THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING

Department of Nuclear Engineering
Laboratory for Fluid Flow and Heat Transport Phenomea

Technical Report No. 08153-3-T

LABORATORY SCALE DEVICES FOR RAIN EROSION SIMULATION

F. G. Hammitt
J. F. Lafferty
R. Cheesewright
M. T. Pitek
D. J. Kemppainen
T. M. Mitchell

For Presentation at the Second Meersburg Conference
on
"Rain Erosion and Associated Phenomena"
August 22-25, 1967
Meersburg, Federal German Republic

Financial Support Provided by:

U. S. Naval Air Development Center
Contract N62269-3745

Administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR, MICHIGAN

March 1967

TABLE OF CONTENTS

Page

LIST OF FIGURES

I. INTRODUCTION

The testing of materials to determine their resistance to rain-erosion has involved to date large, expensive, and cumbersome pieces of equipment such as rocket sleds and, high-speed whirling arms. Hence a simple, reliable, inexpensive, laboratory-scale device capable of producing realistic results for the preliminary screening of materials of interest, and also of allowing the study of the details of the damage mechanisms would be highly desirable. In order to develop and perfect such a device our laboratory has been investigating the various possible systems, and conducting preliminary tests to compare the results obtained with test results from the more conventional large-scale devices. We are also attempting to investigate the mechanisms involved in some of these laboratory devices to gain a basic understanding of the damage phenomena which is necessary to relate results from laboratory systems to those obtained in the field or with large-scale devices which more closely model field results.

In addition we hope to correlate the damage to various materials of interest with easily measurable properties of the materials and parameters of the droplet impact.

II. SELECTION OF SUITABLE DEVICES

A. Limitations and Criteria

The chosen device must be capable of testing the various types of materials which are of interest in applications where rain erosion is a problem. Such materials include laminates, elastormerics, plastics, ceramics, and sandwich-type composites, as well as various metals. This diversity of materials provides a limitation on the type of device which is useful in that some of these materials cannot be fabricated into the particular test specimen configuration required for some types of test facility.

Assuming that a test device is applicable to the required range of materials, it must be capable of providing damage data, in the form of volume or weight loss, under realistically simulated rain condition, or under conditions with a reasonable well known relation to actual rain conditions, if it is to be used for the preliminary screening of candidate materials. On the other hand its purpose may be the obtaining of basic data significant to the improved understanding of this multiple-impact phenomenon. This understanding is desirable for the designing of materials with superior rain-erosion resistance, and yet with otherwise suitable properties for the applications of interest. Hopefully, the laboratory device, or devices, selected will be useful from both aspects.

Finally, the device, or devices, must be simple, reliable, economical to construct and operate, and capable of the rapid attainment of results.

B. Alternative Approaches

There are at least two very basic decisions to be made regarding the choice of a suitable device: that between a moving and stationary drop system, and that between essentially single impact and multiple impact devices. Probably the more basic of these, is that between a moving or stationary drop.

1. Stationary vs. Moving Drop

In all rain erosion applications, the damaging event is a collision between a fast-moving solid object and a relatively stationary, approximately spherical water droplet. In a given situation, the distribution of droplet diameters has a mean value of the order of 1.8 to 2.0 mm, which generally increases somewhat as the rate of rainfall increases.(1,2) In modeling such a collision it is clear that, for a given droplet mass, and target material and geometry, the relative velocity between droplet and target, and the shape of the droplet are likely to be of paramount importance. Hence it may be that the maintenance of the spherical shape of the impacting droplet is necessary for good modelling.

From the viewpoint of a laboratory device simplicity appears to favor those arrangements in which the droplet is accelerated to high velocity against a stationary target. The obvious difficulties with high-velocity targets include that of recovering the target undamaged after the test, the fact that the types of materials involved are often not suited to complicated fabrications or high stress levels, the more complex photographic problems that are likely to be encountered with devices such as whirling arms, and the fact that the velocities desired (range of

1000 to 3000 or more ft/s, or ~ 300 to 1000 m/s) are not easily obtained with the relatively poor structural properties of the materials involved without damage to the test speciment.

However, the predominent question involved with devices which accelerate the water droplet against a stationary target (which may obviate the other obvious advantages of these systems) is that of the effect of droplet shape upon the damage produced. This question arises since it does not appear possible to accelerate spherical water droplets of a mass equivalent to that of a typical rain-drop (about 4 mg) to a velocity in the range required without fragmentation of the droplet. The stability of such an initially spherical droplet passing through a gaseous region is measured by a critical Weber number, which empirically has a value of about 20:(3)

$$We_{crit.} = \frac{\rho_g (V_g - V_\ell)^2}{\sigma_\ell} \cong 20.$$

From this it is possible to estimate that a rain-drop with diameter of 2 mm would be unstable for velocities above about 80 ft/s (~ 25 m/s) in atmospheric air. In such a case the instability is due to the interaction between the droplet and the air through which it passes. However, realistic rain-erosion tests should be conducted in atmospheric air since cushioning of the impact due to an entrapped air film along the target surfact could be important. Further, it is clear that spherical droplets above a certain size will be unstable, even when accelerating through a vacuum, due to the interaction of inertial forces within the droplet tending to cause distortion of the initially spherical shape while the surface tension forces attempt to maintain it. In a rain-erosion device these inertial effects, with or without a surrounding air atmosphere, will be very important since the drop must be accelerated from rest. A possible solution to the dilemma might be obtained if forces could be applied during the acceleration and up until impact, which would maintain the initially spherical shape. However, such restraining forces would need to be low enough so that the liquid behavior during impact would not be affected. For example, the liquid droplet could conceivable be encapsulated within a thin membrane which would maintain its spherical shape during flight but be too fragile to interfere with the flow patterns developing after impact. On the other hand, it might be possible to obtain a fluid, otherwise sufficiently similar to water, but with surface tension sufficiently greater to prevent droplet distortion. Since, according to the Weber number relation, several orders of magnitude increase in surface tension would be required, this does not seem a likelihood.

It thus appears likely that if it is indeed necessary to utilize spherical droplets, stationary target devices may not be possible. One is then driven to the consideration of moving target devices such as rocket sleds, rotating arms, or systems such as that developed by Jenkins et.al.(4), wherein the target material is accelerated in a gun-like device against a stationary droplet and then decelerrated and recovered for examination. From the viewpoint of optimum simplicity and economy we felt that none of these devices are particularly attractive. Hence we chose to pursue the alternative route of investigating the effect of droplet shape to determine whether or not any significant shape effects existed, both from the viewpoint of the screening of materials for rain erosion resistance, and from that of the study of basic mechanisms. If it can be shown either that the shape of the impacting liquid mass is not important in the present context, or that its effect can be predicted, then devices producing high-velocity liquid slugs, for example of approximately cylindrical rather than spherical shape, would be adequate.

2. Single vs. Multiple Impact

A single impact device seems especially adapted to the study of basic mechanisms, whereas the multiple impact type is preferable for the screening of materials for rain erosion resistance. In some cases the latter may be simply an adaptation of the former. Both have their place as laboratory scale devices and we have experimented with devices of both types, as will be explained later.

