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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT--ETC F/G 20/11  
MANUAL ON THE FATIGUE OF STRUCTURES. II. CAUSES AND PREVENTION --ETC(U)  
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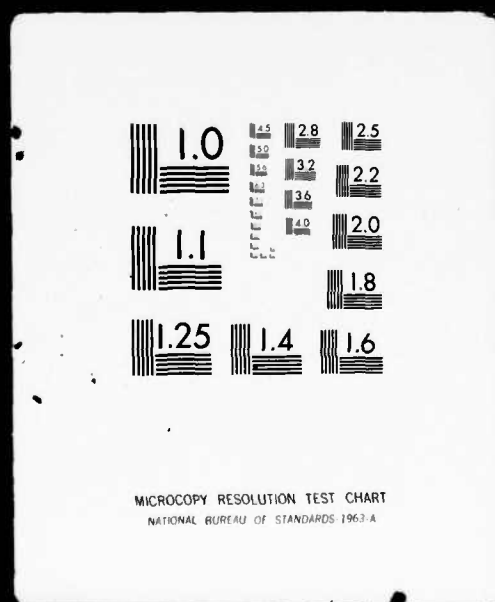
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### 7.5.2.2 - a - Changes in the material during incubation

During the incubation period of erosion by liquid impact or cavitation under repeated microjets due to the collapse of bubbles, the changes which occur in ductile materials are essentially the same as during metal fatigue: cold working of initially ductile materials and creation of residual surface compressive stresses.

In the case of 99.999% pure aluminium Vyas and Preece<sup>240</sup> investigated the changes in the surface finish of the metal under the electron microscope, with scanning after 2 seconds exposure to cavitation, and then every two seconds. Cavitation was achieved by an ultrasonic device with a frequency of 20 kHz in which the test specimen was kept stationary in distilled water at 25°C, 115  $\mu\text{m}$  beneath the surface of the vibrator. For a polycrystalline specimen the grain boundaries were below the level after 5 seconds, some grains flowed to the boundaries of adjacent grains and undulations of the surface and of grain boundaries were formed. The behaviour was very similar to that observed by Laurent<sup>241</sup> when studying fatigue in pure aluminium where the movement of the grains away from the surface and the undulations of the grain boundaries had been observed previously. At the end of the incubation period in the tests performed by Vyas and Preece, the cold worked metal became deformed, with rims being converted into ductile lips at the edges of the impact marks; subsequent impacts tended to flatten the rims by breaking them up.

According to Heymann<sup>242</sup> research on the changes in the mechanical condition of the surface as a result of erosion hammering during the incubation period shows rapid initial variation followed by an asymptotic tendency towards a constant condition, as in shot blasting. Plesset and Devine<sup>243</sup> have shown by means of X-rays that in a surface subjected to cavitation, plastic deformation reaches a stable depth almost immediately after the beginning of exposure and remains appreciably constant during the erosion process. In the case of annealed nickel and of electrolytically polished test specimens cavitation-stressed in distilled water at 25°C at a frequency of 20 kHz and an amplitude of 128  $\mu\text{m}$  to 1.59 mm from the surface of the oscillator, measurements of residual stress by deformation after successive dissolutions of the surface have given values of 40 kgw/mm<sup>2</sup> for the residual stress at the surface, being cancelled out only at a depth of 0.35 mm after a 10 second exposure, and of 0.6 mm after 40 minutes exposure, the value at the surface remaining approximately the same.

With a steel containing 0.25% C, 12% Cr, Ni, Mo, V, Beckwith and Marriott<sup>244</sup> showed during erosion tests using a rotating drum and radial specimens that the first stage of the damage for steel tempered at 250°C and tested at an impact velocity of 345 m/s corresponded to "extrusions" along certain crystalline slip planes. Towards the end of the incubation period, the intense plastic deformation of the surface could be described as "smearing" of the surface by the deformation of numerous plastic "extrusions" along the slip lines (Figure 78).

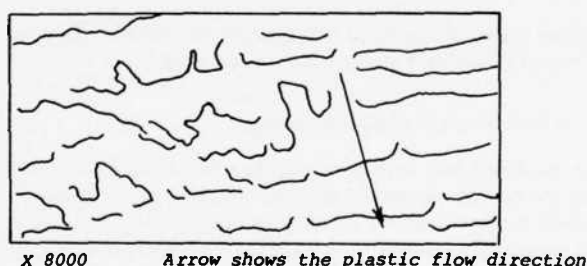


Fig.78 Flattening of "extrusions" along plastic slip lines, from a micro-photograph by Beckwith and Marriott<sup>244</sup>

Several authors have suggested that erosion or cavitation damage occurred by repeated impingement by a process similar to that of fatigue. Figure 79 contains a comparison of the liquid impact fatigue strength curves for aluminium alloys, deduced from the number of impacts, as evaluated during a rotating arm test, and from the calculated impact pressures, with data on the fatigue strength of smooth specimens. The materials investigated by Hoff et al.<sup>245</sup> for rain erosion and by Schütz<sup>246</sup> for fatigue were aluminium and the aluminium alloys used for the construction of aircraft.

With droplets of a diameter of 1.2 mm and a rain density of  $1.2 \times 10^{-5}$  in volume, the erosion incubation times  $t_i$  were

$$t_i = a/V^m, \quad (99)$$

with an impact velocity  $V$ . The maximum erosion rates were

$$(de/dt)_{\max.} = b V^n; \quad (100)$$

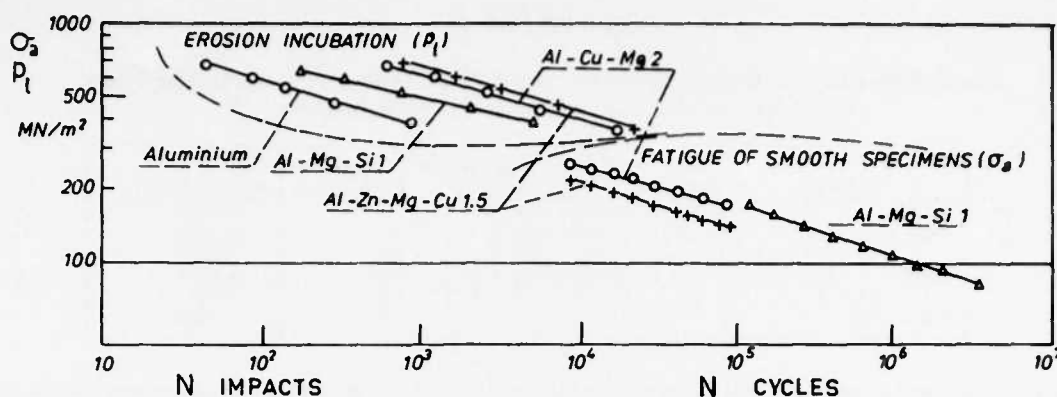


Fig.7.9 Comparison of erosion incubation period curves against hammering pressure with fatigue life curves for aluminium alloys, from Hoff et al.<sup>245</sup>

Schütz's fatigue tests were reflected by

$$\sigma_a = c/V^p. \quad (101)$$

The values of the exponents  $m$ ,  $n$  and  $p$  are given in Table 7.5.2.2 – 1 below.

TABLE 7.5.2.2 – 1

Erosion Incubation, Maximum Erosion Rate and Fatigue Life of Aluminium Alloys, from Hoff et al.<sup>245</sup> and Schütz<sup>246</sup>

| Alloys          | Erosion |     | fatigue<br>$p$ | $m$ , $n$ and $p$ are the exponents of relationships (99) and (100) for erosion and of (101) for fatigue |
|-----------------|---------|-----|----------------|----------------------------------------------------------------------------------------------------------|
|                 | $m$     | $n$ |                |                                                                                                          |
| Aluminium       | 4.9     | 3.6 |                |                                                                                                          |
| Al-Mg-Si 1      | 6.2     | 4.9 | 4.7            |                                                                                                          |
| Al-Cu-Mg 2      | 5       | 5.4 | 5.2            |                                                                                                          |
| Al-Zn-Mg-Cu 1.5 | 5.2     | 4.6 | 6.5            |                                                                                                          |

As in fatigue conditions, certain crystalline phase changes occur as a result of plastic deformation which takes place more readily before a phase change. When discussing a work by Gould<sup>247</sup>, Rieger pointed out that in manganese austenitic steels, the transformation from austenite to martensite takes place under impacts, and that the high strength of this steel would seem to be due to the greater hardness of the martensitic phase. It can also be added that the phase change is accompanied by a volume increase which thus introduces residual compressive stresses at the surface. The cobalt alloys investigated by Gould appear to owe their high cavitation strength to the phase change in the cobalt-chromium alloy from the face-centred cubic phase  $(200)_{fcc}$  to the compact hexagonal phase  $(10\bar{1}1)_{hcp}$ . The composition of the stellite 6B specimens was 25% Cr, 4.5% W, 1.5% Ni, 1% Fe, 1% Mn and the remainder, Co. The hexagonal phase proportion was measured by X-ray diffraction; the very rapid transformation at the surface continued in depth during the erosion incubation period. In the erosion debris transformation was complete. After transformation, the material becomes harder and more brittle. The excellent behaviour of the stellite would appear to be due to the phase change which delays the rupture of the metal by permitting considerable plastic elongation and by increasing the hammering pressure level leading to cracking of the metal. A similar transformation is observed in the cobalt alloy L 605 (0.1% C, 20% Cr, 10% Ni, 15% W, 1.5% Mn, 0.5% Si, remainder Co). Gould<sup>247</sup> characterised the rupture energy of the metal by the expression:

$$E_R = \{\sigma_{0.2\%} + (2/3)(\sigma_R - \sigma_{0.2\%})\}. \quad (102)$$

For the two above-mentioned alloys and the alloys 17-4 PH (0.07% C, 16.5% Cr, 4% Ni, 1% Mn, 1% Si – remainder = Fe) and INCO 718 (0.05% C, 19% Cr, 53% Ni, 19% Fe, 3% Mo, 0.8% Ti, 0.6% Al, 5.2% Nb, 0.004% B). Table 7.5.2.2 – 2 gives the mechanical properties and the stabilised erosion rate in mm/h during cavitation at 20 kHz and an amplitude of 50.8  $\mu$ m in deionised water at  $11 \pm 1^\circ$ C. It will be seen that stellite 6B shows the best behaviour.

Hoff et al.<sup>245</sup> showed, however, that forged stellite was very sensitive to the direction of the rain impact compared with the direction of rolling, deep pitting being observed when a side surface of a test specimen was perpendicular to the velocity of impact of the rain droplets. When applying these findings to steam turbine blade shields, Hoff et al.<sup>245</sup> considered the various practical possibilities of protecting the steel blades with a stellite covering. During deposition by fusion on the surface of the components the stellite becomes compressed after cooling and applies residual tensile stresses to the steel. These residual stresses can be only slightly reduced by annealing after welding, a fact which excludes

TABLE 7.5.2.2 - 2

Tensile Properties and Stabilized Cavitation Erosion Rate of Alloys for Steam Turbine Blades,  
 $f = 20$  kHz, ampl. =  $50.8 \mu\text{m}$ , De-Ionized Water, from Gould<sup>247</sup>

| Alloys          | R <sub>C</sub><br>Hardness | $\sigma_{\text{ult.}}$<br>MN/m <sup>2</sup> | $\sigma_{0.2\%}$<br>MN/m <sup>2</sup> | Elong.<br>% | Rupture energy*<br>MN/m <sup>2</sup> | Erosion rate<br>$d_e/dt$ , mm/hour |
|-----------------|----------------------------|---------------------------------------------|---------------------------------------|-------------|--------------------------------------|------------------------------------|
| 17-4 PH         | 36                         | 1030                                        | 930                                   | 17          | 169                                  | 0.0082                             |
| INCO 718 aged   | 42                         | 1470                                        | 1300                                  | 38          | 538                                  | 0.0015                             |
| 70% cold rolled | 52                         | 2000                                        | 1990                                  | 10          | 200                                  | 0.0022                             |
| L 605           | 23                         | 1030                                        | 480                                   | 65          | 545                                  | 0.0014                             |
| 30% cold rolled | 47                         | 1480                                        | 1450                                  | 14          | 206                                  | 0.0014                             |
| 6B Stellite     |                            |                                             |                                       |             | 156                                  | 0.0008                             |

the use of this method of protection for steam turbine blades where the sum of the applied stresses and the residual stresses would exceed the elastic limit. Leading edge shields can still be cast and the edges welded by electron bombardment. During discussion on the above Heymann stated the Westinghouse was using rolled bands which were fitted to the blades by a semi-automatic controlled brazing process; the bands were initially drawn in the direction of rolling but were curved in the other direction to fit the aerodynamic profile of the blades.

#### 7.5.2.2 - b - Erosion and cavitation propagation

As shown in Figure 77, there is a continuous increase in the mean erosion depth  $e_m$  after the incubation period  $t_i$ ; the erosion rate  $d_e/dt$  passes through a maximum, then decreases and tends towards a stable value. Quite frequently, erosion tests are not taken far enough to show the stabilisation of the cracking rate after the maximum value has been reached. In practice, a longer service life than that for the maximum erosion rate will be assumed in the case of materials with a very high strength such that the erosion depth remains well below the operating tolerances, e.g. as found by Smith et al.<sup>248</sup> in the case of steam turbine blade shield materials, characterised by the relationship between a stabilised erosion rate and that of a standard tool steel (18% W, 6% Cr, 0.7% C, remainder Fe, hardness number: 630 DPH) taken as a reference. Tool steels, cobalt alloys and tungsten carbides subjected to liquid impacts totalling a quantity of water of  $50 \text{ kg/cm}^2$  tended towards final erosion rates of  $0.3 \times 10^{-6}$  to  $2 \times 10^{-6}$  g of metal per g of water. For these materials, the final erosion rate would correspond in practice to a penetration of 2.5 mm; so the maximum value of the erosion rate curve is of little practical importance. This is demonstrated by a cobalt alloy with 31% Cr, 14% W, 1% C which was initially 40 times stronger than the standard tool steel but which was less than 1.5 times as strong after the impact of  $100 \text{ kg}$  of water per  $\text{cm}^2$ . Tests show that the erosion rates converge after impacts of more than  $40 \text{ kg}$  of water per  $\text{cm}^2$ . The use of a reference material is necessary if the precise conditions of impact are disturbed by the aerodynamic flow and the absolute pressure, such as occurred during the tests by Smith et al. Figure 80 refers to liquid impact tests in a rotating device in which the specimens and the rain ejectors rotate in opposite directions at 12,000 revolutions a minute in a relative-vacuum chamber with an absolute pressure which varies between 50 and 250 mm Hg. At an absolute pressure of 724 mm Hg, Figure 81 shows the development of the weight losses by erosion as a function of time or the weight of liquid projected per  $\text{cm}^2$ .

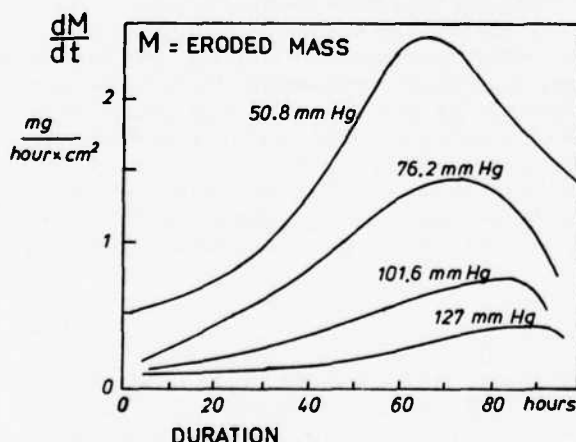


Fig.80 Erosion rate under liquid impact of reference high-speed steel. Influence of the absolute pressure, from Smith et al.<sup>248</sup>

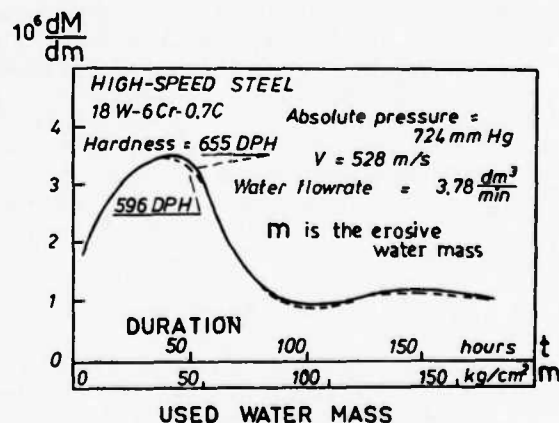


Fig.81 Erosion rate of reference steel under pressure of 724 mm Hg, from Smith et al.<sup>248</sup>

Erosion measurements are performed by weighing the dismantled specimens, the erosion rates being obtained by numerical derivation – a procedure which makes extrapolations very much open to discussion. Starting from a relatively smooth surface and before any crack initiation, plastic deformation causes the build up of residual compressive stresses at the surface. Erosion starts slowly, the erosion rate increasing until the majority of the surface has been damaged, a large number of damaged elements therefore contribute at approximately the same time to the detachment of fragments. The subsequent fatigue development will give rise to a smaller number of fragments with a lower erosion rate after the maximum has been passed. As necessary, other variations in the erosion rate might occur before a stable value is achieved. This phenomenon is fairly general in fatigue conditions. For example, if fatigue crack propagation has been accelerated due to the existence of a local weak point, the material in front of the point of the crack is subjected for a shorter time to the alternating fatigue strains and is more resistant, which reduces the rate of propagation.

When erosion and cavitation tests are carried out in comparable conditions, cavitation erosion and erosion by liquid impact show similar losses and in approximately the same proportions for both types of erosion classification. This was found, for instance, in the multiple liquid impact erosion tests and the cavitation tests performed by Thiruvengadam<sup>249</sup> and referred to in Table 7.5.2.2 – 3.

