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# Practical Aspects of Rain Erosion of Aircraft and Missiles

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# XII. Practical aspects of rain erosion of aircraft and missiles

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[Plates 30 and 31]

All-weather operational requirements have added considerably to aircraft and missile design problems as the effects of various meteorological hazards, predominantly rain, are aggravated by high speed flight. Typical damage patterns are reproduced and discussed. The problem of rain erosion is reviewed with regard to the functional requirements of the components, the flight plan of the vehicle and the occurrence of rain over the geographical terrain of operation. The factors affecting rain erosion characteristics such as type of material, surface finish, shape of component, speed and rainfall intensity are discussed and empirical data derived. The translation of significant results into practical applications is described with particular reference to supersonic transport aircraft. Details given of equipment for the simulation of rain erosion are concerned principally with the R.A.E. 'whirling arm' and rocket runway high speed sled techniques. Correlation of test results from these facilities with those from flight tests are briefly discussed.

Degree of erosion of a material is defined in relation to the particular application of the material and details are given of the characteristics of numerous materials, both metals and non-metals. The utilization of these materials for such applications as radomes, transparencies, high temperature materials, de-icing systems are briefly discussed together with methods of extending the rain erosion 'life' of materials by design or by use of protective coatings.

## 1. Introduction

The field of aircraft and missile design yields a vast complex of engineering problems. Not the least of the difficulties encountered are those arising from the atmospheric conditions in which high speed vehicles must function. The economics of airline operations and the requirements of round-the-clock vigil defensive systems dictate the need for all-weather operational capabilities for civil aircraft and missile alike. Weather hazards are many, and some indication of the extent of the designer's difficulties may be given by listing some of these hazards. They are: the effects of atmospheric radiation of all kinds, wind gusts and wind shear, lightning strikes, and the assortment of impact phenomena, ranging from encounter with ice crystals, raindrops, hailstones and even with large birds. In this impact group, the speed of the hazard is generally unimportant being low relative to the vehicle speed but the advent of space flight and the consequent encounter of very high speed meteoric particles is adding an extra threat to such hazards.

The effect of rain encountered during flight has been manifest in various forms since the beginning of aviation history. With the advent of high speed flying, however, the problem went beyond that of prevention of ingress of water and of its removal for the purpose of vision. A new phenomenon was encountered in the erosion of paint coatings and of structural plastic, ceramic, glass and even metallic components by the impingement of raindrops on forward-facing surfaces. The damage may be so severe as to affect the performance and eventually the airworthiness of aircraft or missile. The problem is, therefore, a very real one and together with other high speed phenomena such as kinetic heating, constitutes a threat to the safe advance of high speed aviation.

Historically, the observation of the phenomenon of rain erosion dates back to 1945, when U.S. Air Force personnel reported the deterioration of an antenna installation on B-29 aircraft. This 'Eagle Wing' antenna was made of plastic reinforced with glass fabric. Laboratory investigations established the fact that water, free from dust or other abrasive particles, would cause erosion of glass fabric laminates. The phenomenon had obviously been present at much lower speeds but had only been witnessed as removal of paint or of madapolam-dope schemes, and had been attributed to other causes, such as erosion by sand or dust, or stone impact on takeoff or landing. The severity of rain erosion damage has increased with higher flight speeds and the extent of the erosion has been aggravated with the wide use of non-metallic materials in aircraft.

## 2. General survey of the problem

Rain erosion resistance must now be considered as a design factor for many present and all future aircraft and missiles, whose operational speeds will exceed 350 mi./h at comparatively low altitudes. Many components incur damage during flight through rain; it is believed that all forward-facing areas will be affected at high speed.

A multiplicity of factors such as type of material, surface finish, shape of component and speed, influence erosion characteristics. Present results indicate that over a wide range of differing materials, properties such as surface hardness, strength, tear resistance (in the case of protective coatings), resilience or high elongation at break may be contributory factors to rain erosion resistance. Prediction of erosion resistance at higher velocities by extrapolation from phenomena observed at speeds up to 500 mi./h may be totally unrealistic as the erosion mechanisms may change radically with increased speed. At the high rates of straining involved, the process may be expected to become essentially a single impact failure, with every drop causing individual damage.

