PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Rain Erosion Properties of Materials [and Discussion]

H. Busch, G. Hoff, G. Langbein, Geoffrey Taylor, D. C. Jenkins, M. A. Taunton, A. A. Fyall, R. F. Jones and T. W. Harper

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XIII. Rain erosion properties of materials

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[Plate 32]

A rotating arm apparatus capable of circumferential speeds up to 475 m/s (Mach 1·4) has been used to make quantitative measurements of the velocity and angle dependence of rain erosion for a wide range of materials. It has been possible to relate the mechanical properties of some materials with their rain erosion resistance. The behaviour of the drops during impact has been studied by high speed photography.

1. Introduction

Honegger (1924) reported for the first time on the destructive effect of water drops impinging at high velocities on solid surfaces. On account of the damage occurring to materials in steam turbines, Honegger investigated the fatigue of materials caused by the repeated impact of water jets at velocities of 200 m/s. Although these investigations of material behaviour under high speed deformation are of great importance, they were developed further by only a few authors (Ackeret 1928; Ackeret & de Haller 1931; Vater 1937, 1938, 1951; Schwarz 1941; Mantel 1937; Schwarz & Mantel 1943). Damage observed in 1945 on antenna coatings of B29 bombers and damage on radomes, air inlets and wing leading edges as well as on the front shields of modern high speed aircraft gave new impulse to this field of material research. Recently damage of the infrared shields of the F104G Starfighters was also attributed to the effect of raindrops. For this reason systematic investigations of erosion of materials, caused by rain of high relative velocity, have been started in several parts of the world.

This paper reports on comparative investigations of the rain erosion behaviour for all classes of materials. This comparison is possible since testing of rain erosion resistance constitutes an investigation method practicable for all solids without changing test conditions. In other words, it is not necessary to change the test method when changing over to another class of material, as it is necessary, for example, in measurements of material-hardness. Test facilities will be described in §2. Section 3 refers to testing parameters and their standardization. In §4 a survey is given of methods of investigating rain erosion resistance, while relations between other physical quantities and rain erosion behaviour are described in §5. Finally we discuss the dependence of erosion damage on impact velocity and angle of incidence of the drops (§6).

2. Test equipment

The principal part of the test equipment shown in figure 1, plate 32, is a rotating arm with a radius of 120 cm. The arm is driven by a 250 PS Otto-motor over a mitre gear. The presently attainable maximum speed is 475 m/s. At this speed, the specimen attached to the outer end of the arm is exposed to a centrifugal acceleration of 19000 **g**. The thickness

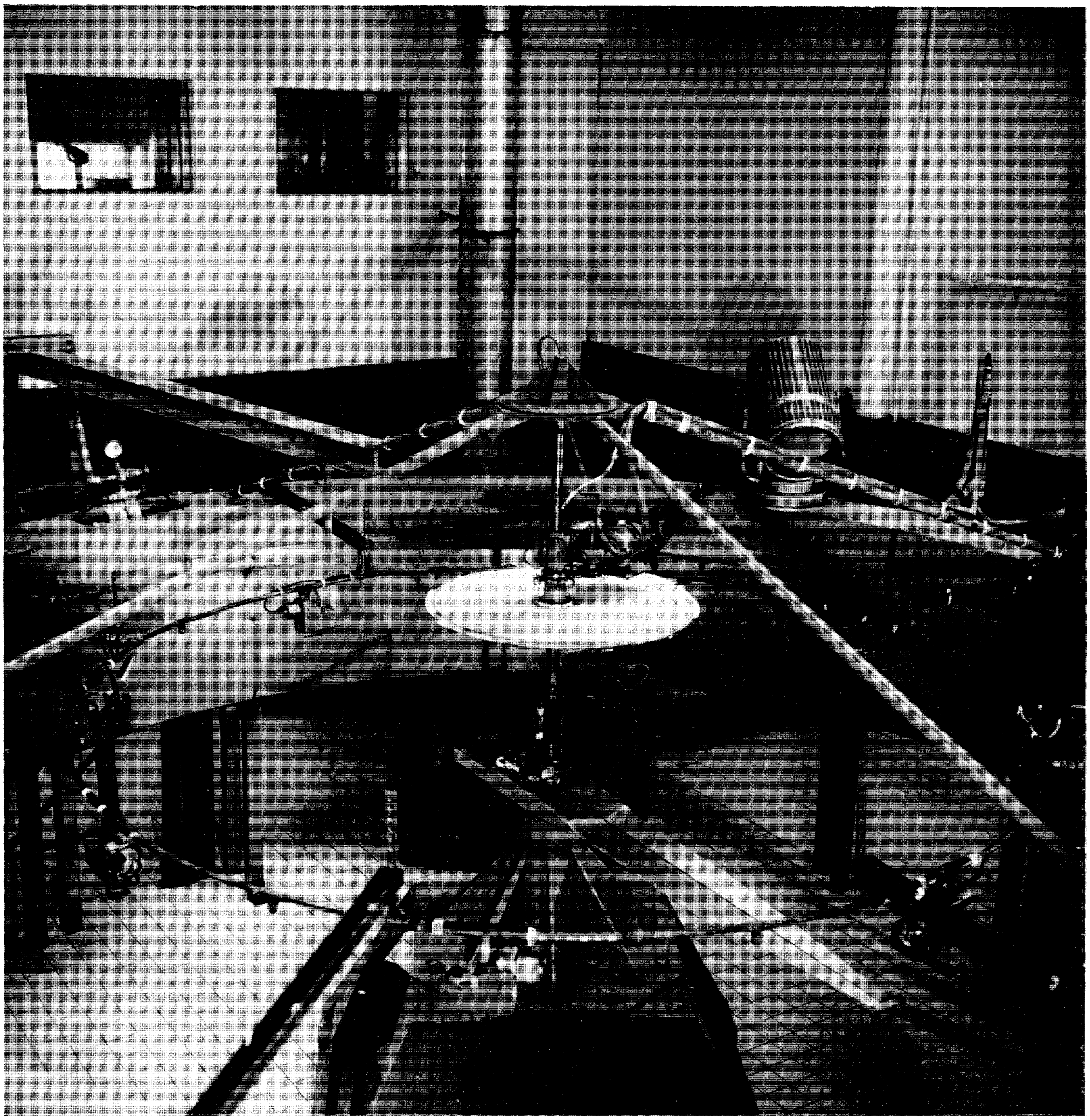

FIGURE 1. Whirling arm equipment for testing rain erosion behaviour.

