasing velocities to about 3,000 feet per second showed increased damage in the form of radial cracks. The cracks appear to extend down into the material well below the surface. A further increase in velocity brings large-scale cracking and fracture. Some fractures extend to 50 percent of the specimen depth (>1/4 inch). Damage extends well outside the impact area.

Undamaged specimens caught at over 4,000 feet per second show no apparent damage due to the catching process.

EXTENDED CATCHING CAPABILITIES

The basic catching technique using flexible polyurethane foam was developed as described in reference 1. The technique used initially employed slabs or sheets of foam and was satisfactory for a variety of materials up to velocities above 3,000 feet per second.

To improve the mechanism of decelerating the model-sabot combination and increase the capabilities of this method to higher velocities, several modifications were investigated. The one found most effective was to increase the catching length and combine the slab foam material with shredded or chopped material. This was satisfactory in providing an improved deceleration and extended capability to well over 4,000 feet per second for materials such as vitreous ceramics, cast silicas, and nitrides. The effectiveness of the catching technique was demonstrated by firing undamaged specimens without impacting a water drop, catching the specimen, and subjecting the captured specimen to detailed examination. The performance of the catcher was considered acceptable if no damage could be detected.

In materials where softening due to aerodynamic heating or impact and in shattered or deeply cracked specimens, there will obviously be rearrangement and damage upon catching. In these cases, the technique can probably be extended by proper design of sabot or protective measures for the specimen. No attempt was made to carry out this further development in this program, since the technique as used appeared adequate for the materials investigated. A sketch of the catcher is shown in Figure 7. The voids were incorporated into the design to facilitate "finding" the captured specimen after firing. Tracing techniques and other methods proved too cumbersome or time-consuming and the use of open sections or voids was adopted.

The previous text summarizes the work completed in FY72 on the basic program. This work comprised effort on the first two phases of what might be considered as a five-phase program.

Limited effort in several other areas was supported by in-house funding in order to obtain some additional information not in the basic program task and in order to keep the program active when the basic tasks were delayed, awaiting characterization or manufacture of material lots.

A few of the preliminary results of these in-house efforts are presented in the following pages, since they appear of sufficient general interest to impact and erosion investigators.

SIMPLE METHODS OF QUANTITATIVE DAMAGE EVALUATION

The major task in the original program was to investigate for definite visual damage patterns and thresholds in slip-cast fuzed silica materials. This effort disclosed the definite and repeatable patterns and thresholds indicated in Figure 5. In a complete program, as outlined earlier, and for materials that do not display the definitive visual thresholds of SCFS, a more thorough quantitative evaluation of damage areas is required. Elaborate techniques are certainly justified to scientifically evaluate material damage. The two simple and unsophisticated methods to be discussed here are presented only because of their ease of application and for their possible value for interim or screening evaluations.

The use of standard roughness profilometers and surface measurement instrumentation found in many laboratories can be applied to the evaluation of pitting and surface roughening as indicated in Figures 4 and 6. The profilometer is also directly applicable to surface deformation evaluation as indicated in Figure 8.

The evaluation of larger scale surface damage and crater characterization can be economically and quickly measured when scanning microscopes or computerized densitometers are not available by the method illustrated in Figures 9 and 10.

In this technique, a high stability molding compound can be used to take male impression models of the crater or damage area. These molds, after curing, can be cut into thin sections and a standard type shop comparator used to make tracings or photographs to the appropriate magnification. The material used for the moldings shown was G. E. Dimethyl RTV-41, a silicon rubber molding compound. Linear shrinkage in these materials can be kept to ~.2 - .5 percent, and, therefore, accurate data on crater shape and volume are easily obtainable.

A need for evaluation of subsurface damage, cracking, and other modes of failure in some materials is obviously of importance. These measurements (except for visual evaluation by special lighting) were beyond the scope of the present program.

RESULTS OF PRELIMINARY IN-HOUSE STUDIES

In addition to the main task reported in the preceding pages, impact with glass spheres, lead spheres, and water encapsulated with wax were carried out on a limited scale.

There appears to be no satisfactory substitute at this state-of-the-art for actual impact of the water drop with the material of interest under exact velocity conditions (references 2-5).

It will be useful for rough engineering tests and for material screening evaluations, however, if a solid can be substituted for water to provide a simple means of studying relative erosion resistance of materials.

Several investigators have studied the impact of substitute materials on control specimens and compared them with water (e.g., Fyall's work, references 3, 4, and 5). Although attempts have been made to match density, mass, and/or size of impacting particle with the properties of a water drop, no really satisfactory correlation has been found.

The preliminary work with lead in Plexiglas and other materials was reported in reference 1. Work with lead on Plexiglas was not continued in the present effort because it appears that for quick comparisons for screening or material testing, the valid comparisons for lead impact may come in comparing lead impact at low velocities

(~500 feet per second) with water at much higher velocities (2,000 - 3,000 feet per second). The comparisons with a material like Plexiglas have little meaning, since damage with Plexiglas at these upper velocities is so great as to be of little value for design evaluations.

In order to carry out more valid studies, it is suggested that another control material suitable for higher velocity impact be selected. It may be necessary to also employ existing techniques for heating the models before flight or aerodynamically in order to assess the water impact on the heated surface for valid comparison.

The damage in water droplet impact appears to result from the pressure built up within the materials and the deforming drop in the period just after impact. The deformation history of the impacting droplet and shock wave pressures resulting all play important roles in the damage mechanism.

The pressure in a simple case can be expressed in terms of shock wave velocity relationships. A typical approximation after Heyman (reference 4) is given below.

$$P = \rho_o C_o V \left(1 + K \frac{V}{C_o}\right)$$

where

P = pressure generated at impact

ρ_o = density of undisturbed liquid

V = particle velocity

C_o = acoustic velocity of the undisturbed liquid

k = for water, the value is taken as 2.0

This simplification is based upon assumption of a rigid target, a relationship of shock to particle velocity, and other restrictions. In the actual case where the target material is not rigid and mutual interaction of impacting drop and target takes place, no completely successful approximation is available. Peak pressures and damage mechanism during impact are not fully predictable at this time.

In the work done by Fyall and others, the failure of the substances substituted appeared to be due to two major characteristics. The materials were either too elastic in nature and deformed readily, but not in the same manner as the water drop, or the materials were relatively rigid and did not show deformation and splashing characteristics even remotely similar to water. Water encapsulated in wax has often been suggested as a substitute material for investigation.