Precise criteria for resistance may be evolved when fundamental studies reveal the exact nature of the high rates of straining involved and erosion resistance may then be correlated with the physical properties of the materials measured under such loading conditions.

The final performance of materials for aircraft use may be modified by data accumulated over many thousands of flying hours under a wide variety of conditions.

Parameters to be considered include those of natural rainfall, of aerodynamic design, of flight plans, of materials, and most important, of the specific purpose of the end-product.

## 3. Evidence of rain erosion damage

The effects of high speed rain impact are observed by airline operators and by military groups. The latter usually employ faster aircraft under more severe conditions than the former and it is from service conditions that most evidence is available (Roys 1961). Figure 1, plate 30, shows the damage sustained by the reinforced fibreglass sandwich radome of a Hawker Hunter aircraft after 5 min at 500 mi./h in rain (intensity unknown). Figure 2, plate 31, shows the damage sustained by the cap of a pitot boom made of aluminium alloy. This was flown on a Gloster Javelin aircraft during trials in the Singapore area. Speeds were in the region of 550 knots and a total flying time in rain of 4 h 20 min was recorded, with intensities between 1 and 4 in./h. Such damage was predicted from

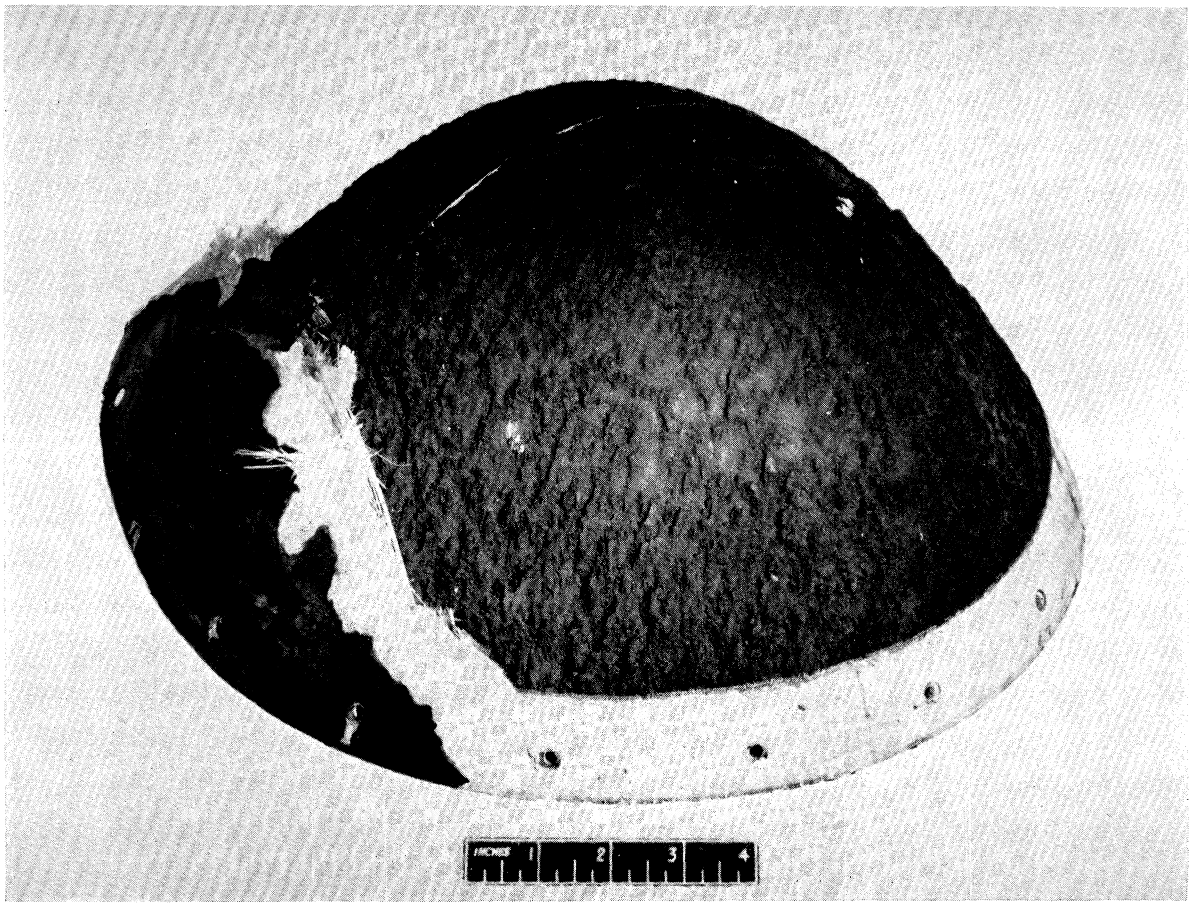


FIGURE 1. Sandwich type radome of Hawker Hunter after flight in rain.





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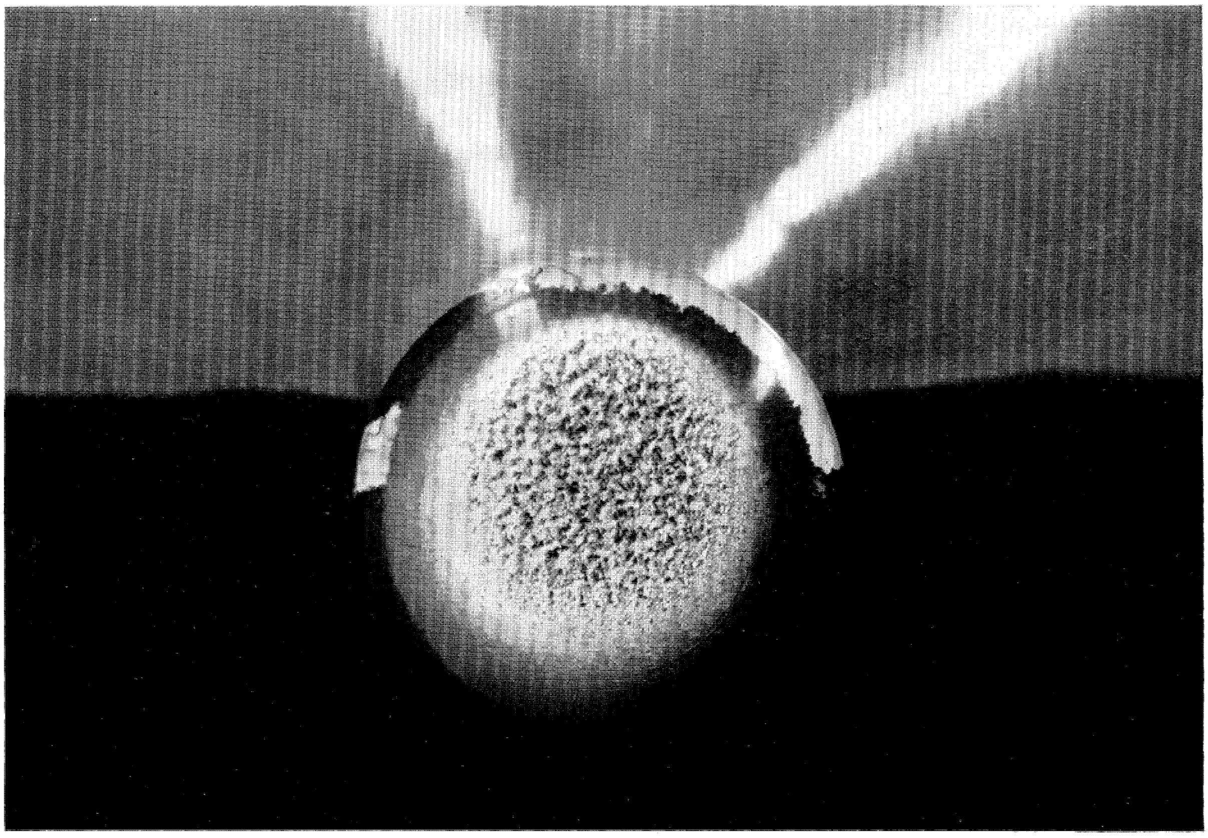