(*Facing p.* 168)

of the arm increases towards the centre so that tensile stresses are kept approximately independent of the radius. The apparatus is surrounded by a 30 cm thick wooden ring to protect against specimen detachment. To produce the rain, eight spray nozzles are arranged at regular intervals above the specimen trajectory. These nozzles oscillate in a radial direction causing the water jet to separate into drops. The experiments can be observed from a sound insulated cabin by means of a telescope and stroboscopic illumination. Speed measuring is carried out photoelectrically, using a disk with 60 holes which is attached to the arm.

3. Standardization of test parameters

The erosion of a material which is caused by rain depends on a great number of test parameters. The most important parameters are the impact velocity, angle of incidence of the drops, density of rain measured as the ratio water volume/air volume, drop size, temperature of water and specimen, and gas content of the water.

For investigations serving to compare different materials, the following standard conditions were chosen so that all materials, reaching from the most instable glass to the best steel, can be tested under the same conditions:

impact velocity	$v = 410$ m/s
water volume concentration (rain density)	$\rho_{W/L} = 10^{-5}$
medium drop diameter	$D = 1{\cdot}2$ mm
angle of incidence	$\theta = 0°$
specimen temperature	$T_p = 40$ °C
water temperature	$T_w = 25$ °C
gas content of the water	almost nitrogen-saturated water (20 °C, 5 atm nitrogen)

The tests are carried out on flat cylindric specimens of 16·8 mm diameter and thickness from 2 to 10 mm. The area F exposed to rain is 1·76 cm^2.

4. Comparing material investigations

For quantitative measurements of the erosion the difference of weight $G_0 - G = \Delta G$ is measured where G_0 is the weight at the beginning and G the weight after some time of testing. From this the average erosion depth is calculated as

$$E_m = \frac{\Delta G}{\gamma F},$$

where γ is the specific weight of the specimen and F the area exposed to the rain. If the average erosion depth E_m is plotted against the running time in rain, most of the materials show the following characteristics. Up to a certain time no weight loss is detectable, thereafter material breakup begins, and after a transition range, which is explainable by use of impact statistics, the weight loss increases linearly (figure 2). This normal progress of erosion can be signified by the following three factors:

(1) Time of incubation t_K, defined as the interval from the beginning of test to the intersection of the linear portion of the destruction curve with the time axis.

(2) Erosion rate $(\mathrm{d}E_m/\mathrm{d}t)_\infty$; that is the rate of the linear destruction increase.

(3) Erosion resistance t^*, the time that is necessary for the removal of an average layer thickness, as, for example, 0·1 mm. The latter is particularly important for the designer.

In the following figures part of the results which were achieved at different materials under standard conditions are summarized. The scale for erosion depth is the same in all

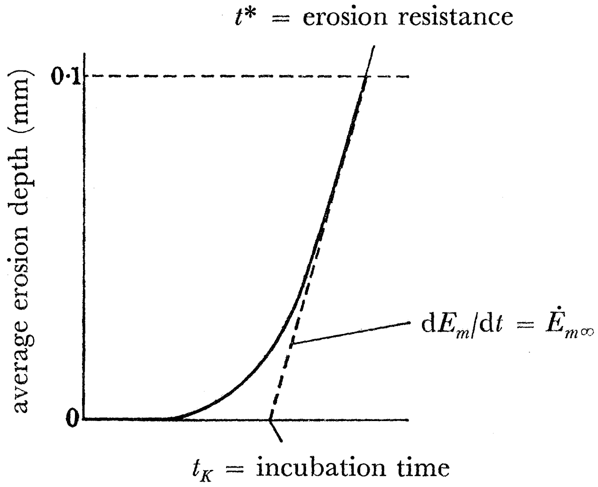

FIGURE 2. Development of average erosion depth during the erosion process. t_K is the incubation time, t^* the erosion resistance and $\dot{E}_m$ the erosion rate.

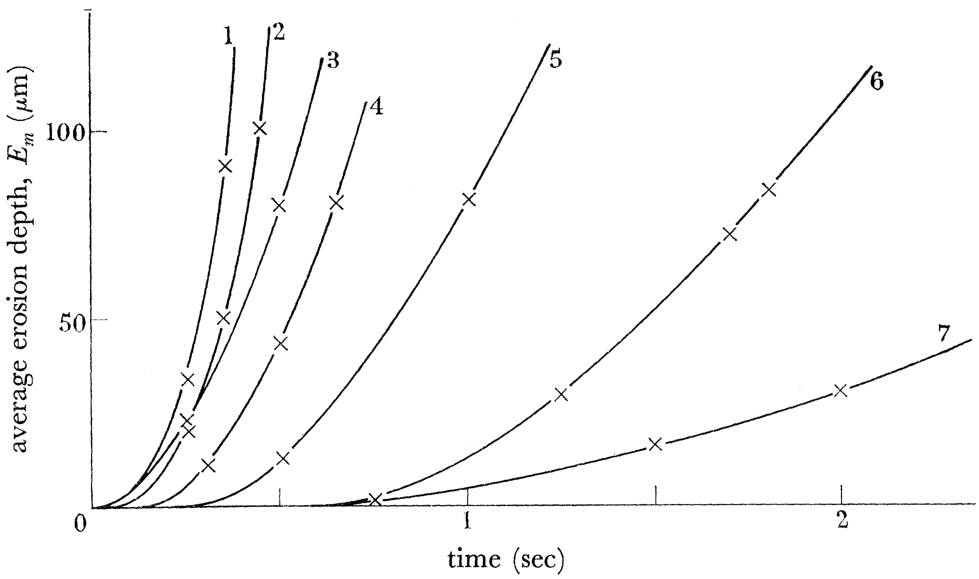

FIGURE 3. Erosion curves for inorganic glasses and brittle polymers with incubation times in the range of 1 s, water volume concentration = 10^{-5}, impact velocity = 410 m/s. Curve 1, clear white plate glass; 2, polystyrol; 3, twin ground quality glass; 4, polyester resin; 5, Perspex 1560N; 6, Cellidor BMsp; 7, Plexidur T.

