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FIFTH INTERNATIONAL CONFERENCE ON EROSION BY LIQUID AND SOLID IMPACT, CAMBRIDGE

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The Fifth International Conference on Erosion by Liquid and Solid Impact was held at Cambridge University, 3-6 September 1979. ~~The general chairman was~~ the renown Prof. David Tabor. The major topics treated during the meeting were (1) particle-caused erosion of brittle solids, (2) of ductile solids and (3) cavitation erosion of materials. The meeting provided a useful forum for new ideas on all aspects of erosion, as well as opportunities to couple parallel work underway across the world.

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FIFTH INTERNATIONAL CONFERENCE ON EROSION BY LIQUID AND SOLID IMPACT, CAMBRIDGE

The Fifth International Conference on Erosion by Liquid and Solid Impact (ELSI-V) was held at Cambridge Univ., 3-6 September, 1979. The past four ELSI conferences dealt primarily with rain erosion but this fifth conference included basic and applied work on solid impact, cavitation erosion as well as various aspects of liquid impact and erosion. Prof. David Tabor, the conference chairman, outlined the conceptual framework of the meeting in these words: "Erosion usually involves the repeated application of high local stresses. In many cases, the individual stresses are applied for very short intervals of time. To understand the way in which a given material fails by erosion it is therefore necessary, in the first instance, to study its mechanical properties under the eroding conditions. This often turns out to involve plastic deformation, adiabatic shear, or brittle fracture. Clearly the conditions determining the ductile-brittle fracture transition are of major importance. Secondly, we need to be able to analyze the stress situation during erosion, not only because it may indicate how and why the materials fails, it may also provide ideas for reducing erosion by modifying the geometry of the body or the composition of its surface. Finally, and best of all, it is desirable to watch erosion while it actually occurs...".

Tabor speaks as one who, together with the late Prof. Bowden, did classic work on friction, wear and lubrication (*ESN* 33-6:231). Their work included important research on contact stresses, hardness, elastic deformation and surfaces. All these areas received significant emphasis in ELSI-V.

The contributors to the conference came from over 15 countries around the world and were greeted by Tabor in English, Arabic, Hebrew, Japanese and Russian. The over 160 participants came from many more lands. They represented fields as varied as mechanical engineering, tribology, and the materials sciences, applied mathematics, physics, meteorology, chemical engineering and metallurgical engineering. These participants, with their varied backgrounds and their emphasis on industrial, academic or governmental interest, enriched the interdisciplinary atmosphere of the conference. In large measure, the presentors themselves were doing leading work on erosion.

The conference was held at an opportune time. It had been five years since the preceding conference and significant work had been done since then on theory, materials response to impact, test facility development, surface analysis and numerical methods, experimental observations, applications, and methods of reducing erosion effects. Interest in the topic has increased owing to the development of areas such as coal conversion, electromagnetic transparencies, and turbomachinery. No other meeting in recent years has pulled together this broad spectrum of activities on erosion.

The style in which the meeting was run was superb. Facilities for lectures, discussions, lodgings, and meals were pleasant and in close proximity to each other. An overwhelming majority of the authors met the deadline for publication. Thus, it was possible to read, or scan, papers before they were presented, and to pay close attention to each presentation. Unfortunately, the proceedings in their present form will not be part of the archival literature. The lack of plenary lectures to provide concise background information was a disappointment. The sessions were chaired by knowledgeable people who often acted as leaders of lively discussions. Finally, there was much time for individual discussions during breaks in the schedule.

This attendee came away from ELSI with several strong impressions. One was that basic understanding of erosion processes generally has progressed markedly in the past five years. Fundamental understanding is most advanced for solid particles impacting upon brittle solids. However, there is need for more examination of impact-target interactions in their earliest stage. Relationships also have been developed for damage velocity threshold and materials removal rate, both in terms of materials and impacter properties. Similarly, there has been progress in basic understanding of the damage threshold for liquid particles impacting brittle solids, although not for materials removal. However, comparisons still need to be drawn between mechanisms of damage owing to water-drop impact on pristine and on multiple-particle impacted surfaces.

Few unifying basic ideas seem to be developing as yet in erosion of metals. The most useful framework for treating particle erosion of these materials still seems to be that of I. Finnie, developed well over ten years ago. One is left with a strong impression that many approaches to the problems which are currently being proposed are in competition with each other. Several investigations conducted on rather ductile solids were concerned with 90° impacts, yet phenomena near 25° impingement angle are also important from the viewpoint of maximum materials removal and/or damage. It would be interesting and important, too, to see more erosion work done on higher-strength and higher-hardness alloys, both for practical reasons and to obtain a better understanding of the process.