TABLE 7.5.2.2 – 3

Comparison of Liquid Impact Erosion with Cavitation Erosion, Thiruvengadam tests<sup>249</sup>

|                        | LIQUID IMPACTS<br>V = 106.75 m/s<br>jet diameter = 0.79 cm<br>specimen diam. = 0.375 cm | CAVITATION<br>Specimen diameter = 0.95 cm<br>f = 13.5 kHz, distilled water<br>double amplitude = $3 \times 10^{-3}$ cm |
|------------------------|-----------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|
| Nickel                 | $(\frac{de_m}{dt})_{\max} = 3.5 \times 10^{-3} \text{ cm}^3/\text{h}$                   | $(\frac{de_m}{dt}) = 2.8 \times 10^{-3} \text{ cm}^3/\text{hr.}$                                                       |
| 316 stainless steel    | 2                                                                                       | 1                                                                                                                      |
| 6 Al-4V titanium alloy | 0.4                                                                                     | 0.9                                                                                                                    |
| 1100-0 aluminium       | 70                                                                                      | 100                                                                                                                    |

Nevertheless, any similarity in the behaviour of a material during erosion by repeated liquid impact and erosion by cavitation may be considerably overshadowed and even masked by the predominant influence of vapour tension on cavitation. As pointed out by Schulmeister<sup>250</sup>, the temperature has a simultaneous effect on the quantity of gas absorbed in the water and on the chemical and electrochemical reactions which together determine the effect of the temperature on both cavitation erosion and corrosion. If the static pressure remains less than the vapour tension, the bubbles produced do not collapse and there is no erosion. If the difference between the static pressure and the vapour tension is greater than the depression produced by the movement of the vibrator, no bubble is formed. Maximum damage occurs between these two limits. Starting from boiling point, the damage increases with the distance to the vapour tension, that is, with the static pressure if the temperature is constant, since implosion of the bubbles occurs all the more suddenly, the quicker the increase in the pressure of the fluid. Due to the absence of a bubble the upper limit is reached on the oscillator before the bubbles cease to be formed in an undefined environment at rest, the reason for this being the narrowing of the area which produces the bubbles on the front face of the specimen. Reproducible tests can be achieved in the range of conditions in which the damage increases with the pressure.

#### 7.5.2.2 – c – Behaviour during accelerated tests and in service – Effect of corrosion

In addition to the effect of static pressure and temperature on cavitation damage, an important difference in the damage observed during laboratory tests, as compared with behaviour during service, is due to the effect of corrosion. Kallas<sup>251</sup> has summarised the development of ideas and of research results regarding the part played by corrosion in cavitation damage.

In the first place, pitting of the surface, and then the cavernous appearance of oxidised components, such as hydraulic turbine blades and marine propellers, would seem to suggest that there had been a great deal of corrosion. As in the case of the effect of stress on corrosion, some experts have advanced the theory that cavitation erosion is due to the combined action of mechanical and chemical effects, the oxide film protecting the metal being continually torn away by the hammering caused by the implosion of bubbles, so that there is no slowing up of the chemical action which continues at a high rate.

In 1919, however, Parsons and Cook<sup>252</sup> showed that, in the case of steel, the detached fragments were rust, in sea water, and iron in alcohol.

In the same way as for the effect of corrosion on fatigue, consideration must be given to the relative rate at which the metal is damaged under corrosive conditions or as a result of pure mechanical stressing. Although corrosion acts very slowly on sound metal and removes fairly rapidly only the metal which has already become damaged by repeated impact, it is not possible to speak of additional corrosion damage. Laboratory tests are most frequently performed in accelerated conditions as compared with actual service conditions. In agreement with Preiser and Tytell<sup>253</sup> it is possible to conceive of three different areas covered by cavitation erosion, namely, cavitation deformation or fracture, cavitation fatigue and cavitation corrosion, depending on the duration of the test according to the intensity of cavitation. For low cavitation

intensities and long test periods, corrosion might play a significant part, whereas it would be negligible in the usual high speed tests. It was in the field of the cavitation pressures which develop stresses much below the plastic flow limit of the metal that Preiser and Tytell conducted their rotating propeller experiments. With still lower cavitation intensities it is assumed that the cavitation forces can merely destroy the protective oxide film and remove the corrosion products.

Lichtman et al.<sup>254</sup> investigated a number of incidents to ship components in contact with the water and concluded that cavitation was the main cause of damage only in the case of propellers. The damage to tie-rods, rudders and other ancillary equipment was due to corrosion which became more serious as a result of mechanical action. They also came to the conclusion that the slowest laboratory test was performed at a higher speed than that of ships in service and that the damage suffered in service conditions was mainly corrosion accelerated by cavitation turbulence.

One method of increasing the relative importance of corrosion is to apply intermittent cavitation in a device in which the immersed specimen is continuously subjected to corrosive action, as in the tests by Waring et al.<sup>255</sup> in which cavitation increased the damage only in the case of corrosion sensitive materials.

To study the effect of corrosion on cavitation erosion, McGuinness and Thiruvengadam<sup>256</sup> carried out comparative cavitation tests in sea water and in distilled water on specimens made from steel, Al-Mg alloy 5086 H117 and the cupro-nickels 90-10 and 70-30 mounted in the standard ASTM (Ref.257) piezo-electric device. Figure 82 shows some significant results of these tests: for the treated hard steel HY 130, the maximum erosion rate is higher and is reached earlier in sea water (S) than in distilled water (D). This effect of dissolved salt is less pronounced for the semi-hard SAE 1020 steel; it is negligible in the case of the Al-Mg alloy and the cupro-nickels. The authors expressed the assumption that the major effect on a treated and relatively brittle steel was due to the additional embrittling action of hydrogen.

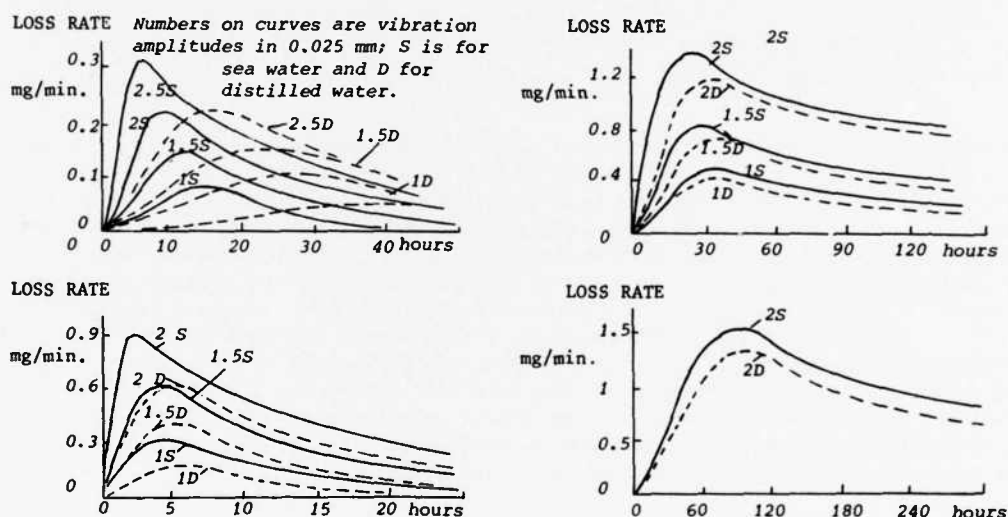


Fig.82 Cavitation mass loss of 15.9 mm diameter specimens in sea water (S) and in distilled water (D), from McGuinness and Thiruvengadam<sup>256</sup>

Certain practical problems such as reducing cavitation damage in cooling systems of marine Diesel engines have been resolved after systematic tests using corrosion inhibitors. In the prior study of such a problem Schulmeister<sup>250</sup> investigated the loss by cavitation in cast iron, iron, carbon steel and Al-Cu-Mg 2 alloy specimens in baths of (1) distilled water, pH 5.8; (2) hard water, pH 6.1 containing 134 mg of  $\text{CaCl}_2$  and 156 mg of  $\text{CaSO}_4$  per litre and (3) three soluble commercial oils a, b, and c, normally used as corrosion inhibitors during machining operations with cutting tools. In certain conditions corrosion inhibitors are an excellent means of protecting components against cavitation. Their effectiveness depends, however, on a large number of influence factors<sup>257</sup>. For example, Figure 83(b) shows that the soluble oil, a, which is very effective on cast iron (Fig.83(a)) attacks the aluminium alloy. Two other similar anti-corrosion soluble oils, b and c, protect aluminium at low temperatures but accelerate erosion at high temperatures. The series of tests carried out by Schulmeister enabled him to draw the following conclusions:

- (1) Chlorides and sulphates dissolved in water considerably accelerate cavitation attack in corrosion sensitive materials, such as cast iron or carbon steel; austenite and copper alloys are much less sensitive to salts. The acceleration process is further hastened by oxygen and is greatly affected by temperature and the size of the mechanical stresses.
- (2) Corrosion inhibitors can reduce significantly the deterioration of the material; they can also intensify an attack. Their effect depends on the type and concentration of the inhibitor, on the material attacked, on

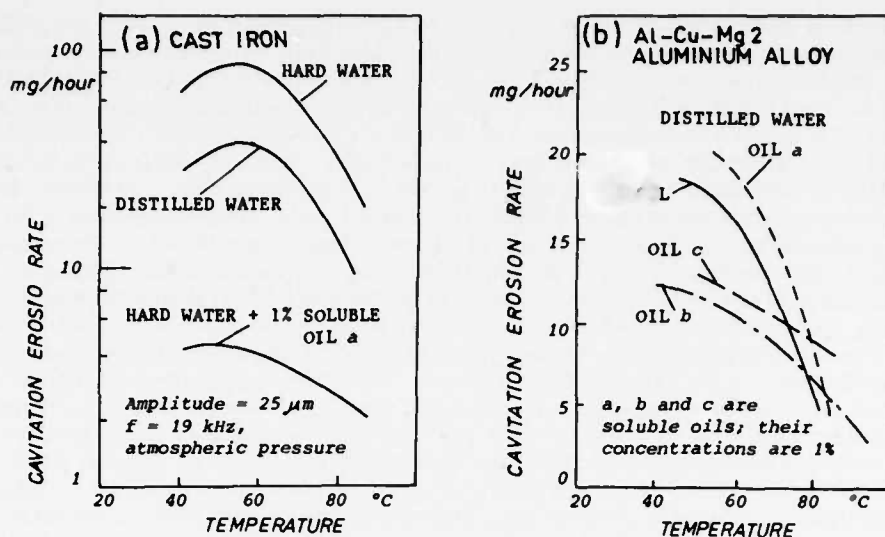


Fig.83 Influence of corrosion inhibiting soluble oils on cavitation erosion of cast iron (a) and of Al-Cu-Mg 2 aluminium alloy, from Schulmeister<sup>250</sup>

temperature, on the intensity of the mechanical cavitation, on the other substances included in the liquid and on the age of the inhibitor solution.

- (3) The dissolved gases can accelerate or reduce attack by cavitation or corrosion. The actual effect is determined by the type and quantity of gas, the material attacked, the composition of the liquid, the temperature and the intensity of the mechanical cavitation stresses.

The most important fundamental result shown by Schulmeister was that the relationship between the rate of damage and a particular condition or a particular parameter is very complicated and is determined by the various boundary conditions and extent of the other influences. It is therefore impossible to make firm useable statements about the intrinsic significance of a particular influence. Research such as the above examples may merely indicate the particular importance of an influence or a group of influences, and their inter-relationship. If remedies are sought for a specific case of damage, special tests suitable for the case in question must be carried out. This type of work has been undertaken in Darmstadt, aimed at preventing the deterioration of the Diesel engine cooling system. The result gave rise to a series of recommendations for practical application, including choice of cooling water, a suitable inhibitor, control of the inhibitor concentration, gas content of the cooling liquid and treatment of aged inhibitor solutions. The in-service value of these suggestions on treatment of the cooling fluid was proved during field tests carried out by the Federal German Railways in their ferry, the "Theodore Heuss"<sup>258</sup>. A saving of 250,000 DM a year was effected on the cost price of a ship's engine.

According to Lichtman<sup>259</sup> cavitation was reduced to a minimum in the cooling water system in Diesel engines by chemical additions, including corrosion inhibitors, detergents to prevent the formation of foam and wetting agents to produce a liquid film which adhered to the metal by decreasing the surface tension, factors which affected bubble formation.

Steller et al.<sup>260</sup> simulated the service conditions for cavitation damage of hydraulic turbine components by placing cylindrical specimens in the impeller of a "Kaplan" propeller hydraulic turbine in such a way that the front of the mounting and the surface of the specimen just touched the surface of the impeller. The damage which occurred was compared with that observed on other specimens, subjected to magnetostriction (frequency: 8.5 kHz, amplitude: 55  $\mu$ m, 14 mm diameter specimen submerged to a depth of 3 mm in the supply water at 20°C), or tested on a rotating disc at 2890 revolutions per minute, the 30 mm diameter specimens being mounted on a 270 mm diameter circle together with cavitation exciters consisting of 12 mm diameter pins, the liquid being the supply water functioning in a closed cycle. An examination of the surface of the specimens and of their micro-sections showed (a) in the magnetostriction tests the damage corresponds to surface pitting; (b) in the rotating disc cavitation tests the pits are deeper and there are micro-cracks; finally, at the wall of the force chamber of the turbine, irregular pitting develops in the three dimensions, as well as cavities the profile of which has become smooth from the simultaneous action of cavitation and corrosion. The grain joints do not constitute preferential damage points. The conclusion reached is that for the materials tested — annealed Armco iron, brass with 52% Cu and 38% Zn and cast steel (0.26% C, 5% Mn, 0.4% Si, 0.2% Cr) — corrosion occurs only in the natural conditions of slow cavitation. The thickness of the worked layer was 10 times greater in natural cavitation than during magnetostriction, which may account for the slower development of the microcracks. The authors mention the existence of cases in which materials considered to be excellent, according to the results of accelerated tests, turned out to be of mediocre quality in actual conditions of use.

In certain problems involving both corrosion and erosion by liquid impact of water droplets, the conditions are sometimes such that corrosion attacks act reciprocally on one another and that the parameters of the problem, as yet not fully understood, cannot be simulated during tests of a simple type. It was these conditions for example which were described by Van der Horst and Sloan<sup>261</sup> relating to the damage in service of a converted gas cooler in an ammonia production factory. The gas came from the conversion by catalysis of  $\text{CO}_2 + \text{H}_2\text{O}$  into  $\text{CO} + 2\text{H}$  and contained hydrogen,  $\text{CO}_2$ , nitrogen and water. The cooler removed the water by condensation. The gas entered the inlet at a temperature of  $127^\circ\text{C}$  and a pressure of  $1650 \text{ MN/m}^2$ ; the outlet temperature was  $50^\circ\text{C}$  and the pressure  $1630 \text{ MN/m}^2$ . It contained 13.2 mol per cent of water at the inlet as against 0.7 mol per cent at the outlet. The partial pressure of the  $\text{CO}_2$  was  $269 \text{ MN/m}^2$ . The water circulated in finned tubes, and the gas, in the cooler around the tubes. The condensation water, however, remained between the fins spaced at 1 mm intervals, thus eliminating any advantage afforded by the fins. The first finned tubes were made of brass but were then replaced by carbon steel tubes. The steel fins were then attacked and disappeared quickly. Incidentally, re-calculation of the heat transmission showed that the fins served no useful purpose. The surface of the corroded finned tubes was completely covered with rhombohedral crystals of ferrous carbonate. It is known that, when dissolved in water,  $\text{CO}_2$  corrodes carbon steel. At medium temperatures, velocities and pressures, this type of corrosion ceases of its own accord since, in the absence of oxygen, the corrosion product is a ferrous carbonate which is only very slightly soluble in water ( $0.0067 \text{ g/100 cm}^3$  at  $25^\circ\text{C}$ ). The much more soluble ferrous bicarbonate would appear to be formed at partial pressures of  $\text{CO}_2$  and at much higher temperatures. The author then calculated the gas velocities which at the most were  $51.8 \text{ m/s}$  and therefore less than the threshold values quoted by Thiruvengadam<sup>215</sup> or Heymann<sup>230</sup> for liquid impact erosion of carbon steel. There is therefore a mutual reinforcing effect between erosion and corrosion.

### 7.5.2.3 Data on Erosion Resistance

We have already discussed the correlation between the resistance to sand erosion and the resistance to cavitation of materials used in the construction of hydraulic turbines and marine propellers (see 7.5.1.1 — a). It has been shown that, generally speaking, damage is the result of plastic deformation which governs the rupture of components or the development of fatigue effects, due to impact by abrasive grains, liquid drops or cavitation microjets. The existence of a common damage mechanism, with different levels of the extent of the plastic deformation occurring after each impact explains the possible ways of correlating resistance to various forms of erosion with the static resistance and with the fatigue resistance. As in the case of correlations of the wear resistance with the modulus of elasticity, the present correlations are very rough and are influenced by the effect of the parameters more specifically related to each material.

#### 7.5.2.3 — a — Classification lists of erosion resistant materials

In 1962 Rheingans<sup>262</sup> discussed damage to hydraulic turbines resulting from erosion by foreign particles in suspension such as sand, clay or ice particles and, in the area of hydrodynamic depression, the formation of pits resulting from cavitation and making their appearance in the high velocity areas where there are changes of direction or flow separation and where vapour bubbles form at rates of 10,000 to 20,000 a second. The complete life of a bubble is a few microseconds; it collapses, producing a point pressure of 350 to  $700 \text{ MN/m}^2$ . The material in contact is destroyed immediately or as a result of fatigue under the repeated action of the bubbles. A direct relationship exists between the flow velocity and the pressure for the initiation of bubble formation:

$$K_i = \frac{p - p_v}{\rho V^2/2}, \quad (103)$$

in which  $K_i$  is the number for the initiation of cavitation,  $p$  is a characteristic pressure of the system,  $p_v$  is the vapour pressure of the liquid and  $\rho$  is its specific mass,  $V$  being a characteristic velocity of the system. For hydraulic turbines the cavitation discriminant is used again:

$$\sigma = \frac{H_b - H_s - H_v}{H} \quad (104)$$

where, in metres for the height of the water,  $H_b$ ,  $H_s$ ,  $H_v$  and  $H$  correspond respectively to the turbine inlet pressure, the outlet suction height, the vapour tension for the temperature and  $H = \rho V^2/2$  is the dynamic pressure.

From his experience of the behaviour in service of hydraulic turbines, accumulated from 35 years of use, Rheingans<sup>263</sup> published a qualitative classification list of a number of materials based on their actual behaviour (List 1 in Table 7.5.2.3 — 1). A second list was drawn up<sup>262</sup> from cavitation tests performed on vibrating devices and on various test machines giving quantitative results which were hard to compare but which nevertheless made it possible to classify the materials.

It will be seen that there is an excellent correlation between the two classifications, probably due to the fact that corrosion plays only a very small part in the damage to materials originally chosen for their high corrosion resistance, and justified by the common erosion mechanism, by the entrained particles and, in cavitation, damage by repeated impact pressures.