The problem anticipated with the wax-water capsules was that they also would not deform or splash with the same characteristics as water. It was felt, however, since they offered possibilities not found with some of the other materials, it would be of value to observe their impact through a range of velocities on a control material such as Plexiglas.

The capsules of interest for this investigation were the 1mm-diameter size.

The first series supplied as samples by the 3M Company, Paper Product Division, was not used immediately and had lost most of its liquid content during storage. A second series was contributed by 3M, and because of the problem of water loss, the following procedure was established to select samples for firing.

Capsules soaked in a pure alcoholic solution appeared to show no evidence of softening or deterioration. Therefore, capsules were first graded for sphericity and size, and selected specimens were placed in a 100 percent alcoholic solution to which water was added in 1mm steps. Time was allowed for settling after stirring, and entrapped air was removed.

Some of the capsules sank to different depths and others rose to the surface. It was found that all of the second series would float in a solution ~.973 specific gravity.

The control finally established was to eliminate all capsules that floated in a solution of 33 percent alcohol (S.G. ~ .956) and to use capsules that would sink in this solution. Approximately eight percent of the capsules screened were discarded by this method of selection.

Using capsules selected for sphericity, size, and density as outlined above, Plexiglas material samples were placed in sabots and fired at several velocities to impact individual capsules held on supporting filaments of Duco cement using the techniques for solid impacts described in references 1 and 8.

The general characteristics of the impact site are the same at lower velocities as those found with several materials. A permanent deformation of the Plexiglas surface is formed consisting of a central plateau surrounded by a depressed annular ring (see Figure 11a).

The wax-water capsules that were empty or not properly filled always formed a much smaller diameter indentation and plateau than the filled capsules.

Fyall, references 4 and 5, has studied the impact of water in wax on Plexiglas with 2.5mm pellets at about 1,000 per second.

At this velocity, he finds the plan view characteristics (looking at the face of the specimen) of the impact sites similar to those for water, but the depth and volume of the impressions for water in wax are only about one-half the values of those for water.

Preliminary results at NOL are presented using only plan view comparisons and are limited by the scatter obtained with the wax-water capsules.

A large variation in damage site diameters was experienced with the 1mm pellets at similar firing conditions. This may be a result of variations in water content since it appears that a 20 to 30 percent variation could still occur with the preliminary screening method used. Based upon this, the results discussed here are limited to the larger impact sites for water in wax, since they were predominant for screened pellets and appear to represent more reasonable results for this investigation.

In spite of the limitations just discussed for the present data, two major differences appear in the plan view of the higher velocity sites for the water compared to the water in wax.

In the range from 1,200 to 1,600 feet per second, the damage appears similar to the previous sketch, but diameter of the damage site is greater for the water impact (~1mm ring for water, ~1/2mm for water in wax).

In the velocity range from 1,600 to 2,200 feet per second, the damage site appears to go through a significant transition for water impact. The characteristic ring depression no longer appears, but significant cracking (probably subsurface) appears with occasional small dents or depressions on the surface. This is indicated in Figure 11b. The depth and characteristics of the subsurface cracks are approximated since the method of examination used in preliminary evaluations does not define them accurately.

The diameter of the cracked regions at the higher velocities appears slightly smaller in diameter in some cases than the depressed rings at velocities just below the transition value.

The damage sites with water in wax do not appear to go through this transition for the velocities investigated. The ringed depressions and plateau damage site continue to appear with velocities above 2,000 feet per second.

At the present state of knowledge of water impact, the use of substances other than water for study of the damage mechanism has very limited applications.

Damage sites with some materials of the many investigated do show similarity to water impact sites. These characteristics could be of value at some velocities for relative ranking of materials.

Data from materials investigated at lower velocities (~1,000 feet per second) indicate that polytetrafluoroethylene (PTFE), water in wax, and lead show some characteristic impact sites similar to water impact. It appears that solid paraffin wax might fall into roughly the same category as the water in wax capsules, but the problem of smearing and deposition found with most substitute solids will be noticeably present with wax.

No significant conclusions can be drawn from the limited data at higher velocities except that substances other than water appear to have only limited applications. The experimental difficulties encountered with water in wax appear to greatly outweigh some of the original advantages anticipated for this substitute.

Several photographs illustrating results with several materials are presented in Figures 11c through 14.

SUMMARY AND RECOMMENDATIONS

The complex problem of rain erosion and water-impact damage is still not completely understood in spite of impressive progress in theoretical and experimental approaches to the problem.

No single technique or facility has provided the information necessary to fully describe the complete mechanism over a range of conditions for every material.

It has also been demonstrated that the thresholds of damage in erosion of most homogeneous materials and some others are not necessarily the same as the thresholds of damage indicated by discrete impact. This is the result of the incubation period and the fatigue mechanisms of the erosion process. Nevertheless, it has also been clearly demonstrated that there are definite thresholds of damage defined by discrete impact, particularly in brittle materials. Knowledge of these thresholds and the conditions that cause them to appear is invaluable in understanding the failure mechanism in some materials and in interpreting certain types of erosion and multiple-impact data.

The data showing dependence upon drop size that has been shown by discrete impact provide a definite upper guideline for flight velocities where large raindrops can be encountered. Extrapolation of erosion data using nominal or mean rainfall parameters is not dependable for some brittle materials since such an extrapolation may traverse a discontinuous failure threshold. The present program has been of limited scope, but has contributed to the first three phases of a five-phase approach that appears necessary before a thorough understanding of water-impact damage can be reached.

1. Development of controlled experimental techniques

2. Accumulation of accurate and controlled data on new materials and control specimens

3. Development of simple but dependable methods of damage evaluation

4. Correlation of damage characteristics with material properties

5. Comparison with theories and correlation where possible of discrete impact and erosion results

More effort on phases three, four, and five is needed for the data already obtained. The extension of one and two to include heated materials and angled impact is also indicated.

The need for simple screening techniques is still a requirement for test laboratories and design procedures. Continued effort to find "shotgun" methods or quick simulations for screening out bad material lots or rough evaluation of design configurations is indicated.

In summary, the technique of discrete impact with controlled water drops over a closely spaced range of flight velocities in a ballistics range has provided valuable basic data on damage characteristics in various materials. The technique has proven valid over a continuous range of velocities from subsonic to over 4,000 feet per second. The capability thus far has been accomplished with relatively economical and simple experimental techniques. Extension of the ballistic approach to heated materials, angled impact, and higher velocities has been shown to be feasible in preliminary investigations. The cost and complexity of extended capability will be greater than the work reported here.