The situation is somewhat different regarding cavitation erosion. Much work seems to have been done about cavitation mechanics and stress levels developed from bubble collapses and jetting effects. There has also been a significant amount of materials screening under cavitation conditions. However, a careful and thorough understanding of the mechanisms of materials damage and materials removal for the cavitation situation has yet to be developed. One can conclude from the proceedings of this meeting, that the fluid dynamics and solid mechanics and materials science approaches are not yet well enough integrated to understand mechanisms of materials removal or to propose predictive models for cavitation erosion.

All across the erosion research field, it appears that more *in situ* measurements would be desirable. Much more attention must also be paid to trying to understand what the various test methods, from single particle impact through to flight tests, really do to the materials being examined. Furthermore, ranking and screening schemes have not been fully evaluated as to the phenomena and mechanisms involved. We need a sounder understanding and more careful examination of modes of loading of various research, screening and ranking schemes in order to make maximum and proper use of data comparisons. There is also reason for concern about an apparent failure in some investigations to examine impact and erosion phenomena in poorly characterized materials. An attitude sometimes held even now is that an equivalent property defines equivalent materials! Finally, numerical methods workers need more physically determined data to keep oriented to physical reality.

Approximately 75 papers were presented in 14 sessions during the four days of the conference.

Seven papers were presented in the session entitled "Liquid Impact: Theoretical, Pressure Measurement." Those by Lesser, and by Field, Lesser and Davies dealt with the complex situation of the early stages of liquid-solid impact. The first paper proposed a theory for the fluid mechanics of the impact of rounded front liquid drops with a rigid surface. For collisions on the order of 300 m/s and below, the resultant shocks sweep over the liquid faster than major distortion of the liquid can occur. Also, the contact zone can be treated as quasi-incompressible. Although boundary conditions were simplified, some useful results were obtained for crop collision problems.

The second paper gave the results of a study of the impact of a solid with a two-dimensional wedge of liquid. This wedge geometry maintains a constant angle between the liquid and solid interface which simplifies the theoretical analysis. In the experimental work on two-dimensional liquid shape, it was found that very small changes in contact surface inclination can produce high pressure pulses. This is likely to occur in practice, since most liquid surfaces are not perfectly smooth. Thus, multiple-pulse generation at local sites can be expected routinely and needs to be factored into explanations of liquid impact erosion.

A.G. Evans (Univ. of California, Berkeley, and California Research and Technology, Inc., Woodlands Hills, CA) presented a paper entitled "Impact Damage Thresholds in Brittle Materials Impacted by Water Drops." This important study was a combined analytic and numerical approach, designed to obtain solutions for impact stress fields and dynamic stress intensity factors. Expressions for the damage threshold were derived from these solutions. The threshold was taken as the activation of pre-existing surface cracks. Their activation depends upon their location relative to the impact site and three important target parameters are fracture toughness, elastic wave velocity, and pre-existing flaw size. Experiments concerned with thresholds were difficult to perform. They were useful, however, for defining conditions under which pre-existing cracks will propagate. Damage in brittle solids is well-described by the criterion of stress intensity factor K, reaching the critical value, K_c. Time dependent effects were seen for crack opening, suggesting that the pulse duration of the stress ahead of the crack must be slow enough for crack growth to occur. In other words, the smaller the crack is, the larger will K be, but the stress wave may go by a crack too rapidly for K to reach K_c. The stress intensity factor reaches a maximum after the applied stress reaches a maximum; this is reflected in the time that it takes for cracks to open. It was also found that for small cracks, K increases to a maximum value as water drops grow larger, but can drop off for larger cracks. In short, large cracks can be less effective for failure than smaller cracks.

The threshold value of K is important because it is the condition that must be designed to. The relation:

$$V^3 = \frac{\lambda (K_c^2\ C)_t}{(r\rho^2\ C^2)_p}$$

was developed, where V is the threshold impact velocity of the particle, λ is a constant, K_c is the critical stress intensity factor for threshold damage, r is the radius of the particle, and C is the wave velocity in the target or drop. In limited experiments under similar conditions, V for ZnS was found to be in the 100-200 m/s regime, compared with values for Si_3N_4 of 500 m/s.

The work done by Evans and his associates indicates that there are several methods for making improved materials (i.e., with higher impact damage thresholds). They include: (1) Tailoring the flaw sizes to a very narrow size distribution; (2) Developing surface compressive stresses; (3) Maximizing the ratio K_c/C via microstructural modification (C is that of the drop. These three suggestions have yet to be broadly verified across several classes of materials. If these three suggestions can be verified for several classes of materials, then processors will have clear design guidelines.