FIGURE 2. Pitot tip showing rain erosion of aluminium alloy.

simulated ground tests (Warren & Water 1961). Airlines operating Boeing 707 aircraft report various types of damage including the peeling and shearing of rivets, the edges of which have presented high local impact angles on otherwise smooth surfaces of high aerodynamic sweepback. Test flying at higher speeds must therefore be considered hazardous and thus research in this field must be aimed at an early understanding of the phenomenon. Some limited flight testing, on polymethylmethacrylate specimens, was done by the Royal Aircraft Establishment and the correlation of results with simulated ground tests was excellent.

## 4. Relevant characteristics of rain

The first consideration of the factors influencing the problem must be of the raindrops themselves.

### (*a*) *Drop size*

As worldwide operation will ensure the encounter of the complete spectrum of drop sizes, the effect of drop size will be of importance, a range of diameters from 0·25 to 7 mm being relevant for simulation purposes. As damage to brittle materials is expected to change from genuine erosion to impact failure with increasing speed, the kinetic energy of large single drops may become the dominant feature of the failure process.

### (*b*) *Intensity*

It is accepted that rainfalls of 0·1 to 4·0 in./h may be encountered (Jones 1959). As rain erosion damage may be considered to be the result of multiple impacts causing alternating stresses in a material, the rainfall intensity will govern the repetition frequency of such impacts. Such a range of intensities will mean a wide range of repetition frequencies which may be important for metals from a fatigue aspect and for polymers where relaxation phenomena will play a decisive role in their efficiency as protective coatings; the time between strikes should be sufficient to allow complete recovery of the energy-absorbing medium.

### (*c*) *Extent*

The horizontal and vertical limits for rain occurrence within the flight plan of a vehicle will govern the total time in rain. In conjunction with intensity, this will determine the total number of stress cycles to be sustained. From this aspect, rain erosion as a long term fatigue phenomenon may not be relevant to weapons, as they have relatively short flights, usually of a few minutes' duration. By contrast, it must be considered as a factor in the erosion problems associated with supersonic transport aircraft with a total flying life of, say, 30,000 h.

The possible height of occurrence of rain is at present the subject of some controversy. High altitude flying is associated with the high speed phase of supersonic transport flight envelopes and thus the determination of the rain cutoff level is extremely critical. Figure 3 indicates that, on a typical flight by the proposed Anglo-French Concorde aircraft, the $-20$ °C isotherm is taken as this limit (28000 ft. in the tropics). This implies a maximum impact velocity of some 680 mi./h. There is some evidence to suggest, however, that rain may be associated with cumulo-nimbus cloud activity at 8000 ft. beyond the tropopause, which extends to 55000 ft. in tropical latitudes (Crutcher 1962). This implies that rain could be encountered during the supersonic cruise phase with impact speeds of up to 1450 mi./h.





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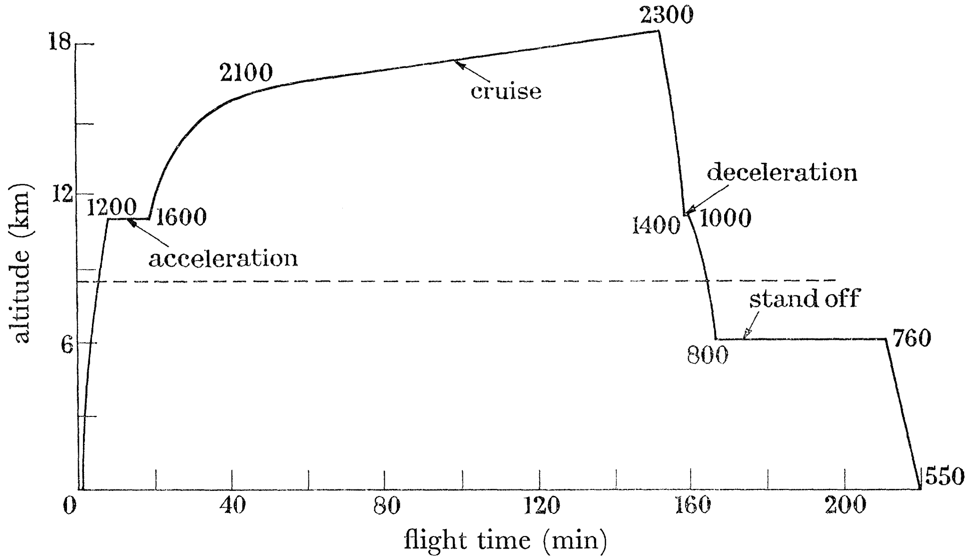