III. SPECIFIC DEVICES SELECTED FOR STUDY

A. Single Impact Devices

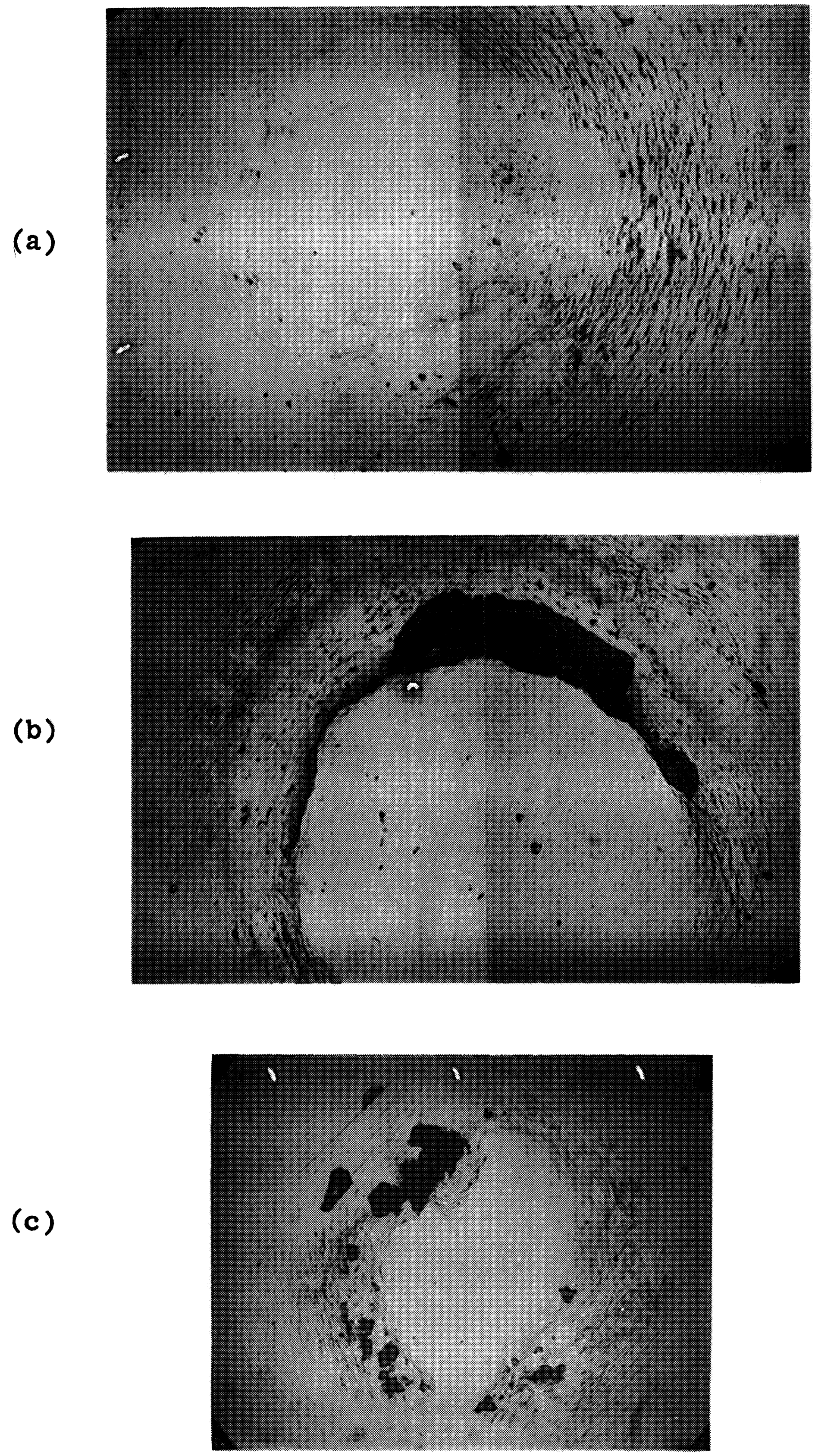
1. Momentum Exchange Gas Gun

We have performed preliminary experiments using a gas gun momentum exchange device similar to that originally developed by Bowden and Brunton(5) and since utilized by DeCorso(6) and Scher,(7) wherein a lead pellet from a gas gun is made to exchange momentum with an initially static liquid slug which is then ejected through an orifice to impinge against the target material. Such a device is ideally suited to a basic study of the interactions between a high velocity liquid mass and a stationary target, and allows the relatively easy use of high speed cinematography. It produces an approximately cylindrical jet, the length to diameter ratio of which, for a given total mass of water, depends upon the orifice diameter as well as other independent parameters of the experiment. Hence some information on the effect of liquid slug shape can be gained.

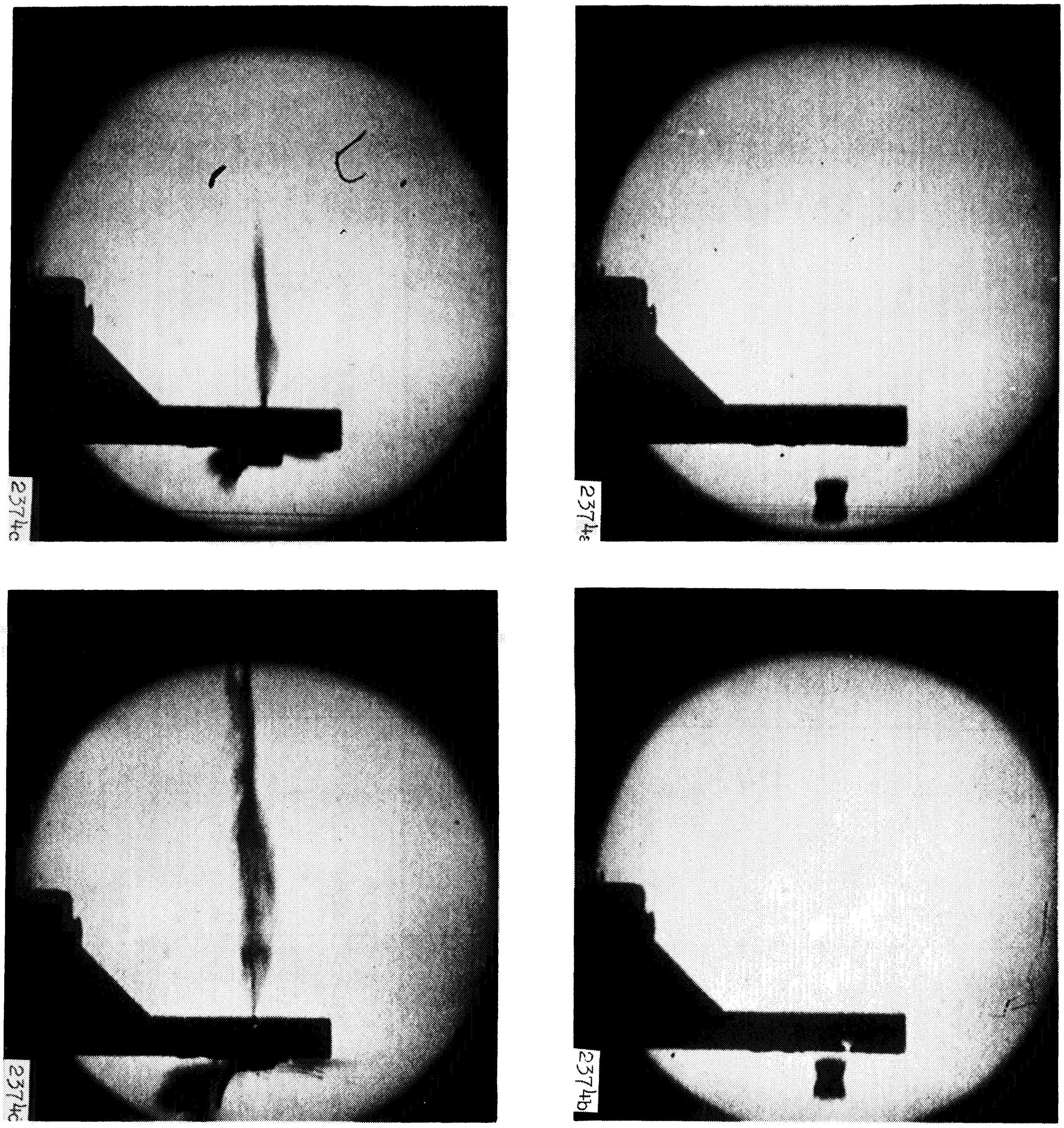
In his experiments Scher(7) found that the peak force and pressure exerted upon the target material depended upon orifice diameter, with the force maximizing at an intermediate diameter and the pressure maximizing at the minimum diameter used. He also found that the jet velocity depended upon orifice diameter although the impulse delivered from the lead pellet to the slug of water from which the jet is formed was essentially constant.

