AD715100

ONR LONDON CONFERENCE REPORT

C-25-70

OFFICE OF NAVAL RESEARCH

BRANCH
OFFICE
LONDON
ENGLAND

THIRD INTERNATIONAL CONFERENCE ON RAIN EROSION AND ASSOCIATED PHENOMENA

By E. I. SALKOVITZ

20 October 1970

UNITED STATES OF AMERICA

33

THIRD INTERNATIONAL CONFERENCE ON RAIN EROSION AND ASSOCIATED PHENOMENA

INTRODUCTION

The Third International Conference on Rain Erosion and Associated Phenomena was arranged by the Materials Department, Royal Aircraft Establishment, Farnborough, under the sponsorship of the British Ministry of Technology. It was held 11-13 August 1970 at Elvetham Hall, Hartley Wintney, near Basingstoke, about 40 miles west of the center of London. I believe some readers may find the historical background of Elvetham Hall sufficiently interesting to merit a few comments. An entry in the Domesday Book indicates that one Hugh de Port held the land of Elvetham (of the Abbey of Certesye). In the next few centuries ownership transferred back to the hands of the Abbots, but in 1403 Henry IV granted a license "to enclose and make a park of some of the land." Elvetham, in the normal course of events, passed into the possession of Roger St. Maur (later Seymour). A direct descendant was created Duke of Somerset and Lord Protector in the reign of Edward VI. Unfortunately, by royal decree, decapitation brought a close to his brilliant career, but Edward Seymour, his eldest son was restored to favor (a raised eyebrow would not be unwarranted!) with title, by Elizabeth I. Alas, in 1560 he incurred the jealous Queen's displeasure by marriage to another. He was fined £15,000 and imprisoned for nine years, his wife for life. Many years later, 1591, to regain the Queen's favor, Seymour organized a magnificent entertainment which lasted 72 hours! In commemoration, Elizabeth planted an oak in the above-mentioned park, which still stands and measures 30 feet around six feet up from the ground. In 1649 the estate was sold to Sir Robert Reynolds, one of Cromwell's generals.

The recent history of the estate seems uneventful. A few years ago the late owner sold the house and 30 acres to Imperial Chemical Industries. Elvetham Hall, it might be added, was completely rebuilt in 1860. The church, whose Registers go back to 1649, was rebuilt in 1840 and is on the site of the chapel built in the days when the Abbots owned the land. Today, Elvetham Hall is owned by Lansing-Bagnall, manufacturers of electric fork lifts, etc., who operate the Hall as a management training center.

The "call for papers" issued in January 1970 indicated the Conference would deal with "the meteorological environment, service experience and flight trials, simulation techniques, the behavior of materials, mechanisms of erosion including aerodynamics effects, theoretical concepts of collision and damage processes and design philosophy," and that contributions from research in allied areas, e.g., cavitation erosion, would also be welcome. With some amazement I can report that all these topics were covered to some degree, even though there were only thirty papers given. Attendance, about 80, was by invitation. Of those registered, 40 came from the United Kingdom, 19 from the United States, 17 from the Federal German Republic and one each from France, Netherlands, Sweden and Switzerland. About 50% of the papers came from the US.

In some of his writings Derek de Solla Price has stated that progress in various branches of science and technology is made via "invisible colleges." That is, the leaders in a given field keep in close touch with each other and are thus well aware of what is going on in each other's laboratories and can build upon each other's results before disclosures appear in the general literature. A kind of special camaraderie is built up. This certainly seemed the case with the "rain erosionists." Most of the attendees knew each other on a very intimate basis; families had already planned to vacation together after the conference. This was truly a close-knit congenial group. There is a historical reason for this. In the early 60's Dornier System GmbH, in Germany and the RAE were independently engaged in rain erosion research. In 1964 the German organization, as a result of a successful exchange of ideas with the RAE workers, proposed to hold a small conference with limited attendance. This was subsequently done at Meersburg on Lake Constance in 1965, followed by a second international meeting in 1967. And these led to the present meeting. Many of the participants have attended all three meetings.

Several features of the meeting can be clearly delineated. New, highly sophisticated testing equipment has been developed to simulate rain and erosion as well as high-speed photography to photograph the erosion process. The latter has been of great assistance in developing phenomenological descriptions of erosion in terms of a variety of variable parameters. Finally, serious attempts have been made to formulate predictive modelling techniques.

At this point I would like to repeat an observation which I made in a recent ESN item (ESN 24-10;298). In essence it seemed to me that most of the investigators were interested in the phenomenological aspects of the rain erosion. To date, however, outstanding materials experts have not entered the field, and I strongly believe they have a contribution to make as was indicated in a paper by Dr. George C. Gould of General Electric Company.

Finally, I might add that the sunny August climate of rural Hampshire and the beautiful setting of Elvetham Hall provided a fitting atmosphere for this excellent conference. But primary credit for its success should be given to Andrew Fyall (RAE), conference organizer.

THE PAPERS

Below are reviews of about two-thirds of the papers presented. The complete program will be found in the Appendix.

1. Design and Operation of Mach 3 Rotating-Arm Erosion Test Apparatus - Norman E. Wahl (Bell Aerospace Co., Buffalo, N. Y.).

Wahl described a test apparatus employing a "whirling arm" upon which air foil or turbine blade-shaped materials were mounted and subjected to the continuous impact of water or sand. Conditions could be obtained which simulated protracted flight through these environments at subsonic or supersonic velocities up to Mach 3. The size of the apparatus may be appreciated if some numbers are cited. The "whirling arm" had a 9-ft radius and was enclosed in a 26-ft-dia. vacuum chamber embedded in a 36-ft square concrete pit. A 3000-kVA substation was required to operate the unit. Operation was controlled and monitored on a console in another building located 250 ft away from the test chamber. The rotational speed of the blade was 3600 rpm and each pound of weight located at the tip resulted in a centrifugal force of 37,500 pounds. To absorb the heat developed in driving the blade, refrigeration was required inside the evacuated chamber and was provided by flowing liquid nitrogen through cooling panels. Rainfall was simulated through the use of spray nozzles designed in 1950 by the Cornell Aeronautical Laboratory. The drop size and amount of water delivered per unit time was a function of geometry and applied water pressure.

This rain system, with four nozzles operating at a water pressure of thirty psi, produced a rain intensity of 1 inch/hour and 2-mm droplet size. Experimentally, it was observed in the TV monitor that the drops did not break up before they impacted the specimen up to velocities of 2800 ft/sec at chamber pressures of 1/3 atm.

For sand erosion tests the sand particle sizes ranged from 20 to 1000 μm in size. By means of elliptical stainless steel nozzles, air and sand were injected normal to the surface of the test specimen mounted on the blade. The exit velocity (660 ft/sec) of the mixture was controlled by pressure maintained in the vacuum chamber.

The materials selected for initial evaluation at various speeds from 730-2240 ft/sec and 1 in/hr rainfall were based upon the results obtained in previous tests at the Air Force Materials Laboratory and rocket sled tests conducted at the Holloman Air Force Base test facility. For these materials Wahl gave the following results:

a. Thermoplastics

Polycarbonate polymer (Lexan) possessed the greatest resistance to erosion by rain, followed in order by polyphenylene oxide, polymethylomethacrylate, and finally the poorest of the four in this regard, polytetrafluoroethylene (Teflon TFE).

b. Metals

Of the three metals tested (1145 aluminum, annealed electrolytic copper, and 403 stainless steel) 1145-H-19 aluminum being the softest and the most ductile, exhibited the highest rate of erosion. Copper being harder, Rockwell F-62, exhibited greater erosion resistance than aluminum, while tempered 403 stainless steel with a Rockwell hardness of B-95 had the greatest erosion resistance.

c. Plastic Laminates

An epoxy-glass-fabric proved more rain erosion resistant than a phenolic-glass-fabric.

d. Ceramics

Similarly Pyroceram 9606 proved superior to Alumina 753 which was superior to Fused Silica 7941.

e. Elastomeric Coatings

Polyurethane eroded less than Neoprene.