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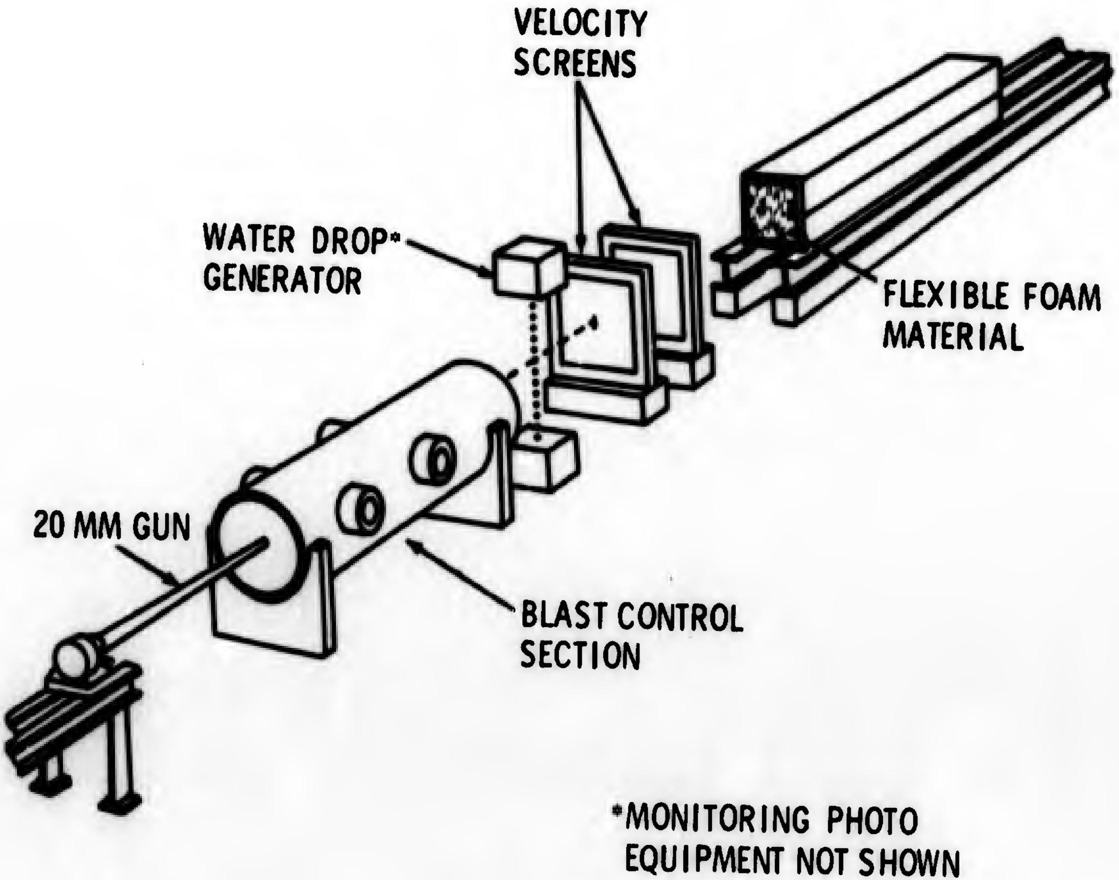
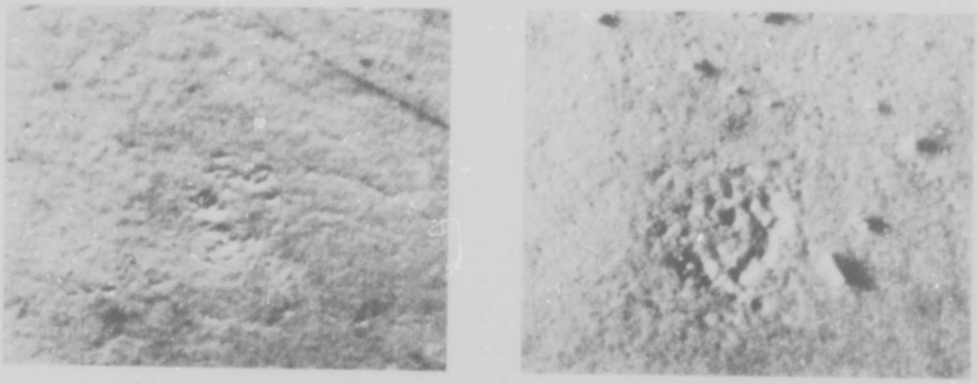


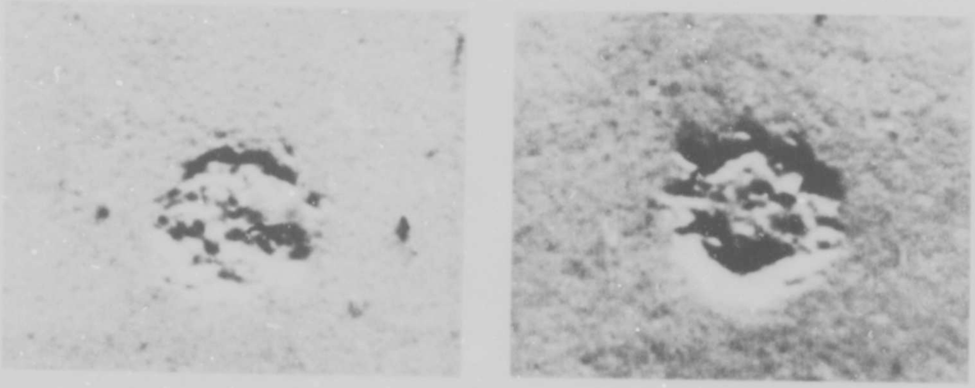
FIG. 1 EXPERIMENTAL APPARATUS FOR DISCRETE IMPACT STUDIES (ATMOSPHERIC TEST)