In our preliminary tests with approximately similar device we found that, at lease qualitatively, the damage created by an impacting water jet of about 2000 ft/s (~650 m/s) upon plexiglas maximizes with an orifice diameter of about 1.7 mm, which is roughly consistent with the maximum force from Scher's experiment, rather than maximum pressure. Figure 1 shows the damage patterns created in plexiglas in our experiments with orifice diameters of 0.5, 1.7, and 3.0 mm. It is apparent that considerably more damage is incurred at the intermediate orifice diameter than at the larger or smaller of those tested. The mass of liquid and the injecting impulse are essentially the same in all cases. If the same proportion of the total water volume is ejected in all cases, and the jet completely fills the orifice diameter, then the length to diameter ratio of the jets varies from about 700 to 3.0. A typical jet(8) from an orifice of 0.5 mm is shown in the sequence of photographs of Figure 2. The liquid volume is approximately equivalent to that of a spherical drop of about 5.0 mm diameter, and hence is about an order of magnitude larger than that of an average rain-drop. No quantitative damage measurements from these tests are yet available. However, it does appear from these tests that the damage depends on liquid slug shape even if the impacting velocity and liquid mass remain constant. It may apparently also be concluded that the damage correlates more closely with total force imposed on the target surface than with pressure. Thus it is possible that satisfactory modelling of the impact of a spherical liquid drop on a target surface may be achieved if a liquid slug of arbitrary shape merely exerts the same total force and presumably the impact velocity is maintained in about the same range.

The momentum exchange process involved in generating a high-velocity liquid jet with a device of this type is highly complex due to



2441 Fig. 1. - Photographs of damage to plexiglas resulting from liquid jet impingement from (a) 3.0 mm, (b) 1.7 mm, and (c) 0.55 mm diameter nozzle.

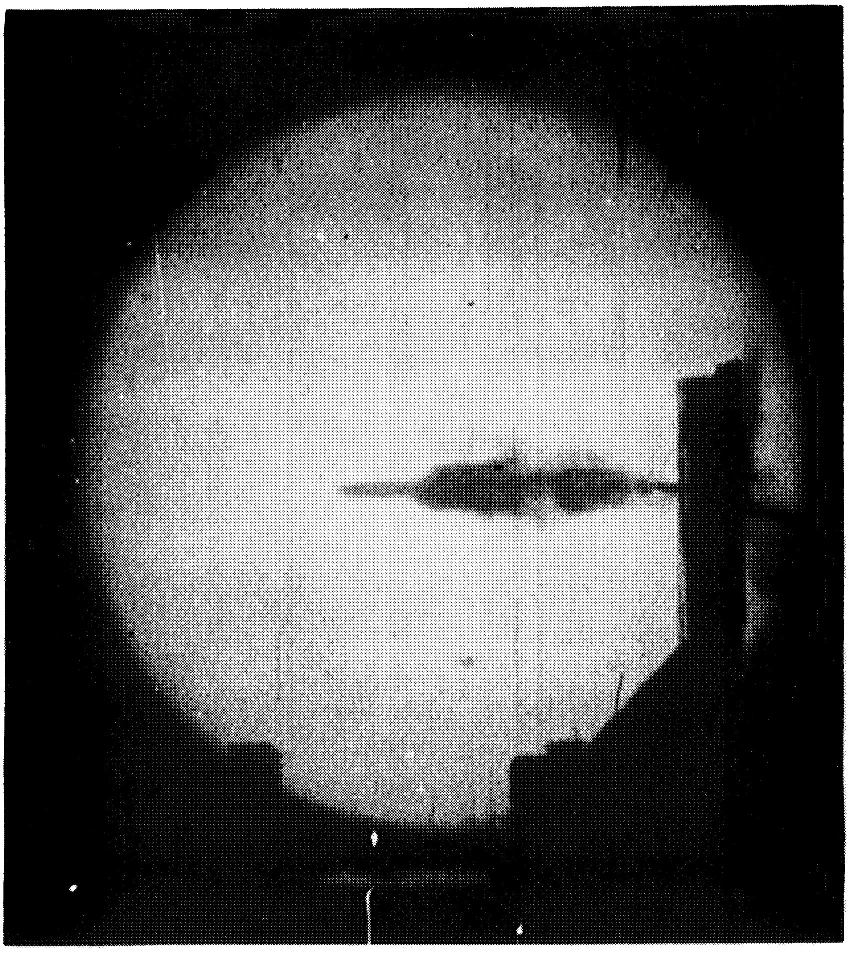


2374 Fig. 2. - Typical picture sequence of jet from gas gun momentum exchange facility. Jet velocity is approximately 1000 m/s, and orifice diameter is 0.5 mm.

the very short time scale of the process. It may well be dominated by the shock waves which are generated by the initial impact between lead pellet and the intially quiescent water, and reverberate within the small momentum-exchange chamber. Hence it may be merely fortuituos if as appears to be approximately true in some of our experiments as shown in Figure 2 the velocity of the emerging jet is uniform with respect to time and radial position within the jet. Figure 3 and 4 indicate such a lack of uniformity in some of our tests. The Christmas-tree appearance of the jet in Figure 3 indicates that in this case the velocity must approximate a wave function with relation to axial position in the jet. Presumably the "branches" of the tree result when a slower moving forward portion is overtaken by a higher-velocity portion of the jet. For such a case, an observer in a center-of-mass coordinate system, located at the position of one of the branches, would see two portions of the jet collide at his location with a resultant radial flow giving rise to the "branch". It appears likely that the spacing between branches is a result of shock waves reflecting within the momentum-exchange chamber.

Figure 4 shows another non-uniform velocity configuration wherein a small central jet appears to pass ahead of the main jet. This occurrence may be related to the Monroe-jet phenomenon previously reported by Bowden from this type of device.(9) In the present instance it may also indicate a relatively slow-moving forward portion of the jet which is overtaken and pierced by the higher-velocity portion behind. It is clear that the design of a device must be so arranged that an approximately uniform jet velocity is produced if the damage results obtained are to be subject to theoretical interpretation. We believe that various minor modifications of the design will produce the desired effect.

2377 Fig. 3. - Liquid jet from momentum exchange device showing the standing wave type of instability observed in some cases.



2368 Fig. 4. - Photograph of Monroe-type produced by the gas gun momentum exchange device.

B. Repetative Jet Concepts

1. General Requirements

The desirable characteristics of a repetative jet facility include the capability of producing impacts randomly distributed over the surfact of the speciman as well as the capability with regard to droplet shape and velocity previously ascribed to the single impact device. In order to allow a reasonably rapid test, the frequency of impact on a given target area should be as high as possible without encountering serious interference between consecutive droplets.

The requirement for producing droplets having a length to diameter ratio close to unity imposes very severe restrictions. To produce a stream of such droplets having the diameter of a typical rain-drop and a velocity of 2000 ft/s ($\sim$ 700 m/s) would require either an on-off valve system open for periods of 5 μs per slug (which is clearly beyond the capability of any mechanical system) or a "chopping" arrangement of similar performance. In the latter case it is possible to conceive a contInous jet interrupted by a rotating disc equipped with radial slots. If the tangential velocity of the rotating chopper disc was made approximately equal to the jet velocity, a set of radial slots, the tangential extent of which was equal to the desired liquid slug length, would achieve the desired effect. The mechanical difficulties of such an arrangement are, however, very great. The disc would either have to be very thin compared with the required length of slug, or the slots would have to be slanted to prevent the slug being impacted tangentially during its passage through the slot.

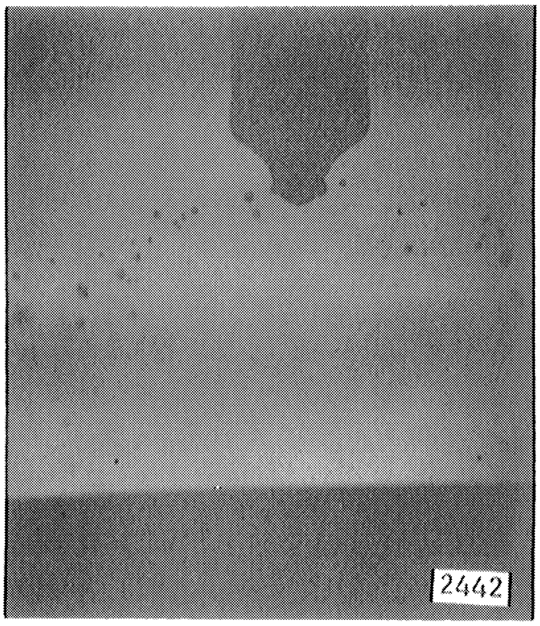
The above considerations cast considerable doubt on the feasibility of the repelative jet concept if slugs of a length to diameter ratio of the order of unity are required. We have nonetheless started preliminary tests in this laboratory with this concept in mind, hoping that it may prove possible to model the desired phenomena using slugs of much larger length to diameter ratios.