of the five figures, while on the time axis the scale is changed by the factor 10 from figure to figure. In this manner, the different stabilities of various classes of materials are clearly demonstrated. In figure 3 (time unit, 1 s) glasses are compared with brittle synthetics. Figure 4 comprises tougher synthetics compared with aluminium and MgO (time unit, 10 s). In figure 5 the most stable synthetic, i.e. rubber elastic polymeres are compared with Duraluminium and molybdenum (time unit, 100 s). Figure 6 (time unit, 1000 s) includes tantalum, molybdenum, iron and various less stable steels. The last in this series (figure 7) (time unit, 10000 s) shows the erosion progress of the most resistant materials,

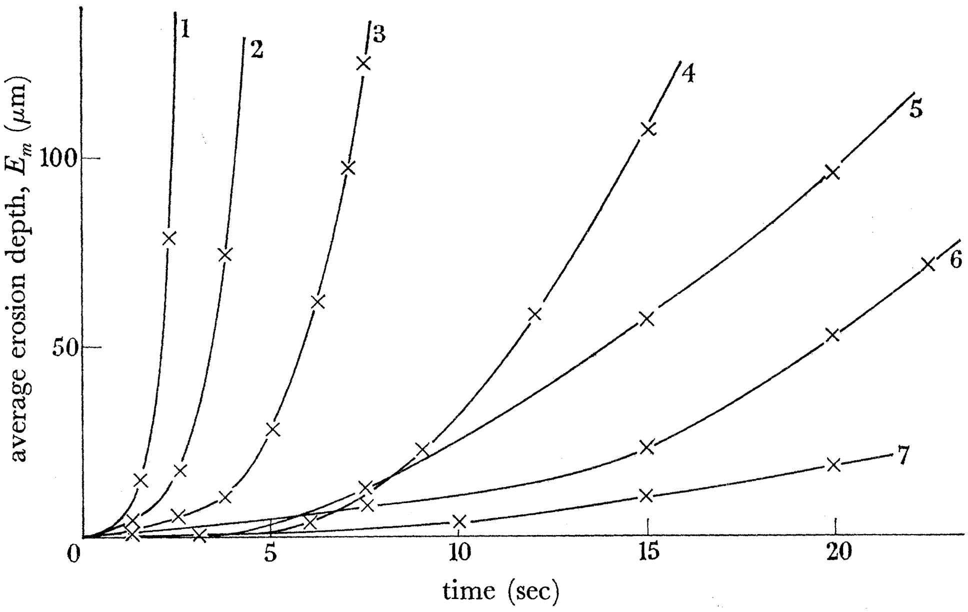

FIGURE 4. Erosion curves for polymeres of medium resistivity in comparison with pure aluminium and a ceramic substance MgO with incubation times in the range of 10 s, water volume concentration = 10^{-5}, impact velocity = 410 m/s. Curve 1, Plexidor T; 2, Plexigum S; 3, Makrolon; 4, pure aluminium; 5, high pressure polyethylene; 6, polyamide 02N86; 7, MgO 2354.

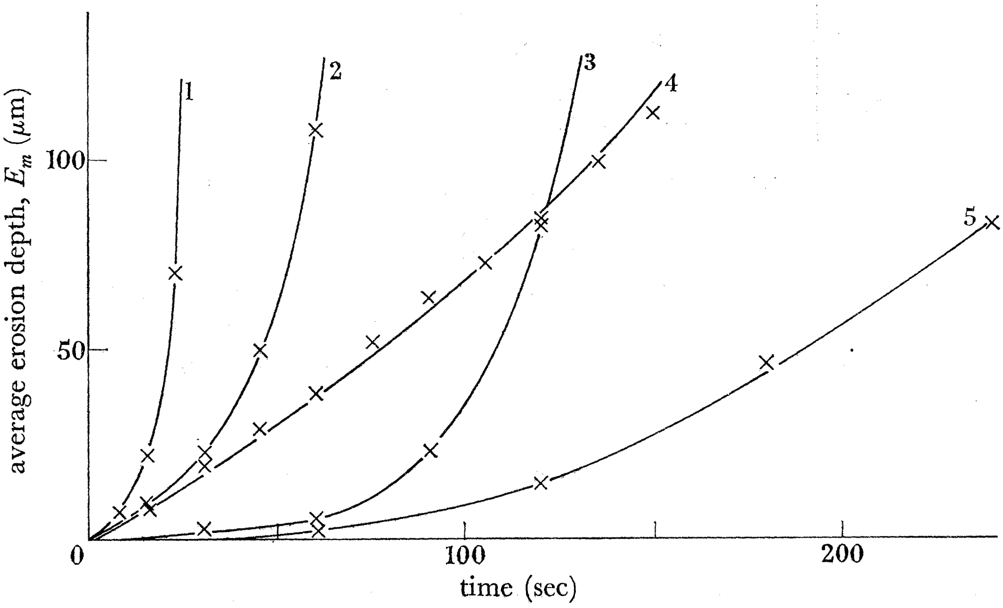

FIGURE 5. Erosion curves for rubber elastic polymeres in comparison with a polyamide, Duraluminium and molybdenum, incubation time range = 100 s, water volume concentration = 10^{-5}, impact velocity = 410 m/s. Curve 1, polyamide 02N86; 2, polyurethane 9490; 3, Dural (AlCuMg) F40; 4, polyurethane 9486; 5, molybdenum.