FIG. 2 DROP IMPACT PHOTOGRAPHS



LIGHT PITTING

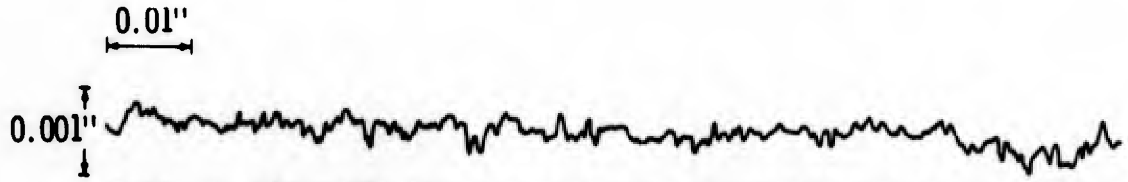
MODERATE PITTING



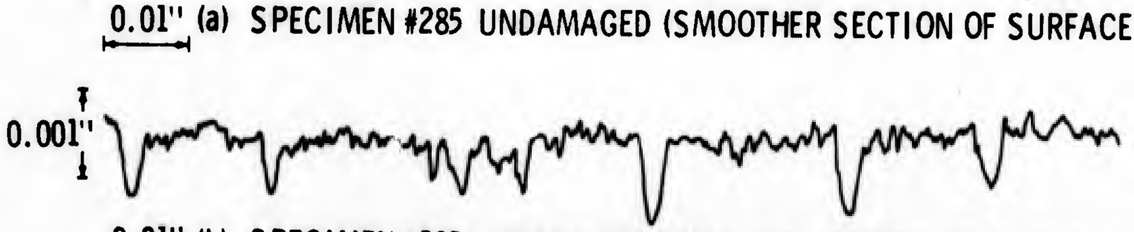
IRREGULAR CRATER

RINGED CRATER

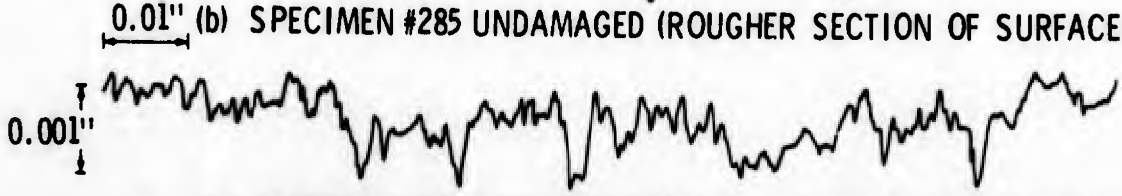
FIG. 3 CHARACTERISTIC DAMAGE IN UNTREATED SCFS (1.2MM DROPS)



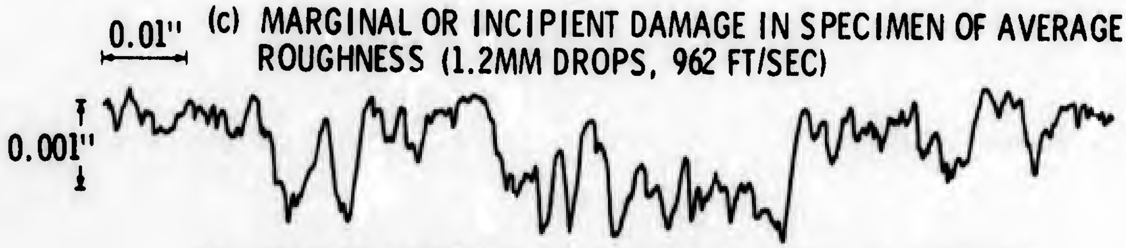
(a) SPECIMEN #285 UNDAMAGED (SMOOTHER SECTION OF SURFACE)



(b) SPECIMEN #285 UNDAMAGED (ROUGHER SECTION OF SURFACE)



(c) MARGINAL OR INCIPIENT DAMAGE IN SPECIMEN OF AVERAGE ROUGHNESS (1.2MM DROPS, 962 FT/SEC)



(d) LIGHT TO MODERATE PITTING IN SPECIMEN OF AVERAGE ROUGHNESS (1.2MM DROPS 1450 FT/SEC)

FIG. 4 SURFACE PROFILES IN SLIP CAST FUSED SILICA
(UNTREATED MATERIAL - VARIATIONS IN ORIGINAL SURFACES COMPARED WITH INCIPIENT DAMAGE)

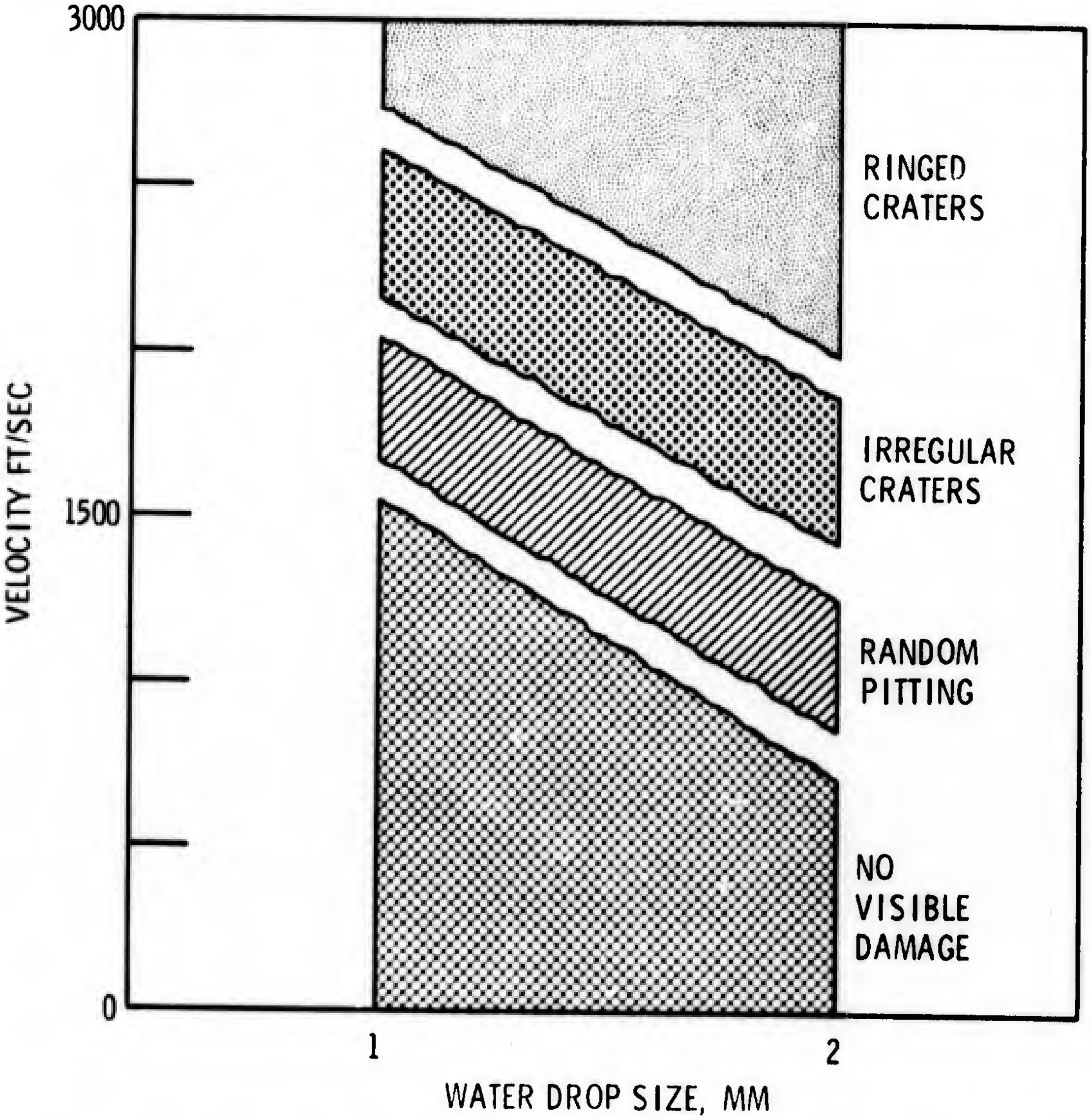
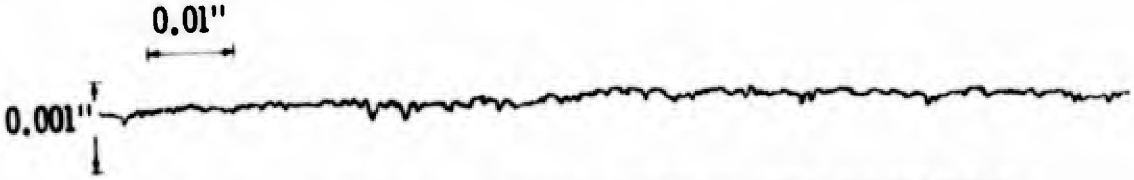
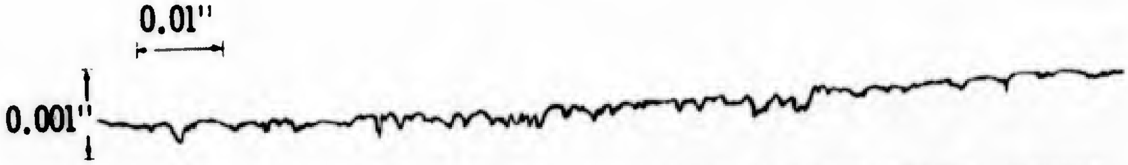