For all the results cited, Wahl gave qualitative and quantitative data accompanied by photographs of the damaged samples. In some cases serious erosion occurred within a few seconds. It was also evident that the nature of the pitting changed with the onset of aerodynamic heating as the velocity was increased from 760 mph to 1520 mph. Typical data, referring to aluminum, are in the table below.

Velocity	730 ft/sec 500 mph	1120 ft/sec 760 mph	2240 ft/sec 1520 mph	2800 ft/sec 1900 mph
Test Duration	90 min	10 min	1 min	1/2 min
Weight Loss	92 mg	69 mg	109 mg	?

2. Rain Erosion Testing in Support of Engine Design - Mr. M. Alderson (Rolls-Royce, Limited).

In a complementary paper to the first, Alderson stated that the problem of damage to component parts by rain erosion has not been significant on existing Rolls-Royce engines with Inlet Guide Vanes and aluminum or titanium stage 1 rotor blades. The introduction into gas turbine engines, however, of higher speeds of the rotor blade tips, sharper leading edges, and present fiber composite materials, which in their unprotected state have a considerably lower erosion resistance than metals, has made necessary an investigation into methods of protecting the components from erosion. The damage to the leading edge of the blade blunts it (reducing the chord) and alters the aerofoil nose shape, with consequent reduction in efficiency. A typical first-stage rotor blade will have a rotational velocity range of 150 to 450 m/sec, root to tip. The air mass flow through a gas turbine engine is approximately 170 kg/m^2, bringing 150 m^3/sec into a Conway engine and 450 m^3/sec into the RB.211 fan engine. Thus in a typical 25 mm/hr rain encounter (with a water content of 1.5 g/m^3) an RB.211 engine can ingest up to 0.7 liters/sec or 540 gals/hr of water. Further, it is apparent that airflow conditions in the inlet duct can cause droplet breakup. Alderson then described a test facility used by Rolls-Royce for studying rain erosion. It will not be discussed here, since the principle of design and operation is not very different from the one described by Wahl, although the Rolls-Royce unit is smaller. Here it might be mentioned that drop size in naturally occurring rainfall is related to the rainfall rate; larger mean droplet size being associated with higher rainfall rates; sizes between 50 μm and 6 mm are quoted, although measurements indicate that sizes larger than 2 mm are rare even in the tropics. Consequently, conditions were adjusted in the facility so that droplets of 1/2, 1 and 2 mm nominal diameter were obtained. It must be appreciated that on a rig with a discrete number of nozzles, the impact of water droplets on the specimen occurs only a few times per revolution; this means that the time interval between successive impacts can be markedly different from that occurring in natural rainfall.

The first series of Alderson's tests were programmed to examine the erosion protection of the first generation of large composite material blades. For comparative purposes, sections cut from new aluminum compressor blades were submitted, for varying periods, to each of the drop sizes. These blades in turn, were compared with the leading edge of a Conway LP1 blade after 20,000 hours' service. A photograph of the latter showed considerable pitting plus large single indentions which Alderson said was caused by debris ejected from the acoustic paneling of the test facility which fatigued during the test. In the case of the commercially pure aluminum test pieces, the degree of damage increased with increased test time. With a blade velocity of 400 m/sec, raindrop size of 1 mm, and rainfall rate of 4 mm/hr, damage comparable to that of the 20,000-hour Conway blade was achieved in the neighborhood of 10 minutes. Alderson next showed photographs comparing a solid titanium leading edge and a metal foil-wrapped carbon fiber composite (Hyfil) blade. The titanium blade suffered considerable damage at the end of 90 minutes; the Hyfil blade showed very little damage. Indeed the Hyfil blade eroded only along the 90° impact line. On the other hand, unprotected carbon fiber composite showed very early failure (1 sec) even at a light rainfall rate of 0.15 mm/hr. A sample of this material was tested then at a rainfall rate of 25 mm/hr, using a drop size of 2 mm. The test was stopped at the end of four seconds, and it was observed that large chunks of material had flaked away. Finally, Alderson gave results which indicated that at least for aluminum a very sharp leading edge increased the rain erosion resistance of a compressor blade.

3. Erosion Behavior of Polymeric Coatings and Composites at Subsonic Velocities - George F. Schmitt, Jr. (U. S. Air Force Materials Laboratory, Dayton, Ohio).

Schmitt's particular interest concerned radome coating materials damaged even at low impingement angles. At present the problems of interest are in the subsonic regime because current aircraft do not operate supersonically, if at all possible, in rain environments. Schmitt described the AFML rotating arm apparatus used for these tests which consists of an 8-ft-dia. propellor blade capable of attaining speeds up to 900 mph at the blade tip where the specimens are inserted. Comparative rankings and modes of failure obtained with the apparatus were borne out in actual flight experience in rain using an F-100F aircraft.

All reinforced plastic materials were shown to require rain erosion protection even at subsonic velocities. Polymeric coatings such as epoxies, polyesters, and amideimides, however, are brittle relative to impacting water droplets which rapidly rupture the film.

Schmitt's investigations demonstrated that elastomeric coatings such as pure polyurethane provide increased subsonic protection over other polymeric coatings. The explanation he gave implied that the stress-strain characteristics and the Hugoniot (shock) response to the loading associated with droplet impact attenuated the stress pulse, thereby protecting the substrate. (In the discussion period, Dr. Andrew F. Conn of Hydronautics, Inc., suggested that an elastic-plastic theory could be given which would give better quantitative agreement with the data.) For thicknesses up to 40 mils, times for failures were approximately 2/3 as long at 600 mph as at 500 mph regardless of elastomer type or method of application. He also indicated that the erosion resistance of a thermoplastic resin was reduced by the addition of reinforcement, whether in the form of conventional glass cloth or chopped fibers (1/4 in. in length). On the other hand, the fracture and brittle behavior of a thermosetting polymer are considerably improved in a rain environment by the addition of reinforcement. Finally, the void content and reinforcement type significantly influence the subsonic rain erosion behavior of organic matrix composites whether uncoated or coated for erosion protection.

4. <u>The Influence of Various Test Parameters on Material Destruction at Drop-Impact</u> - Dr. H. Rieger (Dornier-System GmbH, Germany).

In a very detailed paper Rieger cited the following test parameters as having the strongest effect on rain erosion: test velocity, angle of impact, drop diameter and drop density. Unfortunately, it is difficult to formulate a generally valid functional connection between these parameters and material damage because of (1) insufficient knowledge of the stress distribution in the solid which results from drop-impact, (2) inadequate information concerning the mechanical properties of the solid, and (3) complex superposition of several effects associated with the individual parameters. Thus there may be simultaneous variations in angle of impingement, magnitudes of the normal and tangential components of impulse as well as the number of impinging drops per unit time and per unit area. Running tests on samples of alumina, aluminum, polyethylene, polyurethane and glass placed on a rotating arm and at velocities ranging between 250 m/sec and 400 m/sec, Rieger showed that decreasing the diameter of raindrops increased fatigue life and corrosion effects but decreased the temperature rise at drop impact, the energy absorption by the impact material as well as aerodynamic influences. (Aerodynamic frictional forces not only cause a deceleration of the drops, but also their destruction.) An explanation for these effects is not obvious since one would expect the pressure of impact is independent of drop diameter. Rieger also summarized tests which showed that as the frequency of raindrop impact decreased, the temperature rise due to local heating decreased. A superposition of internal stresses due to mutual impacting droplets results in an increase in the amount of erosion. As the impact frequency is decreased, this effect also decreases, but corrosion effects increase. It is worth noting that water which flows laterally at the impact of drops, forms a protecting liquid film on the specimen. An increase in the density of drops causes an amplification of the water-film's protective role; i.e., an increase in impact frequency decreases rain erosion. Rieger found that by increasing the velocity of the rotating arm large increases in rain erosion appeared for all substances studied, the quantitative relationship depending, of course, on materials parameters. In turn, this velocity dependence of rain erosion was itself influenced by drop size and density. (Much work seems necessary here.) Rieger discussed many other related topics, including for example the role of angle of impingement, and the effects of centrifugal force. Finally, he presented a phenomonologically derived mathematical model to describe the velocity dependence of rain erosion. These topics are covered in detail in his paper to appear in the forthcoming proceedings of the Conference.