TABLE 7.5.2.3 - 1

Qualitative Classification Lists of the Erosion Resistance of Materials from Service Behaviour in Hydraulic Turbines (List No.1) and from Cavitation Tests (List No.2), from Rheingans<sup>262</sup>

| List No. 1 - Service behaviour       | List No. 2 - Cavitation tests      |
|--------------------------------------|------------------------------------|
| 1 Stellite                           | 1 Stellite                         |
| 2 17-7 Cr-Ni Stainless steel         | 2 17-7 Stainless steel, welded     |
| 3 18-8 Cr-Ni Stainless steel, welded | 3 18-8 Stainless steel, welded     |
| 4 Ampco no. 10, welded               | 4 Bronze al. Ampco no. 18, welded  |
| 5 25-20 Cr-Ni steel, welded          | 5 Bronze al. Ampco no. 18, casting |
| 6 2-24 eutectic-xyron, welded        | 6 Ni-Al bronze, casting            |
| 7 Ampco bronze, casting              | 7 18-8 stainless steel, casting    |
| 8 18-8 stainless steel, casting      | 8 13% Cr steel, casting            |
| 9 Ni-Al bronze, casting              | 9 Mn bronze, casting               |
| 10 13% Cr steel, casting             | 10 Carbone steel, casting          |
| 11 Mn bronze, casting                | 11 Bronze, casting                 |
| 12 Sprayed 18-8 steel (coating)      | 12 Cast iron                       |
| 13 Cast steel                        | 13 Sprayed 18-8 steel (coating)    |
| 14 Bronze                            | 14 Rubber                          |
| 15 Rubber                            | 15 Aluminium                       |
| 16 Cast iron                         |                                    |
| 17 Aluminium                         |                                    |

Reiger<sup>264</sup> has compared the behaviour of various materials in:

- (1) impact tests by liquid droplets in a rotating arm device under uniform test conditions: impact velocity  $V = 410$  m/s, 1.2 mm diameter droplets, rain density:  $1.1 \times 10^{-2}$  droplets/cm<sup>3</sup> at 25°C;
- (2) cavitation tests performed in a magnetostriction device at a frequency of 20 kHz with specimens fixed to the vibrating head, to investigate cavitation resistance.

Figure 84, taken from Table 1 of Reference 264, shows the correlation between the durations of the incubation periods (Fig.84(a)) and between the maximum erosion rates (Fig.84(b)) obtained in rain erosion tests or in cavitation tests. These correlations are fairly weak, even if we exclude glass and the polycarbonate "Makrolon"; this implies some difficulty in predicting the resistance to rain erosion from the results of cavitation tests.

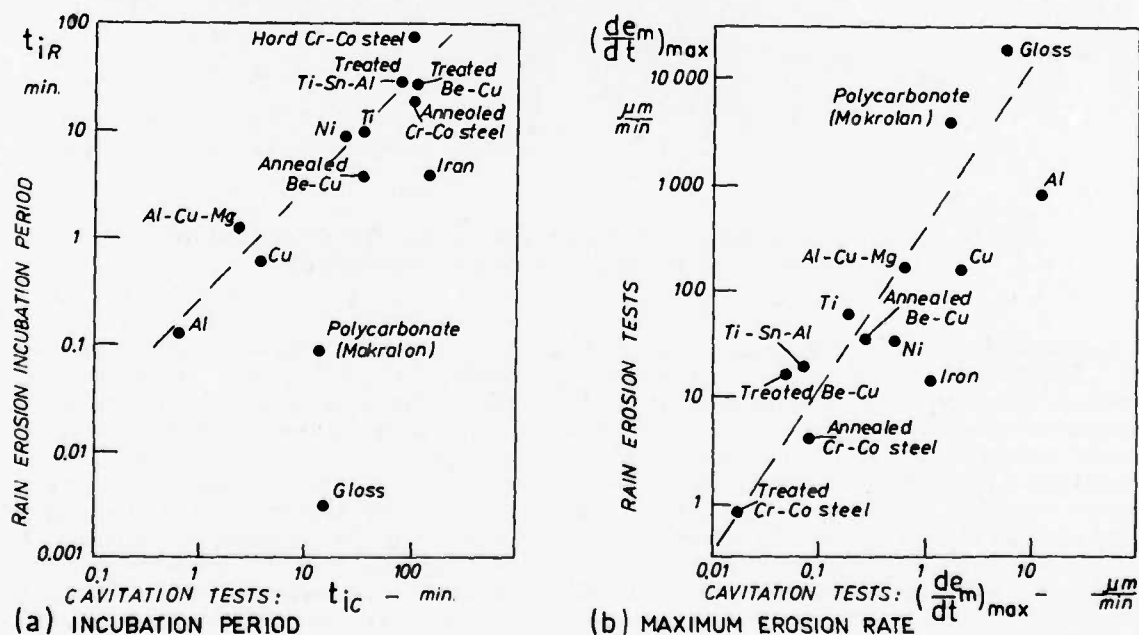


Fig.84 Correlation of incubation period and maximum erosion rate experienced in rain erosion with those of cavitation in water, from tests of Reiger<sup>264</sup>

According to Speidel and Keser<sup>265</sup> erosion damage in 12% chromium steel tubes used in steam turbine installations is due to the growth of cracks which originate from erosion pits. The cracks are transgranular compared with austenite grains. The problem of the erosion resistance of these steels is complicated by their susceptibility to stress corrosion and

to corrosion fatigue. An early investigation of the mechanical properties of this type of steel and of their correlation with erosion resistance had been made by Beckwith and Marriott<sup>244</sup> (see 7.5.2.2 - a) on a steel containing 0.25% C, 12% Cr, Ni, Mo, V, austenitised at 1050°C, air cooled and tempered for 1 hour at one of the following temperatures: 150, 250, 450, 550, 600 or 650°C. They had determined the fracture toughness  $K_{Ic}$  by slow bending of specimens pre-cracked in fatigue conditions. The erosion tests were carried out by repeated impacts of liquid jets hitting specimens mounted radially on a rotating drum. Table 7.5.2.3 - 2 below gives the results of these tests.

TABLE 7.5.2.3 - 2

Strength Properties of a 12% Cr Steel for Various Tempering Temperatures, from Beckwith and Marriott<sup>244</sup>

| Tempering temperature °C | Hardness HV 30 | $\sigma_{0.2}$ MN/m <sup>2</sup> | $\sigma_{ult}$ MN/m <sup>2</sup> | Reduction in area % | Charpy Impact test | $K_{Ic}$ MN/m <sup>3/2</sup> | Strain-hardening exponent n |
|--------------------------|----------------|----------------------------------|----------------------------------|---------------------|--------------------|------------------------------|-----------------------------|
| 150                      | 610            | 921                              | 1706                             | 5                   | 6                  | 60                           | 0.09                        |
| 250                      | 545            | 932                              | 1661                             | 28                  | 17.5               | 98                           | 0.13                        |
| 450                      | 512            | 1018                             | 1434                             | 47                  | 8                  | 66                           | 0.17                        |
| 550                      | 595            | 1041                             | 1730                             | 27                  | 4.5                | 63                           | 0.10                        |
| 600                      | 570            | 1142                             | 1470                             | 43                  | 4                  | 61                           | 0.09                        |
| 650                      | 385            | 776                              | 1041                             | 37                  | 7.5                | 98                           | 0.11                        |

Figure 85 shows the progression of losses by erosion under repeated liquid impact, and the gradual reduction of the erosion rate with the test duration. As in the case of the mechanical strength properties, the losses by erosion depend a great deal on the tempering temperature and pass through a maximum during tempering at 450°C, return to a low value during tempering at 550–600°C and increase again during tempering at 600°C. This phenomenon should be compared with the known instability of austenite which promotes plastic deformation, the hardness assuming a higher value if the austenite/martensite transformation takes place locally at the point of impact.

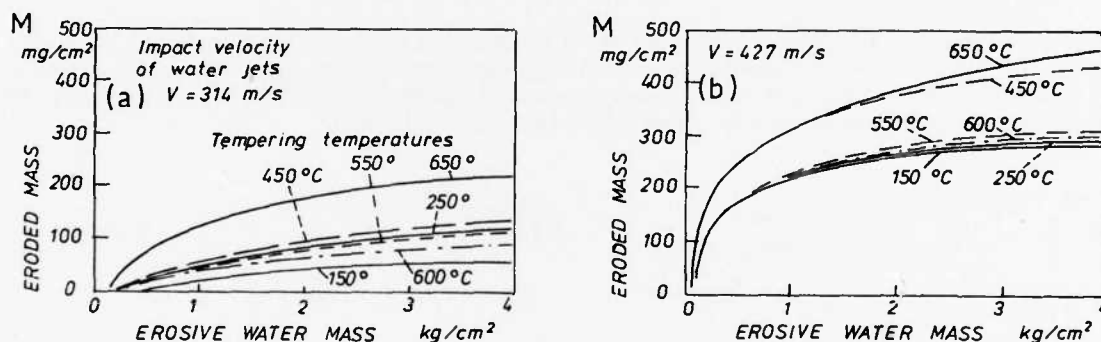


Fig.85 Influence of tempering temperature on erosion losses of a 12% Cr steel undergoing repeated impacts with liquid jets, from Beckwith and Marriott<sup>264</sup>

Speidel and Keser<sup>265</sup> have made a more complete study of the American type 420 martensitic stainless steel with 0.2% C, 12% Cr, 1% Mo, 0.3% V and 0.5% Ni. After annealing at 1060°C for a 0.5 hour, cooling in air and tempering for 10 hours at various temperatures, the investigation included measurement of the tensile strength characteristics and determination of the incubation periods and the maximum erosion rates following the erosion tests performed on the "Dornier" rotating arm with a normal impact velocity of  $V = 410$  m/s and 1.2 mm diameter droplets with a volume concentration of  $1.2 \times 10^{-5}$ . The development of the erosion characteristics, that is, the incubation time  $t_i$  and the maximum erosion rate  $(dM/dt)_{max}$ , as a function of the tempering temperature, is shown in Figure 86. Again, slightly variable values are obtained for tempering temperatures between the ambient and 500°C; beyond this temperature the incubation time decreases considerably and the erosion rate increases very quickly. Figure 87 contains the fracture toughness values  $K_{Ic}$  and the stress corrosion cracking rate in distilled water, and a constant value for the stress intensity factor  $K$  (45 MN/m<sup>-3/2</sup>) applied to DCB (Ref.266) type specimens for various values of the tempering temperature. There is some degree of correlation between the reduction in ductility, as measured by the reduction in the tensile elongation at break, and that in the fracture toughness  $K_{Ic}$ , with an increase in the stress corrosion rate during tempering at 400 to 500°C, but no clear correlation with the resistance to erosion. The cracks observed in the final phase of the rain erosion are transgranular while the stress corrosion cracks are intergranular; stress corrosion is therefore not the mechanism responsible for rain erosion cracks.

In fatigue there is a correlation between the peak-to-peak variation  $\Delta K = 2K_a$  of the stress intensity factor and the crack propagation rate in mm per cycle. For high values of  $\Delta K$ , tests in a vacuum of  $10^{-5}$  mm Hg and a frequency of 2.3 Hz, the fatigue propagation rate measured for different tempering temperatures is in agreement with the expression

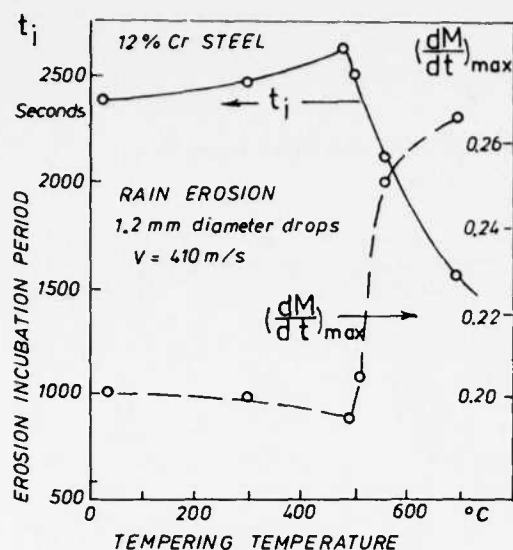


Fig. 86 Incubation period and maximum rain erosion rate of a 12% Cr steel at an impact velocity of 410 m/s, from Speidel and Keser<sup>265</sup>

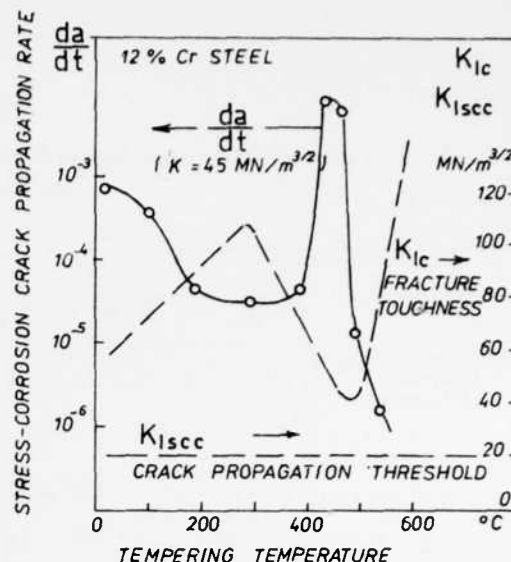


Fig. 87 Maximum stress-corrosion crack propagation rate and critical fracture toughness, from Speidel and Keser<sup>265</sup>

$$\Delta a / \Delta n = 6 \left( \frac{\Delta K}{E} - 2.7 \times 10^{-5} \right)^2 / \left( 1 - \frac{\Delta K}{K_{Ic}} \right), \quad (105)$$

in which the critical value for static fracture,  $K_{Ic}$ , occurs by the Forman correction: at low values of the stress intensity factor, the tempering temperature does not appear to have any effect on the fatigue crack rate. Figure 87 also shows that the threshold value  $K_{Isc}$  for initiation of stress corrosion cracking is not related to the heat treatment.

Two distinct correlations emerge from all the tests performed: a linear correlation between the alternating bending fatigue limit and the tensile strength of smooth, polished specimens subjected to tests in air at ambient temperature, and a linear correlation between the rain erosion incubation period and the 0.2% tensile yield point. Taking into account the more approximate correlation between the tensile strength and the yield point, a correlation therefore exists between the erosion incubation period and the development of plastic deformation leading to fatigue rupture. The instability of the residual austenite and the creation of corresponding residual compressive stresses in the area of the surface subjected to erosion impact is, however, a fairly complex function of the tempering temperature which affects in different ways the surface indentation of the edges of the craters produced by impacts, and the propagation in depth of the fatigue cracks which originate at the surface.

The damage, measured by the ratio of the erosion rate to the flow of the erosive liquid, first of all increases very quickly with the covered proportion of the surface, reaches a maximum and then decreases asymptotically tending towards a very low value which is only very slightly dependent on the heat treatment (see Figures 85(a) and 85(b)). In the final state with a very low erosion rate, the weight losses are slight, although deep cracks may compromise the use of actual components.

The use of 12% Cr, Mo, V martensitic steels (American types 410, 420, 422 and 436) is based mainly on the very low general corrosion rate for heat treatments giving a static strength and a fatigue strength of the same order as the slightly alloyed carbon steels which are very susceptible to oxidation. Their service use is, however, compromised by corrosion with large cavities, stress corrosion and hydrogen embrittlement<sup>267</sup>.

Gould<sup>268</sup> carried out cavitation tests using a piezoelectric device at a frequency of 20 kHz in which the 12.7 mm diameter specimens were screwed on to the moving horn. The tests, made on stainless martensitic steels, an austenitic steel, a Ni-Cr INCO 82 T alloy, a Cr-Co stellite 6B alloy, titanium alloys, pure molybdenum, 1100 aluminium and magnesium, were performed at one or more values of the vibration amplitude of the specimen. The test conditions and results are contained in Table 7.5.2.3 - 3. In all cases the erosion rate increased very rapidly after the incubation period, reached a maximum and then tended asymptotically towards a stabilised value which was achieved relatively quickly because of the high vibration frequency. The Table merely gives the stabilised value of the erosion rate. It can be observed that the intensity of the stabilised erosion rate is proportional to the square of the amplitude. For the same hardness value the titanium alloys are superior to the steels. The best material is stellite 6B. In addition, examination under the electron microscope revealed fatigue marks in the eroded area of a specimen made from the IMI 680 titanium alloy.

TABLE 7.5.2.3 - 3

Comparative Cavitation Tests of Materials Used in Blades of Aircraft Engine Compressors and Turbines, from Gould<sup>268</sup>