Figure 3. Typical flight plan for supersonic transport. The dashed horizontal line is the −20 °C isotherm. The speeds are given in kilometres per hour (true air speed).

## 5. Relevant characteristics of components

Consideration of the surface of an actual component being impacted reveals a number of factors affecting its rain erosion 'life'. The major features are briefly discussed.

### (a) *Aerodynamics*

This aspect may be aptly illustrated by reference to a supersonic airliner of Concorde characteristics.

(i) *Shock wave*

Subsonically, airflow will have little or no influence on deflecting or breaking up raindrops impacting on forward-facing areas, although there may be a slight masking effect on tail areas because of the attitude of the aircraft (the angle to the line of flight for Concorde is plus 4°). Shockwave phenomena, which occur because of geometric configurations, from a Mach number of 0·8 upwards, are too weak to be significant.

At supersonic speeds, which may have to be considered if the height aspect of §4(*c*) changes, the problem is more complex. Several shock patterns are associated with the Concorde shape, the major one being the body shockwave, with its stagnation point at the nose. Further patterns are associated with the wings and those appear to screen the tail fin to some degree.

It has been established by tests with a supersonic sled that water drops can be broken up by shockwaves, provided that the 'dwell' time within the shock system is sufficiently long to ensure drop breakup before it strikes the afterbody. From empirical data evolved by Jenkins, it has been estimated that for the case of the Concorde radome at a Mach number of 1·13 (equivalent to raising the rain 'ceiling' to 30000 ft.) all drops of up to 2 mm diameter (median for 1 in./h intensity) will be shattered in a distance of 1·3 ft. along the radome axis. The proposed use of a rain erosion resistant ceramic tip of this length on the radome would therefore eliminate possible rain damage.

(ii) *Kinetic heating*

Another aerodynamic aspect is that of kinetic heating. Suffice it to say, that this aspect must not be overlooked in simulation studies, particularly with reference to reinforced plastics whose physical properties are temperature dependent.

(iii) *Sweep-back*

For aerodynamic considerations, many surfaces present considerably angles to the line of flight and the result is a considerable reduction in impact velocity, normal to the surface, with a subsequent minimization of erosion damage. If the normal component of velocity can be reduced below the so-called 'threshold velocity' for the materials of the component, no erosion will occur. Typically, this velocity is approximately 250 mi./h for glass-reinforced plastics. This feature has been successfully employed in the design of radomes for weapons systems. The concept is, however, dependent on smooth surfaces and the presence of local defects or surface excrescences, e.g. rivet heads, may give rise to near-normal impact angles. Strike at these angles may result in the complete negation of the protection afforded by such a design.

## (*b*) *Materials*

A wide variety of materials is used on aircraft and missiles ranging from the hardest alloys and ceramics to the reinforced polymers and even occasionally to wood and treated fabrics.

The assessment of such a range of materials must be made on two broad bases: first, their intrinsic rain erosion characteristics as materials under standard test conditions so that some order of merit may be established and, secondly, their performance when fabricated as end items. The first set of conditions is easily specified. Typically, basic evaluation of materials at the Royal Aircraft Establishment has been conducted under standard conditions of normal impact at a test speed of 500 mi./h in a rainfall, typified by 2 mm drop diameter, of 1 in./h intensity.

The degree of erosion may be assessed in a number of ways, the most usual of which is on a rate of weight-loss basis.