5. Rain Erosion Testing from 1 to 6 km/sec - René B. Mortensen (Aerospace Corp., San Bernardino, California).

In this paper Mortensen turned to hypersonic rain erosion studies, indicating that two test techniques are now available: rocket sleds and ballistic ranges using light gas guns as launchers. The monorail rocket sled facility at Holloman has a seven-mile track, offering the possibility of launching and recovering large-size test panels through extended rain fields at velocities as high as 1.98 km/sec (6500 ft per sec). The rainfield section starts approximately 2400 m down the track and extends for 1800 m leaving 6400 m for sled deceleration and recovery. The rainfield consists of a series of vertical standpipes, 2.45 m apart, positioned 2.75 m to either side of the track. Rain nozzles are placed 84 cm above the track and approximately 65 degrees above the horizontal. With a discharge pressure of approximately 6.1×10^4 Newtons/m^2, a rainfall rate of 3.5×10^{-2}mm of water per second is generated on the track. The droplet diameter is nominally 1.5 mm. A storage tank facility of 95,000 liters permits a 25-minute rainstorm to be generated. Actually, with these conditions it is believed that the artificial rainfall corresponds roughly to that encountered over an 18 km distance in a 3.5 X 10^{-3}mm per second (0.5 in/hr) natural rainstorm. The Holloman facility is particularly well equipped to obtain inflight data using high-speed cameras, flash X-ray cameras, etc., but limitations do exist. The first and foremost is the inability to recover vehicles at velocities above 2 km/sec. Another is related to the quality and control of the rainfield.

Higher velocity regimes are provided by ballistic ranges using light gas guns as launchers, capable of launching small models at velocities of 6 km/sec and above. Recently a rain environment capability has been added to the range located and operated by the Naval Ordnance Laboratory at White Oak (J. L. Lankford: Final Technical Report, NOL 1000 Foot Hyper-Ballistic Range Program, Period Oct 1968, Optical Instrumentation and Rain Program, U. S. NOL, White Oak, Md.) The range is 300 m long. The test samples are mounted in conical launch models which are surrounded by plastic sabots. When launched at velocities of 5 km/sec, the models experience peak pressures as high as 2 X 10^8 Newtons/m^2 (30,000 psi). The rainfields are downstream from the blast chamber and are produced by banks of acoustically activated hypodermic needles. Typically, rainfall rates ~ 8.3 X 10^{-4} mm/sec (0.12 in/hr) are produced. Data are gathered through inflight photography using a laser source which permits accurate erosion measurements at the high velocities mentioned. It is still difficult to obtain top quality front-lighted laser photographs when the target materials are dark, but Mortensen showed excellent photographs of a sample traveling at a velocity of 4.93 km/sec where the material was light in color. Each strand was clearly visible and individual erosion craters were easily observed. In general, data reduction is accomplished by reading target contours on blowups of these inflight laser shadowgraphs. An automatic readout card punch telereader is employed. The target nose profiles are then plotted and compared with original profile to determine change in shape and loss in mass. These erosion studies can be made with control of drop size and impact frequency. Mortensen concluded by noting that an improvement would be the incorporation of holography stations which would allow a complete analysis of the actual surface damage. In addition, it would be desirable to incorporate accurate techniques for measuring surface temperature.

6. Erosion Processes - Dr. John E. Field, Mr. John J. Camus, and Mr. David A. Gorham (University of Cambridge, England).

For the past decade the Surface Physics Group at the Cavendish Laboratory, Cambridge, has been publishing their results on liquid/solid impact studies. Field, Camus and Gorham (the latter acting as spokesman) reported on recent work on single-impact erosion processes. The present research of the group concerns the behavior of fiber-reinforced solids, neoprene coatings and polymers under high-velocity impact. Present composite materials do not withstand liquid impact particularly well because a feature of such an impact is the sharp stress peak caused by the initial compressible behavior of the material on impact. In fact, the stress waves produced by impact lead to interlaminar failure. As soon as failure has occurred, the fracture surface reflects subsequent stress waves and further spall fractures result. Once liquid flows between the layers, the erosion rate accelerates near the front surface. Gorham suggested that a possible advantage of a composite system is that stress waves could be attenuated or dispersed by multiple reflection processes. He went on to show that protective neoprene layers on composite systems can be beneficial provided the adhesion between coating and solid is maintained. When the angle of impact was varied, it was demonstrated that most disruption and loss of coating occurs at angles of impact between 25° and 30° of the normal to the surface. For impact velocities of 650 m/sec the front surface of glass fiber resin composite was afforded no protection by a neoprene coating unless the latter was thicker than 1 mm, and 2 mm was required to prevent damage completely. For uncoated specimens upon every impact of liquid, rear surface damage occurred in the form of spall fractures for composites up to 13 mm in thickness. For thicknesses greater than 20 mm, no damage ever occurred on the rear surface. Again, if coatings are to prevent rear surface damage to thinner sections, the coatings must be 1 mm thick and preferably 2 mm. Thus it seems clear that "cushioning" of the impact stresses only occurs once a critical thickness of coating is reached.

For polymers (polymethylmethacrylate) the form of the damage produced by a single liquid drop impact at a velocity of 650 m/sec may be described as follows: There is a critical region enclosed by a ring of heavily eroded material surrounded by many short circumferential cracks. The diameter of the ring corresponds approximately to the head diameter of the water jet. The central region is subjected to compressive stresses during impact and so remains unfractured at the surface. Below the surface occurs a region where high shear stresses exist, and this is manifested by "star" shaped damage at the center. Outside the region of contact tensile stresses cause extensive fracturing: the main ring of damage is a prominent feature, since material has been eroded away by the outflowing liquid. Tensile pre-stressing and compressive pre-stressing in different ways change the shape and extent of the damage and this can be discussed in terms of a Griffith crack model. Gorham then demonstrated that the interesting effect of lowering the temperature to 80°K was to minimize all the features of damage. For example, the polymer became more resistant to rain erosion. This was attributed to increases in both Young's modulus and fracture surface energy. Gorham also discussed the complex effect of predeformation (crazing) on the erosion behavior of polymers.

7. Prediction of Rain Erosion Resistance From Measurement of Dynamic Properties - Dr. Andrew F. Conn (Hydronautics, Inc.)

Conn described an investigation of the basic dynamic properties of rain erosion resistant coatings. He then went on to relate these properties to the ability of the coatings to withstand the random high-strain rate loading of raindrop impacts, often at elevated temperatures due to aerodynamic heating. A split Hopkinson pressure bar apparatus enclosed in a specially designed furnace had been developed earlier to make measurements of dynamic properties up to 1500° F. To the reader who may not be familiar with the Hopkinson bar technique, the attached simplified figure shows the principle of the apparatus Elastic strain waves are transmitted through a system consisting of two long pressure bars with the test specimen sandwiched between them. A projectile impacts the first elastic bar creating the incident strain pulse, E_I. This pulse is partially reflected E_R and partially transmitted E_T upon reaching the specimen. The second pressure bar then receives the transmitted strain pulse, E_T. These strain components are measured by strain gauges (placed fore and aft of the specimen) whose outputs are fed to two fast-rise time oscilloscopes. In early work by other workers it has already been established that the following relationships hold:

$$\sigma_s = \frac{EA}{2A_s} (E_I - E_R + E_T)$$

$$E_s = \frac{C}{L_s} \int^t (E_I + E_R - E_T) dt$$

$$\dot{E}_s = \frac{C}{L_s} (E_I + E_R - E_T)$$

where:

σ_s - average stress in the specimen

E_s - average strain in the specimen

$\dot{E}_s$ - average strain rate in the specimen

L_s - original length of the specimen

A_s - original cross-sectional area of the specimen

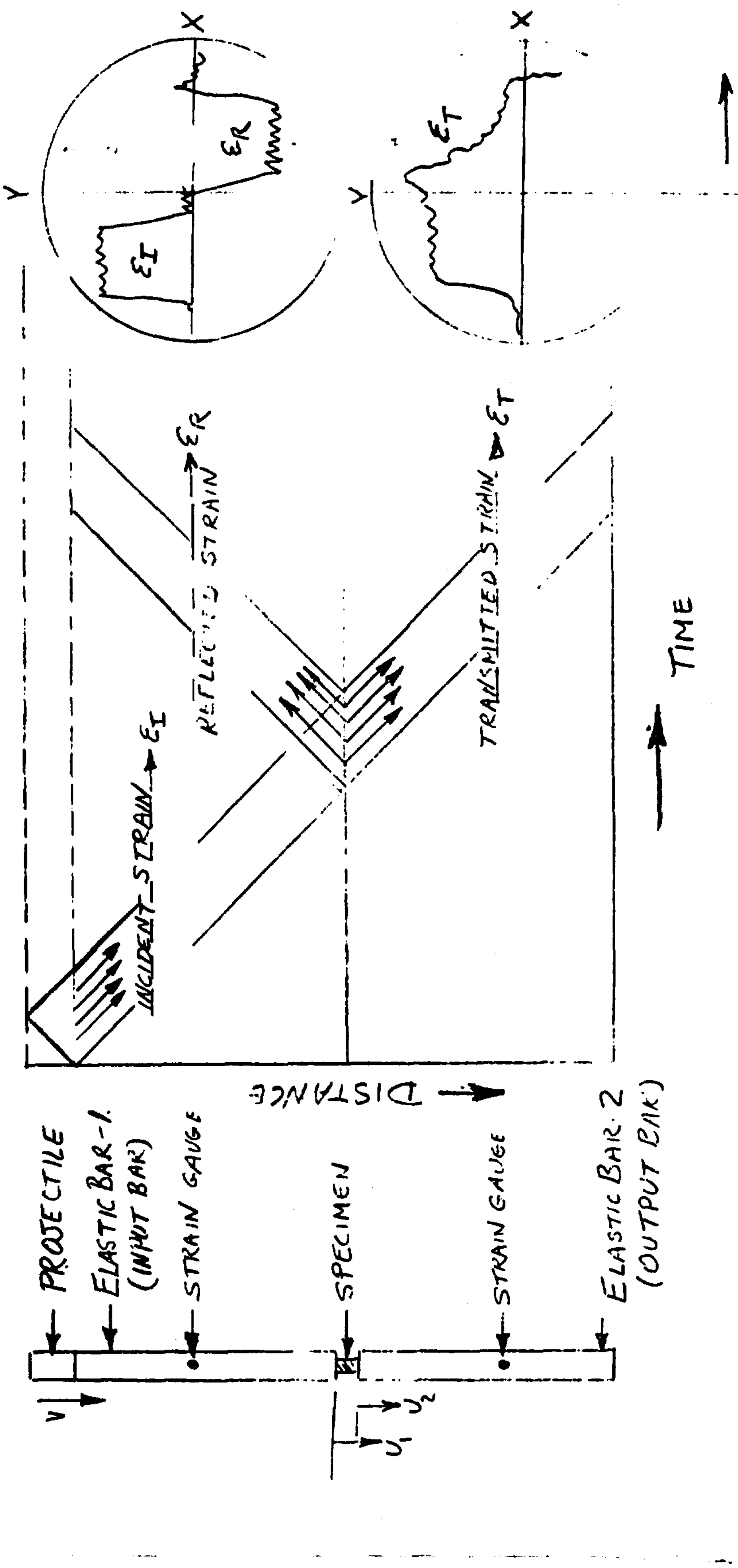
A - cross-sectional area of the pressure bars

E - elastic modulus of the pressure bars

C - elastic wave velocity in pressure bars

t - time

As written above, absolute values of each strain wave component must be used.



PRINCIPLE OF SPLIT HOPKINSON PRESSURE BAR APPARATUS

In a typical experiment, the pressure bars were 30 in. long and 1/2 in. in diameter, while the specimen was about 3/16 in. thick and 3/8 in. in diameter.

Coupled with this apparatus was high-speed photography which was used to record the dynamic deformations of materials during impact. In this manner measurement of the relaxation times after impact loading and the response of materials to multiple impulsive loading could be determined.

A metal (1100-0 aluminum), rigid thermal plastics, and elastomers were investigated. The rigid plastics included an acrylic plastic (polymethylmethacrylate) polyvinyl chloride, and polytetrafluoroethylene. Among the elastomers were included several different polyurethanes plus a neoprene. Conn found that the dynamic response of a polyurethane at strain rates of the order 10^3 sec^{-1} showed stresses three times higher (at comparable strains) than the stresses obtained statically. The lesson, here, obviously is that one can be badly misled if he draws conclusions about rain erosion capabilities based on statically measured data. As did other speakers, Conn emphasized the important influence aerodynamic heating has on the response of coating materials to dynamic stress. Thus a polyurethane was found to be only 1/6 as strong at 250°F as it was at 74°F. Such temperature-induced reductions of a stress-strain curve may be beneficial, if the impact stress does not exceed the tear strength of the coating, since the stress transmitted to the substrate will be proportionately lower. Conn then showed high-speed photographs which in a succession of frames vividly revealed the sequence of compression and relaxation of a soft neoprene coating test specimen in the Hopkinson bar (frame speed 50 μ sec and shutter speed 2 μ sec). He was able to follow the deformation history over several milliseconds; i.e., well beyond the 100-μ sec duration of the applied stress pulse. Even when simulating an extremely heavy rainfall of 4 in/hr at 1000 mph, preliminary studies indicate that the mean period between raindrop impacts is considerably larger than the relaxation time of the material.

From the data obtained above, a dynamic stress-strain curve could be plotted for each material. The slope of the curve yielded the elastic modulus E, which in turn permitted the calculation of the elastic wave speeds $C = (E/d)^{1/2}$ where d is the density. It was next possible to calculate dynamic impedances, $Z = dC$, and show their importance in reducing the raindrop impact stresses. Elastomer coatings were found to have small impedances, and in effect, were able to "give" easily under the impact of a raindrop. Said differently, these materials are able to suffer large, reversible amounts of deformations without being damaged. This ability to minimize the stresses at the area of impact is, in Conn's opinion, a key reason why elastomeric materials, at lower velocities, are capable of resisting raindrop erosion damage. As long as the impact velocities are sufficiently below the level required to fracture the elastomer, little permanent damage is sustained at room temperature except after extremely prolonged exposures.

An important aspect of Conn's presentation was his ability in the case of several rigid plastics to correlate data obtained with the split Hopkinson pressure bar facility and the rocket sled rain erosion experiments of Schmitt, reported above. Finally, Conn demonstrated that for an acrylic plastic its rain erosion behavior can be described by a fatigue curve which consolidates a wide range of testing procedures and rain environments.

8. Evaluation of Ceramic Coatings for Rain Erosion Protection - Prof. J. D. Walton (Georgia Institute of Technology, Atlanta)

In his paper Walton argued that the mechanism of rain erosion is not sufficiently understood to enable the erosion resistance of a material to be determined a priori, based on mechanical and physical property data alone. Further, it is not practical to replace an existing material with one that promises to be more rain resistant, if the original material had been selected for critical functional purposes as would be the case for example with radome materials. From electrical and thermal consideration certain plastics should perform satisfactorily in the Mach 2-3 regime, but are not capable of withstanding typical rain environments. Ceramic coatings are a promising means of providing this additional capability, but successful development of such coatings is extremely complex. Rain erosion resistance of ceramic coatings is influenced by surface finish, surface flaws, thickness porosity, grain size and distribution, modulus residual stresses, internal flows and impurities. These material parameters have not, as yet, been systematically studied with respect to their effect on rain erosion, nor have the roles of the interfaces, method of preparation and application. Needless to say, many of these factors would influence the operation of the radome itself. Clearly then, evaluation of all these parameters, though necessary, would be a large undertaking in view of the above descriptions of the usual tests and facilities. Walton indicated that a single rocket sled test could cost between $5000 and $15,000. He then discussed two alternatives. In the first he described a simple static point load device to determine the load bearing capability of ceramic-coated systems. Unfortunately, however, at present no direct correlation between such tests and the sled tests has been made. In the second, apparently, based on earlier work by Andrew A. Fyall, (RAE), organizer of the Conference, Walton has made considerable progress to show that lead pellets fired by a shotgun provide high velocity impact which can be used to predict the performance of ceramic coating systems in sled tests. The relationship between the two kinds of tests was predicated on the premise that impact pressure was the governing factor in impact damage. Much of evidence supporting simulation is indirect, but appears to be sufficiently valid to permit the use of the shotgun as a valid laboratory screening test.