2. Preliminary Tests in this Laboratory

a. Diesel Injection Nozzle

We have made some preliminary tests utilizing a standard Bosch injection nozzle fed from a Bosch pump. As is well known such a device is capable of producing the pressures necessary to attain velocities of the desired magnitude and the volume per stroke can also be made about equal to that of a typical rain-drop. The primary difficulty is to tailor the resultant slugs or jets to provide a reasonably realistic model of typical raindrops. Figure 5 shows numerous spherical drops generated from this injector using the standard nozzle arrangement, i.e. four holes of 0.5 mm diameter. The drop diameter is about 0.5 mm, which is far too small for the present purpose. The velocity of the drops is assumed to be somewhat less than the ideal spouting velocity which for the nozzle pressure of about 6000 psig (400 bar) is 1000 ft/s (300 m/s). This velocity estimate is also consisten with the lack of blurring in the pictures which were taken with an exposure time of 1.2 μs.

A secondary difficutly with a standard diesel nozzle in this application is that it cannot operate with water without prohibitive corrosion problems. Hence, it is likely that a pressure transfer device



2442 Fig. 5. - Photograph of liquid droplets produced by diesel injector nozzle operating at 400 bars.

will be needed between the pump, or conventional nozzle if such is included, and the actual jet-producing nozzle. Conceptually such a device could be simply a small metallic bellows to separate the oil which is necessary for proper operation of the diesel system from the water system which is required for the droplet impact test. Future tests may of course show that there is no significant difference between impact tests with water or oil in which case such a pressure transfer device would not be necessary. Another alternative might be to fabricate the pump and nozzle system of materials for which water operation would be feasible. However, it is likely that galling and other difficulties would be encountered in addition to corrosion.

It is hoped that appropriate shaping of the liquid slug can be achieved with this system either through the action of a check valve in the injection nozzle or through the limited stroke feature of the pump. In either case special designs of the nozzle head will no doubt be required. A possible alternative is the chopping of a relatively continuous jet from the injector into proper length segments by ultrasonic vibration or electromagnetic means.

3. Cavitation Tests

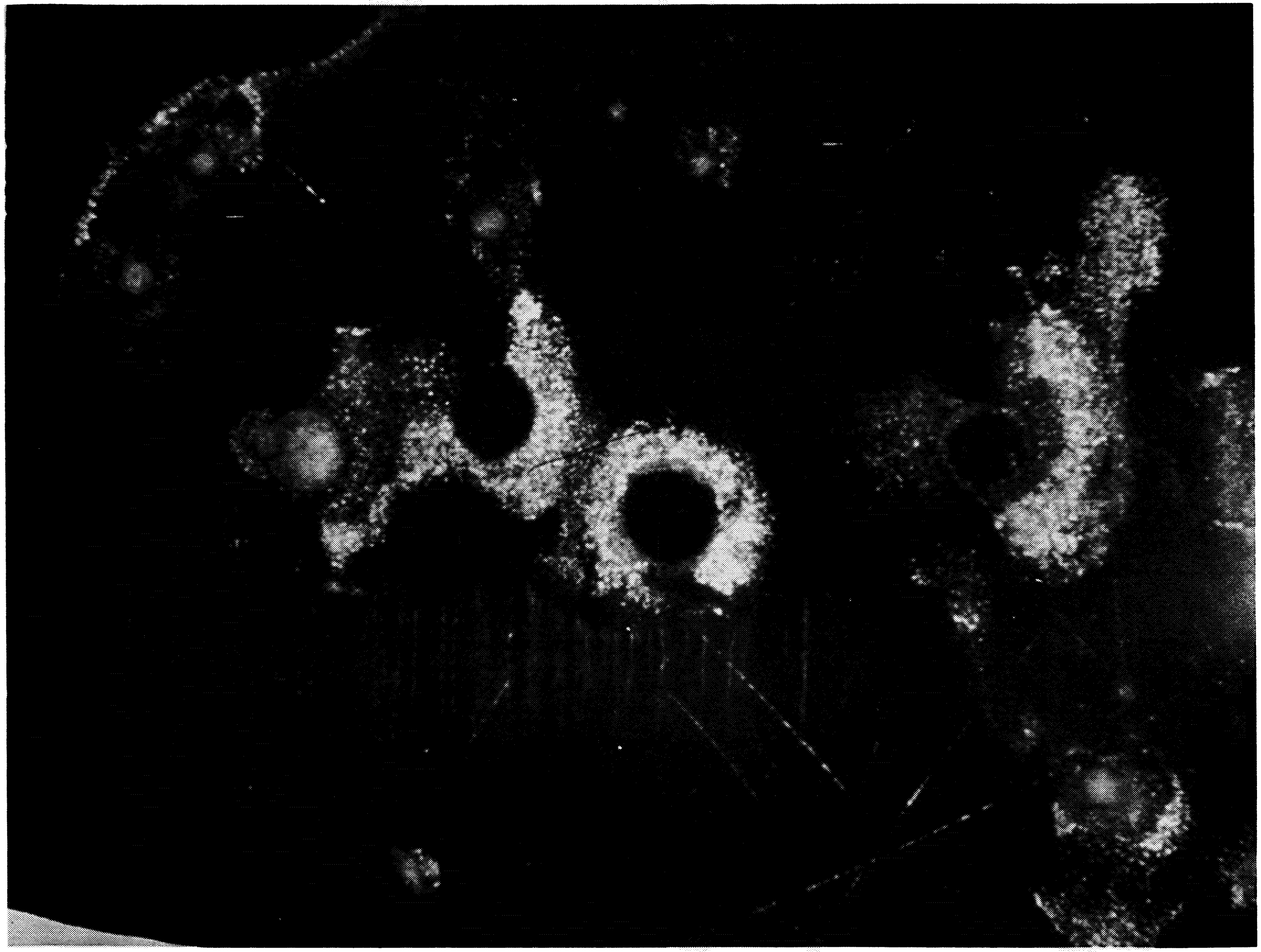
a. General

Cavitation damage tests can be considered as a special form of multiple-jet impact test, and in the past impact tests have often been used to rank materials for cavitation resistance.(10,11) It was first suggested by Kornfeld and Suvorov(12) that cavitation damage in fact results from the collapse of initially spherical bubbles in an asymmetric mode such that a resultant high velocity micro-jet impinges upon the specimen surface. This model of bubble collapse was later strengthened by the experimental and theoretical work of Naude and Ellis(13) with spark-generated bubbles attached initially to a solid surface in a static system, and later still by the experimental work of Shutler and Messler(12) in a similar system. At about the same time considerable experimental evidence supporting primarily the asymmetric collapse, microjet damage theory as opposed to the classical Rayleigh spherical-collapse, shock-wave theory was gathered in this laboratory(15,16) for cavitation in a flowing system (cavitating venturi). This has been further supported by very recent experimental work in this laboratory which is(17) reported below. It has also been supported by theoretical investigations here(18) and elsewhere(19) of the spherical collapse model using real fluid parameters. In both cases it was shown that the shock pressures are not sufficient to cause the observed damage unless the center of collapse shifts significantly toward the solid boundary during the collapse. Some shift in this direction is theoretically predicted, but as yet there is no quantitative information regarding the significance of such a shift. In any case it appears highly unlikely that a spherically-symmetric collapse could occur close enough to a solid boundary to be damaging. On the other hand, the above analyses did show that in the case of bubble rebound, which is sometimes observed, damaging pressures are much more likely. Hence, at the present time it is not certain that the shock wave model is not important, but it appears to us highly likely that the microjet model is importantly involved in most cases of cavitation damage.