| Material                                                  | Composition %                  | $\rho$<br>g/cm <sup>3</sup> | DENSITY<br>REDUCTION<br>IN AREA % | BRINELL<br>HARDNESS | $\sigma_{ult.}$<br>MN/m <sup>2</sup><br>(estimated<br>from hardness) | $\sigma_{2\%}$ | Peak-to-peak<br>vibration<br>amplitude<br>$\mu$ m | Stabilized erosion rate                       |                                              |
|-----------------------------------------------------------|--------------------------------|-----------------------------|-----------------------------------|---------------------|----------------------------------------------------------------------|----------------|---------------------------------------------------|-----------------------------------------------|----------------------------------------------|
|                                                           |                                |                             |                                   |                     |                                                                      |                |                                                   | in mass<br>g/hour                             | in depth†<br>mm/hour                         |
| <u>Martensitic steels</u>                                 |                                |                             |                                   |                     |                                                                      |                |                                                   |                                               |                                              |
| 12Cr-Mo<br>(B50A 332A)                                    | 12Cr-0.10C-<br>0.20Mo          | 7.7                         | 60                                | 236                 | 690                                                                  | 483            | 35.6<br>104.1<br>124.5<br>35<br>95.3              | 0.0097<br>0.043<br>0.053<br>0.0021<br>0.0075  | 0.01<br>0.044<br>0.053<br>0.002<br>0.077     |
| Maraging 455 steel                                        | 11.3Cr-8.8Ni<br>1.3Ti          | 7.7                         | 75                                | 465                 | 1608                                                                 |                | 35                                                | 0.0018                                        | 0.0018                                       |
| Maraging X15 steel                                        | 15Cr-20Co-<br>2.8Mo            | 7.7                         | 75                                | 465                 | 1656                                                                 | 1550           | 35<br>95.3                                        | 0.0018<br>0.0059                              | 0.0018<br>0.0060                             |
| Maraging 10-10-2                                          | 10Cr-10Ni-2Mo                  | 7.7                         | 71                                | 380                 | 1346                                                                 | 1311           | 35                                                | 0.0042                                        | 0.0043                                       |
| 12Cr "ausformed"                                          | 12Cr-0.5Mo-V                   | 7.7                         | 68.5                              | 330                 | 1118                                                                 | 890            | 35                                                | 0.0038                                        | 0.0039                                       |
|                                                           |                                |                             |                                   | 345                 | 1166                                                                 | 945            | 35                                                | 0.0038                                        | 0.0039                                       |
| 12Cr 434                                                  | 12Cr-1Mo-<br>0.2C-0.2V         | 7.7                         | 69                                | 295                 | 932                                                                  | 656            | 35                                                | 0.0042                                        | 0.0043                                       |
| 12Cr 481                                                  | 12Cr-1Mo-<br>0.22C-0.25V       | 7.7                         | 69                                | 315                 | 1014                                                                 | 690            | 35                                                | 0.0029                                        | 0.0029                                       |
| Tool steel                                                | 11.7Cr-1Mo-<br>1V-1.5C         | 7.7                         | 82.5                              |                     |                                                                      |                | 35                                                | 0.00051                                       | 0.0005                                       |
| <u>Austenitic steel</u>                                   |                                |                             |                                   |                     |                                                                      |                |                                                   |                                               |                                              |
| SAE 347                                                   | 18Cr-11Ni-1Cb                  | 8                           | 34<br>60                          | 85<br>230           | 483<br>828                                                           | 345<br>621     | 35<br>35                                          | 0.0048<br>0.0075                              | 0.0047<br>0.0074                             |
| <u>Refractory alloys</u>                                  |                                |                             |                                   |                     |                                                                      |                |                                                   |                                               |                                              |
| INCO 82T                                                  | 67Ni-18Cr-<br>3Cb-3Fe          | 8.14                        | 48                                | 160                 | 656                                                                  | 393            | 35<br>89                                          | 0.0011<br>0.050                               | 0.0106<br>0.048                              |
| STELLITE B                                                | 3Ni-2Si-28Cr-<br>1.2C-reste Co | 8.38                        | 70                                | 360                 | 1035                                                                 | 621            | 53.3<br>95.3                                      | 0.00068<br>0.0035                             | 0.00064<br>0.0033                            |
| <u>Titanium alloys</u>                                    |                                |                             |                                   |                     |                                                                      |                |                                                   |                                               |                                              |
| A 110 AT                                                  | Ti-5Al-2.5Sn                   | 4.46                        | 69                                | 342                 | 925                                                                  | 856            | 35<br>57.2<br>95.3<br>127<br>146.1                | 0.0017<br>0.0028<br>0.0055<br>0.0125<br>0.017 | 0.0030<br>0.0050<br>0.0097<br>0.022<br>0.030 |
| V3275                                                     | Ti-2Ni                         | 4.54                        | 48                                | 141                 |                                                                      |                | 89                                                | 0.0125                                        | 0.021                                        |
| D6860                                                     | Ti-7Al-2.5Mo                   | 4.46                        | 66                                | 290                 |                                                                      |                | 89                                                | 0.0055                                        | 0.009                                        |
| V3272                                                     | Ti-8Mo                         | 4.54                        | 62                                | 230                 |                                                                      |                | 89                                                | 0.0100                                        | 0.0174                                       |
| V3278                                                     | Ti-2Al-4Zr-<br>4Mo             | 4.5                         | 61                                | 235                 |                                                                      |                | 89                                                | 0.0082                                        | 0.0142                                       |
| D9760                                                     | Ti-6Al-4V-<br>low O            | 4.44                        | 62                                | 230                 | 966                                                                  | 897            | 89                                                | 0.0070                                        | 0.013                                        |
| D1184                                                     | Ti-6Al-4V                      | 4.44                        | 66                                | 297                 | 966                                                                  | 897            | 89                                                | 0.0067                                        | 0.012                                        |
| IMI 680                                                   | Ti-2.2Al-4Mo-<br>11Sn-0.2Si    | 4.85                        | 72                                | 402                 | 1311                                                                 | 1187           | 35                                                | 0.00154                                       | 0.0024                                       |
| <u>Maraging steel</u><br>nitrided 482°C<br>48 h at: 454°C | 10Cr-10Ni-2Mo                  | 7.7                         | 86                                |                     |                                                                      |                | 35<br>35                                          | 0.005<br>0.0056                               | 0.005<br>0.006                               |
| <u>Pure Molybdenum</u>                                    | wrought<br>recrystallized      | 10.2                        | 53                                |                     |                                                                      |                | 35<br>35                                          | 0.0089<br>0.0115                              | 0.007<br>0.009                               |
| <u>1100 Aluminium</u>                                     | wrought                        | 2.7                         | 61                                |                     |                                                                      |                | 35                                                | 0.032                                         | 0.093                                        |
| <u>Magnesium</u>                                          | wrought<br>annealed            | 1.76                        | 92                                |                     |                                                                      |                | 35<br>35                                          | 0.0087<br>0.0094                              | 0.039<br>0.041                               |

† Values computed by assuming a uniform erosion on the front surface of the 12.7mm diameter specimens.

This Table can be supplemented by Table 7.5.2.2 - 2, from more recent studies by the same author<sup>247</sup> using the same piezoelectric device but with thin specimens (1.27 mm thick) brazed on to a mounting screwed into the head of the vibrator.

Cobalt and chromium alloys of the stellite type, used as welded shields for steam turbine blades, were also investigated by Hoff et al.<sup>245</sup> from the point of view of rain erosion. A direct comparison of behaviour as between the erosion due to cavitation impacts and that caused by rain drop impacts is very difficult to achieve except in the form of fairly imprecise correlations, such as those shown in Figures 84 and 85 for incubation periods and maximum erosion rates for various materials, between the values arising out of the rain erosion tests and the cavitation tests in water. Any direct comparison is impossible since, although it is possible to determine the impact pressure and the diameter of the craters and their number per unit area in the repeated rain drop impact erosion tests, the values of these parameters are not known in the cavitation tests, where the main indicators in the stress conditions are the pulsation frequency, its peak-to-peak amplitude, the nature of the liquid and its static pressure.

Figures 88 and 89 show the increase in the erosion depth in relation to the test duration respectively for cavitation and rain erosion, in the case of titanium alloys and some other alloys, after Hoff et al.<sup>245</sup>.

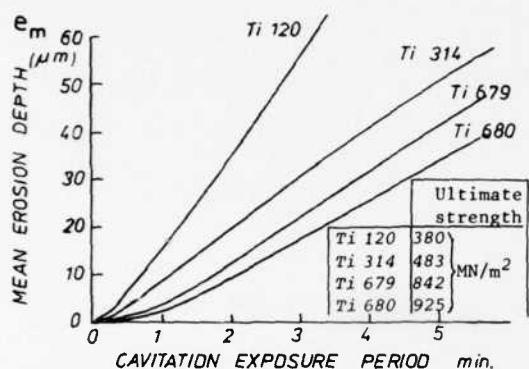


Fig.88 Mean cavitation erosion depth for titanium alloys, from Hoff et al.<sup>245</sup>

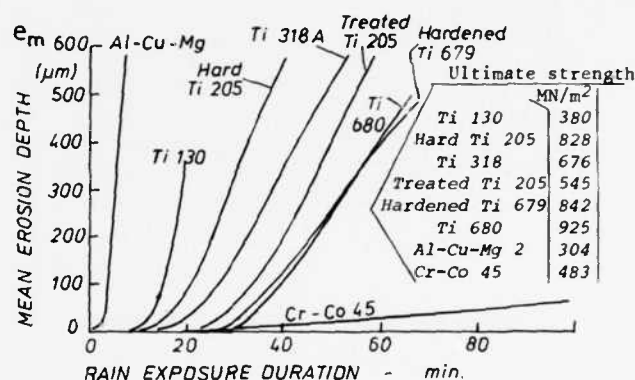


Fig.89 Mean rain erosion depth for titanium alloys ( $V = 410$  m/s), from Hoff et al.<sup>245</sup>

### 7.5.2.3 - b - Effect of liquid properties on cavitation erosion

The use of liquid metals as power transmission agents or for cooling purposes in atomic reactors and in gas turbines has led to cavitation damage in the liquid metal circulating system. Using a magneto-strictive oscillator at a frequency of 25 kHz, Young and Johnston<sup>269</sup> investigated the cavitation wear of various steels or refractory alloys in liquid sodium at  $427 \pm 5.5^\circ\text{C}$  and mercury at  $149 \pm 16.7^\circ\text{C}$ , the vapour tensions being 0.1 bar and the vibration amplitude  $44.45 \mu\text{m}$  to within  $\pm 1.3 \mu\text{m}$ . The tests were performed in a heated chamber under a partial vacuum. The 14.3 mm diameter specimens were screwed on to the end of the amplifier horn (see Figure 90(a)) which was fixed to the core of the oscillator and provided with a water-tight skirt around the tank containing the liquid metal. During the discussion Wilson, R.W. drew attention to the fact that accelerated cavitation tests minimise the part played by corrosion, although in actual service conditions this may increase the effect of the mechanical damage suffered. Even non corrosive liquids may react with metals as a result of the local pressure and high temperatures reached during collapse of the cavitation bubbles. The composition of the metals used and the results of the cavitation tests are contained in Tables 7.5.2.3 - 4a and 4b.

Figure 90(b) shows the variation in the erosion rate with the period of exposure to cavitation in liquid sodium at  $427^\circ\text{C}$  (vapour tension = 1 atmosphere). We again find the maximum already noted in other cases and a very clear tendency to stabilisation of the erosion rate. Figure 91 refers to an attempt by the author to show the correlation between the tensile strength properties and the corrosion strength, measured by the time required to erode  $1 \text{ mm}^3$  of the material at the surface of a 14.3 mm diameter specimen when the corrosion rate has been stabilised at its lowest value. It will be seen that stellite B is outside this correlation by a value 6 times higher, for which the explanation is the same as in Gould's tests<sup>247</sup>.

In a series of more recent tests Young and Johnston<sup>270</sup> examined the influence of the static pressure of the liquid on cavitation losses in liquid sodium at various temperatures. The tests were made on 14.3 mm diameter L-605, stellite 6B and AISI 316 steel specimens attached to the end of a magneto-strictive oscillator vibrating at 25 kHz with a peak-to-peak amplitude of  $44.5 \mu\text{m}$ , the surface of the specimens being 3.3 mm below the surface of the liquid. The heated water-tight tank containing the liquid sodium had previously been emptied of air at a partial pressure of  $10^3 \text{ mm Hg}$  ( $0.13 \text{ N/m}^2$ ) and then filled with argon the pressure of which was controlled to within  $1.7 \times 10^3 \text{ N/m}^2$  for each test.

TABLE 7.5.2.3 - 4a

Composition and Treatment of High-Temperature Resistant Materials Subjected to Cavitation Tests in Liquid Sodium or Mercury by Young and Johnston<sup>269</sup>

| Materials                 | Treatments                            | Composition, per cent |           |             |             |            |            |     |             |             |             |             |          |                       | density |
|---------------------------|---------------------------------------|-----------------------|-----------|-------------|-------------|------------|------------|-----|-------------|-------------|-------------|-------------|----------|-----------------------|---------|
|                           |                                       | Fe                    | Ni        | Co          | Cr          | Mo         | W          | Cb  | Ti          | Al          | C           | Mn          | Si       | Others                |         |
| Stellite 6B               | Sol. 1230°C<br>air quenched           | 3                     | 3         | rem.        | 30          | 1.5        | 4.5        |     |             | 1.4-<br>1.8 | 1.1         | 2           | 2        |                       | 8.38    |
| René 41<br>(AMS 5712)     | Sol. 1079°C<br>rapid quenched         | 5                     |           | 10-<br>12   | 18-<br>20   | 9-<br>10.5 | 14-<br>16  |     | 3-<br>3.3   |             | .12         | .1          | .5       | Boron:<br>.003 to .01 | 8.25    |
| L 605<br>(AMS 5759)       | Sol. 1230°C<br>Water quenched         | 3                     | 9-<br>11  | rem.        | 19-<br>21   |            | 0.2<br>- 1 |     |             |             | .05-<br>.15 | 1-<br>2     | 1        |                       | 9.13    |
| Hastelloy<br>(AMS 5754)   | Sol. 1177°C<br>rapid air<br>quenching | 17-<br>20             | rem.      | 0.5-<br>2.5 | 20.5<br>-23 |            |            |     |             |             | .05-<br>.15 | 1           | 1        |                       | 8.23    |
| A-286<br>(AMS 5736)       | Sol. 1010°C<br>Water, 16hr. 718°C     | rem.                  | 24-<br>26 |             | 13.5<br>-16 |            |            |     | 1.9-<br>2.3 | .35         | .08         | 1-2         | .4-<br>1 | .3 V<br>.01 boron     | 7.94    |
| Inconel 600<br>(AMS 5665) | annealed                              | 6-10                  |           | 1           | 14-<br>17   |            |            | 1   | 0.5         |             | .15         | 1           | .5       | .5 Cu                 | 8.43    |
| Stainless<br>AISI 318     | annealed                              | rem.                  | 13-<br>15 |             | 17-<br>19   |            |            | 0.8 |             |             | .08         | 2.5         | 1        |                       | 7.99    |
| AISI 316<br>(AMS 5648)    | annealed                              | rem.                  | 12-<br>14 |             | 17-<br>19   |            |            |     |             |             | .08         | 1.25<br>- 2 | 1        | .5 Cu                 | 7.98    |
| Sicromo 9M                | ann. 1 hr. 954°C<br>1 hr. 732°C, air. | rem.                  |           |             | 8-<br>10    |            |            |     |             |             | .20         | .35-<br>.65 | 1        |                       | 7.61    |

TABLE 7.5.2.3 - 4b

Results of Cavitation Tests in Liquid Sodium and Mercury of the Materials Listed in Table 7.5.2.3 - 4a

| In sodium at 426°C  | Volume losses (mm <sup>3</sup> )<br>after (hours) |      |      |      | Stabilized<br>erosion rate<br>mm <sup>3</sup> /hour | Surface roughness ,µm ,<br>after (hours) |      |      |       |
|---------------------|---------------------------------------------------|------|------|------|-----------------------------------------------------|------------------------------------------|------|------|-------|
|                     | 1                                                 | 2    | 3    | 4    |                                                     | 1                                        | 2    | 3    | 4     |
| Stellite 6B         |                                                   | 0.04 | 0.13 | 0.39 | 0.5                                                 |                                          |      |      | 1.27  |
| René 41             |                                                   | 0.20 | 1.12 | 2.42 | 1.3                                                 | 0.38                                     | 1.01 | 1.65 | 2.16  |
| L 605               |                                                   | 0.22 | 1.25 | 2.58 | 1.4                                                 | 0.9                                      | 1.4  | 1.9  | 2.5   |
| Hastelloy X         | 0.66                                              | 3.10 | 5.78 | 8.14 | 2.4                                                 |                                          |      |      |       |
| A-286               | 1.40                                              | 4.70 | 7.67 | 10.4 | 2.8                                                 |                                          |      |      |       |
| AISI 318            | 2.7                                               | 6.40 | 10.3 | 13.4 | 3.1                                                 |                                          |      |      |       |
| AISI 316            | 2.9                                               | 7.16 | 11.8 | 15.9 | 4.1                                                 | 2.03                                     | 2.5  | 2.9  | 3.05  |
| Annealed Sicromo 9M | 6.4                                               | 15.5 | 24.7 | 33.9 | 9.2                                                 | 6                                        | 7.4  | 8.13 | 8.51  |
| In mercury at 149°C |                                                   |      |      |      |                                                     |                                          |      |      |       |
| Stellite 6B         | 0.34                                              | 0.75 | 1.28 | 1.81 | 0.6                                                 | 1.65                                     | 2.5  | 3.17 | 3.8   |
| Hardened Sicromo    | 1.07                                              | 3.45 | 6.8  | 10.5 | 3.4                                                 | 3.94                                     | 6.6  | 11.4 | 17.8  |
| L-605               | 1.12                                              | 4    | 7.6  | 11.3 | 3.6                                                 | 6.7                                      | 9.27 | 13.3 | 19.05 |
| Hastelloy X         | 5.02                                              |      |      |      | 8.2                                                 | 8.2                                      | 13   |      |       |
| Annealed Sicromo 9m | 18.2                                              |      |      |      | 17.4                                                | 17.4                                     | 19.4 |      |       |

Figures 92(a), (b) and (c) show the development of the mean erosion rate in mm<sup>3</sup>/h for each of the materials. The mean rate of propagation of the erosion in depth,  $de_m/dt$ , would be obtained by dividing the erosion rate by the area of the front face of the specimen,  $A = 169.6 \text{ mm}^2$ .

With increasing values of the static pressure the maximum erosion rate increases to a greater extent than the subsequent stabilised minimum value and occurs earlier. Stellite 6B has greater erosion resistance than the other two alloys and can maintain this resistance in the event of a static pressure increase.

The dynamic pressure generated by the vibrations is governed by the amplitude, the frequency and the viscosity of the liquid opposing its flow; it is zero at the edge of the front face of the specimen and there is no uniform pattern in the cavitation damage, which is non-existent at the periphery. To allow for this factor Young and Johnston corrected the stabilised erosion rate, corresponding to the minimum erosion rate after the first maximum value, by multiplying the uncorrected values in the Figure by the ratio of the apparent area of the front face of the specimen to the area actually eroded.

The corrected stabilised erosion rate, the variation of which is shown in Figures 90 to 93, corresponds to the product of the severely eroded area of the face of the specimen and the mean rate of penetration of the erosion over this area, i.e.:  $\text{corrected erosion rate} = A_{\text{eroded}} \times de_m/dt$ .