9. Comparison Between Some Characteristic Parameters of Rain and Sand Erosion - W. Herbert (Dornier System GmbH, Friedrichshafen, FRG)

Damage due to sand erosion can occur when an airplane flies over a desert at a low altitude. It is also possible for such damage to occur when airplanes land or take off. The primary problem concerns the sand erosion which takes place at the compressor blades of the engine. Similar problems, of course, arise for both helicopter engines and their propellers. The primary objective of Herbert's paper was to compare the behavior of materials under conditions of sand and rain erosion. For this purpose, he described a system quite similar to others that had been described consisting of the so-called "rotating" or "whirling" arms on which were fastened samples to be tested. In one cycle it was found that the sample was met by approximately a hundred grains of sand, while in rain erosion tests at the same velocity, only six impacts were observed. In making a comparison between water and sand erosion, Herbert used the same list of variables that his colleague, Dr. Rieger, had used in an earlier talk. He noted, however, that if a grain of sand enters the sample material and remains there, then the energy of both sample and grain will remain with the sample. On the other hand, a grain of sand can also be reflected and thereby be thrown away from the sample. In this case the energy remaining in the sample is found from the impulse parameters of the sand particles. Detailed calculations of this aspect of the problem have not yet been made. Herbert went on to describe studies made on pure aluminum, pure iron, and upon an age-hardened maraging steel. He presented data in the range of velocities from 250 to nearly 700 m/sec, using water and SiO_2 and SiC. In the case of rain erosion, droplets with 1.2 mm diameters were considered, while the grain size for the two sands varied from 0.2 to 0.4 mm. It should be mentioned that according to the Mhos scale, the hardness of SiO_2 is 7.5, while that of SiC is 9.5. Herbert indicated that erosion depended markedly upon hardness. He summarized his work by saying that the pressure which accompanies impact on a sample is much greater for solid particles than for liquid particles. Further, ductile materials undergo a "loading" during sand erosion. The penetration depth of the granule is dependent upon the impact velocity and the ductility of the sample. Such a loading effect is not observed for rain erosion. He also found that the damage due to sand erosion increases approximately with the third power of the velocity, while for rain erosion an increase to the fifth power was observed by himself and other investigators. One reason for the difference of the two exponents may be due to an uneven distribution of pressure in one case and a breakup of the water droplets in the other. In general, the variables that Rieger showed to cause an increase in erosion resistance for water did not change for sand erosion. As a result of his findings Herbert concluded that the methods used in sand erosion studies could be used as a general model for bombardment experiments.

10. Solid Impact - A. Behrendt (Dornier System GmbH, Friedrichshafen)

The objective of this paper was to identify and define the damage mechanism of various materials (in addition to those studied by Herbert) when subjected to erosion due to solids. The materials studied included glass, polyurethane and other synthetic materials. Behrendt noted that the behavior of aluminum when exposed to various kinds of sand particles is characteristic for most metals. After the start of a rotating arm experiment, a greater or lesser increase in mass occurs which can be explained by the fact that the sand particles embed themselves in the surface. Although this loading effect was found for metals and polyurethane, it did not seem to occur for glass and other synthetic materials tested.

11. The Influences of Rain Erosion Damage on Subsequent Fatigue Strength of Materials - R. B. King and N. J. F. Gunn (Royal Aircraft Establishment, Farnborough).

In his introductory remarks, King stressed that heretofore most research on rain erosion has been directed to establishing the "life" of materials and most specimens have either been tested to a predetermined degree of damage or to destruction. Since such degree of damage could not be tolerated in a vital area of an aircraft, an attempt was made to correlate the effect of light erosion, insufficient to reduce the tensile strength appreciably but possibly sufficient to have an effect on the subsequent fatigue life. Therefore, nominal one-inch square specimens were prepared and exposed on the RAE "whirling arm" test rig (already described in the literature) for various periods and were then made into specimens suitable for evaluation in a suitable fatigue testing machine. Finally, one specimen from each batch was tensile tested.

Normal test conditions of operation were 500 mph, in 1 in. per hour rain intensity, with a predominant raindrop diameter of 2 mm. In effect this corresponds to a rain density of 1.16 grams per m^2, and if all the drops were 2 mm in diameter, the specimen would be struck twice per revolution.

The material used for study was RR-58, a high-copper-content aluminum alloy used in the construction of the Concorde because of its high-strength performance and the elevated temperatures experienced in supersonic cruise velocities. The properties of the alloy may be of interest. Its ultimate tensile strength is 5.6×10^4 lbs/in.^{2}, and its Young's modulus is 1.04×10^7 lbs/in.^{2}, while its elongation is 6 % and Brinell hardness ranges between 120 and 135. Specimens were prepared from a milled plate 0.0625 in. thick. Specimens were eroded for periods varying from one to eight hours in the test facility. From these specimens, fatigue specimens were prepared, and these were tested under direct stress conditions, mostly until failure had occurred. Specimens prepared from uneroded material were used as controls. The stress cycle was so arranged that no compressive load was experienced. In summary of this work, the original erosion damage was mostly deformation of the metal surface, as the weight losses were extremely small, varying from 0.15 mg on each face for one hour exposure to 1.90 mg for eight hours' exposure, and there was very little change in tensile strength. Little difference in effect occurred between one and two hours' exposure, each specimen showing a slight deterioration when compared with the controls. Four hours' duration had a more damaging effect, and there was a marked loss in fatigue strength after eight hours' exposure.

12. Water Droplet Breakup in High-speed Airstreams - Arthur A. Ranger (Purdue University) and J. A. Nichols (University of Michigan).

Ranger gave the paper and indicated that water droplets, created by using a vibrating capillary technique, were introduced into the test section of a shock tube. Here the droplet interacted with the convective flow established by the passage of an incident shock wave. In a series of experiments, the initial droplet diameter, convective flow Mach number, and airstream density were systematically varied to obtain results covering a wide range of aerodynamic conditions. Magnificent high-speed photographic techniques, utilizing both image converter and rotating drum-type cameras, were used to photograph the disintegration process in its entirety. The data obtained from the photographs were presented and interpreted to yield such quantities of interest as the breakup time and distance of travel, the drag coefficient, the secondary droplet or residue size, etc. Correlations were presented which indicate that the results can be analyzed in terms of a nondimensional breakup time. In effect, the study indicated that the impact by a strong shock wave is an insignificant element in producing the aerodynamic shattering of liquid drops. The main function of the shock is to produce the high-speed convective flow which is responsible for the ensuing disintegration. Under the conditions of high-dynamic pressure, breakup begins almost simultaneously following interaction with a shock front. A water droplet, which is originally spherical, is deformed into a planetary ellipsoid with its major axis perpendicular to the direction of flow. The shearing action exerted by the high-speed flow causes a boundary layer to be formed in the surface of the liquid. These studies further support the fact that the breakup time is proportional to the drop diameter, inversely proportional to the velocity, and proportional to the square root of the ratio of liquid to gas densities. The studies further reveal a secondary Mach number effect on the breakup time and distance a disintegrating drop travels. Again, mention should be made of the magnificent photographs produced by Ranger.