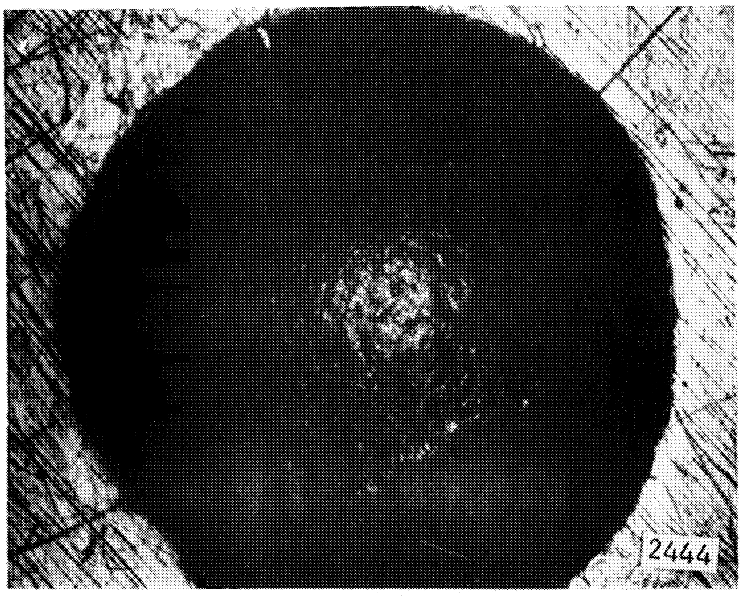
Figure 6 shows one of several craters generated in a cavitating water venturi in this laboratory upon a cadmium-plated stainless steel speciman. In this case the thickness of the cadmium plate was 0.5 μm. As shown in the photograph the cadmium was apparently "washed off" over a circle with a diameter of approximately 60 μm, and partially removed over a somewhat larger circle (120 μm diameter). This appearance is quite consistent with the model of a microjet impacting the center of the region and washing out radially. Experiments by others,(20, etc.) as well as our own work,(17) show that the radial velocities in such a case may be several times the initial impact velocity. The high shear at the surface with such a high velocity radial flow could cause the removal of the cadmium plate over the area surrounding the impact. However, it is difficult to imagine how such a damage pattern could result from the impingement of shock waves upon the surface, which would merely press the plating material into the surface.

Figure 7 shows a similar cadmium-plated specimen impacted with a steel sphere of about 3 mm dia at a few hundred ft/s, and a profilometer trace across the crater. In this case a small crater is formed but the cadmium plate is not displaced radially, or squeezed-out, as in the cavitation record.

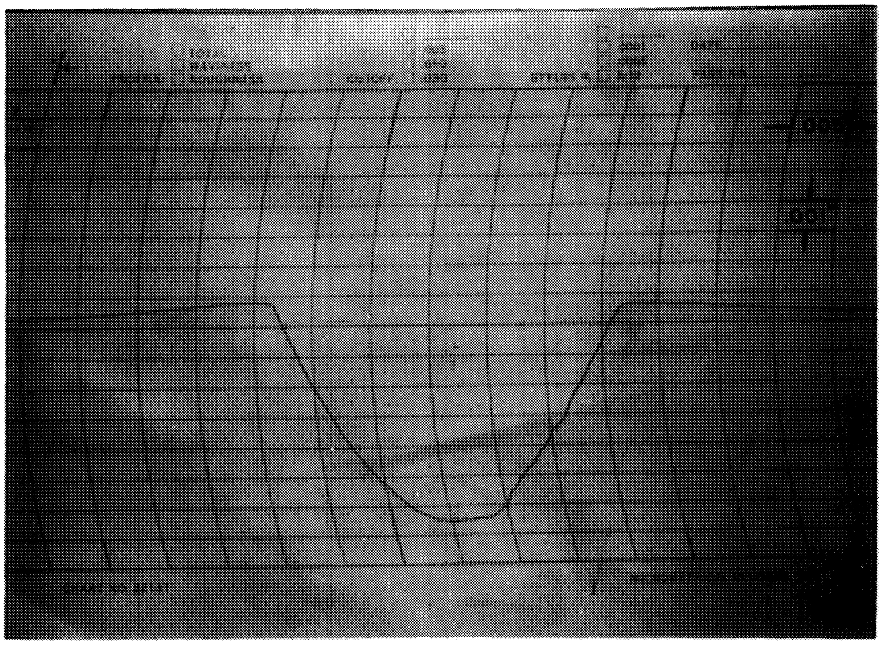
A comparison between craters caused by jet impact in other laboratories with cavitation craters generated here(15) indicates that the cavitation microjet diameter is probably typically well less than one mil (0.025 mm) and has a velocity up to several thousand feet per second (1000 m/s). It is likely to have a large length to diameter ratio, although no quantitative estimates are available as yet. Hence cavitation



2443 Fig. 6. - Photograph of cavitation craters on cadmium plated stainless steel specimen. Cadmium plate thickness is 0.6 mm and width of photograph is about 1.0 mm.



Pit Shape



Pit Contour

2444 Fig. 7. - Pit damage to coated specimen caused by impingement of a solid sphere.

tests should provide a multiple-jet impact test wherein the jet velocities are in the range of interest although the jet diameter is far below that which would be desirable. If the cavitation is generated in a conventional vibratory facility, the frequency of impacts upon the test material is very large so that only short tests should be required. In such a device with soft aluminum we have observed(21) a rate of pit generation of approximately 3000 pits/second on a specimen of 0.56 inches diameter (1.4 cm) operating at about 20 kc/s, 2 mil (50 μm) amplitude.

It is apparent that the shape of the impacting liquid "slug" in the cavitation test differs very widely from that of a typical raindrop, having a very much smaller diameter and a large length to diameter ratio. If the material rankings achieved in cavitation tests are closely similar to those from conventional impact tests it is a good indication that droplet shape is not of primary importance in the relative ranking of meterials. Tests of previous investigators(10,11) have indicated that this is generally the case. However, the cavitation tests cannot be expected to provide absolute damage results that are directly applicable to conventional impact tests unless they are correlated against such tests.

It is to be expected that size and shape factors of the impinging liquid slug may be more important for some target materials than for others. For example, a special scale factor, beyond that expected from consideration of the usual similarity parameters, might be found to exist between the microjet damage produced in a cavitation test and that produced by raindrop impingement for some materials. The microjet diameter may be in the general size range of the grains of certain metallic alloys so that preferential reactions with different components of the material might be expected. Another possibility of a scale factor exists for certain composite materials, wherein a hard brittle thin surface layer of material is supported on a softer, more resilient filler material. Large droplets, imposing relatively large forces over a substantial area, might cause such a surface layer to fail in bending due to the insufficient rigidity of the filler, whereas such a failure would not occur in the case of the small microjets even though the local pressures generated were similar or even higher. Also, the likelihood of spalling of the reverse side of a thin material is probably a function of the absolute size of impacting liquid slug.