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that are hardened steels and electrodeposited nickel layers. It points out very instructively the range of erosion resistance and erosion rate extending over 4 to 5 orders of magnitude.

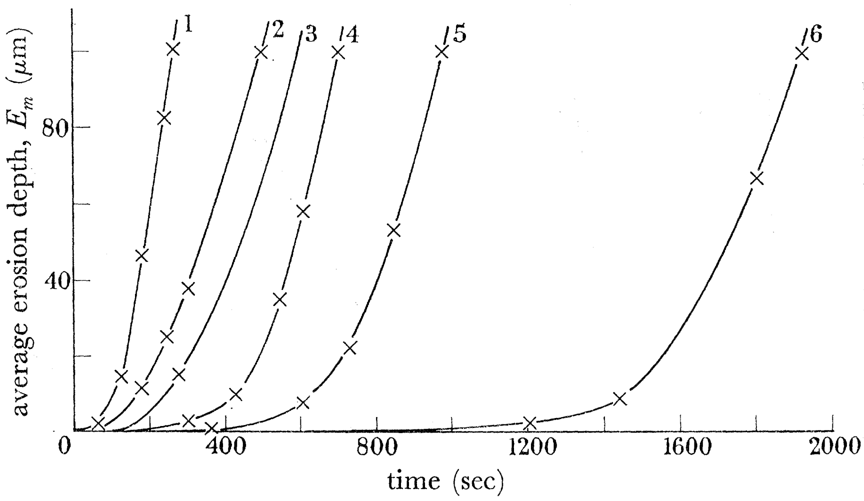

FIGURE 6. Erosion curves for metals of medium resistivity in comparison with Al_2O_3. The incubation times are in the range of 1000 s. Water volume concentration = 10^{-5}, impact velocity = 410 m/s. Curve 1, molybdenum; 2, iron; 3, Al_2O_3; 4, tantalum; 5, steel FMB; 6, steel X20 Cr13.

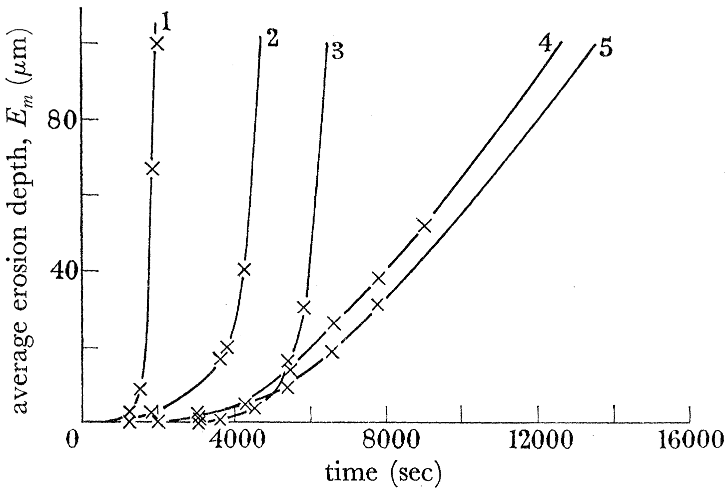

FIGURE 7. Erosion curves for the most resistant materials (time unit: 10000 s): Hardened steels and electrodeposited nickel layers, water volume concentration = 10^{-5}, impact velocity = 410 m/s. Curve 1, steel X20 Cr13; 2, deposited nickel 8; 3, deposited nickel 18; 4, CK60 30′ 850°/H_2O; 5, 100Cr6 30′ 850°/H_2O.

5. Relation of rain erosion behaviour to other physical properties

It is interesting to try to find relations between known physical properties and the erosion behaviour of materials. To obtain these relations it is useful to consider the energy balance during the stationary phase of erosion, that is the phase of constant erosion rate. During the time Δt a layer of average thickness ΔE_m may be eroded. If ϵ is the increase of the internal energy during erosion per volume and F the specimen surface, the layer will absorb the energy

$$\Delta E_m F \epsilon = E_1.$$

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At the time the specimen is impacted by the energy

$$\phi\,\Delta t F = E_2,$$

ϕ being the energy flux of the drops (their energy per unit surface area per unit time). The ratio of these energies may be defined as a factor of absorption δ.

$$\delta = \frac{\Delta E_m}{\Delta t}\frac{\epsilon}{\phi}; \tag{1}$$

δ, like ϵ, is a function of the material. Rearranging equation (1) to give the erosion rate $\dot{E}_m$, we have,

$$\dot{E}_m = \phi\delta/\epsilon.$$

Thus we have expressed the different influence on rain erosion as a factor ϕ, which is clearly defined by the test conditions,

$$\phi = \tfrac{1}{2}\rho_w v^2\,\rho_{W/L}\,v, \tag{2}$$

where ρ_w = density of water, and the two material constants ϵ and δ. ϵ is the increase of the internal energy by plastic deformation and the formation of new surface during the whole erosion process. δ defines the portion of the total energy absorbed at impact. This absorption factor is increased with rising impact pressure of the drops. The ratio of the irreversibly accumulated energy to the employed energy at impact must be determined by the ratio of the impact pressure and the strength p_0 of the material and will monotonically increase therewith. This can be formulated mathematically by the equation

$$\delta = f\left(\frac{p}{p_0}\right) \quad \text{with} \quad \frac{\partial f}{\partial p} > 0. \tag{3}$$

Assuming ideal elastic (compressible) behaviour of the drops,† the impact pressure is

$$p = v\,\frac{\sqrt{(E\rho)}\,\rho_w c_w}{\sqrt{(E\rho)}+\rho_w c_w} \tag{4}$$

where c_w is the velocity of sound of water, ρ, the density and E, Young's modulus of impacted material. This leads to

$$\dot{E}_m = \phi f\left(\frac{v}{p_0}\frac{\sqrt{(E\rho)}\,\rho_w c_w}{\sqrt{(E\rho)}+\rho_w c_w}\right)\Big/\epsilon \tag{5}$$

for the erosion rate.