M. Rosenblatt's (California Research and Technology, Inc., Woodland Hills, CA) presentation, "Numerical Simulations of Ceramic Target Response to Water Drop Impacts Including Effects of Surface Flaws and Pores" was based upon a non-analytical approach as well as on prior numerical works to set pressure boundary conditions. Water drop impact on ceramic targets generates a tensile stress wave with a steep near-surface gradient. Because of this, the depth of surface flaws controls crack activation. A large flaw can modity the stress field so that crack activation near the flaw may be suppressed.

The second part of this investigation involved a water drop hitting a surface pore. When this happens, crack formation and growth is enhanced, because stress wave effects accelerate the free surface of the water as it flows into the pore. As a result, on-axis water hits the pore bottom with a velocity much higher than that of initial impact, and a relatively large pressure pulse occurs. The resultant tensile stresses at the bottom of the pore (simulated in silicon nitride material) are large and last long enough that failure of silicon nitride at the pore bottom is possible.

It is important to note that numerical techniques as used by Rosenblatt, et al., are very valuable to develop general understanding of complex phenomena, especially when detailed phenomena cannot be controlled or varied experimentally.

Several other papers were included in this session. "Mechanisms of the Initiation of Erosion of Lithium Fluoride by Water Drop Impacts," by R. Hoagland (Battelle Memorial Institute, Columbus, OH) described deformation processes occurring due to droplet impact. An interesting aspect of the work was that the properties of the LiF single crystals (flow strength and fracture toughness) were varied widely by gamma-irradiation (10^6R, 10^7R). The dislocations produced were easily shown by etch-pit methods. It was concluded that very high pressures were produced in a small fraction of the impacts. "Pressure Distribution Driving Drop Impact," by M. Rochester (Department of Engineering, Cambridge Univ., UK) described work on the impact of 5 mm diameter water drops on solids. The pressures generated were as large as 2.5 that of the water-hammer pressure, which means that the yield stress of some tough materials would be exceeded at velocities as low as 200 m/s. In addition, the high velocity jets flowing from under the drops could hit grain boundaries exposed by the impact. Very high stresses tangential to the surface occur in these impacts and could be large enough to remove materials from the surface. Rochester also found that the high pressures generated lasted longer and covered a greater area than previously thought. This could lead to greater damage.

The session entitled "Liquid Impact: Material Response" covered a range of materials including polymers, ceramics, metals and composites.

"Single Water Drop Impacts on Polymethlmethacrylate," by W. Alder, (Santa Barbara, CA) was a review paper. The material (PMMA) has been used advantageously as a good post-test record of damage produced by single drops of water at subsonic and supersonic velocities. It was found that quantitative agreement existed between measurements of dimensions of the characteristic depressed annulus in the range 200-700 m/s. Alder's radii of the undamaged central region, determined experimentally, agree with predicted values. This comes from the condition that the rate of expansion of the central zone is equivalent to the shock-wave velocity in water. At 600 m/s, short circumferential cracks about 5 micrometers long formed as a ring going into the interior of the specimen. For a 1.9 mm drop the central zone was no longer well defined at this velocity. This is in contrast to lower velocities at which the central zone is clearly integral. In general, the circumferential crack rings were found to broaden and deepen as the velocity was increased.

J. Hackworth (Bell Aerospace Co., Buffalo, NY) presented "A Mechanistic Investigation of the Rain Erosion of Infrared Transmitting Materials at Velocities to Mach 2." The materials examined were ZnSe and ZnS (both formed by CVD process), and single crystal Si, MgF_2, $MgAl_2O_4$ and α-Al_2O_3. In a 2 mm drop, fracture occurred upon impact at a unique threshold velocity for each material. When velocities greater than the threshold value were used, a complete ring fracture formed around a central uncracked area. Annular patterns were shown by ZnSe and ZnS. Si and MgF_2 showed square patterns (4-fold symmetry), spinel exhibited equilateral-triangular patterns [3-fold symmetry about (111) direction], and sapphire gave hexagonal patterns (6-fold symmetry). Once a region was damaged and showed ring fractures, subsequent impacts had little effect. Predictions of field damage from small rain drops were greater than the erosion damage measured.

Threshold values found for fracture are presented below:

ZnSe	137-152 m/s
ZnS	175 m/s
Si	274 m/s
MgF_2	274-320 m/s
$MgAl_2O_4$	396 m/s
α-Al_2O_3	457-533 m/s

General features were observed for all specimens. Transmittance was most sensitive to damage at shorter wavelengths (2.5 μm). The transmittance drop was nearly linear with exposure time in the range 2.5-10 micrometers.