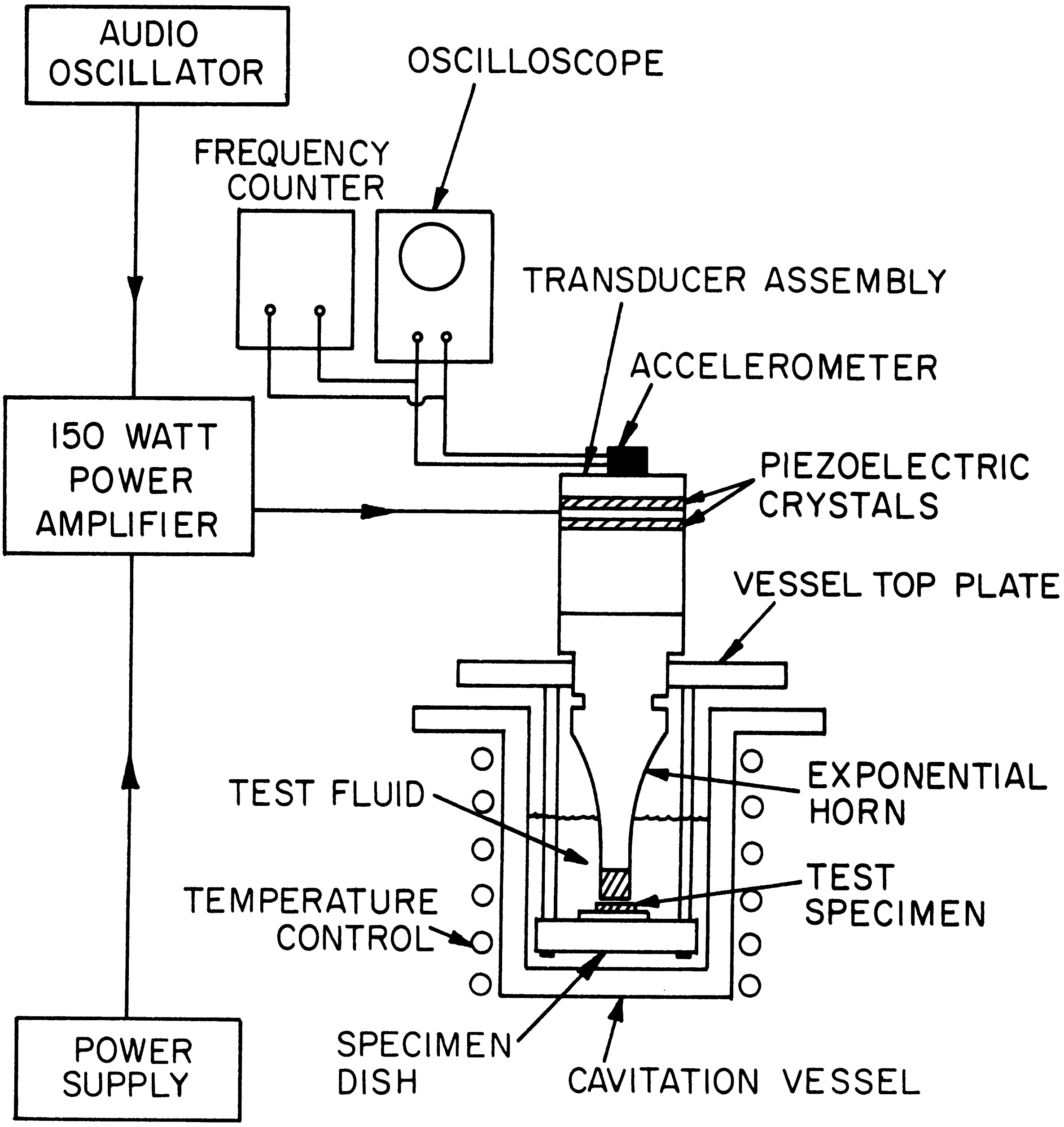
b) Preliminary Cavitation Test Results

The simplest and most commonly used test today for cavitation damage resistance of materials is the vibratory test wherein a test "button" is attached to a high-frequency driver and oscillated at a frequency of the order of 20kc/s, submerged in the test fluid such as water, through a stroke of the order of 2 mils (50 μm). Such buttons conventionally have a diameter of about 5/8 inches (1.6 cm). A very firm attachement between the button and driver is required to transmit the high-frequency vibration from driver to button. While this system is well adapted for the testing of metals, its application to various materials of interest for rain erosion may not be feasible. For this particular purpose it was felt that a test wherein the test specimen was stationary would be preferable.

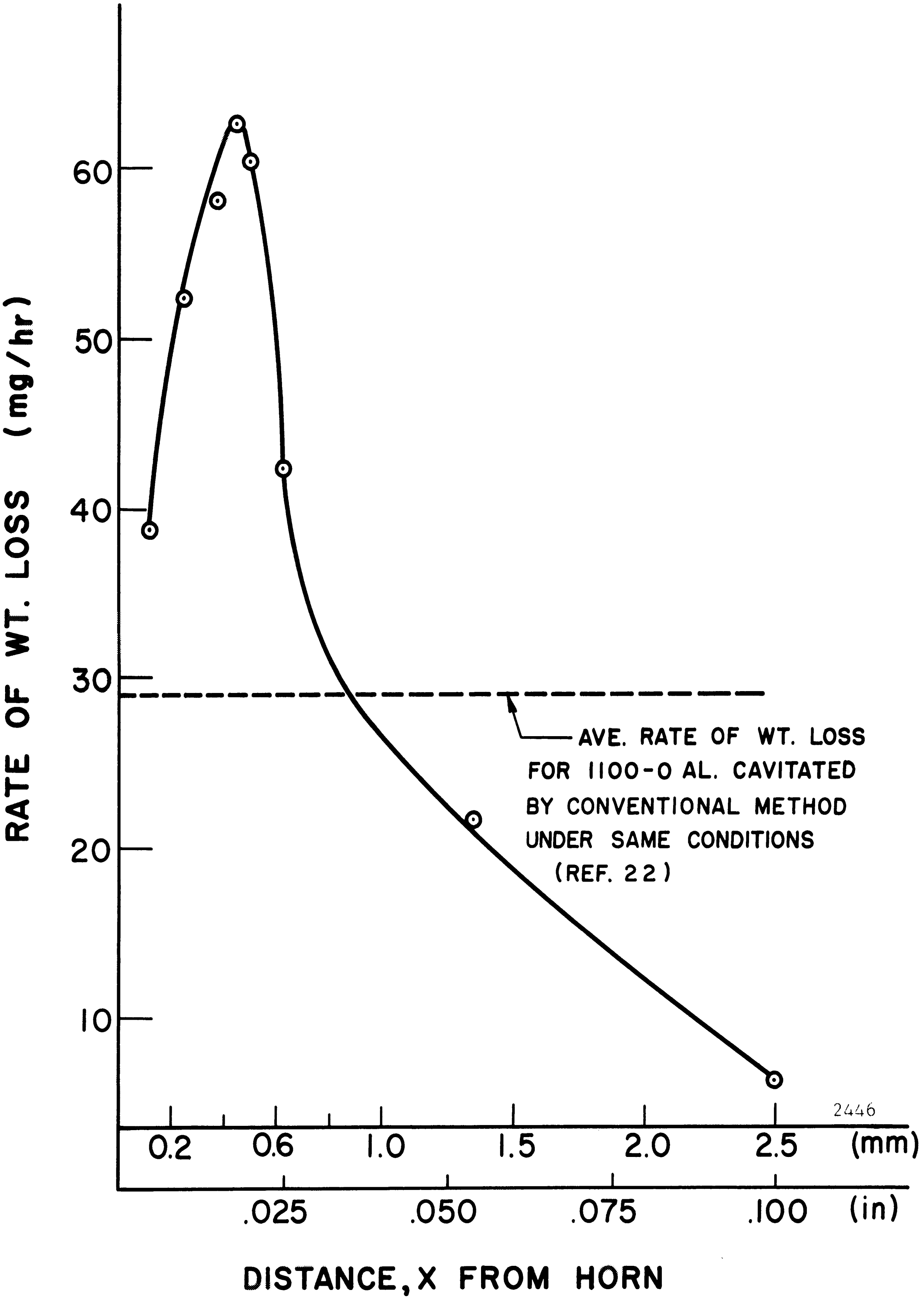
Since the cavitation "cloud" covers a substantial region beneath the vibrating specimen in the conventional vibratory cavitation test, it seemed likely that a stationary specimen placed in this region would incur substantial cavitation damage. However, the most appropriate clearance between vibrating horn and stationary specimen to obtain maximum damage rate was not known. Hence, a series of tests using stationary soft aluminum (1100-0, Alcoa designation) specimens and our ultrasonic vibratory unit(22) with room temperature tap water as test fluid was initiated(23) in order to determine the general characteristics of the damage and its dependence upon the location of the stationary specimen. Hence, clearance between vibrating horn and stationary specimen (in the form of a square of material, 0.6 inches (1,5 cm) on the side and 1/4 inch (6.3 mm) thick) was the only test variable. The frequency was 20 kc/s, and the stroke 2 mils (50 μm) for all tests. Figure 8 is a schematic of the arrangement.

The resultant weight loss from tests of one hour duration is plotted in Figure 9 as a function of clearance between the stationary specimen and the tip of the vibrating horn (in its equilibrium position). Figure 10 shows the resultant damage patterns on the aluminum for several of the clearances used. It is noted that both damage pattern and the quantity are strong functions of clearance, with the damage maximizing for this test at a clearance of about 0.46 mm. As shown in Figure 9 the peak damage rate for the stationary specimen test is about twice of that of the damage rate observed previously for a conventional vibratory cavitation damage test with the same material at the same horn frequency and stroke.(24) Hence this appears to be a thoroughly practical cavitation damage test for the rain erosion materials.