The effects of such parameters as thickness, angle of impact, surface finish or grain structure, intensity, or drop size may be empirically deduced by this means using homogeneous materials such as polymethylmethacrylate or polyethylene.

Boundary conditions are of particular importance in the design of suitable specimens and of specimen holders and care must be taken to avoid using specimens which are of so small a surface area that edge damage effects mask the intrinsic erosion of the material.

Because of the wide variety of configurations in which materials are used on aircraft and missiles, it is necessary to obtain as much detail of the erosion performance of a material as possible. This introduces the second concept which is to assess the material as used in practice. Typically, an alumina ceramic radome for use at X-band radar operation may be perfectly satisfactory in rain with the wall thickness of approximately 0·25 in., as dictated by microwave considerations. The same alumina when used under identical flight conditions, but in thinner sections may exhibit cracking because of impact failure. Again, in the assessment of protective coatings, perhaps the most important feature is the efficiency of the bond at the coating-substrate interface. This is particularly relevant in the case of deicing systems for the leading edge of wing, intake or propeller blades. The appraisal of such a multilayer system of heating element, substrate and protective coatings, is only of significance if the rain erosion tests are made after typical cycling of the heating sequence.

In practice, the most important feature is the erosion which will cause malfunctioning or failure of the end item. A radiofrequency dielectric, e.g. a reinforced plastic, may have a factor of safety from strength considerations and therefore may function adequately although extensive erosion has occurred. A similar construction but used at microwave frequencies, e.g. in a radome, will only tolerate removal of a few thousandths of an inch of the surface before it becomes inoperative. At even shorter wavelengths as for infrared or vision windows only minimal surface damage is permissible.

Some indication of the influence of rain erosion consideration on design can be given by reference again to Concorde. Generally, the hazards are greatly minimized by the high sweep-back angles of forward facing surfaces. However, attention will be paid to the areas where discontinuity of surface will occur. Of particular note will be window fittings, butt joints and rivets, which may not be flush to the surrounding surface. Some alleviation by shockwave breakup is predicted in the area of the fin but the radio aerial cover will be of ceramic as an additional precaution.

An area of particular concern is that of the windscreen. Fabricated of glass, this presents an angled surface of some 43° to the line of flight. Most glasses have relatively poor rain erosion resistance and this hazard will therefore be minimized by the raising of the aerodynamic vizor in adverse weather conditions.

Should the contingency of supersonic flight in rain arise, alleviation of radome damage will be minimized by protecting the initial 1 to 2 ft. of its length, or by fabricating this section of ceramic. Provision of a pitot tube at the radome tip would further assist in the breakup of drops by the shockwave.

## 6. Test methods

Apart from the difficulties of monitoring precipitation characteristics in flight, test flying is both hazardous and costly (Bigg *et al.* 1956). Numerous simulated tests exist with various advantages and shortcomings.

### (*a*) *Whirling arm techniques*

In this method, the specimen is rotated in a simulated rainfield. Advantages are mainly in the ability to conduct prolonged tests thus allowing of an assessment of multiple impacts, especially at speeds where individual impacts are not sufficient to cause surface breakdown. The major disadvantage is the imposition of high centrifugal forces on the specimen which would not be present in use. A speed of Mach number 1·5 is the highest achieved to date by such means.

### (*b*) *Single impact studies*

These are usually directed towards a basic understanding of impact and failure phenomena (Jenkins *et al.* 1958). Disadvantages are artificial boundary conditions imposed by specimen dimensions and inability to assess long term effects.



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### (*c*) *Sled tests*

Apart from flight testing, these constitute the only practical scheme for testing full size components or sections thereof (Fyall *et al.* 1962). The limitations, particularly in Great Britain, lie in the length of test tracks. These permit a rocket-propelled vehicle moving at speed on rails to pass through a simulated rainfield of limited length. Thus the representation of flight time by multiple firings is costly, time-consuming and often impractical.

## 7. Conclusions

Experimentation and practice have amply demonstrated the hazards of rain erosion to the present and future generation of aircraft and missiles. Engineers must be supplied with much information to combat the problem by suitable choice of materials and design. Each test method has its own particular merit, which, it is hoped will eventually contribute to an adequate understanding of this hazard which has resulted from the advance of aviation.