13. An Investigation of Water Drop Disintegration in the Region Behind Strong Shock Waves - W. G. Reinecke and G. D. Waldman (Avco Corporation, Wilmington, Massachusetts)

Reinecke began by discussing the basic mechanism behind the phenomenon of water drop disintegration in the region behind a strong shock wave in air. He demonstrated that the pressure exerted by the stream caused the drop to be accelerated and flattened in various modes. An experimental program was conducted to determine these modes of water drop disintegration. At very low relative speeds, an oscillatory motion is set up in the drop which eventually produces two drops. At slightly higher speeds, the drop becomes severely deformed into a bag shape and soon shatters completely. At still higher speeds, a continuous mode of breakup is observed in which spray is formed at the periphery of the drop and swept into the wake. Finally, at extremely high speeds, drops have been observed to shatter very rapidly in a mode of breakup distinct from those already mentioned. Reinecke described how relevant dimensionless parameters for these modes were determined experimentally and how the data were then correlated in terms of the parameters. The experimental data were derived from spark shadowgraphs and flash X-radiograms of water drops disintegrating in a shock tube. Radiograms of lead-acetate doped drops permitted the direct measurement of the instantaneous mass remaining unstripped in the original drop. The shock Mach numbers varied in these tests from 3 to 11, initial pressures from 760 to 140 torr, and drop diameters from 0.5 to 2.5 mm. Examination of the shadowgraphs demonstrated conclusively that material was being stripped from the drops continuously at all test conditions in the Mach range cited. At more severe test conditions, a second catastrophic mode of breakup became dominant, and the drop was shattered before all of its material could be removed by stripping. This catastrophic mode of breakup, Reinecke said, is related to the unstable growth of waves on the front surface of the drop caused by the rapid acceleration of the drop by the airstream. In this mode surface waves are observed to grow rapidly until their amplitude is comparable to dimensions of the drop at which point the drop is torn apart. An additional effect which is superimposed on these modes of breakup is the initial flattening of the drop as mentioned above. This is caused by the imposed pressure differential between the poles and the equator of the drop. Because deformation of the drop may effect the breakup process, shadowgrams also were taken at the early stages of the process to determine the rate of deformation.

14-16. A series of three papers were now given by associates of Professor Rudolf Friedrich of the University of Karlsruhe, the Federal Republic of Germany. The first was given by Gunter Hassler and was entitled Time and Mechanism of Disintegration of Large Water Drops under the Influence of Aerodynamic Forces. This was essentially a progress report on erosion caused by the fine mist droplets in steam turbines under conditions of subsonic velocities. The water flowing off the stator blades mostly falls on the suction side leading edge of the following rotor blade. In Hassler's experiments conducted in a special chamber, water drops of 1 to 4 mm in diameter are released periodically and exposed to a horizontal steady stream flow which has a Mach number less than 0.7. The behavior of the droplets after entering the stream is recorded through suitable observation windows by means of slow-motion spark camera or a Stroboscope synchronized with the frequency with which the drops are released. In this work the main parameters are drop diameter, flow velocity, liquid density, density of the steam and surface tension of the liquid drops. These parameters can be varied, and the motion-time behavior is then studied, as well as the erosion time and the dimensions of the residual drops produced by bubble formation. Hassler points out that many stability criteria can be found in the literature, which it would appear would make it possible to predict whether or not a liquid drop would disintegrate under certain aerodynamic conditions. The criteria are usually related to a critical Weber number where the Weber number is defined as the ratio of the inertial energy of the drop to its surface energy. The critical Weber number would be that number for which no breakup occurs. Hassler's work, however, does not show satisfactory agreement with any of the criteria found in the literature. Instead, he finds that the critical Weber number lies between 6 and 14. He shows that three different breakup processes may occur in the test machine considered and that these mechanisms vary as the dynamic pressure increases.

The next paper from Karlsruhe was given by D. Wurz, and was entitled Flow Behavior of Thin Water Films under the Effect of a Unidirectional Airflow of Moderate to High Subsonic Velocities: Effect of the Film on the Airflow. Problems concerning liquid film flow under the effect of a unidirectional gas stream arise in many fields of technology; for example, in conveying liquid-gas mixtures in pipelines, in vaporization apparatus and condensers, in the cooling of reactor-combustion elements and in connection with erosion damage in steam turbines. To handle these problems, data are required with regard to such parameters as: thickness of the film, minimum liquid flow for formation of closed films, the distribution of turbulence and velocity profile, the beginning of drop formation and the size spectrum of drops. Numerous investigations have been carried out on various phases of the problem, but for range of velocities that are rather low, that is, below a gas-phase velocity of 100 m/sec Wurz stated that it was his intention in conducting his experiments to insure that the following conditions were fulfilled as closely as possible, since in fact, they usually have not been fulfilled in the work of others. These conditions were:

a. No exchange of heat or material between the two phases (air and water) considered.

b. Constancy of shear stress at the phase boundary of the liquid flow in the film and of the film temperature over the length and width of the wetted wall.

The range of velocities that Wurz considered extended from 50 m/sec to 280 m/sec. The mean film thickness which he obtained ranged between 14 and 200 [illegible]. Wurz emphasized that there is no general theory concerning any form of the appearance of the film flow and that calculations of compressible, turbulent, single-phase boundary layers have failed so far. The difficulty is considerably increased as the result of the liquid wall which itself is partly turbulent and is constantly changing in form and which finally flows with the film. He showed a remarkable set of photographs demonstrating that this was actually the case. Unfortunately, no details were given of how the photographs were made. The shear stress at the phase boundary was determined experimentally, and from this a mean film thickness was calculated. Additional parameters that he indicated were useful for discussion were the coefficient of resistance, Reynolds number, and the specific liquid flow. The latter is essentially the ratio of the liquid volume flow to the width of the film itself, giving a quantity which has the dimensions of centimeter^2 per second. In this work values of interest for the liquid flow ranged from 0.047 to 0.86. Wurz showed that a simple relationship existed between these parameters and therefore they are useful in describing limitations and criteria for the occurrence of interference waves in the film or the formation of droplets. In the discussion period, he again emphasized that this was a progress report and that certain important aspects of the problem where raised by the audience had not yet been investigated. These concerned the influence of roughness of the wall on the flow properties of the films, stability in terms of time, and other important questions of this nature.

The third paper from Karlsruhe was given by D. Barschdorff and was entitled Droplet Formation, Influence of Shock Waves and Unstable Flow Patterns through Condensation Phenomena at Supersonic Speeds. Using a correction factor of 10^{-3}, classical nucleation theory, beginning with that of Becker and Doering, can describe very well the onset of condensation at the expansion of steam in nozzles with temperature gradients of 1.8 to 6°C/cm, and inlet stagnation pressures of less than 1 bar. Coupling this theory with a suitable droplet growth law, Barschdorff was able to calculate flow patterns at some supercritical heat conditions. He found that the droplet growth rate was actually diminished by the shock wave, and that the calculated droplet radii were between 3 and 6.5×10^{-8} meters. If the condensation zone occurs very near to the nozzle throat, the flow cannot absorb all the produced heat of condensation. The shock wave in this case moves upstream into the subsonic part of the nozzle. No stable shock position is possible there, and the flow becomes nonstationary because a new shock front is formed by the heat addition.