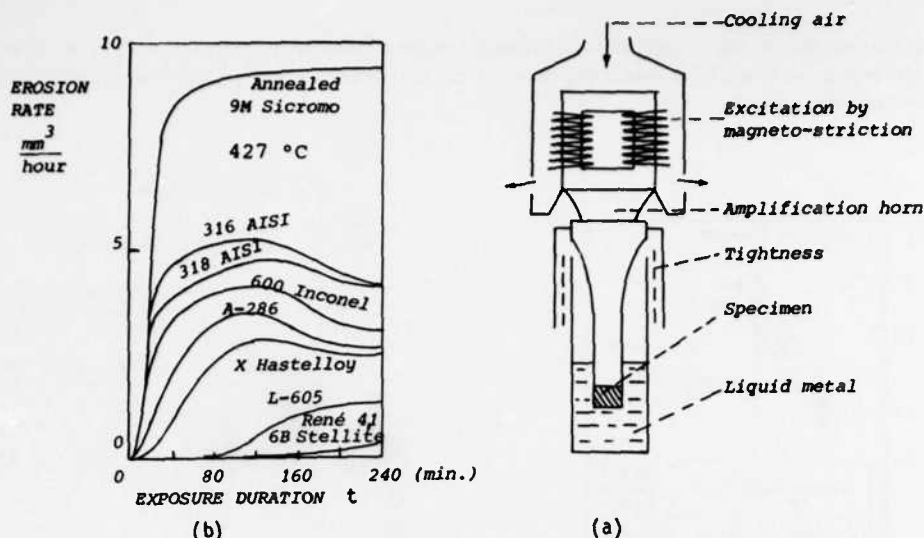


Figure 90

(a) Cavitation test apparatus using liquid metals  
 (b) Test results with liquid sodium. From Young and Johnston<sup>269</sup>

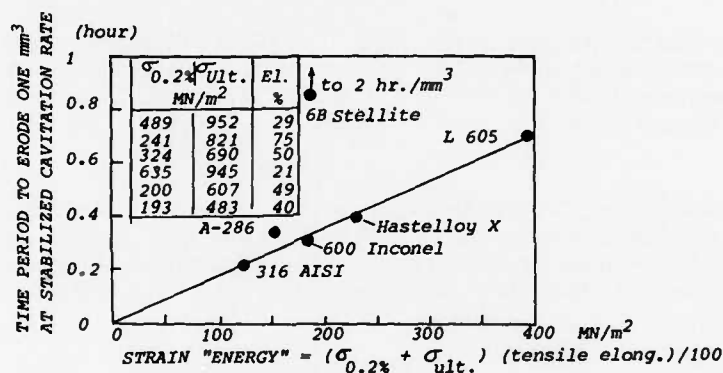


Fig.91 Correlation of the time for unit cavitation erosion in liquid sodium at 427°C with the strain energy as defined by Young and Johnston<sup>269</sup>

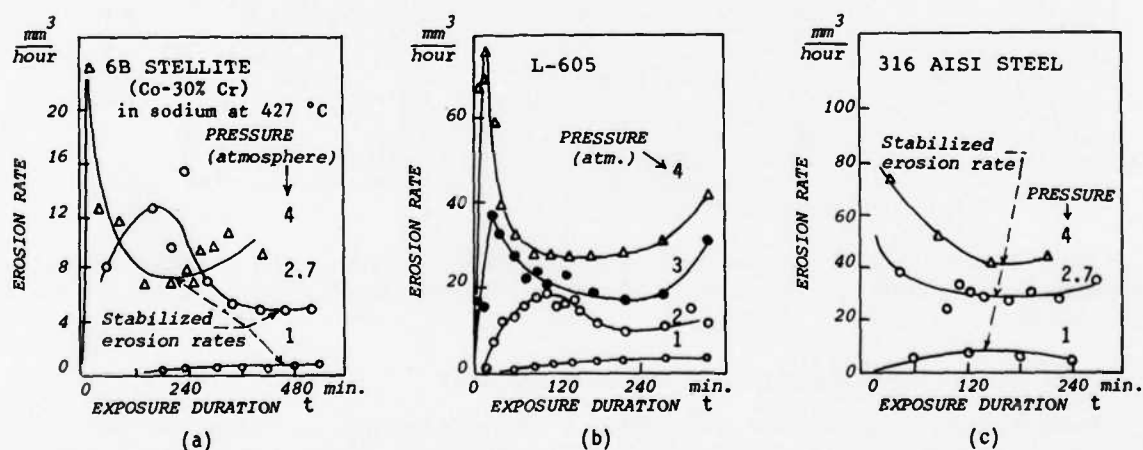


Fig.92 Influence of static pressure on cavitation erosion rate,  $Ade_m/dt$ , in liquid sodium at 427°C, of specimens subjected to magnetostriction vibrations of 44.5  $\mu$ m-amplitude at a frequency of 25 kHz, from Young and Johnston<sup>270</sup>

In logarithmic coordinates the straight lines in Figure 93 make it possible to interpolate the pressure/corrected erosion rate relationship, while the level curves in Figure 94, marked as erosion rates, permit an interpolation to show the effect of temperature and pressure.

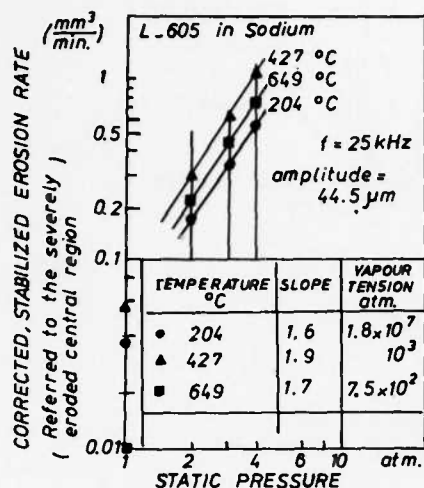


Fig.93 Stabilised erosion rate, corrected for the severely eroded central area as a function of the pressure at temperatures of 427°C, 649°C and 204°C in liquid sodium<sup>270</sup>

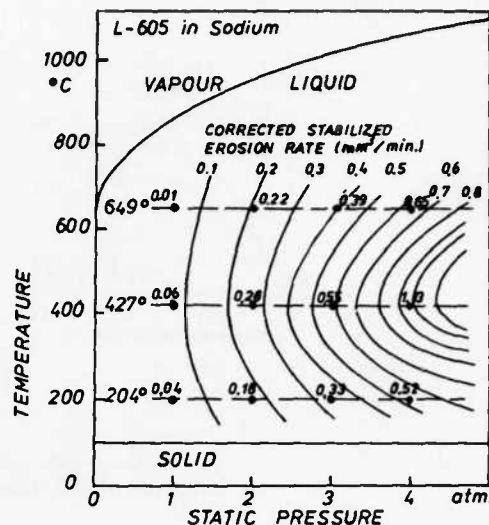


Fig.94 Distribution of the corrected stabilised erosion rate within the pressure-temperature domain for cavitation in liquid sodium. From Young and Johnston<sup>270</sup>

Garcia, Hammitt and Nystrom<sup>271</sup> collated their results of cavitation erosion tests on different metals and alloys in water and mercury at 21°C (Ref.272), mercury and a Pb-Bi 70-30 alloy at 260°C (Ref.273), and the Pb-Bi alloy at 816°C (Ref.274). These tests were performed in a piezoelectric 150 W oscillator at ultrasonic frequency, the cylindrical specimens being screwed on to the end of the oscillator horn. Table 7.5.2.3 – 5a details the properties of the fluids used as cavitation baths.

TABLE 7.5.2.3 – 5a

Physical Properties of Fluids used in Cavitation Tests carried out by Garcia et al.<sup>271</sup>

| Properties                                            | Units | Water, 21°C           | Mercury, 21°C         | Mercury, 260°C        | Pb-Bi, 260°C           | Pb-Bi, 1500°C         |
|-------------------------------------------------------|-------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------|
| Acoustical impedance ( $c\rho$ ), g/cm <sup>2</sup> s |       | $1.46 \times 10^{-5}$ | $1.97 \times 10^{-5}$ | $1.88 \times 10^{-5}$ | $1.505 \times 10^{-5}$ | $1.34 \times 10^{-5}$ |
| Density, $\rho$ , g/cm <sup>3</sup>                   |       | 1                     | 13.55                 | 12.98                 | 10.38                  | 9.64                  |
| Surface tension, dyne/cm                              |       | 72.8                  | 465                   | 419                   | 397                    | 367                   |
| Suction height, m                                     |       | 11.13                 | 0.823                 | 0.854                 | 1.0675                 | 1.159                 |
| Bulk elastic modulus, MN/m <sup>2</sup>               |       | 2139                  | 28359                 | 27186                 | 21800                  | 20150                 |
| Cinematic viscosity, cm <sup>2</sup> /s               |       | 0.01                  | 0.0011                | 0.00077               | 0.00165                | 0.0012                |
| Thermal conductivity, cal/s cm°C                      |       | $1.41 \times 10^{-3}$ | 0.021                 | 0.030                 | 0.025                  |                       |
| Vaporization heat, cal/g                              |       | 585                   | 69.7                  | 69.7                  |                        |                       |
| Vapour pressure at 21°C, N/m <sup>2</sup>             |       | 0.0025                | 0                     | 0.0133                | 0                      | 0                     |

$c$  is the sound velocity within the liquid.

The results of these tests are contained in Figures 95(a) and 95(b) and in Table 7.5.2.3 – 5c, showing the mean rates of penetration in depth,  $de_m/dt$  in  $\mu\text{m/h}$ , for the region of the linear relationship between  $e_m$  and  $t$ , that is, the maximum values.

#### 7.5.2.3 – c – Cavitation in lubricating systems and hydraulic equipment

Problems relating to cavitation in lubricating systems of machines and in hydraulic equipment for transmitting force or movement have been reviewed by Hobbs and McCloy<sup>275</sup>. Cavitation bubbles may originate from the gases dissolved in the liquid if the pressure falls below the saturation pressure, or from vaporization of the liquid at a lower pressure which is less than the vapour tension.

The solubility of a gas in a liquid is proportional to the pressure. For example<sup>275</sup>, mineral oils dissolve per atmosphere of pressure a 10% volume of air considered to be at 21°C and a pressure of 1 atm. If the liquid is saturated

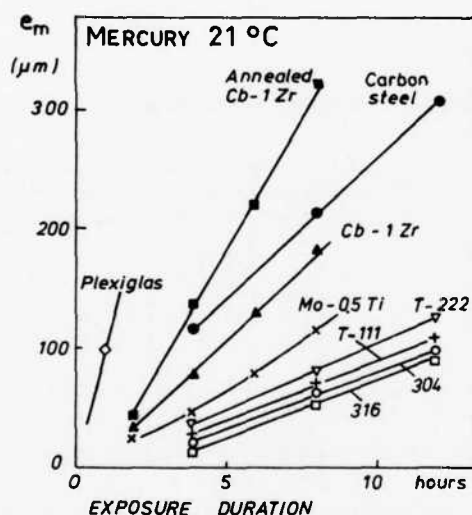
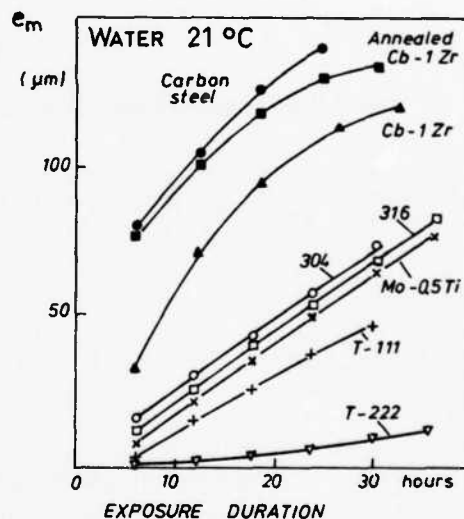
TABLE 7.5.2.3 - 5b

Mechanical Properties of Materials Tested in Cavitation by Garcia et al.<sup>271</sup>

| Materials                                         | $\sigma_{ult.}$<br>MN/m <sup>2</sup> | $\sigma_{0.2\%}$ | $\int \sigma \epsilon d\epsilon$ | True strain energy <sup>††</sup><br>MN/m <sup>2</sup> |       | DPH <sup>†††</sup><br>Hardness | Ductility<br>Elong. % ar. red. $\Sigma$ |      | Modulus<br>E, MN/m <sup>2</sup> |
|---------------------------------------------------|--------------------------------------|------------------|----------------------------------|-------------------------------------------------------|-------|--------------------------------|-----------------------------------------|------|---------------------------------|
| <b>Tests at 21°C</b>                              |                                      |                  |                                  |                                                       |       |                                |                                         |      |                                 |
| 304 austenitic stainless steel (19%Cr, 10%Ni)     | 652                                  | 446              | 395                              | 285                                                   | 328   | 237                            | 63.8                                    | 77.9 | 200000                          |
| 316 austenitic Stainless steel (18%Cr, 13%Ni, Mo) | 602                                  | 439              | 337                              | 264                                                   | 342   | 227                            | 57.8                                    | 80.3 | 200000                          |
| T-111 Tantalum alloy                              | 908                                  | 862              | 116                              | 110.4                                                 | 473   | 308                            | 14.8                                    | 80.4 | 193000                          |
| T-222 Tantalum alloy                              | 1064                                 | 1063             | 105                              | 111                                                   | 485   | 338                            | 10.6                                    | 55.6 | 193000                          |
| do., annealed                                     | 751                                  | 629              | 165                              | 153                                                   | 361   | 288                            | 23.1                                    | 61.1 | 193000                          |
| Molybdenum, 0.5% Ti                               | 1144                                 | 1038             | 147                              | 101                                                   | 80    | 295                            | 9.3                                     | 7.9  | 310500                          |
| Columbium, 1% Zr.                                 | 408                                  | 407              | 46                               | 43                                                    | 204   | 151                            | 14.3                                    | 88.4 | 103500                          |
| do., annealed                                     | 250                                  | 132              | 91                               | 7.2                                                   | 12.1  | 99                             | 41.9                                    | 91.4 | 103500                          |
| <b>Tests at 260°C</b>                             |                                      |                  |                                  |                                                       |       |                                |                                         |      |                                 |
| 304 stainless steel                               | 638                                  | 391              | 111.4                            | 125.5                                                 | 257   | 154                            | 30.8                                    | 72.9 | 179400                          |
| 316 stainless steel                               | 500                                  | 361              | 125                              | 122                                                   | 262   | 203                            | 30.4                                    | 78.2 | 179400                          |
| T-111 Tantalum alloy                              | 702                                  | 695              | 104                              | 74                                                    | 351   | 218                            | 13.8                                    | 86.2 | 186300                          |
| T-222 Tantalum alloy                              | 923                                  | 923              | 88.7                             | 89                                                    | 468   | 286                            | 10.9                                    | 71.5 | 186300                          |
| do., annealed                                     | 637                                  | 437              | 142.4                            | 233                                                   | 291   | 209                            | 23.6                                    | 66.9 | 186300                          |
| Molybdenum, 0.5% Ti                               | 580                                  | 550              | 73.8                             | 75.9                                                  | 306.4 | 207                            | 15                                      | 75.9 | 296700                          |
| Columbium, 1% Zr                                  | 377                                  | 377              | 44.5                             | 35.8                                                  | 191   | 133                            | 12.7                                    | 88.7 | 100000                          |
| do., annealed                                     | 172.5                                | 80               | 56                               | 26                                                    | 54.4  | 71                             | 35.9                                    | 92.2 | 100000                          |

(†)  $\int \sigma \epsilon d\epsilon$  is the "strain energy" computed from the engineering static stress-strain curve,  $\sigma_{nominal} - \epsilon_{apparent}$ .(††) Two values of the "true strain" are used. The first value ascribes the true strain, computed from the reduction in area of the cross section  $\Sigma$ , to the whole specimen length; the second value takes account of necking by computing the local  $\epsilon$ .

(†††) Diamond Pyramid Hardness.

Fig.95(a) Cavitation erosion in mercury at 21°C pressure = 1 atm., ultrasonic frequency, from Garcia et al.<sup>271</sup>Fig.95(b) Cavitation erosion in water at 21°C, pressure = 1 atm., ultrasonic frequency<sup>271</sup>

with dissolved air in a tank in which it is in contact with the air, and is then subjected in turn, because of the flow, to a lowering of the pressure caused by suction of a pump, to pressure increases in front of the flow barriers and reductions behind these barriers, gas bubbles form during the low pressure periods and collapse when the pressure rises again.

At low pressures which are below the vapour tension of the liquid, vapour forms on the free surfaces of the liquid and, within the liquid, on the surface of the gas bubbles imprisoned in the roughnesses or cracks on the surface of the mechanical components.

Pressure variations are encountered wherever there is a fluid flow or vibration from a wall, in particular:

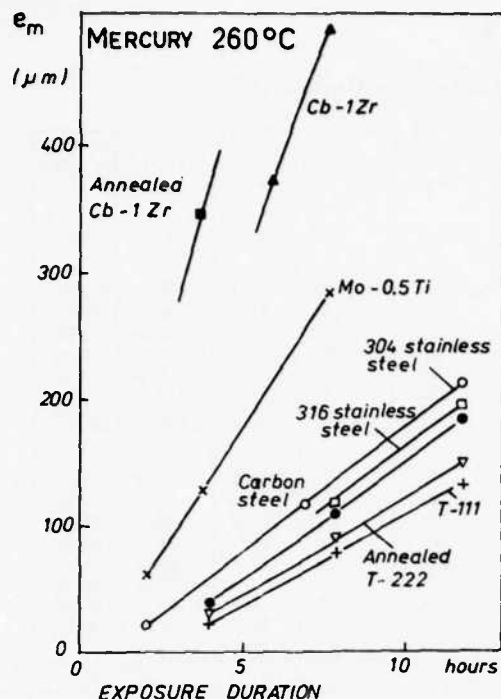


Fig. 95(c) Cavitation erosion in mercury at 260°C pressure = 1 atm., ultrasonic frequency<sup>271</sup>

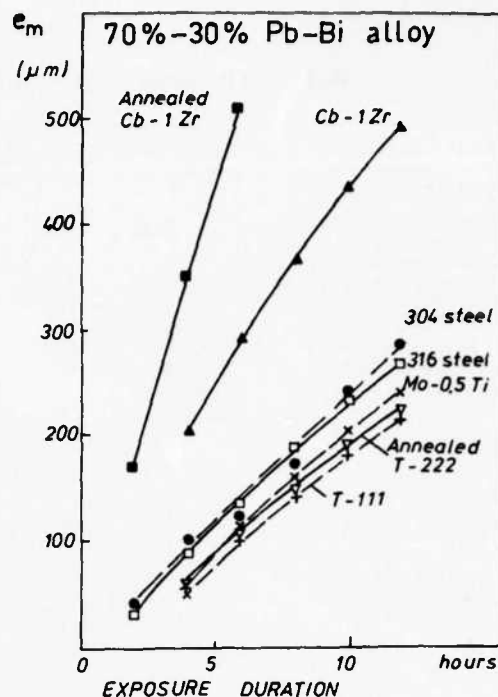


Fig. 95(d) Cavitation erosion in the melted 70-30 Pb-Bi alloy at 260°C, pressure = 1 atm., ultrasonic frequency<sup>271</sup>

TABLE 7.5.2.3 – 5c

Values of the Stabilised Erosion Rate,  $(de_m/dt)_{max}$  in Cavitation Tests with Various Liquids, from Garcia et al.<sup>271</sup>

| Bath and temperature | Stainless steels |      | Tantalum alloys |       |                | Mo- $\frac{1}{2}$ Ti | Cb-1Zr | annealed Cb-1Zr | Carbon steel | 2024 T351 | 6051 T651 | Plexi-glas | Aluminium 1100-0 |
|----------------------|------------------|------|-----------------|-------|----------------|----------------------|--------|-----------------|--------------|-----------|-----------|------------|------------------|
|                      | 304              | 316  | T-111           | T-222 | annealed T-222 |                      |        |                 |              |           |           |            |                  |
| Water 21°C           | 2.5              | 2.3  | 1.5             | 0.5   |                | 2.3                  | 3.8    | 4.6             | 5.8          | 14.5      | 18.3      | 1390       | 2700             |
| Mercury 21°C         | 8.2              | 8.4  | 8.9             | 10.9  |                | 14.5                 | 23.4   | 40.9            | 26.2         |           |           | 101        |                  |
| Mercury 260°C        | 17.5             | 11.7 | 10.9            |       | 11.7           | 27.7                 | 61.7   | 94.7            | 15.5         |           |           |            |                  |
| Pb-Bi 260°C          | 22.4             | 19.8 | 18.3            |       | 19.3           | 19.8                 | 41.4   | 90              |              |           |           |            |                  |
| Pb-Bi 816°C          | 287              | 71.1 | 21.3            |       | 22.4           | 27.4                 | 55.6   | 96.5            |              |           |           |            |                  |

- in the turbulent region of the fluid flow, e.g. after passing through an immersed hole, or through an annular gap in a flowrate or pressure regulating device, tap, valve or slide valve;
- in the turbulent boundary layer of the flow at the wall of tubing comprising changes of direction or roughnesses;
- in the case of fluid flow along a wall excited by high frequency vibrations, as in the cavitation of cooling jackets in internal combustion engines, or of the plain bearings in these engines.