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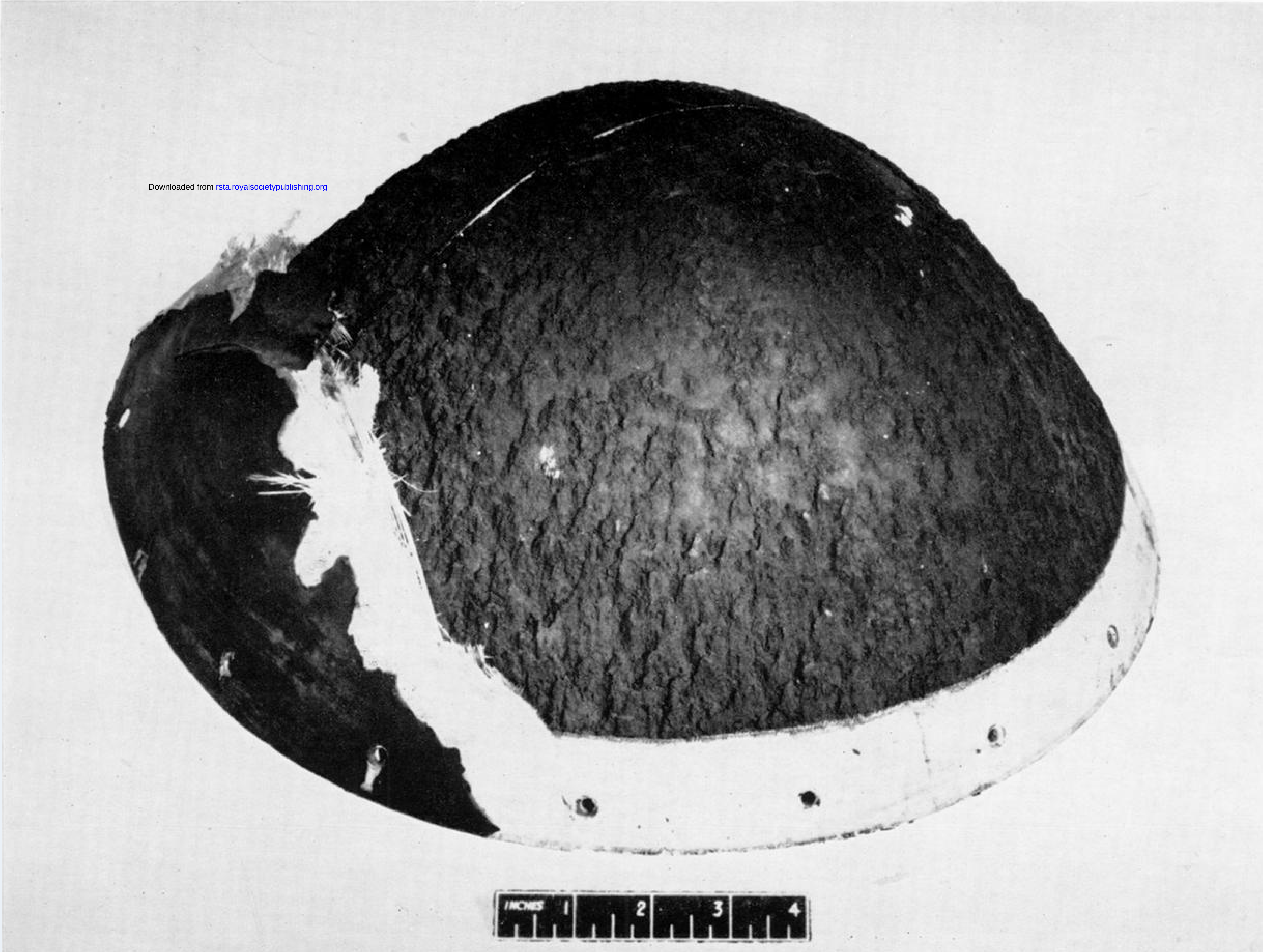


FIGURE 1. Sandwich type radome of Hawker Hunter after flight in rain.