The following relations between erosion rate and notch impact strength, the Shore hardness of rubber elastic materials and the Vickers hardness of metals, can be drawn from this formulation for $\dot{E}_m$.

First we consider the dependence of $\dot{E}_m$ on ϵ. A measure of the energy absorption during complete erosion of a material should be the energy absorption up to fracture during a tensile test. During the notch impact test particularly high deformation velocities occur in the fibre that is stretched most. Therefore the notch impact strength should be a good measure of erosion resistance. Figure 8 demonstrates that in fact erosion rate decreases with increasing notch impact strength from the values at $\dot{E}_m$ = 1000 μm/s for brittle plastics

† This seems to be true at the first instant of impact for, according to Brunton (1965), the destruction is essentially accomplished at the first instant of the impact process.

such as Perspex, to the value $\dot{E}_m = 10\ \mu/\mathrm{s}$ for tough high molecular polyethylene. This is equivalent to the decrease of erosion rate with ϵ^{-1} in equation (5).

For sufficient† low E moduli, equation (5) may be simplified to

$$\dot{E}_m = \phi f\left(\frac{v}{p_0}\sqrt{(E\rho)}\right)\Big/\epsilon.$$

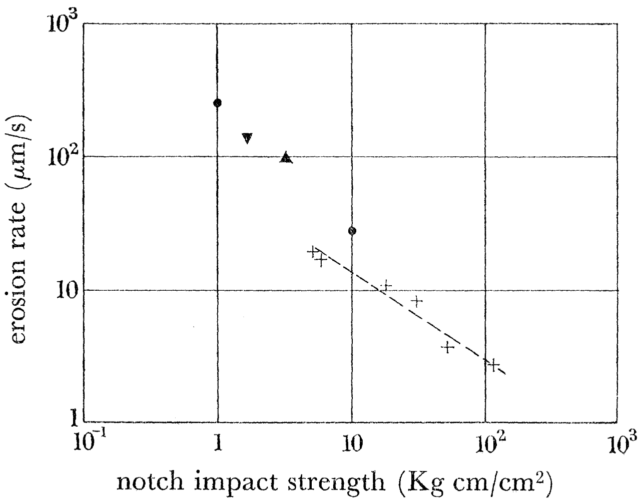

FIGURE 8. Relation of erosion rate to notch impact strength. ●, Polyester resin; ▼, Perspex 1560N; ▲, Plexigum S70; +, low pressure polyethylenes with different molecular weights.

The absorption factor will increase monotonically with its argument; therefore the erosion resistance should increase with decreasing E modulus. This result is confirmed by table 1. Here in some cases several elastic substances of the same class but of different Shore hardnesses are compared. The Shore hardness is a measure of the modulus of elasticity. In all cases the material with the lower Shore hardness and lower E modulus was the more stable material.‡ The simple explanation of this result is that the high flexibility of soft rubbers prevents the buildup of high pressures during the impact of water drops. This property must exist up to high frequencies. In this respect the relaxation behaviour of a substance is also a decisive factor in erosion behaviour.

From equation (5) a further correlation between rain erosion behaviour and classical material parameters may be derived. Since function f is a monotonically increasing function, erosion rate should decline with increasing p_0. A measure for p_0 is the hardness of a material. For this reason, erosion rate of steels against their hardness is plotted in figure 9. This figure shows that among a series of uniform materials, which are different only with respect to the hardness due to differences in their structure, the erosion rate really decreases with increasing hardness. Since with crystalline materials the deformation occurs by the movement of dislocations, this result can also be explained in the following way:

† The E moduli have to be so small that the acoustic impedance $\sqrt{(E\rho)}$ of the impacted material is comparable with the acoustic impedance of the water.

‡ This certainly will be valid only in a range of Shore hardness which is limited to low values. The lower limit of the Shore hardness, for which this law will still be valid, has not yet been determined because we could not get elastomers with E moduli which were sufficiently variable over a wide range.

With the growing concentration of dislocation obstacles, which are distributed as homogenously as possible, the hardness as well as the erosion resistance are increased.†

In future investigations we hope to show to what extent the suggested formulation for the dependence of erosion rate on impact conditions and material parameters is useful in explaining further details of the rain erosion behaviour of materials.

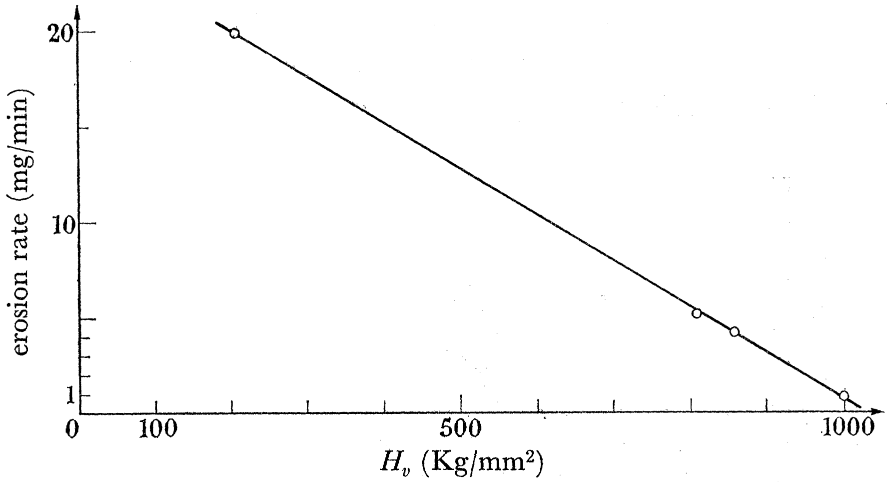

FIGURE 9. Relation between erosion rate and hardness. $v = 410$ m/s; rain concentration $= 10^{-5}$ g/cm³; $p_w = 8$; $n_k = 8$.