The usual type of high frequency cavitation tests involves a moving immersed specimen which is caused to vibrate in a piezo-electric or magneto-strictive device, or a fixed immersed specimen which undergoes pressure variations induced by a similar fixed specimen screwed on to the vibrating device at a short distance from the first-mentioned fixed specimen. This arrangement has the advantage that the inertia of the specimen is no longer a limitation. There is, however, the disadvantage that the quantity of gas dissolved in the fluid cannot be checked separately from the fluid pressure. To meet this requirement Hobbs and Rachman<sup>276</sup> used apparatus, shown in Figure 96, which made it possible to measure the temperature and the pressure of the pulsed fluid film between a fixed and a moving specimen.

The fluid film is continually being renewed; there is no parasitic mechanical stressing of the specimen and two different materials can be used to simulate electrolytic effects of contact. The apparatus is very suitable for tests on oils, anti-friction metals and plastic metal coatings.

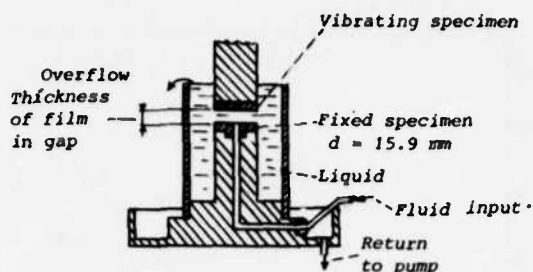


Fig.96 Magnetostriction oscillator, frequency = 20 kHz, amplitude = 50  $\mu$ m

The static pressure, measured through orifices with an outlet at the surface of the lower fixed specimen, varies from a pressure drop in the centre to an overpressure which falls to zero, at the edge. The radial static pressure distribution is shown in Figures 97(a) and 97(b) for two different widths of the gap and various values for the water flowrate. The unit of pressure has not been stated.

As illustrated in Figure 98, the temperature rises fairly rapidly from the centre and varies only slightly thereafter. The mean temperature rise depends on the fluid and its flowrate.

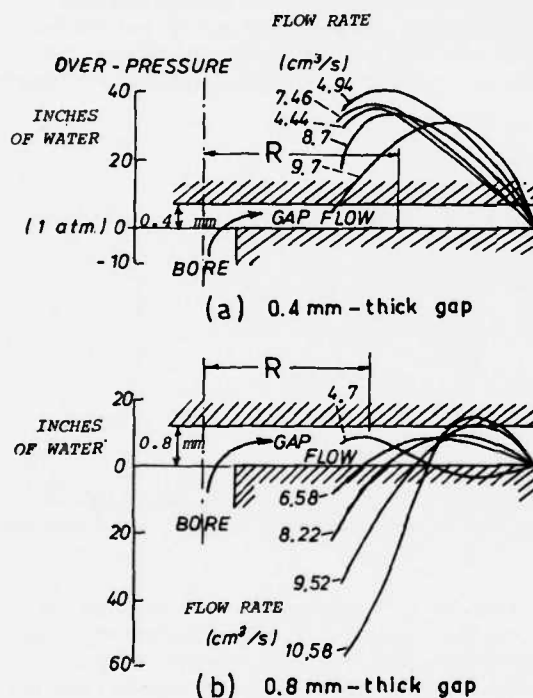


Fig.97 Radial pressure distribution in cavitation tests with central water supply, from Hobbs and Rachman<sup>276</sup>

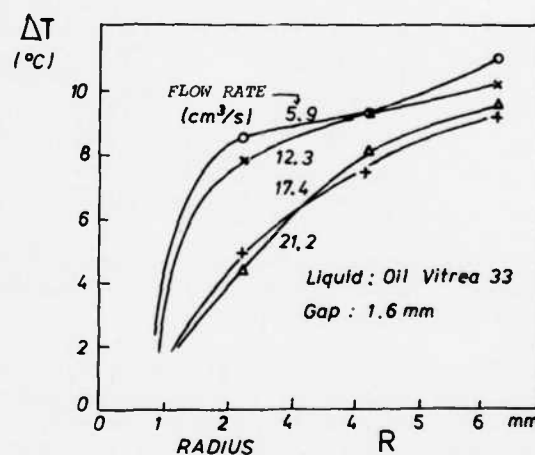


Fig.98 Temperature rise due to the vibration energy<sup>276</sup>

The authors investigated the behaviour of a tin based anti-friction coating (90% Sn, 7% Sb, 3% Cu) deposited on a steel bearer, for coating thicknesses of 0.075, 0.2, 0.25 and 0.46 mm. The erosion losses in mg are shown in Figure 99 as a function of time and the thickness of the coating. The 0.46 mm thick specimen behaved in the usual way, the erosion rate being lower after a certain time. Examination of the specimens under the microscope showed considerable hardening of the 0.46 mm specimen after 12 minutes; a test conducted on a 1.3 mm specimen suggested that cracks originate at the ends of the  $\text{Cu}_6\text{Sn}_8$  needles and are propagated along the interfaces with the matrix. Once the cracks have reached the surface of the bearer metal, the material begins to peel, which explains why the specimens with a thin coating did not reach the steady cavitation erosion rate.

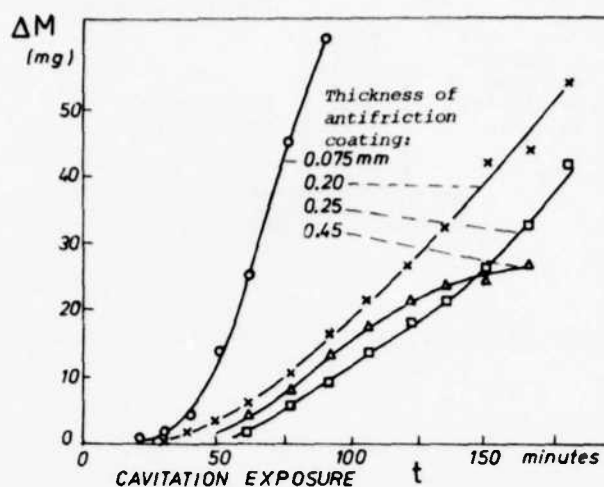


Fig.99 Mass loss of an anti-friction coating on a steel bearing due to cavitation within an oil film, from Hobbs and Rachman<sup>276</sup>

Kosirev<sup>277</sup> investigated oil drop impact erosion using oils of varying viscosity and a rotating arm carrying steel specimens which hit a jet of oil perpendicular to the plane of rotation at impact velocities of between 40 and 100 m/s. Erosion decreased with increased viscosity, disturbing the lateral flow of the fluid and penetration into the pits. Table 7.5.2.3 - 6 shows the effect of the fluid viscosity on the relative mass loss by erosion, as compared with that produced by water.

TABLE 7.5.2.3 - 6

Relative Mass Losses by Liquid Impact at  $V = 60$  m/s, from Kosirev<sup>277</sup>

| Fluid               | Kinematic viscosity at 30°C<br>$\nu$ (cts) | Mass loss<br>M | Relative mass loss<br>$M_{\text{Water}} / M_{\text{Fluid}}$ |
|---------------------|--------------------------------------------|----------------|-------------------------------------------------------------|
| Water               | 0.18                                       | 394            | 1                                                           |
| Gas-oil             | 2.6                                        | 294            | 0.746                                                       |
| No. 2 oil (spindle) | 27.7                                       | 144            | 0.365                                                       |
| Diesel DC-11 oil    | 185                                        | 58             | 0.147                                                       |
| Automobile oil      | 381                                        | 22             | 0.055                                                       |

These fluids are classified in the same order as that relative to the pitting fatigue observed in the fatigue tests on bearings<sup>278</sup>. Tichler and Seott<sup>279</sup> had noted a correlation between cavitation erosion and rolling contact fatigue resistance in the case of ball bearing steels.

In the cavitation tests the pits appear before the deep eraters. Tichler et al.<sup>280</sup> investigated chromium steels and came to the conclusion that two periods of uniform erosion could be observed during the process of magnetostriction cavitation erosion at 20 kHz. During the first period, the erosion rate is high and the surface is attacked uniformly, although isolated pits ( $d \sim 100 \mu\text{m}$ ) form after a certain time. During the second period of a uniform erosion rate, the surface is saturated with deep individual craters (500 to 1000  $\mu\text{m}$ ) and the erosion rate is relatively low. In the case of the chromium steels studied, there is a linear relationship between the inverse  $dt/de_m$  of the erosion rate during the first period and the true tensile strength  $\sigma_R^*$ .

In a subsequent paper when studying 6 chromium steels and 6 Cu-Ni alloys, Tichler et al.<sup>281</sup> found a correlation,  $R_e = A(\sigma_R^*)^n$ , with  $n$  close to 2.3, between the erosion resistance  $R_e = dt/de_m$  and the true tensile rupture stress  $\sigma_R^*$ . The mean erosion depth at the first pit,  $(e_m)_p$ , was determined for two stellite type cobalt alloys and three steels (case hardening, nitriding and maraging) during cavitation tests at 20 kHz in water at 35°C with a bichromate corrosion inhibitor at a pressure of 1 bar. The test results showed no correlation between  $(e_m)_p$  and the erosion resistance  $R_e = dt/de_m$  during the first uniform erosion period.

Assuming that the small pits which initiated the eraters were formed by surface fatigue, the authors<sup>280</sup> performed tests on two ball bearing steels (A and B in Table 7.5.2.3 - 7) and two high speed cutting steels (C and D). Cavitation erosion was measured by the uniform rate  $de_m/dt$  in the first period, and the time before the appearance of the first pit was noted after a continuous visual examination. The erosion resistance values,  $R_e = dt/de_m$ , were identical for the four steels at  $17.4 \times 10^{-9}$  s/m. The Table however shows different values for the mean depth of erosion  $(e_m)_p$  at the appearance of the first pits.

TABLE 7.5.2.3 - 7

Comparison of Ball-Bearing Fatigue Life and of Erosion Depth in Cavitation Tests, from Tichler et al.<sup>280</sup>

| Material                    | Ball-bearing fatigue life <sup>279</sup>         |                                                      | Cavitation tests<br>Mean erosion depth at<br>occurrence of first pit<br>$\mu\text{m}$ |
|-----------------------------|--------------------------------------------------|------------------------------------------------------|---------------------------------------------------------------------------------------|
|                             | 15,000 r.p.m.<br>load = 600 kg<br>oil lubricated | 20,000 r.p.m.<br>load = 280 kg<br>diester lubricated |                                                                                       |
| A Ball-bearing steels       | $7.3 \times 10^3$ rev.<br>3.5                    |                                                      | 57<br>29                                                                              |
| C High-speed cutting steels |                                                  | $23.5 \times 10^3$ rev.<br>13.1                      | 12<br>1                                                                               |

In each group the steel with the greatest resistance to rolling fatigue also has the greatest resistance to the formation of cavitation pitting.

#### 7.5.2.4 Liquid Impact Erosion of Transparent Materials, Reinforced Plastics and Laminated Materials

Aircraft cockpit canopies and windows are made of glass or plastic materials which are transparent to light. Front canopies are made of layers of glass and plastic materials bonded together. This lamination of thick sheets of material is designed to provide greater resistance to the tensile stresses set up by impact from birds with which aircraft may collide at high speed. To avoid immediate destruction of transparency by liquid impact due to water droplets the outer surface of the front glass sheet is hardened by quenching or by chemical etching.

The windows to be used for infra-red photography are protected by sheets of quartz which are transparent to infra-red radiation. The radomes must be transparent to electromagnetic waves. They are made of glass fibre reinforced plastics giving the complete unit high mechanical strength, and are protected against damage from rain impact by coatings which are more flexible and more erosion resistant.

#### 7.5.2.4 - a - Liquid impact resistance of solid transparent materials

In addition to the ductile metals and alloys investigated above, the materials used in the construction of aircraft and helicopters, and which are subjected to the erosive action of rain and dust are:

- the glasses and various resins, which admit light;
- the lead glasses and quartz, which admit infra-red rays;
- the glass fibre reinforced resins and ceramics, which admit electro-magnetic waves;
- the elastomers.

An early comparison of the behaviour of these materials and that of metals under repeated rain drop impacts can be found in the tests by Behrendt<sup>282</sup> performed with a rotating arm in a chamber with a partial vacuum of 6 to 18 mm Hg at impact velocities of between 400 and 1000 m/s; the rain was produced by oscillating tubes. The life was measured by the cumulative height of the water which fell on the unit area:

$$h = Vt\rho_{w/a},$$

where  $\rho_{w/a}$  is the volume concentration of the water in air. Tests at constant  $V_{\text{rain}}/V_{\text{sound}}$  Mach numbers of 1.4 and 3 were carried out at impact velocities  $V$  ranging from 200 to 400 m/s for Mach 1.4 and 300 to 1000 m/s for Mach 3,  $V$  and the test pressure being varied.

For the metallic materials the incubation time  $t_i$  and the maximum erosion rate  $(de_m/dt)_{\text{max}}$  vary according to the following expressions (see Equations (99) and (100), as well as Table 7.5.2.2 - 1):

$$t_i = a/V^m, \quad (99)$$

$$(de_m/dt)_{\text{max}} = bV^n. \quad (100)$$

Table 7.5.2.4 - 1 gives the values for the exponents  $m$  and  $n$  for various materials tested by Behrendt.

In addition, Rieger's tests<sup>283</sup>, some results of which are contained in Table 7.5.2.4 - 2, show that the exponents  $m$  and  $n$  vary with the rain drop diameter.

TABLE 7.5.2.4 - 1

Values of the Exponents  $m$  and  $n$  in Relationships (99) and (100) for the Erosion Incubation Period and the Erosion Rate as a Function of the Impact Velocity in Behrendt's Rain Erosion Tests<sup>282</sup> with 1.2 mm Diameter Rain Drops

| Material                                   | m-values         |                              | n-values         |                              |
|--------------------------------------------|------------------|------------------------------|------------------|------------------------------|
|                                            | V = 400-1000 m/s | V = 250-400 m/s <sup>†</sup> | V = 400-1000 m/s | V = 250-400 m/s <sup>†</sup> |
| Metal and alloys                           |                  |                              |                  |                              |
| Pure aluminium                             | 2.6              | 4.9                          | 3.8              | 2.8                          |
| Al Mg Si 1                                 | 3.9              | 4.9                          | 5.3              | 6.2                          |
| Al Cu Mg 2                                 | 3.9              | 5.4                          | 4.8              | 5                            |
| Ti Al 6 Mg 2                               | 4.8              |                              | 7.4              |                              |
| Ti (IMI 680)                               | 4.1              |                              | 6.1              |                              |
| Plastics                                   |                  |                              |                  |                              |
| Polyurethane                               | 4                | 7.4                          | 13               | 4.4                          |
| Fiber-reinforced plastics                  | 3                |                              | 3.7              |                              |
| Transparent acrylic                        | 2.9              | 3.6                          | 1.9              | 2.4                          |
| Various                                    |                  |                              |                  |                              |
| Silicate glass                             | 3.8              | 5.7                          | 6.1              | 7                            |
| Sapphire (Al <sub>2</sub> O <sub>3</sub> ) | 3.4              | 20                           | 9.5              |                              |
| Ceramic "Degussit" Al 72                   | 3.4              | 7.4                          | 7.4              | 5.6                          |

<sup>†</sup> Values from Rieger<sup>283</sup>

TABLE 7.5.2.4 - 2

Variation of Exponents  $m$  and  $n$  as a Function of Rain Drop Diameter from Rieger's Tests<sup>283</sup>

|                                                   | drop diameter, mm | m-values |     |     | n-values |     |     |    |
|---------------------------------------------------|-------------------|----------|-----|-----|----------|-----|-----|----|
|                                                   |                   | 0.5      | 1.2 | 1.7 | 0.5      | 1.2 | 1.7 | mm |
| Aluminium                                         |                   | 4.4      | 4.9 | 3.6 | 3.6      | 2.8 | 4   |    |
| High pressure polyurethane                        |                   | 1.4      | 5.6 | 8.4 | 3.8      | 5.1 | 7.8 |    |
| Polyurethane                                      |                   | 6.7      | 7.4 | 9   | 4.3      | 4.4 | 4.4 |    |
| Polycarbonate (Makrolon)                          |                   | 3.7      | 4.6 | 5   | 3.2      | 3.7 | 3.5 |    |
| Plexiglas                                         |                   | 3        | 3.6 | 3.8 | 2.6      | 2.4 | 1.6 |    |
| Glass                                             |                   |          | 5.7 |     |          |     |     |    |
| Sapphire (melted Al <sub>2</sub> O <sub>3</sub> ) |                   |          | 7.4 |     |          |     |     |    |

The impact frequency (per second on 1 cm<sup>2</sup>) and the rain drop diameter have little influence on the maximum erosion rate. However, in the case of sapphire and polyurethane the volume of rain required for erosion incubation decreases with increasing frequency. The incubation time is reduced and the maximum erosion rate of high pressure polyurethane increases for an increase in the diameter of the rain droplets.

The expression for the maximum erosion rate as a function of the impact velocity is not suitable for investigating the transparency life of aircraft canopies. According to Schmitt<sup>264</sup>, rain erosion damage at subsonic aircraft speeds causes the formation, on the glass, of individual cavities which are likely to become joined together, with subsequent detachment of larger elements. At supersonic speeds<sup>222</sup> catastrophic rupture occurs creating large cracks. At low supersonic speeds all the materials tested lost their transparency (80% transmission loss), even if the material loss was not capable of being measured<sup>285</sup>. The transparent plastic materials investigated were a UV stabilised polycarbonate Lexan 9034 provided by the General Electric Company and a polysulphone Bakelite P-1700 made by the Union Carbide Corporation. These materials, the physical properties of which are given in Table 7.5.2.4 - 3, behave better at high temperatures than the acrylics, are less expensive than the glasses and have good mechanical strength and good optical transmission characteristics. The purpose of the study was to determine the effects of rain at subsonic impact velocities on the transmission of monochromatic radiation with a wavelength of 1.06  $\mu$ m.