17. Hail Impact Studies - I. I. McNaughtan, S. W. Chisman, and J. D. Booker (RAE).

The object of these studies, which are continuing, is to derive engineering guidance data for the design of hail-impact resistant aircraft structures. In the course of this work, similarities were observed in the behavior of hail to that of water drops during the impact phase. It was stressed, however, that the primary task of this project was the derivation of design data and not an investigation of the impact phenomena itself. Ice projectiles, simulating hail, were fired from a high-pressure gas gun against stationary targets. The gun was capable of firing 12.7 mm, 19 mm, and 25.4 mm dia. hail at speeds up to 900 m/sec. Two shapes of projectile were used--circular and bullet shaped. The bullet-shaped projectile had a hemispherical nose with a cylindrical afterbody and the same mass as the spherical projectile of the same diameter. High-speed photography was used, with camera speeds around 500,000 pictures per second, and the impact phase was photographed in silhouette at right angles to the line of fire and also directly, more or less, down the line of fire. Targets consisted of square plates 0.3 X 0.3 m of an aluminum alloy ranging in thickness from 0.6 to 3 mm and of polymethylmethactylate, ranging in thickness from 6.35 to 25.4 mm. Firings were made at impact angles ranging from 0° to 6° where the impact angle is taken as angle between the line of fire and the normal to the target surface. It was noted that whereas the size of the hail particles can be at least one order of magnitude greater than that of the water droplets used in other studies, the shock wave velocity in ice is only twice that in water. The photographs showed that shortly after impact a high-velocity, lateral splash was initiated and that there were no signs of spalling from the rear surface of the projectile. The photographs also showed that the lateral splash is in the form of an anulus not a continuous disk.

18. <u>The Flow of a Liquid Drop during Impact</u> - J. H. Brunton and J. J. Camus (Cambridge University).

In his introductory remarks, Brunton emphasized that in impact studies, stress is usually placed on average properties, such as pressure over the impact area, the yield strength of the solid, or the strain energy to fracture. Without real success, correlations have been sought between such average properties and the erosion damage of a solid. Generally, however, detailed aspects of the deformation and flow mechanisms are neglected. He therefore examined some secondary processes in the liquid drop which could make a significant contribution. In particular, he dealt with two aspects: cavitation in the impinging drop and high-pressure jetting flow from under the drop. Dealing first with cavitation, he demonstrated that cavitation occurs on the impact surface and within the volume of the drop. This means that for the duration of each impact, some bubbles will be collapsing on or near the impact surface. Even at relatively low impact velocities, some are strong enough to show shock waves under conditions where the main impact shock is too weak to be visible. The speeds of collapse have been estimated to be greater than the impact velocity. The effect is to superimpose on the main impact many minor impacts from the bubbles. These can be expected to contribute to the overall damage. The second aspect of flow discussed by Brunton dealt with the high-edge pressures and velocities. The jetting action on the drop can cause heavy local deformation for the edge of the impact area. He demonstrated that waves could be photographed in soft metals undergoing this type of deformation.

19. Cavitation Damage - J. H. Brunton (Cambridge University)

As early as 1917 Lord Rayleigh had discussed the way in which hydrodynamic pressures arise during the collapse and subsequent expansion of a cavity in a liquid. What is less clear today is just how such pressure gives rise to deformation and erosion of a solid surface in a cavitation field. It is generally agreed that the damage is primarily mechanical. For his studies Brunton produced and collapsed disk-shaped air bubbles which were held in a liquid layer between parallel transparent plates. The plane walls of any bubble allowed events inside the bubble to be viewed during collapse. The disk-shaped bubbles were initially about 3 mm in diameter, and collapse was initiated by a pressure wave from a small detonator exploded inside a tank of water. Tap water which had been allowed to stand for several hours was used, and a vibrating core was driven to produce cavitation. During the experiment, temperatures were kept within the range 20° to 22°C. Brunton's photographs showed several features of interest in connection with the potential damage capability of these bubbles.

To begin with there is the very obvious caving-in of the bubble, an involution which produces a fast-moving slug of water. At the start the collapse is everywhere inwards, but the movement is not uniform. The speed of collapse is greatest at one point on the boundary, and decreases on either side to reach a minimum at the opposite point. The behavior is very unlike that visualized in the spherical collapse of the Rayleigh model.

The collapse of disk-shaped cavities involves a surface with two curvatures, one, the meniscus, being much smaller than the other. The collapse of the former produces very fine filamentary jets at high speed but having little damaging capability. Brunton's studies were made on three different kinds of materials: solid gelatin, annealed aluminum and Perspex. By combining evidence on flow during bubble collapse with the corresponding damage to a solid surface, he indicated that it is possible to recognize the basic processes involved in cavitation damage: 1. impact of the intruding wall of a bubble which attaches to the material, 2. shock wave damage from the implosion, 3. flow against the surface of the material during expansion of the bubble. Brunton summarized this phase of his work by stating that attached bubbles are the most damaging due to impact effects. For detached bubbles, the impact is cushioned by intervening liquid. Brunton also studied damage produced by ultrasonic cavitation on metal-coated plasticene, on single crystals of lead, and on annealed aluminum. He concluded that erosion in an ultrasonic field again is caused by attached bubbles. The behavior of cavities in the intervening liquid is of little importance compared with the mechanisms of attachment, coalescence and anchoring of cavities on the surface. In an ultrasonic cavitational field, the collapse of an individual bubble is not judged to be particularly violent or damaging, but a large number will give rise to the observed erosion pits. The great damage produced by such bubbles is caused by repetitive water hammer impact on the same area of the specimen (18,000 blows per second).

20. The Cavitation Erosion of Stellite and Other Metallic Materials - George C. Gould (General Electric Company, Schenectady, New York).

In this paper a metallurgist's point of view was taken. Gould noted that cobalt base stellite alloys have demonstrated the best erosion resistance of all metallic materials, but that erosion resistance cannot be predicted by strain energy values derived from tensile tests. A strain-indicated phase transformation (fcc to hcp) was observed to occur in several cobalt base alloys under conditions of erosion by cavitation. It is the strain energy absorbed by this phase transformation which Gould believes responsible for the exceptional erosion resistance of stellites. To check these findings, Gould examined a cobalt base alloy L605 which also has good erosion resistance, and found the cause to be the same; namely, an fcc to hcp phase transformation.

21. On the Selection of Modelling Materials to Scale Long-term Erosion Behavior of Prototype Systems - Dr. A. Thiruvengadam (Catholic University of America, Washington, D. C.)

Modern high-speed, hydrodynamic systems usually are required to operate trouble free for more than 10,000 hours. The current practice is to select the most erosion-resistant material that meets the structural and cavitation requirements economically. The recent trend is towards higher operational speeds, but at such speeds the intensity of erosion at localized areas has, in some cases, overcome the erosion resistance of even the most resistant materials. In this important paper, Thiruvengadam emphasized that such situations could be avoided in future designs if one could estimate the level of intensity of erosion at the designing stage itself by means of model tests. This necessitates a development of modeling techniques to verify the proposed design changes in the laboratory. There are many problems to be solved before any acceptable modeling technique is established. One problem concerns the relation between resistance of material used in the laboratory model and that used in the prototype system. Assuming that the hydrodynamic conditions may be simulated in the laboratory to produce the same intensity of erosion, it becomes essential to use a weaker material in the laboratory model so that the testing time can be reduced to an economically acceptable value. Therefore, one of the primary objectives that Thiruvengadam had was to explore this possibility. In his view the erosion history of a material may be divided into four periods: incubation, acceleration, deceleration, and steady-state. Clearly, if the relationship between various materials during the four erosion periods can be quantitatively established, then it is, indeed, possible to conduct experiments in the laboratory in a shorter time period, using a weak material and to infer the behavior of more resistant materials in the field. As an example, it is possible to consider the relationship between the rate of erosion and the exposure time in a quantitative manner for a range of materials. The selection of materials for the model will be governed by several requirements, such as structural strength, environmental effects, reproducibility of results, and techniques employed in the manufacture of the models in addition to considerations involving the test procedures. With this as a basic philosophy, Thiruvengadam reduces pertinent erosion data to normalized dimensionless parameters, making it possible to compare the behavior of various materials for various exposure conditions.

APPENDIX

PROGRAM

TUESDAY, 11 AUGUST 1970

Welcome and Opening of Conference by Sir Morien Morgan, C.B., Director of the Royal Aircraft Establishment.
Introductory Remarks by Mr. G. A. Earwicker, Conference Chairman.