FIG. 5 DAMAGE THRESHOLDS IN UNTREATED SCFS



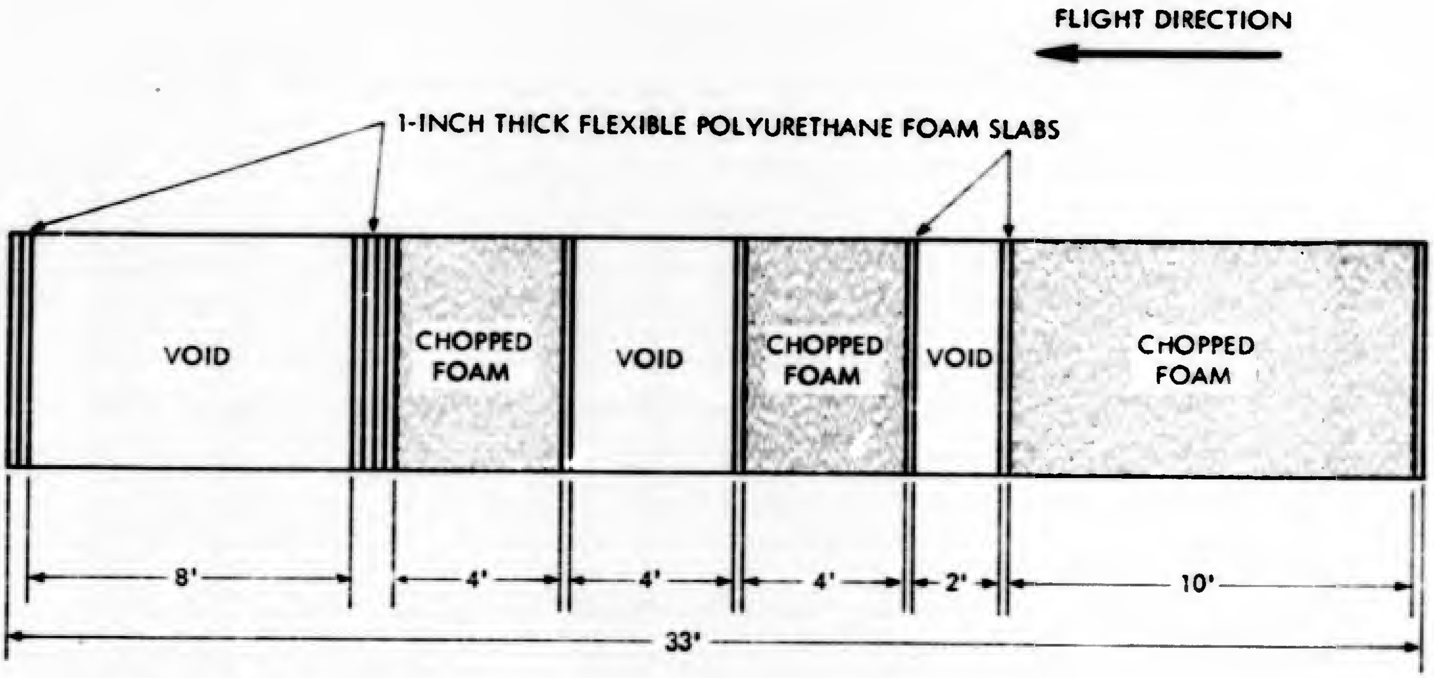
(a) SPECIMEN #12 UNDAMAGED MATERIAL (TREATED MATERIAL)



(b) SPECIMEN #349 ROUGHENING TO LIGHT PITTING (1.2 MM DROPS, APPROX. 2000 FT/SEC) (TREATED MATERIAL)

(c) SPECIMEN #348 LIGHT PITTING (1.2 MM DROPS, APPROX. 2000 FT/SEC) (TREATED MATERIAL)

FIG.6 SURFACE PROFILES IN SLIP CAST FUSED SILICA (INCIPIENT DAMAGE, TREATED MATERIAL)



CROSS SECTION 24" X 24"