The paper, "Liquid Impact Erosion of Structural and Window Materials in the Velocity range up to 1000 m/s" was authored by E. Steinheil and R. Schmidberger (Dornier GmbH, Friendrichshafen, FRG), who investigated infrared-transparent glasses (quartz glass, coated calcium aluminate) in a rotating-arm test facility for rain erosion resistance above Mach 1.5. They also studied sapphire under similar conditions, and found that transparency was reduced for the quartz glass well within the damage incubation period, and that fracture occurred before weight loss at 650 m/s. For coated calcium aluminate glass, transparency dropped rapidly at 400 m/s because the coating was eroded, and then increased until the base glass was damaged. After 10 seconds the specimen fractured at 500 m/s. For sapphire, transparency decreased slightly during damage incubation. However, at 800 m/s the sample fractured at 10 seconds.

The erosion resistance of the polymers studied was very poor above 500 m/s. This was not improved by use of polyurethane coatings. Both glass-reinforced plastic and graphite-fiber-reinforced epoxy composites were evaluted.

Metals evaluted were a maraging steel in the hardened and non-hardened states, an aluminum alloy, and a titanium alloy. The metals, in order of decreasing erosion resistance (up to Mach 3) were aluminum, titanium, non-hardened and hardened steel.

"Rain Erosion of Slip-Cast Fused Silica" by D. Balageas (Office National d'Etudes et de Recherches Aerospatieales, Chatillon, France) was on evaluation of slip-cast fused silica (SCFS). The material was evaluated in four different whirling arm rigs in which velocities varied from subsonic to high supersonic. Impingement angle varied from normal to 15°. A phenomenological law was formulated which held for incidence angles down to 19°. It was demonstrated that for the variety of high-purity SCFS examined, neither a silicone-resin impregnant nor a chromium-oxide coating improved erosion resistance. Roughness due to erosion was found to be greatest for larger drop diameters and to decrease as velocity increased. This consideration of surface roughness or random materials is important, because it leads to an increase in convective-heat transfer within the boundary layer and changes the location of the laminar-turbulent transition.

Prof. J. Field et al. (Cavendish Laboratory, Cambridge, UK) authored the review paper, "Liquid Jet Impact and Damage Assessment for Brittle Solids." Improved nozzle designs which have made reproducible small-diameter jets possible were achieved at the laboratory. The group has used the smaller jets to simulate spherical-drop impact down to drops 2 mm in diameter. A residual strength measurement method was developed for measuring post-impact strengths. Hot pressed-silicon nitride was found to have very high unimpacted strength, a high damage threshold velocity, and relatively small strength decrease above this. Zinc sulfide and zinc selenide were examined as well, and found to exhibit post-impact features similar to other brittle solids.

E. van Rensen, H. Leis and H. Schröder contributed the paper, "Rain Erosion Damage of Boron Aluminum Composite Materials." Boron fibers coated with SiC (US made or B_4C (of German-French origin) were evaluated up to 650 m/s. The West German Researchers are interested in B/Al over graphite/plastic due to higher temperature capabilities, better erosion resistance, higher electrical conductivity and higher shear strength at brazes to the structure. Due to its very good interlaminar shear strength, the B/SiC in plasma-sprayed aluminum, in the TO or T6 state, gave much better erosion resistance than did the B/B_4C material (nearly that of parent aluminum).

Two papers in this session, "The Subsonic Rain Erosion Response of Composite and Honeycomb Structures" by Schmitt, Jr. (Wright-Patterson Air Force Base, OH) and "Influence of Fiber Loading on the Rain Erosion Behavior of Polytetrafluorethylene (PTFE) by K. Letson (Redstone Arsenal, AL) were concerned with screening of materials under multiple-drop impact conditions. Schmitt presented much subsonic data and an important conclusion; namely, that increases in elastomeric polyurethane of fluorocarbon coating coating thickness up to 1/2 mm did not give advantages in performance in comparison to the 1/4-mm coatings. The only thin-skin structure which held up to 223 m/s rain impact was a sandwich of 0.1-mm quartz cloth over a syntatic epoxy resin-glass microballoon material. Letson's experiments were conducted on a Mach 5 sled. The PTFE contained different amounts of aluminum silicate fibers, glass fibers, and mixtures between them. Rain erosion rate was found to decrease with increasing fiber content, and glass was superior to aluminum silicate fibers.