Session I

Chairman - Dr. R. Noel C. Strain, Assistant Director (Organic Materials) Ministry of Technology, London

Design and operation of Mach 3 rotating arm erosion test apparatus	Mr. Norman E. Wahl Advanced Materials Div. Bell Aerosystems Buffalo, New York, USA
Rain erosion testing in support of engine design	Mr. Max Alderson Rolls Royce Ltd. Hucknall, Notts.
Erosion behavior of polymeric coatings and composites at subsonic velocities	Mr. George F. Schmitt,Jr. U. S. Air Force Materials Laboratory Dayton, Ohio, USA
Investigations of the influence of various parameters on rain erosion	Dr. Horst Rieger Dornier System GmbH Friedrichshafen Bodensee Federal German Republic
Rain erosion sled testing from Mach 5 to Mach 18	Dr Rene B. Mortensen Director, Hardened Re-entry Systems Aerospace Corporation San Bernardino, Calif.,USA

Session II

Chairman - Dr. Hermann Oberst
Farbwerke Hoechst AG.
Frankfurt (Main), Federal Republic of Germany

Erosion processes: (i) Fibre reinforced materials (ii) Effect of surface topography	Dr. John E. Field Mr. John J. Camus and Mr. David A. Gorham Dept. of Physics, Cavendish Laboratory, Univ. of Cambridge

Prediction of rain erosion resistance from measurements of dynamic properties	Dr. Andrew F. Conn Hydronautics Incorporated Laurel, Maryland, USA
Development of ceramic coatings for rain erosion protection of fibreglass substrates	Mr. Jesse D. Walton, Jr. Chief, High Temperature Materials Division Georgia Institute of Technology Atlanta, Georgia, USA
Comparison of some characteristic parameters of rain and sand erosion	Herr Werner Herbert Dornier System GmbH Friedrichshafen Bodensee Federal German Republic
The influence of rain erosion damage on the subsequent fatigue strength of metals	Mr. Roy B. King Materials Department Royal Aircraft Establishment Farnborough, Hampshire

WEDNESDAY, 12 AUGUST Session III

Chairman – Dr. Olive G. Engle
Research Institute
University of Dayton

Water droplet breakup in supersonic airstreams	Dr. Arthur A. Ranger Assistant Professor School of Aeronautics Astronautics & Engineering Sciences Purdue University Lafayette, Indiana, USA
An investigation of waterdrop disintegration in the region behind strong shock waves	Mr. W. G. Reinecke and Mr. G. D. Waldman Senior Consulting Scientist Applied Technology Div. AVCO Corporation Wilmington, Mass., USA
Drop breakup in accelerating and decelerating airstreams	Dr. Harry B. Dyner and Mr. Jacques A. F. Hill (Head of Aerosciences Dept.) Mithras Cambridge, Mass., USA

(1) Time and mechanism of disintegration of large drops under the influence of aerodynamic forces	Professor Dr-Ing Rudolf Friedrich Lehrstuhl und Institut für Thermische Strömungmaschinen Universitat Karlsruhe Federal German Republic with Dipl-Ing Gunter Hassler
(2) Droplet formation from liquid films caused by an airflow at high subsonic velocity	with Dipl-Ing Dieter Wurz
(3) Droplet formation, influence of shock waves and unstable flow patterns through condensation phenomena at supersonic speeds	with Dr-Ing Dieter Barschdorff
Hail impact studies	Ian I. McNaughtan Stanley W. Chisman and John D. Booker Engineering Physics Dept. Royal Aircraft Establishment Farnborough, Hampshire

Session IV

Chairman - Dr. John Brunton
University of Cambridge

On the transient response of a droplet to a suddenly applied pressure distribution	Mr. Peter Simpkins and Dr. Edward Y. Harper Engineering Physics Dept. Bell Telephone Laboratories Whippany, New Jersey, USA
Cellular model of erosion rate	r. Olive G. Engel search Institute versity of Dayton O..., USA
The flow of a liquid drop during impact	Dr. John H. Brunton University Engineering Department with Mr. John J. Camus Cavendish Laboratory University of Cambridge
On the role of material micro-structure in erosion phenomena	Dr. Chi-Hung Mok Solid Mechanics Laboratory Re-Entry & Environmental Systems Division General Electric Company Philadelphia, Pa., USA

Rain erosion of aluminum at velocities of 730-2240 ft/s	Dr. J. W. Morris and Mr. C. H. Bates Advanced Materials Div. Bell Aerosystems Buffalo, New York, USA

Session V

Chairman - Professor Frederick G. Hammitt
University of Michigan

On the selection of modelling materials to scale long-term erosion behavior of prototype systems	Dr. A. Thiruvengadam Associate Professor of Mechanical Engineering The Catholic University of America Washington, D. C., USA
Cavitation damage	Dr. John H. Brunton University Engineering Department University of Cambridge
Formation of time dependence of cavitation erosion and the effect of some material properties	Mr. J. Tichler and Dr. A. W. J. de Gee Metaalinstituut TNO Delft, The Netherlands
The cavitation erosion of stellite and other metallic materials	Dr. George C. Gould Metallurgy Applied Research Division General Electric Company Schenectady, New York, USA
Impingement and cavitation erosion tests on rain erosion materials	Professor Frederick G. Hammitt et al. College of Engineering The University of Michigan Ann Arbor, Michigan, USA

Session VI

Chairman - Dr. Gunter Hoff
Dornier System GmbH
Federal German Republic

Influence of particle size and velocity on crater depth	Dr. Robert J. Sullivan et al Consulting Engineer Aeromechanics & Materials Laboratory General Electric Company Philadelphia, Pa., USA

Solid impact	Herr A. Behrendt Dornier System GmbH Friedrichshafen Bodensee Federal German Republic
Design and development of RECAP, an aerodynamic device for rain-erosion protection of optical domes on missiles	Mr. Richard H. Adams Mithras Cambridge, Mass. and Mr. Max R. Smith U. S. Naval Weapons Center China Lake, California, USA
Military service experience and design philosophy in flight vehicle rain erosion	Mr. George Tatnall Naval Air Development Center Johnsville, Pa., USA
Rain erosion - design data for rain encounters	Mr. G. Daniel Sellers Chief Structural Airworthiness Engineer British Aircraft Corp. Ltd. Filton, Bristol

CONFERENCE SUMMARY AND CLOSING SPEECHES

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Office of Naval Research, Branch Office London, England	2a. REPORT SECURITY CLASSIFICATION 2b. GROUP

3. REPORT TITLE

Third International Conference on Rain Erosion and Associated Phenomena

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

N.A.

5. AUTHOR(S) (Last name, first name, initial)

SALKOVITZ, Edward I.

6. REPORT DATE 20 October 1970	7a. TOTAL NO. OF PAGES 27	7b. NO. OF REFS

8a. CONTRACT OR GRANT NO. N.A. b. PROJECT NO. c. N.A. d.	9a. ORIGINATOR'S REPORT NUMBER(S) C-25-70 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) N.A.

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES N.A.	12. SPONSORING MILITARY ACTIVITY N.A.

13. ABSTRACT

The Third International Conference on Rain Erosion and Associated Phenomena at Elvetham Hall near London, England, on 11-13 August 1970 under the sponsorship of the Royal Aircraft Establishment, Ministry of Technology. The 30 papers delivered covered a variety of pertinent topics. Equipment was described to test rain, hail and sand erosion damage to aircraft components flying at sub- and supersonic velocities. Materials were evaluated in terms of such meteorological exposure, and appropriate modeling techniques were described. Analyses were given of various factors influencing rain erosion resistance and investigations were conducted on the nature and consequences of raindrop disintegration on impact.

DD FORM 1 JAN 64 1473

UNCLASSIFIED

Security Classification

UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rain erosion						
Sand erosion						
Cavitation impact						
Supersonic phenomena						
Metals						
Ceramics						
Polymers						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (*corporate author*) issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (*either by the originator or by the sponsor*), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through
_________________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through
_________________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through
_________________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (*paying for*) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (*TS*), (*S*), (*C*), or (*U*).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, roles, and weights is optional.

UNCLASSIFIED

Security Classification