FIG. 7 EXTENDED CATCHER FOR HIGHER VELOCITY INVESTIGATION

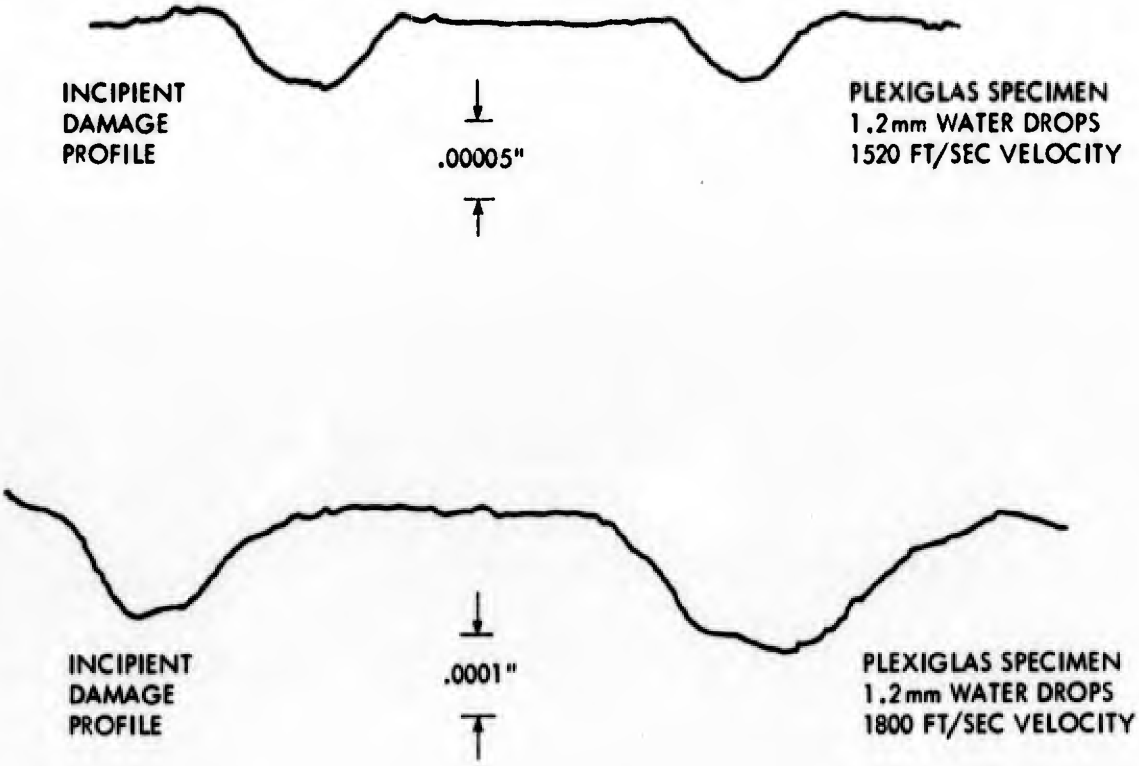


FIG. 8 PROFILES OF SURFACE DEFORMATION USING A ROUGHNESS PROFILOMETER

MAGNIFICATION APPROXIMATELY 50 X

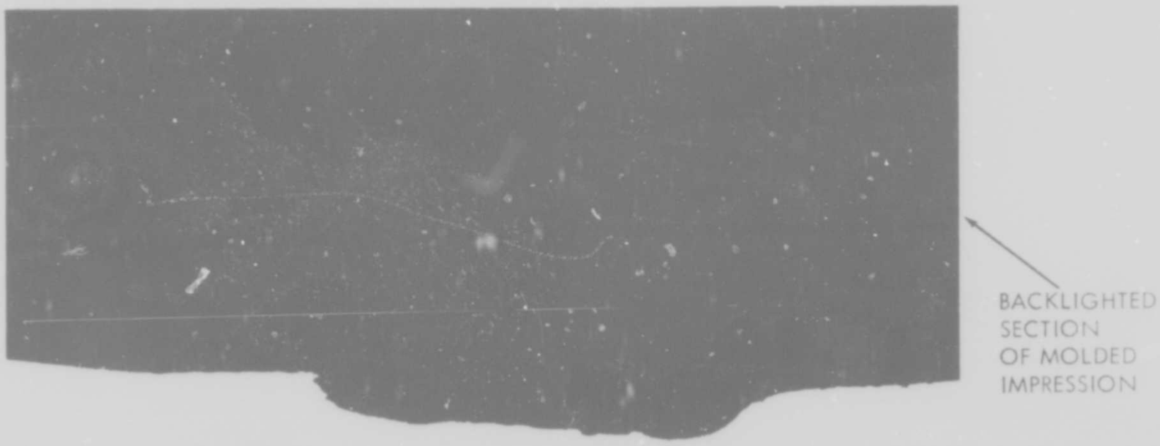


FIG. 9 PROFILE OF CRATER IN SABOT–MOLDED IMPRESSION TECHNIQUE

MAGNIFICATION APPROXIMATELY 50 X

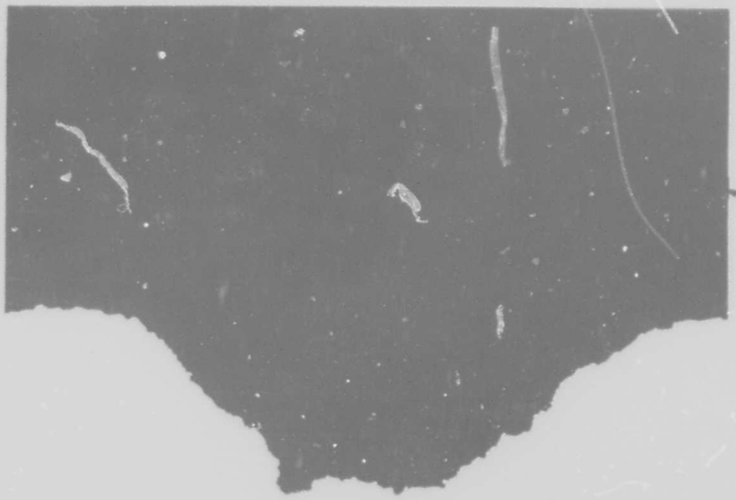


FIG. 10 PROFILE OF DEEP CRATER IN CARBON MATERIAL–MOLDED IMPRESSION TECHNIQUE