Session Four, "Liquid Impact: Test Facilities, Turbines" was comprised of the following: "Conclusion from the Interlaboratory Test Program with Liquid Impact Erosion Facilities," (F. Heyman, Westinghouse Electric Co., Philadelphia, PA); "Erosion Testing On Rails" (R. Mortensen, Aerospace Co., Los Angeles, CA); "Rain Erosion Studies in the S3-MA Transducer Wind Tunnel at ONERA" (C. Armand and G. Fugain, ONERA); "A Contribution to the Erosion-Resistance of Turbine Blade Materials" (M. Orna and Z. Ruml, Skoda, Pilten, Czechoslovakia); "On the Erosion Prediction of Steam Turbine Blading" (J. Kryzanowski, Z. Szprengiel, and B. Weigle, Institute of Fluid-Flow Machines, Goańsk, Poland); "Erosion and Erosion-Corrosion of Metals" (A. Coulon and G. Thauvin, Alsthon Alantique, Belfort, France). Heymann's report on the round robin among liquid impingement facilities presented erosion resistance and incubation resistance rankings of materials including Stellite 6B, stainless steel 316, nickel 270, aluminum 6061-T6, aluminum 1100-0, Neoprene and Plexiglass-55. Predictive accuracy for erosion rates was found to be superior to that for incubation times. Mortensen's and Armand's papers were mostly concerned with range, instrumentation and equipment information for testing erosion of materials and components in rain or dust environment. An order of magnitude of time to destruction for above-supersonic velocities can be measured which correlates with real lifetimes of components in flight. Orna presented data on the erosion resistance of steam turbine alloys up to 600 m/s. Kryzanowski's work on similar materials had to do with the effects of superposition of droplets. Coulon reported on the great concern his company has for erosion-corrosion in nuclear steam turbines. Chrome and cobalt do increase corrosion-erosion resistance. It was observed that dissimilar metals in contact with one another show increased susceptibility to corrosion-erosion.

The session, "Solid Impact: Theory; Brittle-Ductile Transition," was led by B. Hockey and S. Wiederhorn, (National Bureau of Standards, Washington D.C.) with a paper of great clarity and importance, "Erosion of Ceramic Materials; the Role of Plastic Flow." The paper presented evidence for plastic flow during the erosion of brittle solids by solid particles. Studies of microdeformation that accompanies erosion, have increased understanding of the erosion of ceramics. Plastic flow was studied by optical and scanning electron microscopy of single particles sites, by investigation of erosion rate as a function of impact angle, and by examination of impact sites by transmission electron microscopy. Erosion models have been developed for brittle solids which recognize the important role of plastic deformation. Several theories were summarized which include elastic-plastic erosion, as well as fundamental properties of the target material and the impacting particle.

Dislocations were identified in a variety of crystalline ceramics at impact sites. The extent of crack formation compared with plastic deformation is related to the relative magnitudes of hardness, H, and the critical stress intensity factor, K_c. Low H/K_c values favor plastic deformation, while high H/K_c values indicate fracture at the impact site. Experimental evidence showed that local impact temperatures above 900°C are possible. This includes melting and fiber formation on glass surfaces.

Other studies on glass to 600°C indicated that high-temperature erosion of rather soft materials is a brittle-fracture process. Going to impingement angles of 15° allowed plastic cutting to supplement the rate of erosion. When impact at 90°, stress relaxation at the impact and crack-tip blunting modify the fracture process, leading to smaller chips at 600°C than those formed at room temperature. This glass data and that for other ceramics are quite similar.

Erosion appears to be controlled by hardness and critical stress intensity. This is suggested by elastic-plastic erosion models which show that the erosion rate is strongly dependent upon K_c and weakly dependent on H. Models for critical fracture velocity show strong dependencies both on K_c and H. These dynamic properties are thought to be independent of temperature. Currently, it seems that K_c and H are the only materials parameters affecting erosion. If their (non) temperature dependence is verified, it will point the way toward the development of more erosion resistant ceramics. Data for Al_2O_3, Si_3N_4 and glass have confirmed this to-date.

The next paper, "Theory of Elastic-Plastic Impact on Ceramics" by D. Richard and H. Kirchner, (Ceramic Finishing Co., State College, PA) derived theoretical relationships for elastic-plastic impact by rigid spheres on flat plates. The theory related pressure to the indent or contact size. Depth of damage and residual strength were included in the equations derived. The authors showed clearly that the responses for transformation-toughened zirconia impacted by tungsten carbide, and for zinc sulfide impacted by glass, were elastic-plastic.

"A Model for the Multiparticle Erosion of Brittle Solids by Spherical Particles," by G. Sargent, P. Mehrotra and H. Conrad, (Metallurgical Engineering and Materials Science Department, Univ. of Kentucky, Lexington) predicted the erosion rates as functions of particle size velocity. Only the purely Hertzian fracture case was treated. Interacting, cone cracks and chipping were found to account for erosion.

"Mechanisms of Solid Particle Erosion in Crystalline Materials" by D. Rickerby and N. Macmillan (Materials Laboratory, Pennsylvania State University, University, Park, PA) reported on studies of Al, Ni, LiF and MgO single crystals. For the LiF and MgO, they found that material was lost because of cleavage crack formation around the impact crater. For Al and Ni, material was removed through ductile rupture of extruded lips of metal at the impact crater.