TABLE 1. RELATION OF RAIN EROSION OF RUBBER ELASTIC MATERIALS TO THEIR SHORE HARDNESS

weight loss	Shore A hardness	material	exposure time
15	80		
10	79		
8	78	polyurethane	40 s
6	76		
5	74		
22	74	ethylene-propylene (mixed polymeride with carbon)	5 s
20	70		
5	62	ethylene-propylene (mixed polymeride with silicic acid)	5 s
2	60		
7	75	natural rubber	5 s
4	66		

6. DEPENDENCE OF RAIN EROSION BEHAVIOUR ON IMPACT VELOCITY AND ANGLE OF INCIDENCE OF THE DROPS

The test parameters 'impact velocity' and 'angle of incidence' of the drops are the most important of all test parameters affecting rain erosion. To find this influence, the running time in rain was kept constantly at 12 min while impact velocity and angle of incidence were varied.

Figure 10 gives a review of results for the dependence of rain erosion on impact velocity. The loss of weight ΔG of various materials after 12 min exposure time is plotted against

† We thank Mr W. Herbert, Dr H. Rieger and Mr E. Steinebach for supplying the results on the rain erosion of metals.

impact velocity. It is clear that rain erosion becomes very severe above certain velocity limits. The assumption that rain erosion is proportional to the energy flux, ϕ, through the specimen surface per time unit, would result in an increase of the weight loss with the third power of velocity, as the kinetic energy of the drops increases with the second power of velocity and the number of impacting drops for constant running time with the first power of velocity. The measurement results show an essentially larger increase with the velocity. For glass the increase occurs above certain velocity limits with the thirteenth power of velocity, while occurring with the fifth to the seventh power of velocity for most metals, plastics and ceramics. This signifies that the impacted materials absorb a consider-

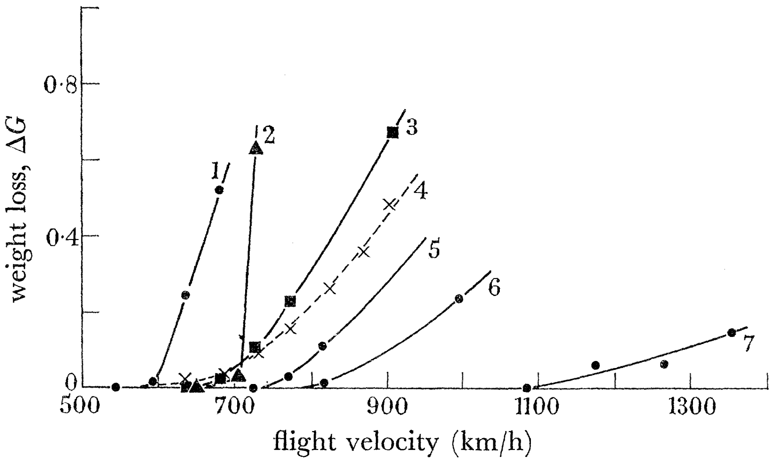

FIGURE 10. Dependence of rain erosion of glasses, ceramics and some polymeres to impact velocity ($\rho_{WL} = 10^{-5}$; $t = 12$ min). Curve 1, Plexiglass; 2, quartz glass (Infrasil); 3, Plexidur T; 4, Makrolon; 5, aluminium; 6, MgO 2354; 7, Al_2O_3 2350.

ably larger portion δ of the offered energy above certain velocity limits, which are specific for every material, than at low velocities. This can be expressed by a sharp increase of the function $\delta = f[p(v)/p_0]$ at certain velocities. This indicates the usefulness of equation (5) in which the different factors influencing rain erosion were separated.

Figure 11 summarizes the results on the dependence of the erosion on 'angle of incidence'. The velocity limit at which rain erosion occurs is plotted as a function of the angle of incidence θ of the drops between the normal on the surface and the direction of impact. The start of rain erosion is defined by the gravimetric provable limit, which was 10^{-4} g at the balance used for this case. At this limit rain erosion is already very well visible. The figure illustrates that the critical velocity mentioned before increases considerably with increasing angle of incidence. For the comparison with measured values (dotted curves), the curves

$$v = v_0/\cos\theta$$

(solid curves) are traced. v_0 is the critical velocity differing from material to material at which erosion occurs at perpendicular drop impact (see fig. 10). These curves represent the angular dependence of the erosion if the erosion is determined by the normal component $v_N = v\cos\theta$ of the impact velocity v only. The measured values only slightly differ from this. In cases where deviations from this law are encountered, they will always tend to larger angles and lower velocities respectively. Following from the measurements of the angular dependence of rain erosion, the practical protective recommendation for high velocity aircraft is as follows.

Surfaces, which may be exposed to the impact of water drops of high velocities must be inclined against flight direction corresponding to the law $v = v_0/\cos\theta$ or slightly more.

This is essentially the same result which was found for lower velocities by Fyall, King & Strain in 1962 and for higher velocities in 1965 (King 1965).