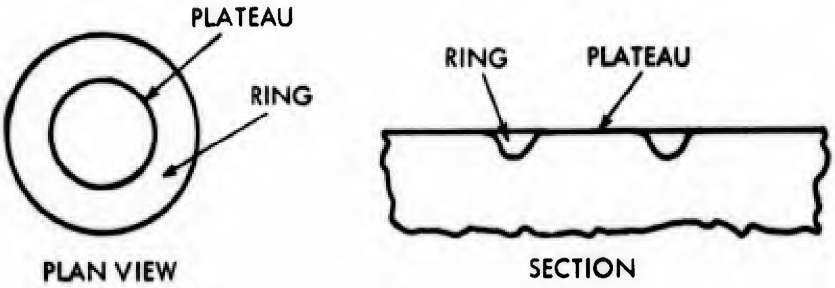


FIG. 11a WATER IMPACT, PLEXIGLAS, VELOCITY <1500 FT/SEC

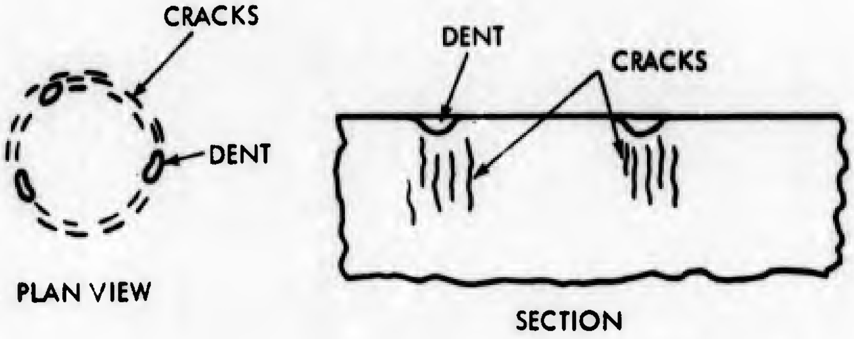
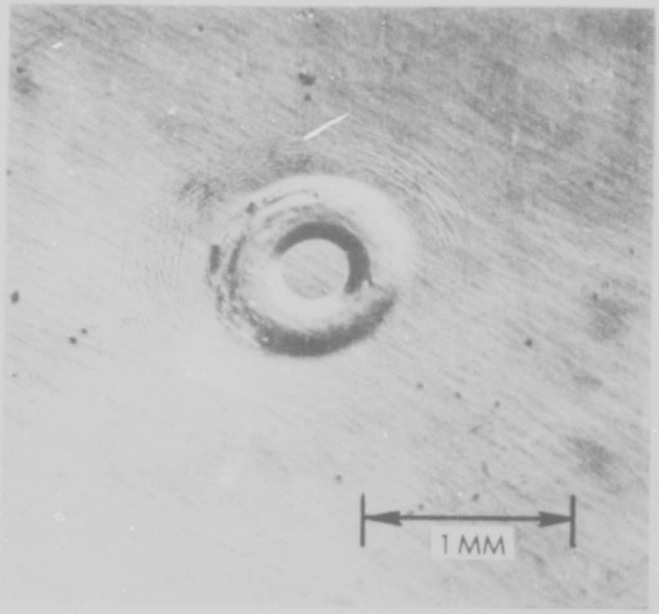


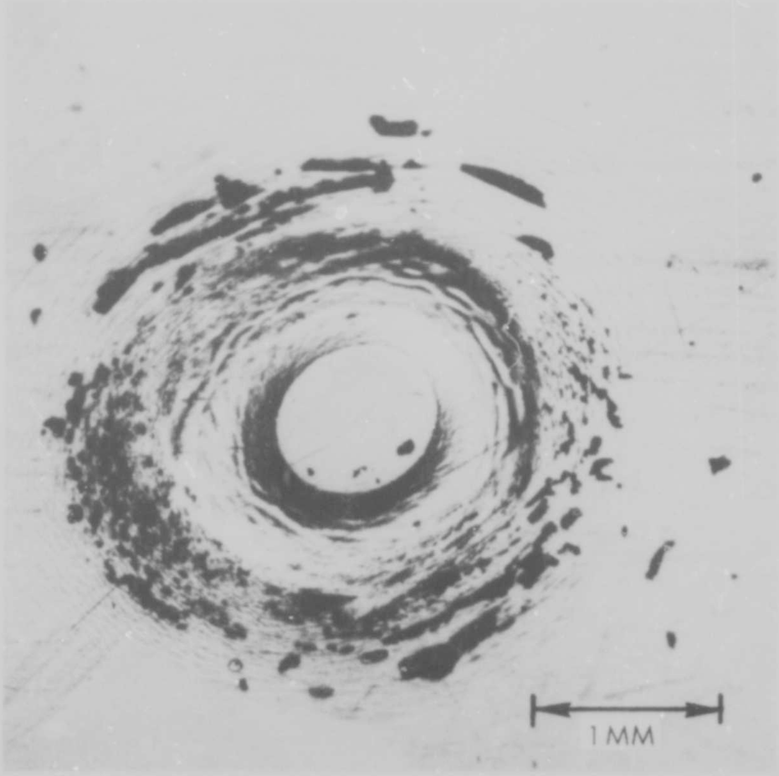
FIG. 11b WATER IMPACT, PLEXIGLAS, 1600 - 2500 FT/SEC



SHOT 295

NOTE: CRACKING OUTSIDE IMPACT SITE
NON CIRCULAR APPEARANCE IS
DUE TO LIGHTING EFFECTS

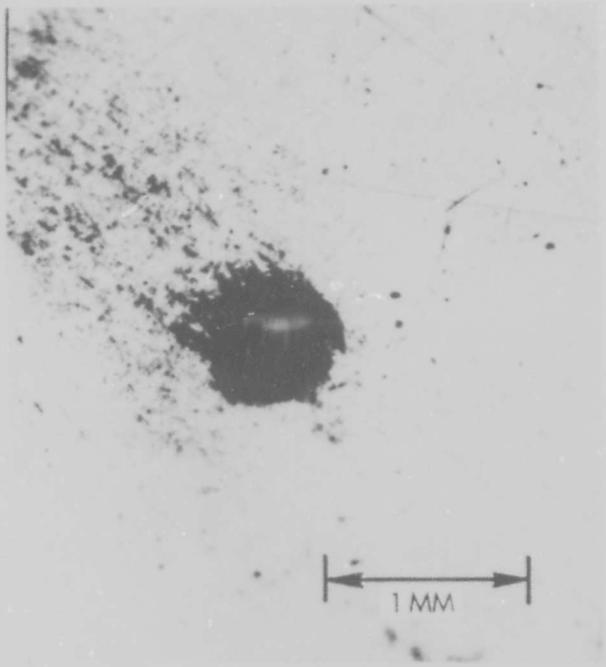
FIG. 11c PLEXIGLAS IMPACTED BY 1MM WATER DROP -976 FT/SEC