The specimens, held by mountings with angles of 90, 60, 45 and 30° between their surfaces and the impact velocity of the rain droplets, were mounted on a 4340 steel helicopter blade with a speed of 400 m/s at the blade tip under a 2.4 m diameter tubular ring provided with 96 hypodermic needles dispensing rain of 25.4 mm/h with 1.5 to 2 mm diameter droplets. The plane specimens were dried in a stove at 38°C, the weight and optical transmission being measured before and after each erosion stage. In 101 of the 110 specimens the weight increased by 0.1 to 0.2% after erosion, probably due to humidity retention. The results show that erosion does not remove any material, although it affects optical transmission. The surface layers become dull or "frosted" by pitting. The tests were terminated during the incubation period of the erosion process. Table 7.5.2.4 - 4 shows that the transparency losses were negligible after 20 minutes' exposure at normal velocities of less than 155 m/s but that in the case of the polysulphone and the polycarbonate when tested at a normal velocity of between 230 and 270 m/s and at an angle of between 90 and 60°, the transparency dropped respectively to 70% and 20% of the initial values. Similar reductions were observed without loss of weight on lead glass which transmits infra-red, quartz, germanium, calcium aluminate, magnesium fluoride, yttrium oxide Y<sub>2</sub>O<sub>3</sub>, silica, magnesium oxide and the sapphire single crystal<sup>285</sup>. It may be concluded that the period of incubation of weight loss by erosion is not a correct measure of the damage which occurs in transparent materials.

TABLE 7.5.2.4 - 3

Physical Properties of Transparent Plastics, Lexan 9034 Polycarbonate and P 1700 Bakelite Polysulphone, given by the Supplier, from Schmitt<sup>284</sup>

| Physical properties                                                                                                                                                     | Lexan 9034 | P 1700 Bakelite |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|-----------------|
| Specific mass (kg/dm <sup>3</sup> )                                                                                                                                     | 1.2        | 1.24            |
| Tensile strength (MN/m <sup>2</sup> )                                                                                                                                   | 62.1       | 70.4            |
| Young modulus (MN/m <sup>2</sup> )                                                                                                                                      | 2380       | 2184            |
| Tensile elongation at failure, %                                                                                                                                        | 110        | 50 - 100        |
| Bending strength (MN/m <sup>2</sup> )                                                                                                                                   | 932        | 1063            |
| Bending modulus (MN/m <sup>2</sup> )                                                                                                                                    | 2346       | 2690            |
| Shear strength (MN/m <sup>2</sup> )                                                                                                                                     | 69         |                 |
| Compressive strength (MN/m <sup>2</sup> )                                                                                                                               | 86         |                 |
| Rockwell hardness                                                                                                                                                       | M70(R118)  | M69(R120)       |
| Izod impact strength at 22°C (ft lb/in.)                                                                                                                                | 16         | 1.3             |
| Hot-deflection temperature, f = 0.254 mm under 1.8 MN/m <sup>2</sup>                                                                                                    | 132°C      | 174°C           |
| Note: These values result from application of the ASTM test standards and have been translated into the International System of Units, except for the Izod impact tests |            |                 |
| Light transmittance at a wave length of 1.06 μm                                                                                                                         | 90.4 %     | 88.2 %          |

TABLE 7.5.2.4 - 4

Variation of the Optical Transmittance of the Lexan 9034 and P 1700 Bakelite Transparent Plastics after Rain Exposure, from Schmitt<sup>284</sup>

| Orthogonal velocity<br>p.p.hr. m/s | Impact angle<br>degree | Nominal velocity<br>m/s | Exposure duration<br>minutes | Transmittance after 25 hr. of rain exposure† |                 |
|------------------------------------|------------------------|-------------------------|------------------------------|----------------------------------------------|-----------------|
|                                    |                        |                         |                              | Lexan 9034                                   | Bakelite P 1700 |
| 400                                | 178                    | 400                     | 5                            | 98.4                                         | 94.7            |
|                                    |                        |                         | 10                           | 98.2                                         | 89.4            |
|                                    |                        |                         | 20                           | 99.1                                         | 87.4            |
| 433                                | 192                    | 500                     | 2                            | 99.9                                         | 94.7            |
|                                    |                        |                         | 5                            | 97.8                                         | 89.3            |
|                                    |                        |                         | 10                           | 97.1                                         | 75.2            |
|                                    |                        |                         | 20                           | 93                                           | 53.1            |
| 424                                | 188                    | 600                     | 2                            | 96.9                                         | 95.1            |
|                                    |                        |                         | 5                            | 97.3                                         | 88.7            |
|                                    |                        |                         | 10                           | 93.4                                         | 82.6            |
|                                    |                        |                         | 20                           | 88.1                                         | 72.7            |
| 500                                | 222                    | 500                     | 1                            | 99.8                                         | 94.1            |
|                                    |                        |                         | 2                            | 98.4                                         | 86.2            |
|                                    |                        |                         | 5                            | 96.6                                         | 77.7            |
|                                    |                        |                         | 10                           | 90.7                                         | 53.9            |
|                                    |                        |                         | 20                           | 74                                           | 18.3            |
| 519                                | 231                    | 600                     | 1                            | 95.7                                         | 84              |
|                                    |                        |                         | 2                            | 94.8                                         | 84              |
|                                    |                        |                         | 5                            | 90                                           | 64.4            |
|                                    |                        |                         | 10                           | 78.7                                         | 46.6            |
|                                    |                        |                         | 20                           | 65.8                                         | 25.4            |
| 600                                | 267                    | 600                     | 1                            | 89.2                                         | 81.7            |
|                                    |                        |                         | 2                            | 82.3                                         | 58.3            |
|                                    |                        |                         | 5                            | 56.6                                         | 52.6            |
| 300                                | 134                    | 600                     | 5                            | 97.3                                         | 95.3            |
|                                    |                        |                         | 10                           | 97                                           | 95.5            |
|                                    |                        |                         | 20                           | 95.8                                         | 91.5            |
| 354                                | 158                    | 500                     | 5                            | 96.5                                         | 93.7            |
|                                    |                        |                         | 10                           | 97.1                                         | 94.6            |
|                                    |                        |                         | 20                           | 97.2                                         | 84.3            |
| 346                                | 155                    | 60                      | 400                          | 97.4                                         | 91.7            |
| 230                                | 112                    | 30                      | 500                          | 97.9                                         | 95.5            |

† Average from two measurements, excepted for 90°-impacts.

King<sup>286</sup> has compared the rain erosion behaviour of "Perspex" plastic materials (polymethylmethacrylate) and polypropylene with that of ceramics (Sintox and UL 995) and of metals (pure aluminium, L85 aluminium alloy, BS1433 copper and Cr 130 steel). Tests were performed at the RAE Farnborough up to velocities of 223.5 m/s and at Dornier up to 450 m/s, on a rotating arm with 1.2 mm diameter artificial rain droplets. The results are contained in Table 7.5.2.4 - 5 where the mean erosion depth is defined as

$$e_m = \frac{\Delta M}{\rho A} = \frac{\text{weight loss}}{\text{specific weight} \times \text{area exposed}}$$

and in which  $h = Vt \times \rho_{w/a}$  is the cumulative height of the water in rain with a water/air density  $\rho_{w/a}$ .

TABLE 7.5.2.4 - 5

Rain Erosion Tests, from King<sup>286</sup>

| Material                            | Impact velocity (m/s) | Erosion duration (min.) | Rain density $\rho_w/a$ $\text{cm}^3/\text{cm}^2$ | Loss (mg) | Maximum erosion rate (mg/min.) | Mean erosion depth, $e_m$ (mm) | Average water height $h_e$ (cm) |
|-------------------------------------|-----------------------|-------------------------|---------------------------------------------------|-----------|--------------------------------|--------------------------------|---------------------------------|
| <u>Plastics</u>                     |                       |                         |                                                   |           |                                |                                |                                 |
| Perspex                             | 450                   | 0.25                    | $2.5 \times 10^{-6}$                              | 274       | 1752                           | 1.3                            | 1.7                             |
|                                     | 400                   | 0.33                    | do.                                               | 302       | 1422                           | 1.41                           | 2                               |
|                                     | 350                   | 0.66                    | do.                                               | 397       | 1194                           | 1.89                           | 3.5                             |
|                                     | 300                   | 2                       | do.                                               | 417       | 307                            | 1.99                           | 9                               |
|                                     | 250                   | 6                       | do.                                               | 402       | 81                             | 1.91                           | 22.5                            |
|                                     | 223.5                 | 12                      | do.                                               | 448       | 71                             | 2.13                           | 40.2                            |
| Polypropylene                       | 450                   | 1.5                     | $2.5 \times 10^{-6}$                              | 81        | 86                             | 0.5                            | 10.1                            |
|                                     | 400                   | 3                       | do.                                               | 133       | 52                             | 0.83                           | 18                              |
|                                     | 350                   | 8                       | do.                                               | 137       | 24                             | 0.83                           | 42                              |
|                                     | 300                   | 12                      | do.                                               | 80        | 13                             | 0.5                            | 10.1                            |
| <u>Alumina ceramics</u><br>"Sintox" |                       |                         |                                                   |           |                                |                                |                                 |
|                                     | 450                   | 10                      | $1 \times 10^{-5}$                                | 436       |                                | 0.67                           | 270                             |
|                                     | 450                   | 15                      | $2.5 \times 10^{-6}$                              | 40        |                                | 0.06                           | 101                             |
|                                     | 400                   | 15                      | $1 \times 10^{-5}$                                | 48        |                                | 0.07                           | 310                             |
|                                     | 300                   | 18                      | $1 \times 10^{-5}$                                | 1.2       |                                | 0.002                          | 324                             |
| UL 995                              | 450                   | 6                       | $2.5 \times 10^{-5}$                              | 230       |                                | 0.35                           | 40.5                            |
|                                     | 300                   | 6                       | $1 \times 10^{-5}$                                | 3.1       |                                | 0.005                          | 108                             |
| <u>Aluminium, 99.5</u>              | 450                   | 2                       | $2.5 \times 10^{-6}$                              | 244       | 134                            | 0.51                           | 13.5                            |
|                                     | 400                   | 3                       | do.                                               | 232       | 81                             | 0.49                           | 18                              |
|                                     | 350                   | 7                       | do.                                               | 356       | 52                             | 0.75                           | 36.8                            |
|                                     | 300                   | 15                      | do.                                               | 303       | 21                             | 0.64                           | 67.5                            |
|                                     | 250                   | 25                      | do.                                               | 140       | 7                              | 0.29                           | 83.8                            |
| L85 Al alloy                        | 450                   | 7                       | $2.5 \times 10^{-6}$                              | 256       | 42                             | 0.53                           | 47.3                            |
|                                     | 400                   | 15                      | do.                                               | 289       | 23                             | 0.60                           | 90                              |
|                                     | 350                   | 40                      | do.                                               | 309       | 11                             | 0.64                           | 210                             |
| BS 1433 Copper                      | 450                   | 6                       | $2.5 \times 10^{-6}$                              | 589       | 114                            | 0.37                           | 40.5                            |
|                                     | 400                   | 10                      | do.                                               | 536       | 74                             | 0.36                           | 60                              |
|                                     | 350                   | 20                      | do.                                               | 573       | 39                             | 0.34                           | 105                             |
|                                     | 300                   | 45                      | do.                                               | 439       | 17                             | 0.28                           | 202.5                           |
| CR 130 steel                        | 450                   | 15                      | $1 \times 10^{-5}$                                | 647       | 71                             | 0.47                           | 405                             |
|                                     | 400                   | 35                      | do.                                               | 414       | 38                             | 0.30                           | 840                             |

Table 7.5.2.4 - 6 below, by the same author, compares the theoretical impact velocity thresholds for the damage, calculated by means of the erosion rate  $d\Delta M/dt$ , such that

$$d\Delta M/dt = k(V - V_i)^m, \quad (106)$$

where  $\Delta M$  is the weight loss and  $V_i$  is the velocity threshold lying at the intersection of the tangent to the  $\Delta M(V)$  curve with the axis of the impact velocities  $V$ .

TABLE 7.5.2.4 - 6

Computed Values of the Threshold Velocity  $V_i$  for Rain Erosion Damage  
and of Equation (105)'s Constants, from King<sup>286</sup>

| Material                         | $V_i$ (m/s) | m    | k                     |
|----------------------------------|-------------|------|-----------------------|
| Polymethylmethacrylate (Perspex) | 90          | 3.23 | $9.70 \times 10^{-6}$ |
| Polypropylene                    | 113         | 2.92 | 4.28 "                |
| Aluminium (99.5 %)               | 127         | 3    | 3.98 "                |
| L 85 aluminium alloy             | 148         | 3.32 | 2.46 "                |
| BS 1433 Copper                   | 140         | 3.04 | 3.37 "                |

Although a rough qualitative classification of the various materials can be deduced from the above Tables by using the materials common to several Tables to make such classifications, a comparison depends too much on the circumstances peculiar to each type of specimen test to give more than a preliminary indication which would have to be supplemented by more representative tests of the structure under consideration before a final direct verification in service conditions could demonstrate the actual value of the comparison.

#### 7.5.2.4 - b - Laminated materials and coatings

Schmitt<sup>222</sup> has provided a set of erosion test results for specimens carried by planes inclined at varying degrees  $\theta$  to a wedge-shaped sled propelled on rails by rockets over a length of 1818 m equipped with nozzles which provide simulated

natural rain (Holloman Track Test Facility). Getting up to speed was effected over a track length of 2424 m, while after braking over a distance of 6514 m through polyethylene foam, the specimens could be dismantled, inspected and weighed.

The mean penetration depth rate in the direction of the impact velocity,  $de_m/dt$ , is proportional to  $(V \sin \theta)^n$  and the number of droplets encountered, is proportional to  $V \sin \theta$ , while the depth of penetration along the perpendicular to the surface is

$$(de_m/dt) \sin \theta = K (V \sin \theta)^p \quad (107)$$

where  $p = n + 1$ .

Table 7.5.2.4 - 7 gives the values for  $p$  and  $K$ , together with the coefficient of correlation  $r$  for the tests on various transparent materials and various plastics.

TABLE 7.5.2.4 - 7

Comparative Tests of Simulated Rain Erosion on the Running Wedge of the Holloman Track Test Facility, from Schmitt<sup>222</sup>

| Material                                  | p      | K                      | Correlation<br>r |
|-------------------------------------------|--------|------------------------|------------------|
| 753 Alumina                               | 9.476  | $5.41 \times 10^{-35}$ | 0.856            |
| 754 Beryl                                 | 4.272  | $2.81 \times 10^{-17}$ | 0.678            |
| 9606 Pyroceram                            | 6.549  | $8.39 \times 10^{-24}$ | 0.874            |
| 701 Cordierite                            | 10.128 | $1.29 \times 10^{-35}$ | 0.815            |
| 7941 fused silica                         | 5.422  | $1.11 \times 10^{-19}$ | 0.888            |
| Furane 3 265 epoxy laminate               | 6.414  | $1.06 \times 10^{-23}$ | 0.981            |
| Epon 828 epoxy laminate                   | 6.548  | $5.01 \times 10^{-24}$ | 0.940            |
| Shygard 700 polyimide laminate            | 6.522  | $1.13 \times 10^{-23}$ | 0.888            |
| Polybenzimidazole laminate                | 5.430  | $8.28 \times 10^{-20}$ | 0.985            |
| Aluminium phosphate laminate              | 5.214  | $7.71 \times 10^{-19}$ | 0.919            |
| 0.254 mm neoprene/epoxy laminate          | 7.034  | $2.37 \times 10^{-20}$ | 0.900            |
| 0.91 mm Rokide A aluminium/epoxy laminate | 6.928  | $7.79 \times 10^{-30}$ | 0.962            |
| C 106 Cer-Vit glass-ceramic               | 8.34   | $9.62 \times 10^{-29}$ | 0.887            |
| 9753 infrared glass                       | 6.59   | $2.88 \times 10^{-23}$ | 0.861            |
| 7913 windshield glass                     | 5.84   | $1.98 \times 10^{-20}$ | 0.760            |
| 1723 glass                                | 9      | $4.4 \times 10^{-31}$  | 0.921            |
| Polyphenylene oxide                       | 6.88   | $1.25 \times 10^{-25}$ | 0.860            |
| Plexiglas                                 | 6.55   | $3.83 \times 10^{-24}$ | 0.982            |
| Teflon                                    | 5.067  | $8.26 \times 10^{-19}$ | 0.965            |
| Polycarbonate                             | 7.73   | $3.19 \times 10^{-28}$ | 0.938            |
| A-1100 aluminium                          | 7.27   | $5.12 \times 10^{-28}$ | 0.948            |

In this type of test at supersonic speeds, the aerodynamic flow is disturbed by the shock waves emitted from the various edges of the running wedge and the specimens. It is possible, however, to establish a preliminary comparison of the behaviour of the different materials which will help to narrow the field of investigation in subsequent tests on more extensive and more representative structures than the small specimens.

At hypersonic speeds, up to 1700 m/s, the speed component tangential to the surface assumes increasing importance and Schmitt et al.<sup>221</sup>, when repeating the running wedge tests with ceramics, laminated plastics and composite materials, reflected the results of these tests in another expression:

$$de_m/dt = K V^p \sin^2 \theta \quad (108)$$

where  $K$  and  $p$  are given in Table 7.5.2.4 - 8. The statistic of the number of water droplets of a mean diameter equal to or greater than  $d$  mm per  $m^3$  of air in the simulated rain in these tests and in those covered by Table 7.5.2.4 - 7 has been determined by the measurements carried out by Mueller and Sims<sup>287</sup> and can be represented by:

$$\log_{10} N \approx 3.55 - 0.91 d. \quad (109)$$

These results show the range of the field of values for weight loss by erosion in simulation tests on specimens. However, as noted more recently by Schmitt<sup>284</sup>, the mean erosion rate is a secondary characteristic for transparent materials as compared with the resistance to impact by birds and the preservation of transparency in erosion conditions affecting transparency, before weight losses become great enough to be capable of measurement.

#### 7.5.2.4 - c - Transmission of pressure and stress waves in laminates - Attenuation by coatings

Certain fibre reinforced plastics are very resistant to mechanical stresses applied in the tangential plane of thin structures but become rapidly damaged by the normal impact of dust and rain. Such impact tends to separate the resin bonded fibres, which have a relatively low cleavage strength. Protective coatings are therefore essential.