A typical presentation in the session entitled "Solid Impact: Brittle Solids" was the paper "A Study of Surface Layer Damage Due To Impingement Fatigue" by E. Iturbe, et al. (University of Delaware, Newark), who reported on the development of a slip system after 50 impacts on Cu which is related to work hardening. The structure of the cracks in the identation base probably is from stress concentration in that region.

Session 7, "Solid Impact: Surface Analysis" included two papers. "Studies of Particle Impact Effects by Holographic Interferometry," by L. Rubin, et al. (Aerospace Co., Los Angeles, CA) was an attempt to observe the response of brittle materials 0.5 to 6 micro-seconds after impact. The impact pressure at the impact site is very high. The author suggested that the technique might have potential for studying the dynamics of solid-particle impact and cratering. The paper, "Surface Analysis—A New Tool in Erosion Research?" by J. Witton and M. Edmonds (School of Mechanical Engineering, Cranfield, UK) discussed the measurement of surface topography.

In the session, "Solid Impact: Theory; Ductile Solids," papers included "Some Comments On The Theoretical Treatment Of Erosive Particle Impacts" by J. Hutchings (Department of Metallurgy and Materials Science, Cambridge Univ., UK); "Mechanism Of Erosion Of Aluminum Alloys" P. Shewmon (Department of Metallurgical Engineering, Ohio State Univ., Columbus, OH); "The Wear Equation For Erosion Of Metals By Abrasive Particles At Moderate Speeds" by E. Rabinowicz (Massachusetts Institute of Technology, Cambridge); "The Role Of Plasticity In Erosion" by A. Levy (Lawrence Berkeley Laboratory, Univ. of California, Berkeley); "The Transition From Ploughing To Cutting In Erosive Wear" by N. Gane (CSIRO, Melbourne, Australia). Hutchings considered erosion of metals impacted at 90°. He believes that the high trancient pressures which might be generated had no effect on the erosion process. Hutchings also showed that low cycle fatigue might explain metallic erosion at a normal impact angle; this mechanism has not been confirmed. Shewmon's paper on the erosion of aluminum alloys had to do with large steel balls impacting on solid surfaces. He concentrated on the fracture surfaces from normal incidence impacts. They were covered with many small globules (1-10 micrometers in size) which were ten times larger for the 7075 hardest tempers than for the softer overaged condition. Shewmon presented evidence for adiabatic shear, causing melting of the metal, which fractured in the molten conditions.

The paper read for Levy had conclusions about the role of plasticity in erosion of materials. Plastic flow can absorb the kinetic energy of impacters. Thus, the greater the ductility within a family of materials, the lower the erosion rate. However, high energy particles can overcome this "ductility protection". It was found that cold working decreased the ductility, and thus caused the erosion rate to rise, even though hardness increased.

Very practical concerns were aired in the session, "Solid Impact, Experimental: Erosion-Corrosion." Much of the concern was related to coal conversion and turbomachinery. Erosion wear of solid particulates in such systems can reduce their useful lifetimes significantly. The following papers were presented: "Impact Erosion Wear Caused by Pulverized Coal and Ash," by E. Raask, (CERL, Leatherhead, UK); "Tube Erosion in Fluidized Beds," by R. Wood (General Electric Co., Schenectady, NY); "A Summary of Erosion Experience in the US Department of Energy Coal Conversion Plants," by S. Dapkunas (Department of Energy, Washington, D.C.); "High Temperature Erosion and Erosion-Hot Corrosion with Various Types of Solid Particles," by R. Barkalow and F. Pettit (Pratt and Whitney, Hartford, CT); "Erosion-Corrosion of Materials in Coal Gasifier Environments," by S. Bhattacharyya (Illinois Institute of Technology Research Institute, Chicago, IL); "Solid Particle Erosion of Oxidation-Resistant Alloys in High Temperature, Low-Velocity Gas Streams," by I. Wright (Battelle, Columbus, OH); "Temperature Effects on the Erosion of Metals Used in Turbomachinery," by W. Tabakoff (Department of Aerospace Engineering, University of Cincinnati, OH); "Particulate Erosion of NiO Scales," by I. Finnie and G. Zambelli (Univ. of California, Berkely, CA); "The Role of Protective Film Removal and Regrowth on the Rate of Erosion-Corrosion in Metals," by J. Zahavi and H. Wagner (Institute of Metals, Technion, Haifa, and College of Technology, Jerusalem). Wood's paper on fluidized bed erosion showed that the erosion rates of tubes were severe. Large particles did not produce more erosion than smaller particles of the same kind. Barkalow's and Petit's work was on erosion-hot corrosion by alumina, magnesia and aluminosilicate powders. In oxidizing environments, test materials were erosion dominated. For hot corrosion conditions, the impacting particles promoted severe sulfidation. In these cases, the effect (erosion coupled to corrosion) is not the simple sum of each mode of attack. Particles as small as 2.5 micrometers can aggravate hot corrosion attack.