SHOT 286

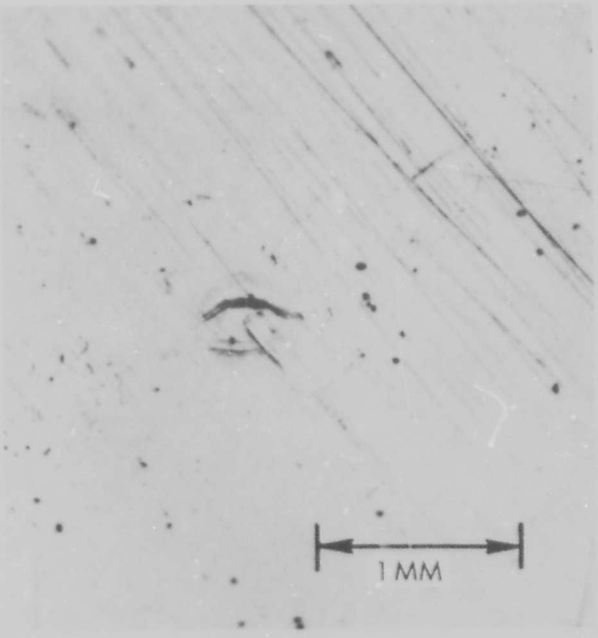
NOTE: CRACKING OUTSIDE IMPACT SITE

FIG. 12 PLEXIGLAS IMPACTED BY 2MM WATER DROP - 1000 FT/SEC [EST]



SHOT 299

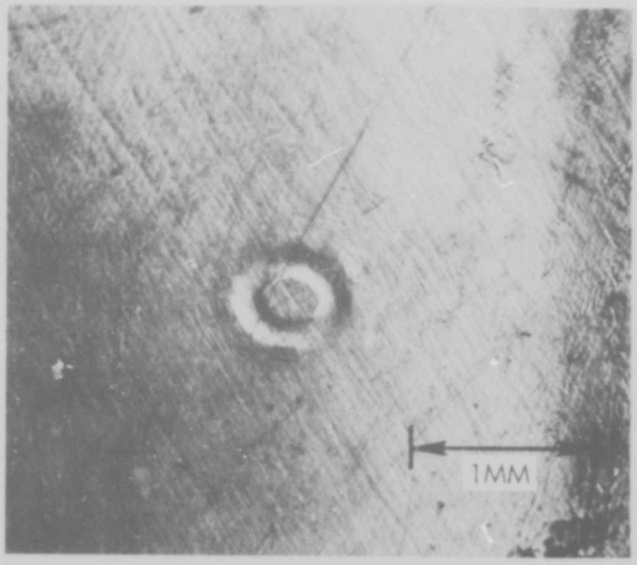
NOTE: WAX DEPOSIT



SHOT 299

NOTE: WAX REMOVED. IMPRESSION NOT
SIMILAR TO PURE WATER IMPACTS

FIG. 13 WATER IN WAX PELLET IMPACT ON PLEXIGLAS - 1MM PELLET - 875 FT/SEC



SHOT 301

NOTE: IMPRESSION SHOWS SOME CHARACTERISTICS
OF WATER IMPACT AT LOWER VELOCITIES
SMALLER IMPACT AREA NO EVIDENCE OF
CRACKING

FIG. 14 WATER IN WAX PELLET IMPACT ON PLEXIGLAS - 1 MM PELLET - 1135 FT/SEC

APPENDIX A

CHARACTERIZATION OF MATERIALS

Data on initial slip-cast fuzed silica material lots are listed in Appendix C of reference 1.

Materials were supplied by the High Temperature Materials Division of the Georgia Institute of Technology Engineering Experiment Station. Mr. J. N. Harris, Head of the Processes and Fabrication Branch, has supplied the materials and characterizations.

The SCFS were shipped from Georgia Institute of Technology on 12 and 24 November 1971.

Mean particle size: fuzed silica slip, 9m

Density, fired samples: 1.90 gm/cc

Modulus of rupture: 4,878 ± 201 psi

Elastic modulus: $5.1 \pm 0.05 \times 10^6$ psi

The data and specifications (Tables A-1 and A-2) were supplied by the Missile Systems Division of the Raytheon Company, Bedford, Massachusetts.

TABLE A-1

RAIN EROSION SAMPLES

Bulk Density

Sample Number	Material Rayceram III	ISCFS*	CGW #7940	Si_3N_4
1	2.47	2.00	2.20	2.69
2	2.47	2.00	2.20	2.64
3	2.47	2.00	2.20	2.63
4	2.47	2.00	2.20	2.70
5	2.48	2.01	2.20	2.69
6	2.49	1.99	2.20	2.65
7	2.49	2.00	2.20	2.68
8	2.48	1.99	2.20	2.64
9	2.48	1.99	2.20	2.68
10	2.48	2.00	2.20	2.62
11	2.48	2.00	2.20	2.66
12	2.48	2.00	2.20	2.69
13	2.48	2.00	2.20	2.67
14	2.49	2.00	2.20	2.69
15	2.49	2.00	2.20	2.62

*Apparent bulk density of impregnated samples

TABLE A-2

TYPICAL CERAMIC PROPERTIES

Property	Rayceram III SCD 10267397	SCFS (Note 2) SCD 10260604	Corning 7940 Handbook Data	Raytheon Silicon Nitride Pressed & Sintered Note 1
Density	2.47 g/cc	1.96 g/cc	2.20 g/cc	2.63 g/cc
MOR	17,500 psi	4,400 psi	7,160 psi	30,000 psi
Young's Modulus	17.8×10^6 psi	5.3×10^6 psi	10.5×10^6 psi	15×10^6 psi
Poisson's Ratio	0.27	0.15	0.168	0.26
Thermal Expansion	2.0/°C	0.55/°C	0.56/°C	2.5/°C
Thermal Conductivity	0.007 cgs	0.002 cgs	0.003 cgs	0.015 cgs
Specific Heat	0.255 cal/g-°C	0.223 cal/g-°C	0.17 cal/g-°C	0.17 cal/g-°C
Dielectric Constant	4.83	3.27	3.85	5.5
Loss Tangent	0.002	0.0016	0.00002	0.002

Note 1: Properties of Raytheon Silicon Nitride are estimated properties at a bulk density of 2.65, based on property value determinations at a bulk density of 2.30.

Note 2: Data for unimpregnated SCFS.