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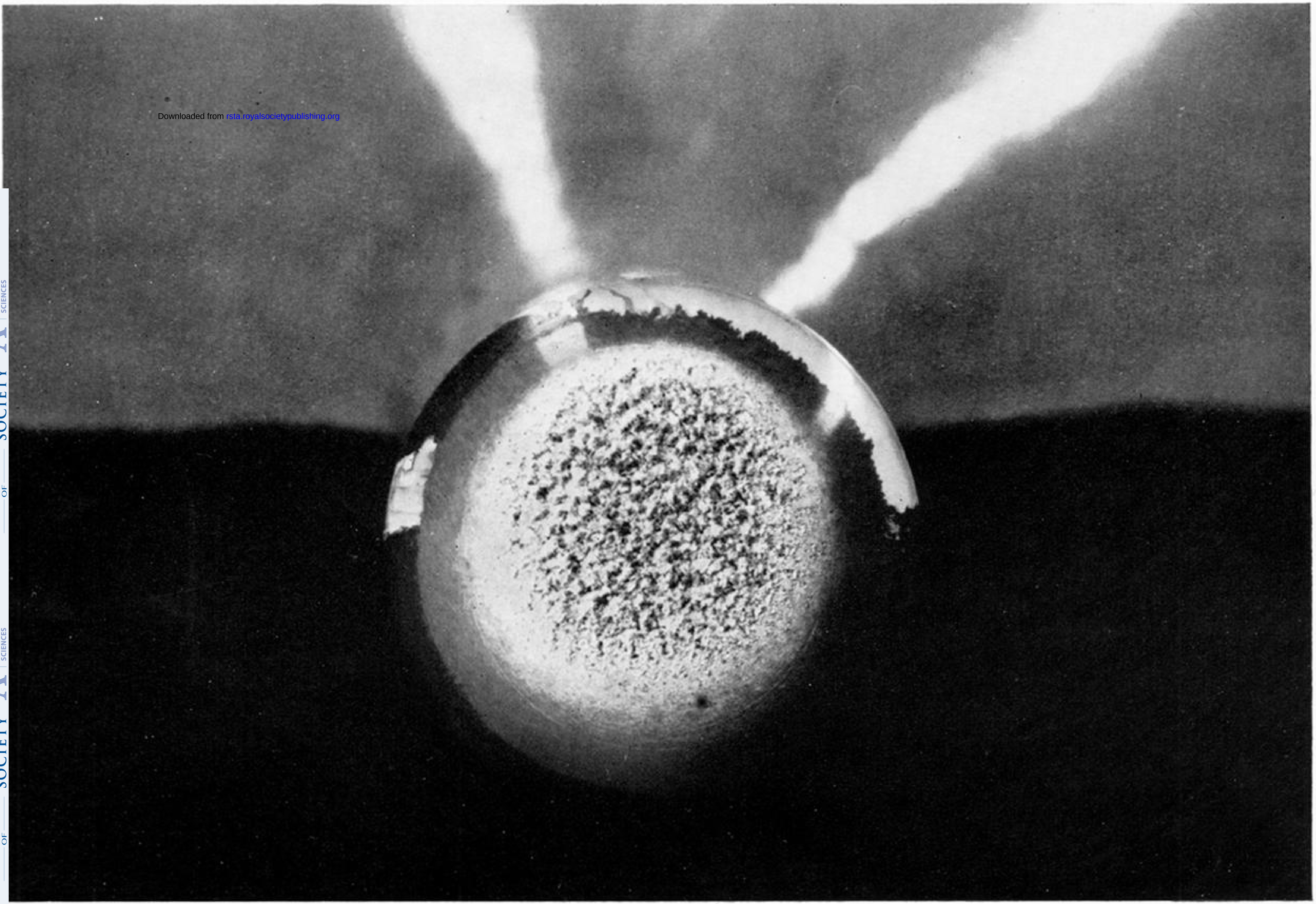

FIGURE 2. Pitot tip showing rain erosion of aluminium alloy.



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