Zambelli and Finnie did work on erosion of NiO scale on pure nickel at 1000°C. When impacted by angular SiC particles at 100 m/s, these scales exhibit several of the mechanisms proposed for brittle solids. Plastic deformation occurred in the outer (columnar) NiO layer, with lateral cracking as well. Then Hertzian cone cracks formed in the inner, equiaxed, somewhat porous layer. This work points out that predictions of erosion rates and mechanisms must consider the real character of the substrate.

Zahavi and Wagner anodized aluminum in a flowing H_2SO_4 bath with SiC particles. Thus, both an anodized film and an eroded area could be prepared. Local erosion degraded overall film characteristics, leading to accelerated corrosion.

Session 9 "Solid Impact: Experimental Erosion Studies; Turbines" was greatly concerned with erosion in turbomachinery. The papers included "Vibratory sand-erosion testing method" by M. Matsurmura, Y. Oka, H. Hatanaka, and M. Yamwaki, (Department of Chemical Engineering, Miroshima and Mazda Pump Co., Nogami, Japan). Matsurmura, and his associates described a vibratory-sand-erosion testing facility which caused impact damage but not cavitation damage to the specimen. The entire specimen surface can be subjected to uniform erosion-corrosion conditions by making a particle slurry in a corrosive liquid. Reproducibility was found to be excellent. Erosion rates could be varied widely.

The next three sessions dealt with cavitation and cavitation damage. A few of the papers are discussed here.

J. Brunton (Department of Engineering, Cambridge, UK) studied mechanisms of cavitation damage in soft materials. Deformation markings included smooth depressions, pits and craters. The most severe damage was due to the repeated collapse of individual bubbles directly onto the solid surface. The collapse of bubbles might also produce compression waves, but there was no evidence of surface damage to confirm this.

I. Hannson and K. Mørch (Department of Applied Physics, Technical University of Denmark, Lyngby, Denmark) showed, for aluminum and austenitic stainless steel eroded by vibratory cavitation and by flow cavitation, that erosion is caused by jet impacts from cavities collapsing close to the specimen.

J. Heathcock, B. Protheroe, and A. Bail (Department of Metallurgy and Materials Science, Capetown, and Chamber of Mines, Johannesburg, South Africa) studied a wide range of materials and found that the following properties were good for impacting cavitation erosion resistance: high elastic resilience, high yield strength, stress induced phase transformations, and toughened microstructures. The materials studied included low-and high-alloy steels, cobalt and nickel alloys, sintered carbides and polymers (PTFE, nylons, polyacetal copolymer and polyethylene). Methods of materials removal observed included (1) low energy transgranular cleavage, (2) intergranular grain removal, (3) high energy ductile extrusion and rupture, (4) fibrous tearing of resilient polymers, (5) plastic deformation.

The first of these occurs in the strain-rate-sensitive ferritic steels such as 409-and 430-type stainless steels. Pure iron loses material by a combination of brittle intergranular and ductile modes. The brittle mechanisms dissipate little energy, so extensive erosion is seen.

Material loss by ductile extrusion and rupture occurs in Monel 400, Incalloy 825, SG 80, austenitic stainless steels and heat-treated high-and low-alloy steels. This mode of materials removal also occurs in the more resistant sintered carbides. The softer matrix erodes preferentially by a ductile mechanism, leaving the hard carbide particle exposed. These are then removed by cavitation.

Polymers such as nylons, high-density polyethylene and polyacetal copolymer all erode by fibrous tearing. Pure PTFE, PTFE with fillers such as graphite, carbon, glass, and bronze have poor erosion resistance. The mode of materials loss here is very different from that of fibrous tearing. Damage is of a plastic nature. The addition of fillers to PTFE increases erosion rates considerably by providing initiation sites for erosion.

J. Hackworth (Bell Aerospace Co., Buffalo, NY) presented "Predicting Cavitation Erosion Of Ship Propellers From The Results Of Model Experiments". It was part of an approach to predict the service life of propellers as a function of ship operating conditions, but was based upon experiments with model propellers in water tunnels. Quantitative measurement was made of the erosive nature of cavitation in terms of the erosive impact intensity (defined as the rate of formation and the size distribution of cavitation bubble collapse pits formed on a soft metal exposed to the cavitation). Tests showed that this erosive impact intensity is very sensitive to propeller design and simulated operating conditions. It might be useful for optimizing propeller design. Measurement of erosive impact intensity for cavitation on a full scale propeller gave scaling factor information for cavitation erosion. Based on this work, an engineering relation was proposed for erosion rates of bronze propellers. It is erosion rate = 0.94 (pit formation rate) (average pit diametry) $^{2.3}$. The erosion predicted for one year of steaming time based on this formula was in agreement with in-service experience.