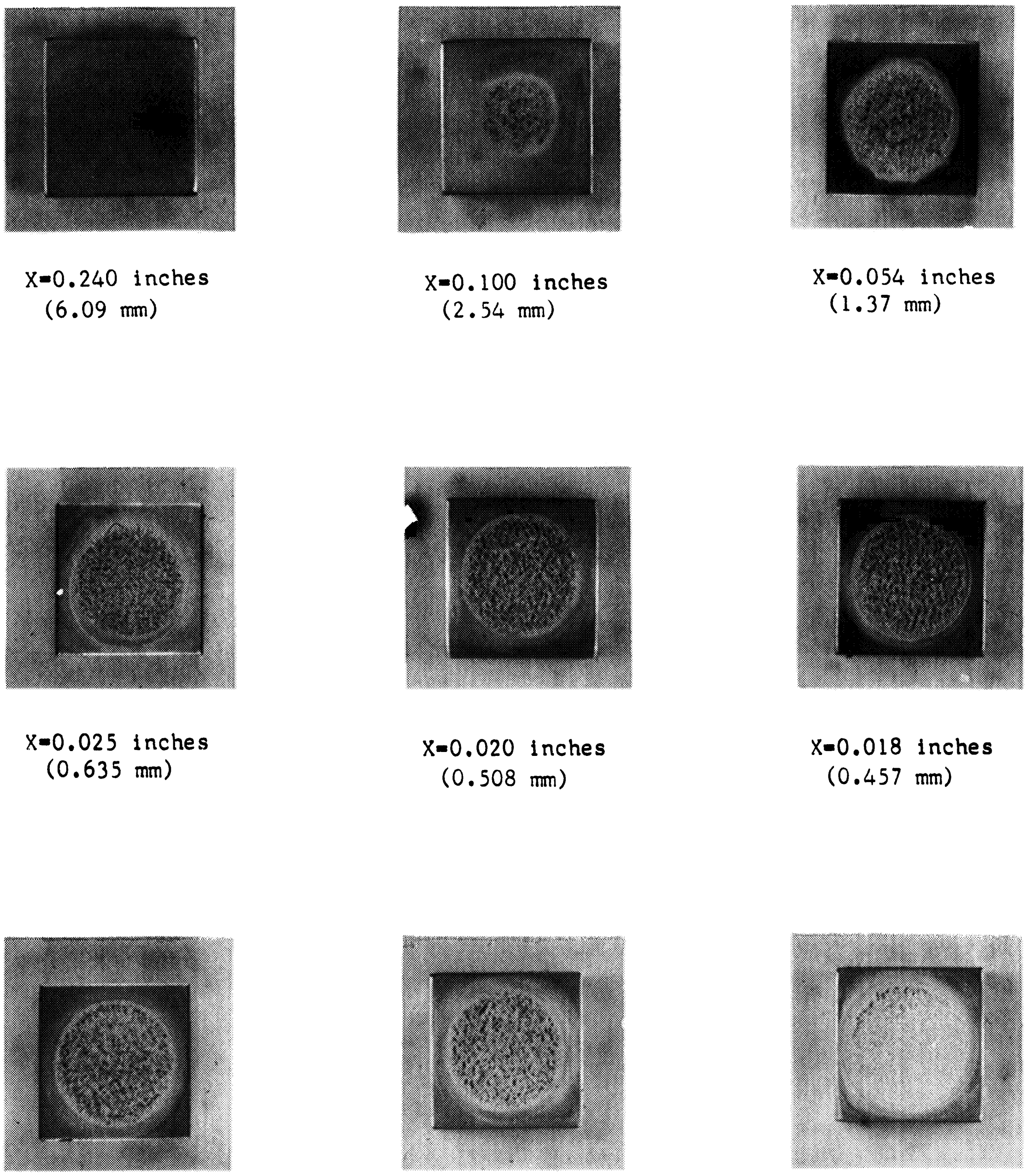
After completing the preliminary tests described above it was found that a somewhat similar series of cavitation damage tests had



2445 Fig. 8. - Schematic representation of the stationary specimen vibratory cavitation test facility.



2446 Fig. 9. - Rate of weight loss vs. distance from the vibrating surface. 1100-0 aluminum specimen in water at room temperature.



X=0.240 inches
(6.09 mm)

X=0.100 inches
(2.54 mm)

X=0.054 inches
(1.37 mm)

X=0.025 inches
(0.635 mm)

X=0.020 inches
(0.508 mm)

X=0.018 inches
(0.457 mm)

X=0.015 inches
(0.381 mm)

X=0.010 inches
(0.254 mm)

X=0.005 inches
(0.127 mm)

2447

Figure 10. Damage on the Surface of the Stationary Specimen as a Function of the Distance of Separation X

been recently completed by Endo, et.al(25) with the objective of studying cavitation in bearings. Their results in terms of damage vs. clearance are very similar with the damage rate peaking at about 0.2 mm clearance for tests in cold water with about the same horn frequency (22 kc/s) and somewhat smaller amplitude (0.8 mils (20 μm)) than used in our tests. They also tested various oils and found that the clearance for maximum damage was then greater, increasing to about 1.1 mm for silicone oil. For spindle oil, with a viscosity about twice that of water, the optimum clearance was about 0,6 mm. While the silicone oil used is clearly more viscous than the spindle oil, its viscosity is not given.

It is further shown by Endon, et.al(25) that there is an appreciable temperature rise of the fluid in the clearance space , and that this too is a function of clearance and viscosity. Maximum temperature clearance approximately coincides with maximum damage clearance. In the case of the water tests, for example, the temperature rise in the maximum damage condition is about 50°F above pool temperature. It is well known,(22,24,etc.) that cavitation damage is very sensitive to water temperature within this range for the vibratory test, coincidentally reaching a peak in a test wherein the water surface is exposed to atmosphere at about the temperature measured in the clearance space in the maximum damage test. Hence, apparently the peaking of damage with clearance is enhanced by the temperature change. It is apparent that more detailed tests are required to separate the effects of temperature, viscosity, clearance, and other speciment and horn dimension and operating parameters. However, the test is basically very simple and may well constitute a good laboratory device for the screening of rain erosion materials.

IV. THEORETICAL APPROACHES

A. Correlation of Damage with Mechanical Properties and Test Parameters

We hope to correlate the damage data produced from testing rain erosion materials in our own laboratory as well as elsewhere with groupings of material mechanical properties and test parameters, using a regression analysis which we formerly applied with some success to our cavitation damage data. In this analysis, a variety of materials, fluids, temperatures, and test parameters were examined.(22,24) We anticipate generating empirical equations applicable to materials not yet tested, or to the effect of variation of test parameters on previously tested materials. At a minimum, those materials and test parameters which statistically are most closely related to the damage data, and the trends in damage rates to be expected from a variation of these, will be indicated. A somewhat similar analysis was recently performed by Bouma and Burkitt(26) for the size and shape of craters generated by the hypervelocity impact of solid particles on solid materials.

B. Computation of Material Reaction to Droplet Impact

Very little has been done to compute the stresses and strains to be expected from the impact of a liquid droplet or jet upon a target material for impact velocities in the rain erosion range of interest. The mathematical formulation using classical methods is extremely complex, perhaps more so than for the hyper-velocity problem where the solid material can be considered as a gas or liquid during much of the interaction. In the present problem plastic deformation of the target material must still be considered as well as compressibility and viscosity effects in the liquid. However, various highly sophisticated computer codes now exist(27) which might be applied to such problems. It is our intention to explore this possiblity further in the future.

V. CONCLUSIONS

The choice of a simple, reliable, inexpensive laboratory-scale test for the evaluation of rain-erosion materials first involves the decision as to whether a stationary or moving drop (and or target) experiment is to be used. From the viewpoint of a laboratory scale device, the complexity of stationary droplet arrangements argues strongly for the alternative arrangement. However, droplets of the size of a typical raindrop with velocity in the range of interest cannot, because of stability difficulties, be spherical, at the time of impact, but will probably be elongated slugs. Hence, if the accelerated droplet, stationary target system is chosen, one must ascertain the effect of droplet size and shape on damage, assuming the correct relative velocity and mass are maintained. In our own investigations we have chosen to follow this path.

A useful essentially single-impact laboratory device for the study of basic mechanisms involved in a droplet-target collision is a gas-gun, momentum-exchange unit similar to that first used by Bowden and Brunton.(5) This can be used to study the effect of droplet shape and size on damage by varying orifice size and design. Some preliminary tests with this objective have been discussed. It has been shown that there are substantial shape and size effects and that damage appears to follow the force more closely than the pressure exerted on the target.