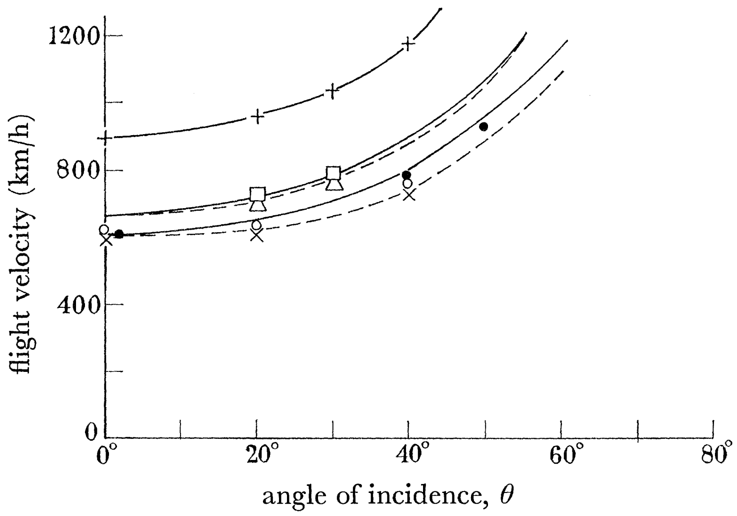

FIGURE 11. Dependence of velocity limit of rain erosion with angle of incidence ($\rho_{WL} = 10^{-5}$; $t = 12$ min). ○, Plexidur T; ×, Makrolon; □, Herasil; △, Infrasil; ●, MgO 2354; +, Al_2O_3 2350.

SUMMARY

A survey is given of the erosion behaviour of all classes of materials at the flight velocity of 410 m/s and water volume concentration 10^{-5}. If the materials are to be classified by increasing resistance of the most resistant representative of each material class, the order, under the above conditions, is the following: inorganic glasses, organic polymeres, ceramics, metals. The relations of the rain erosion resistance to notch impact strength, E modulus and hardness have been shown and explained. Finally, results have been given on the practically very important dependence of rain erosion resistance on impact velocity and angle of incidence of the drops.

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XIV. Discussion

Sir Geoffrey Taylor, F.R.S.

What is the physical nature of the erosion of raindrops? Is the removal of the surface by friction of the air producing a boundary layer which flows off the edge of the drop, or is it the method discovered by Dr Lane of Porton in which the drop turns inside out? I wrote a paper about 20 years ago in which I tried to calculate the rate of erosion. How does my old calculation compare with the empirical formula used by Mr Jenkins in his paper?

D. C. Jenkins

In the R.A.E. tests referred to none of the drops disintegrated by the method described by Lane, in which the drop turned inside out to form a bag shape which then burst. Rather, disintegration of the drop appeared to be an erosion process in which the surface of the drop was torn off to stream behind the main drop in a cloud of small droplets. Whether the manner of removal of surface liquid was one in which the friction of the air flow produced a boundary layer which then flowed off the edge of the drop or whether the removal of surface liquid was by an alternative method postulated by Sir Geoffrey Taylor in which unstable waves are formed on the surface and the crests of these waves break off to form small droplets, it was not possible to resolve by the photographs taken. However, in one test in which the erosion droplets produced were caught and measured it was found that very good agreement was obtained between the average droplet size found and the wavelength of the unstable wave as predicted by Sir Geoffrey who also suggested that the size of droplets produced would be of the same order of size as the unstable wavelength.

The rate of erosion calculated by Sir Geoffrey Taylor used the concept of removal of surface liquid by the air flow producing a boundary layer in the surface of the drop which then flowed off the edge. Use of these calculations leads to a predicted 'life' of the drop considerably in excess of that found in the R.A.E. tests and which formed the basis of the empirical formula.

M. A. Taunton (British Aircraft Corporation)

The rain erosion problem for a supersonic transport aircraft can be considered in relation to two separate phases of flight: (*a*) low altitude flight (below 30000 ft.) during climb and descent; (*b*) high altitude flight in cruise.

In the low altitude phase, flight is subsonic and speeds are not greatly in excess of those of present subsonic jets (600 mi./h as against 500 mi./h). In view of the reduced low altitude exposure time of a supersonic transport, and the higher sweep-back of all critical surfaces, erosion is not likely to be significantly worse than on present aircraft.

In the high altitude, supersonic phase of flight, the frequency of occurrence of rain is extremely low. Therefore it will not be necessary to demonstrate a long life of the more vulnerable parts (such as the radome) but simply to demonstrate that they will remain structurally intact until the end of the flight.

It is necessary, however, to establish the statistical probability of meeting heavy rain at high altitudes. Mr Fyall has mentioned that it is not thought that heavy rain can occur at altitudes up to 50000 ft. (?); if this is so, it will be necessary to establish: (i) the frequency of occurrence; (ii) the statistical probability of the aircraft being in the same place at the same time; (iii) the extent or duration of such rain and its intensity; (iv) whether such rain is associated with storms which could be detected and avoided with the aid of weather radar.

A. A. Fyall

On present evidence, erosion at 600 mi./h will be at least three times as severe as at 500 mi./h.

Possible rain erosion hazards for a supersonic aircraft are indeed greatly minimized by high sweep-back angles of forward-facing surfaces. However, particular attention must be paid to the areas where discontinuity of surface is likely to occur. Of particular note will be window fittings, butt joints and rivets which may not be flush with the surrounding surface.

Every attention will have to be paid to close routine inspection, particularly after flight, through noted high intensity precipitation.

Of particular note will be the windscreen area and it will be advisable to arrange for visor protection as early as possible in any flight involving rain on take-off.

With regard to possible rain erosion hazards during the high speed phase, the vulnerability of the aircraft is that of the most vulnerable component. This is likely to be the windshield or visor glazing and as the optical materials have very poor rain erosion resistance, rain encounters of only a few seconds duration may be sufficient to cause extensive damage at the cruise speed.

There is certainly evidence of the occurrence of rain at high altitudes, although the data required as indicated by Mr Taunton may not be available for some time. While it is certainly necessary to establish these figures to give an adequate assessment of the hazard, nevertheless, I repeat that the possibility of such encounters must not be overlooked.