K. Antony and W. Silence (Cabot Co., Kokomo, IN) found that cobalt-base alloys can surface transform during cavitation into a hcp structure. This phase has a high fracture energy. The proper cobalt-base alloys are combined so as to control the stacking fault energy between 10-15 m^J/m^2. Nickel is harmful in this regard.

"Some Aspects Of Metal Perforation By Liquid Impact" by A. Rozner (Naval Surface Weapons Center, White Oak, MD), had to do with cutting of metals by liquid jet impact. Rozner reported upon liquid jets formed in a pyrotechnic torch. (The jet is made up of the molten products of the exothermic reaction between nickel, aluminum, ferris oxide and Teflon). Steel and aluminum were perforated (up to 10 cm) in 1/2 second. Stresses generated by impact of this liquid jet were above the yield strength of the target material. It is thought that these jets introduced shock waves into the target, resulting in the high stresses generated. At the interface of the jet front and the target a crater was formed. This crater expanded and followed the shock wave which was attenuated with increasing crater size. Subsequently, the jet and target materials were ejected backwards. This liquid jet impact method for cutting metals may be of use in both underwater and more conventional ambient applications.

The final session, "Coatings", was of interest for practical modes of protection. M. Matthewson (Cavendish Laboratory, Cambridge Univ., UK) stated that soft, rubbery coatings protect against erosion damage by complex mechanisms. Of course, compressibility of the coating is important. Coating adhesion assists in stress distribution. When these elements are evaluated, the dynamic values of modulus and Poissons' ratio need to be considered, since their strain rate dependence can vary greatly. One must keep in mind that impact conditions can impose strain rates of up to $10^6 s^{-1}$.

H. Schröder's (Dornier GmbH, Friedrichshafen, FRG) presentation "Rain Erosion of Lightning Protection Coatings For Carbon Fiber Composites," pointed out that the use of carbon fiber-containing materials in aircraft means that lightning protection systems must also be employed. Systems investigated were made of aluminum foils, flame-sprayed aluminum, aluminum-mesh, and metal-powder-loaded paints. All these were evaluated in a rotating arm rig. Polyurethane coatings were investigated as well. The conclusion was that erosion resistance was poor for all of the lightning protection systems.

B. Angell, R. Lang, W. Weaver, and J. Hibbert (Admiralty Laboratory and Department of Mechanical Engineering, Salford, UM) in their report "Cavitation Resistant Coatings for Naval Use," considered the need for a practical coating system for rudders to reduce corrosion and cavitation from the propellers. The group focused on elastomeric properties at high strain rates, and discussed a polyurethane with a test tunnel performance 2000 times better than epoxide formulations. They also presented a theoretical analysis of stresses experienced at the coating/substrate interface.

Two social occasions of note were the Elizabethan feast, held in the beautiful ancient hall of King's College, and the conference banquet, at which Prof. Tabor offered his congratulations to the conference organizers, authors, and participants in general, and expressed his belief that the goals and hopes of the conference organizers were met. In the past several years, much good work has been done in the study and understanding of erosion.

In response, George F. Schmitt of the Air Force Materials Laboratory, one of the Conference organizers, and someone with vast experience in erosion testing of materials delivered a delightful set of remarks to close the banquet. A portion of his talk is quoted below.

..."During this conference, delegates have taken quite a beating. We have been impacted with: spherical waterdrops, cylindrical waterjets, disc shaped drops, angular particles, rounded particles, rain, sand, quartz, SiC, coal, ash, ice, bubbles, jellied wedges. We've been eroded, corroded, ablated, cavitated, oxidized, jetted, shocked, cut, worn, fatigued, plowed, and blown away by torches. We've had our water drop shattered, and if that wasn't enough, we've had our bubble burst, or rather, collapsed. If our Cambridge friends keep simplifying things, we may find a tractable problem yet. While our liquid impact friends are being hammered by the water hammer pressure, Dr. Hutchings showed us that solid impacters will have to find their hammer elsewhere.

"We've learned to erode on rails, vibrate in sand, rain, in the wind (tunnel, that is), holograph and analyze surfaces. The volume that this conference produced will become a major reference work in the erosion literature...

"As a "great gray head"—the only one from the US to attend all five international conferences (the first when I was two),—I want to say thanks. Here's to ELSI(V) (Erosion by Liquid and Solid Impact-V). Let's look to ELSI(VI), wherever and whenever it is."

The volume containing the Conference proceedings is currently available from the Cavendish Laboratory. It is entitled Proceedings of the Fifth International Conference on Erosion by Liquid and Solid Impacts, edited by J.E. Field, (Cavendish Laboratory, Cambridge, 1979).