A multiple impact device which hopefully can produce somewhat similar high-velocity droplets, but at a fairly high frequency, is a diesel injection nozzle. Preliminary tests indicating that the desired results can probably be obtained with a modified device of this sort have been completed.

In the past, droplet impingement tests have been used for the evaluation of the cavitation resistance of materials,(10,11) and it has been found that the relative ranking of materials achieved in this manner is similar to that obtained in conventional cavitation tests. Today there is good theoretical and experimental evidence that the basic damage mechanism in cavitation damage is often a high-velocity liquid jet of very small diameter. Hence, it is proposed that a conventional vibratory cavitation unit be used to provide a cavitation field in the neighborhood of a stationary specimen and thus obtain a relative ranking of rain erosion materials, which in many cases are not suited to the conventional vibratory cavitation test, could be obtained. Preliminary tests of this nature, to determine the characteristics of damage so produced and its relation to the other test parameters involved, have been completed. It is concluded that basically this very simple device can provide a useful ranking of rain erosion materials. However, further tests of the effect of the various significant parameters are required.

ACKNOWLEDGEMENTS

Financial support for this investigation was provided primarily by the U.S. Naval Air Development Center, Contract No. N 62269-3745, under direction of Mr. George J. Tatnall. Aside from the authors a major contribution to the work reported was made by Mr. David J. Brager, Research Assistant, Nuclear Engineering Dept., University of Michigan.

BIBLIOGRAPHY

1. Tatnall, G.J., "Some Observations Concerning Rain Erosion of Radome Materials on U.S. Naval Aircraft and Missiles", Proc. Rain Erosion Conf., Meersburg, W. Germany, 5-7 May, 1965, pp. 8-14.

2. Fyall, A.A., "Meterological and Other Parameters Relevant to the Phenomenon of Rain Erosion", Proc. Rain Erosion Conf., Meersburg, W. Germany, 5-7 May, 1965, pp. 30-42.

3. Smith, A , "Physical Aspects of Blade Erosion by Wet Steam in Turbines", Phil. Trans. Roy. Soc., Series A, No. 1110, Vol. 260, July 28, 1966, pp. 209-215.

4. Jenkins, D.C., Booker, J.D., and Sweed, J.W., "An Experimental Method for the Study of the Impact between a Liquid Drop and a Surface Moving at High Speed", R.d.M. No. 3203, July 1958, Aero. Res. Council, Ministry of Aviation, England.

5. Bowden, F.P., and Brunton, J.H., "The Deformation of Solids by Liquid Impace at Supersonic Speeds", Proc. Roy. Soc., Series A, Vol. 263, 1961, pp. 433-450.

6. DeCorso, S.M., "Erosion Tests of Steam Turbine Blade Materials", ASTM Proc., v. 64, pp 782-796, 1965.

7. Scher, M.P., "Liquid Impact Simulator", Report NOLTR 65-181, V.S. Naval Ordmance Laboratory, White Oak, Md., June 1966.

8. Pitek, M.T., and Hammitt, F.G., "Hypervelocity and Fluid Impact Studies", Report No. 08153-1-T, Dept. of Nuclear Engineering, The University of Michigan, September, 1966.

9. Bowden, F.P., "The Formation of Microjets in Liquids under the Influence of Impact or Shock", Proc. Roy. Soc., Series A, Vol. 260, No. 1110, July 1966, pp. 94-95.

10. Honegger, E., "Concerning Erosion Experiments", (in German), BBC -Mitt., Vol. 14, 1927, pp. 74-95.

11. Hobbs, J.M., "Problems of Predicting Cavitation Erosion from Accelerated Tests", ASME Paper No. 61-HYD-19.

12. Kornfeld, M., and Suvorov, L., "On the Destructive Action of Cavitation", J. Appl. Phys., 15, 1944, pp. 495-506.

13. Naude, C.F., and Ellis, A.T., "On the Machanism of Cavitation Damage by Non-Hemispherical Cavities Collapsing in Contact with a Solid Boundary", Trans. ASME, J. Basic Engr., v. 83, n. 4, Dec., 1961, pp. 648-656.

14. Shutler, N.D., and Mesler, R.B., "A Photographic Study of the Dynamics and Damage Capabilities of Bubbles Collapsing Near Solid Boundary", Trans. ASME, J. Basic Engr., D, 87, 1965, pp. 511-517.

15. Robinson, M.J., and Hammitt, F.G., "Detailed Damage Characteristics in a Cavitating Venturi, ASME Paper 66-WA/FE-39, to be published Trans. ASME, J. Basic Engr., 1967.

16. Ivany, R.D., Hammitt, F.G., Mitchell, T.M., "Cavitation Bubble Collapse Observations in a Venturi", Trans. ASME, J. Basic Engr., v.88, Series D, n. 3, Sept., 1966, pp. 649-657.

17. Hammitt, F.G., "Turbine Droplet Impingement and related Phenomena", Report No. 07738-4-T, Dept. of Nuclear Engr., The University of Michigan, Feb., 1967.

18. Ivany, R.D., and Hammitt, F.G., "Cavitation Bubble Collapse in Viscous, Compressible Liquids -- Numerical Analyses", Trans. ASME, J. Basic Engr., Dec., 1965, pp. 977-085.

19. Hickling, R., and Plesset, M.S., "Collapse and Rebound of a Spherical Cavity in Water", The Physics of Fluids, v. 7, n. 1, Jan., 1964, pp. 7-14.

20. Brunton, J.H., "High-Speed Liquid Impace", Phil. Trans. Roy. Soc., Series A, No. 1110, Vol. 260, July 28, 1966, pp. 79-85.

21. Olson, H.G., and Hammitt, F.G., "Early Damage from Vibratory Cavitation Test in Water", Cavitation Forum, ASME, Nov. 1966, pp. 5-6.

22. Garcia, R., and Hammitt, F.G., "Cavitation Damage and Correlations with Material and Fluid Properties", ASME Paper, presented ASME Fluids Engr. Div. Conf., May 1967, and to be published Trans. ASME, J. Basic Engr.

23. Brager, D., et. al., "Cavitation Erosion Stationary Specimen in Close-proximaty of an Oscillatory Surface", ORA Report 08153-2-T, May 1967, Nuclear Engineering Dept., The University of Michigan, Ann Arbor, Michigan.

24. Garcia, R., "Comprehensive Cavitation Damage Data for Water and Various Liquid Metals Including Correlations with Material and Fluid Properties", Ph.D. Thesis and ORA Technical Report No. 05031-6-T, Department of Nuclear Engineering, The University of Michigan, August, 1966.

25. Endo, K., Okado, T., Nakashima, M., "A Study of Erosion between Two Parallel Surfaces Oscillating at Close Proximity in Liquids", ASME Paper No. 66-LUB-9, to be published Trans. ASME, J. Basic Engr. (1967).

26. Bouma, D.D., and Burkitt, W.C., "Multivariabel Analysis of the Mechanics of Penetration of High Speed Particles", NASA CR-664, Dec. 1966.

27. Harlow, F.H., "Hydrodynamic Problems Involving Large Fluid Distortions", J. Assoc. Computing Mach., v. 4, n. 2, April, 1957, pp. 137-142.

ABSTRACT

A broad program is under way to study the mechanism by which rain erosion occurs and to correlate the type and magnitude of damage sustained by materials submitted to droplet impact, jet impact and cavitation damage. The use of various laboratory devices for the study of rain erosion phenomena are discussed. The relative merits of a facility utilizing a stationary drop of liquid and a moving target are compared to the alternative of accelerating a mass of liquid and permitting it to impinge on a stationary (or moving) target. It is demonstrated that water droplets of the size of typical raindrops cannot maintain their spherical shape under high acceleration and that the acceleration of droplets of this size to the velocities of interest is a major problem; however, the problems inherent in obtaining the relative velocities of interest by means of a moving target appear to be prohibitive for laboratory simulation of rain erosion.

A single-impact laboratory device, for the study of the mechanism by which liquid impact damage occurs, is described and some preliminary results obtained with the facility are presented. Preliminary work with a multiple-impact device is described and evidence is presented to demonstrate the feasibility of using cavitation tests to provide a relative ranking of the erosion-resistance of materials.