R. F. Jones (Meteorological Office)

It is true that occasionally supercooled raindrops will occur in the atmosphere at temperatures below −20 °C but only in association with vigorous convection clouds and over limited horizontal distances. It would be wrong to give the impression, as I think Mr Fyall may inadvertently have done, that a supersonic transport aircraft in the cruise phase would encounter raindrops frequently and over long distances. The probability of any encounter would indeed be very small, but perhaps not negligible, and I should expect the conditions under which it might occur to be detectable by radar.

A. A. Fyall

As I have already indicated, there may be materials in use which will only have a very short 'life' in rain conditions.

There is certainly the possibility of avoiding such conditions by the use of radar, but as the aircraft will be limited in manœuvre for passenger comfort, there may be occasions where avoidance is impossible.

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T. W. Harper (Dunlop Rubber Co., Aviation Division)

The Dunlop Rubber Company have for many years been associated with the design, development and manufacture of aircraft deicing systems and, without exception, all new systems are tested at the Royal Aircraft Establishment in order to determine their resistance to rain erosion. These tests include the complete buildup of any heater mat assembly for accurate information can only be obtained if the entire construction of any such heater mat is evaluated. It is, therefore, evident that if an evaluation is taken on the complete heater the substrata is taken into account. Incorrect results can be obtained if only the top protective cover is tested.

A. A. Fyall

This is an excellent example of the outlook on testing for specific applications in which various combinations of materials may be used. While the data pertinent to the individual materials give some guide as to their suitability for use in a rain environment, the final criterion must be the rain erosion resistance of the complete item. In a multilayer system, such as a heater mat, interlaminar adhesion is of vital importance. The individual layers are usually of such thicknesses as to permit energy from the impacting drop to be transmitted through the depth of the assembly and consequently energy reflexion may occur at each interface.

Testing the entire system ensures that the efficacy of each bond is subjected to in-flight conditions. Final testing of heater mat assemblies often entails the simulation of heating cycles to assess the effect of heat on these bonds.

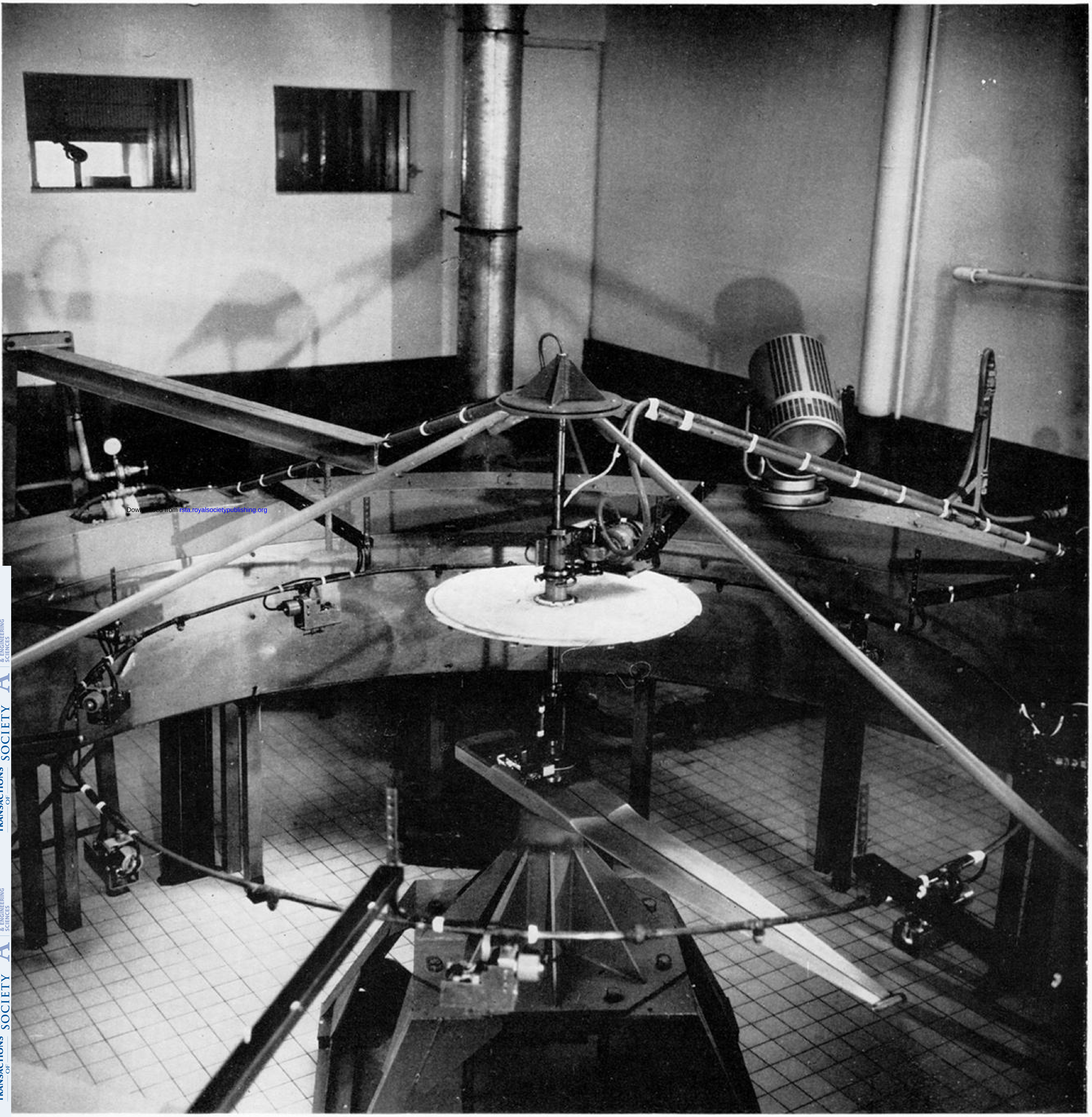

FIGURE 1. Whirling arm equipment for testing rain erosion behaviour.

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