TABLE 7.5.2.4 - 8

Rain Erosion Tests Using the Running Wedge at 1700 m/s-Velocity on Ceramics, Plastic Laminate and Composites, from Schmitt et al.<sup>221</sup>

| Material                                                 | p    | K                      | Correlation<br>r | Test<br>number |
|----------------------------------------------------------|------|------------------------|------------------|----------------|
| <u>Ceramics</u>                                          |      |                        |                  |                |
| 7941 fused silica                                        | 4.48 | $9.22 \times 10^{-17}$ | 0.797            | 36             |
| Pyrolytic isotropous Boron nitride                       | 4.64 | $6.05 \times 10^{-17}$ | 0.902            | 28             |
| Silicon carbide (0.51 mm grains in<br>a graphite matrix) | 5.24 | $1.11 \times 10^{-19}$ | 0.910            | 29             |
| <u>Plastic laminate and composites</u>                   |      |                        |                  |                |
| Glass-epoxy B265 Furane                                  | 6.53 | $1.32 \times 10^{-24}$ | 0.981            | 32             |
| Glass-epoxy 828 Epon                                     | 7.57 | $3.49 \times 10^{-28}$ | 0.970            | 41             |
| Glass-polyphenylene oxide (531-801)                      | 5.76 | $8.9 \times 10^{-22}$  | 0.958            | 35             |
| Glass-polyimide compact                                  | 6.25 | $7.8 \times 10^{-24}$  | 0.956            | 25             |
| Glass-epoxy composite                                    | 4.8  | $1.28 \times 10^{-18}$ | 0.863            | 19             |
| Polyphenylene oxide 531-801 compact                      | 8.72 | $9.80 \times 10^{-33}$ | 0.983            | 29             |
| Plexiglas (type II-UVA)                                  | 6.4  | $5.54 \times 10^{-24}$ | 0.959            | 28             |
| Trifluorethylene resin TFE                               | 4.64 | $1.13 \times 10^{-17}$ | 0.978            | 55             |

Hammitt et al.<sup>226</sup> investigated the behaviour of various elastomers when subjected to impact by discontinuous liquid jets 1.2 mm in diameter, at a velocity of 223 m/s and a frequency of 30 jets a minute. The jets were triggered when a steel hammer struck a diaphragm in contact with a small quantity of water shutting off the rear portion of a cavity comprising a calibrated orifice (see Figure 68, paragraph 7.5.2.1 - a). In the gun tests the incubation period increased and the weight loss decreased for an increasing Shore hardness, from natural rubber with a Shore hardness of 36, to an elastomer with a Shore hardness of 75-80, via several neoprenes.

Calculations of the transmission and reflection of shock waves due to liquid drop impact on the coating and through one or more substrate layers were presented at the same time, at the 4th International Conference in Meersburg on rain erosion and related phenomena, by Springer et al.<sup>288</sup>, Engel<sup>289</sup> and Rieger and Roche<sup>290</sup>. The three papers presented assumed that the stress waves being propagated through the coating and the substrate were plane waves, although the pressure due to liquid drop impact was in fact being propagated radially. All the calculations were made on the assumption of the linear elasticity of the materials, although the viscosity of the plastic materials and the plasticity of ductile metals may be factors in actual conditions. It was again assumed that the liquid droplet and the surface of the coating remained in contact for a long time compared with the multiple reflections of the stresses, although this phenomenon is attenuated before another droplet hits the surface at the same point. No account is taken of any lateral dissipation of energy by shearing between the layers, radial attenuation, viscosity etc.

Springer et al.<sup>288</sup> considered merely the case of the coating and a substrate. The calculations made, like those of Engel<sup>290d</sup> (see paragraph 7.5.1.2 - a), correspond to the axial impact of two bars of different material, one representing the liquid droplet and the other the substrate but with a thin layer of coating in between.  $c = \sqrt{E/\rho}$  is the speed of propagation of a shock wave;  $c_L$  is for the liquid,  $c_C$  for the coating and  $c_S$  for the substrate. In the case of a single resistant material the impact pressure of a droplet on the coating is given by Equation (93), becoming in this case:

$$p = \frac{(\rho_L c_L \rho_C c_C)}{(\rho_L c_L + \rho_C c_C)} V. \quad (110)$$

In the case of a material which has one or more layers of a thin coating negligible thickness  $h_i$  compared with the thickness of the liquid droplet and the substrate, which amounts to neglecting the delayed return of the waves reflected at the front surface of the liquid droplet and at the rear surface of the substrate, it is possible to calculate the stresses due to successive transmission and reflection through and over the interfaces.

The initial wave on the coating surface hit by the liquid is a hydrostatic compression wave

$$\sigma_1 = p.$$

Assuming once more the reasoning used above in 7.5.1.2 - a for a solid sphere impact, we obtain, in the case of plane waves, on the assumption of propagation in a bar of constant cross-section:

- Direct transmitted wave  $\sigma_1$ :

maintenance of the momentum values during the time  $\Delta t$ :

$$c_L \Delta t \rho_L V_1 = (c_L \Delta t \rho_L + c_C \Delta t \rho_C) V_{1C}$$

and

$$V_{1C} = \frac{c_L \rho_L}{c_L \rho_L + c_C \rho_C} V_1.$$

then, noting  $z = c\rho$  the acoustic impedance,

$$V_{1C} = \left( \frac{z_L}{z_L + z_C} \right) V_1 ;$$

shortening of the bar in the sections (see Figure 100); at the left end:

$$\epsilon_1 + (V_1 - V_{1C}) \Delta t / c_L \Delta t = (z_C / (z_L + z_C)) V_1 / c_L ;$$

but the modulus of elasticity is  $E_L = c_L \rho_L^2$  and the stress transmitted is

$$\sigma_1 = E_L \epsilon_1 = \frac{z_L z_C}{(z_L + z_C)} V_1 .$$

– Reflected wave  $\sigma_{1R} = \sigma_2 - \sigma_1$  and transmitted wave  $\sigma_2$ :  
momentum:

$$z_L V_1 = (z_C - z_L) V_{1C} = (z_C + z_S) V_{2C}$$

and, with the value of  $V_{1C}$ , we get:

$$V_{2C} = \frac{2z_C z_L}{(z_L + z_C)(z_C + z_S)} V_1 ,$$

then, taking into consideration the shortening of the bar in the coating section, the stresses are:

$$\begin{aligned} \sigma_{1R} &= E_C \epsilon_{1R} = c_C^2 \rho_C (V_{1C} - V_{2C}) = V_1 z_L z_C (z_S - z_C) / (z_L + z_C)(z_C + z_S) = \sigma_1 (z_S - z_C) / (z_C + z_S) , \\ \sigma_2 &= \sigma_1 + \sigma_{1R} = \sigma_1 (2z_S) / (z_C + z_S) . \end{aligned}$$

Considering the initial stress wave  $\sigma_i$  which hits the interface between the initial environment and the final environment, the stress  $\sigma_{iR}$  reflected by the interface towards the initial material and the stress  $\sigma_T$  transmitted to the final material, we can, as Engel<sup>289</sup> did, generalise the above formulae as follows:

$$\sigma_T = 2\sigma_i z_f / (z_f + z_i) , \quad \sigma_{iR} = \sigma_i (z_f - z_i) / (z_i + z_f) . \quad (111)$$

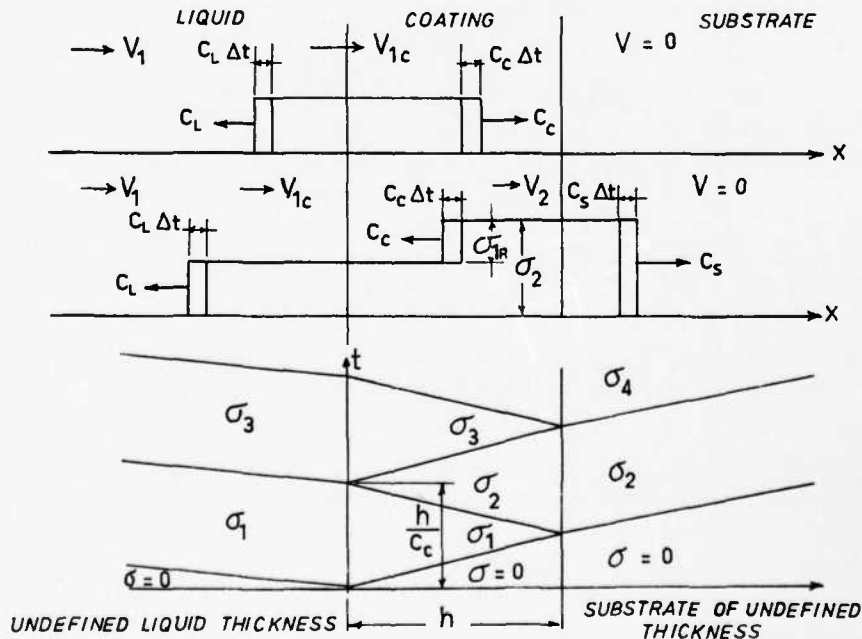


Fig.100 Diagram of stress waves transmitted or reflected during a liquid drop impact on to a substrate covered with a thin coating, from Springer et al.<sup>288</sup>

Continuing the calculations for the successive reflections on the coating/substrate and liquid/coating interfaces, Springer et al. obtained the following expressions

$$\frac{\sigma_{2k}}{\sigma_1} = \frac{1 + \psi_{SC}}{1 - \psi_{SC}\psi_{LC}} [1 - (\psi_{SC}\psi_{LC})^k] \quad \text{with} \quad \psi_{SC} = \frac{z_S - z_C}{z_S + z_C} \quad (112)$$

$$\frac{\sigma_{2k-1}}{\sigma_1} = \frac{\sigma_{2k}}{\sigma_1} - \psi_{SC}(\psi_{SC}\psi_{LC})^{(k-1)} \quad \psi_{LC} = \frac{z_L - z_C}{z_L + z_C}$$

in which  $z = \rho c$  is the acoustic impedance of each material.

The history of the stresses in the coating depends on the relative magnitudes of the acoustic impedance  $z_L$ ,  $z_C$  and  $z_S$ . After a large number of reflections, the theoretical stress in the coating at each of the interfaces approaches the common value

$$\sigma_\infty = \sigma_1 \lim_{k \rightarrow \infty} \sigma_{2k} = \sigma_1 \frac{1 + \psi_{SC}}{1 - \psi_{SC}\psi_{LC}} = \frac{1 + z_L/z_C}{1 + z_L/z_S} \sigma_1 = \frac{z_S + z_L}{z_L + z_C} V_1, \quad (113)$$

that is, the stress in the substrate in the absence of a coating.

In view of the numerous causes of damping not taken into account in these calculations, achieving the theoretical limit can be considered as something to be neglected; it is therefore important that the values close to the start of the series should be as low as possible and, in particular, that the stresses  $\sigma_1$  in the coating and  $\sigma_2$  in the substrate should be low as compared with  $\sigma_\infty$ . According to the results of Springer's calculations shown in Figure 101, this condition is fulfilled by a coating with an acoustic impedance  $z_C$  which is less than that of the liquid and the substrate.

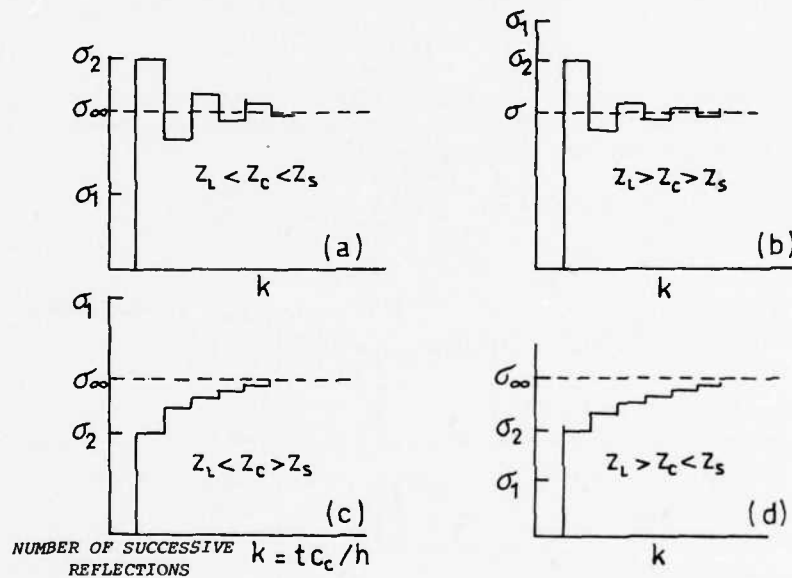


Fig.101 Pressure reduction or rise in the substrate by successive transmissions and reflections of pressure waves through the coating layer, from calculations of Springer et al.<sup>288</sup>

Engel<sup>289</sup> presented similar calculations for a composite coating which included an undercoat. The stress in the wave transmitted to the coating being  $\sigma_1$ , the stress in the wave transmitted to the undercoat will be:

$$\sigma_{T,CU} = \frac{2z_U}{z_C + z_U} \sigma_1.$$

The stress transmitted from the undercoat to the substrate will be:

$$\sigma_{T,US} = \sigma_{T,CU} \cdot 4z_S z_U \frac{z_S + z_U}{z_U + z_C} \sigma_1.$$

The stress of the wave reflected by the coating from the coating/undercoat interface is:

$$\sigma_{R,UC} = \frac{z_U - z_C}{z_U + z_C} \sigma_I$$

This wave will again be partially reflected in the coating by the liquid/coating interface and the reflected wave will be:

$$\sigma_{R,LC} = \frac{z_L - z_C}{z_L + z_C} \sigma_{R,UC}$$

Applying the expressions (111), the numerical calculation can be continued on a computer.

Engel carried out pressure measurements on a coated piezo electric gauge. He considered the various cases: a single soft or hard 0.38 mm thick layer; two layers comprising a hard 0.23 mm thick layer on the surface and a soft 0.15 mm thick undercoat; then the reverse with a soft 0.23 mm surface layer and a hard 0.15 mm thick undercoat. The tests showed excellent behaviour for the hard coating with a single layer and for the double layer coating, the hardest and the thickest layer being at the surface; in these cases the pressures and the rate of loading in the gauge were relatively low. The relative pressure values measured in the four cases showed ratios similar to those of the values calculated by the plane wave theory. It should be noted that the arrival in the substrate of the waves which had undergone various multiple reflections occurred at different times, which may contribute to attenuation.

Rieger and Boche<sup>290</sup> tried to define the shear stresses between the coating layer and the substrate. The following assumptions were made:

- (1) The strains are elastic.
- (2) The liquid flow lateral jets have no effect during drop impact.
- (3) There is only a single reflection at each interface.
- (4) The diameter of the virtual bar is assumed to be equal to that of the droplet (plane waves).

Figure 102 shows the notation for calculating the stresses and strains.

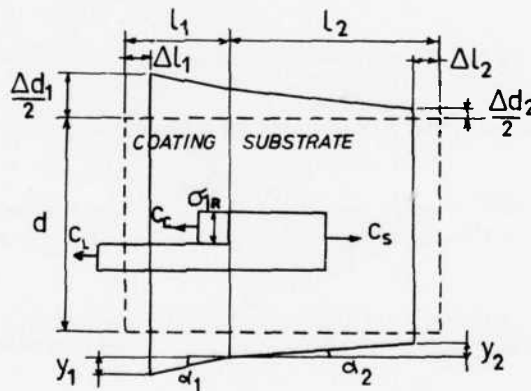


Fig.102 Stress and strain notation used by Rieger and Boche<sup>290</sup> in calculation of the shear between coating and substrate during rain impacts

For a two layer coating the pressure wave  $\sigma_1 = V_1 z_L z_C / (z_L + z_C)$  reaching the surface gives rise to a reflected wave

$$\sigma_{1R} = \frac{z_S - z_C}{z_S + z_C} V_1$$

and to a wave transmitted to the substrate

$$\sigma_2 = 2V_1 z_L z_C z_S / (z_L + z_C)(z_C + z_S)$$

The surface layer undergoes compression in the direction of the impact and transverse expansion. Lateral expansion involves subsurface shear. If there is insufficient adherence, separation under shearing  $\tau_s$  will occur.

Shortening is as follows:

$$\begin{aligned} - \text{layer I} \quad \epsilon_{x1} &= \Delta l_1 / l_1 = \sigma_2 / E_1 \\ - \text{layer II} \quad \epsilon_{x2} &= \sigma_2 / E_2 . \end{aligned}$$

Transverse expansion is such that  $\epsilon_x / \epsilon_y = \nu$ , whence:

$$\text{with} \quad \epsilon_y = \Delta d / d: \Delta d_1 = \nu_1 d \cdot \sigma_2 / E_1 \quad \text{and} \quad \Delta d_2 = \Delta d \cdot \sigma_2 / E_2 .$$

The adherence condition requires:

$$\frac{1}{2}(\Delta d_1 - \Delta d_2) = y_1 + y_2 .$$

In addition,

$$\begin{aligned} y_1 &= x_1 \frac{\tau_s}{G_1} = (l_1 - \Delta l_1) \frac{\tau_s}{G_1} = \frac{l_1}{G_1} \left(1 - \frac{\sigma_2}{E_1}\right) \tau_s , \\ y_2 &= x_2 \frac{\tau_s}{G_2} = (l_2 - \Delta l_2) \frac{\tau_s}{G_2} = \frac{l_2}{G_2} \left(1 - \frac{\sigma_2}{E_2}\right) \tau_s . \end{aligned}$$

We finally get:

$$\tau_s = \sigma_2 \cdot \frac{d}{2} \cdot \frac{G_1 G_2}{E_1 E_2} \cdot \frac{[\nu_1 E_2 - \nu_2 E_1]}{[l_1 G_2 (1 - \sigma_2 / E_1) + l_2 G_2 (1 - \sigma_2 / E_2)]} .$$

where  $\nu_1, \nu_2, E_1, E_2, G_1$  and  $G_2$  are respectively Poisson's coefficients, Young's modulus and Coulomb's moduli for the coating and the substrate;  $d$  is the diameter of the rain droplet and  $\sigma_2$  is the pressure in the substrate and in the coating after reflection on the coating/substrate interface.

The following points were observed in the erosion of bonded laminated materials:

- Erosion without separation of the coating layers: this applies to glass fibre reinforced resins with a fluocarbon coating.
- Detachment of the coating without appreciable erosion: applies to glass fibre reinforced resin specimens which have a polyurethane coating.

In the first case, the strength of the material is determined by the erosion of the coating. Separation frequently occurs in the erosion of laminated plastics.

For coatings consisting of multiple layers of varnish, the conditions of manufacture, such as temperature, air humidity, thickness of each layer, and duration of the drying period between each layer, affect the adherence between the individual layers.

Because of the simplification introduced into the theory, the shear  $\tau_s$  is merely a comparison parameter.  $\tau_s$  increases linearly with the droplet diameter and with the velocity  $V_1$  of the impact; its value tends to decrease with an increase in the thickness.

Good results have been obtained with a carbon fibre reinforced resin and a multi-layer polyurethane coating, the rigidity of each layer increasing from the inside to the outside.

Table 7.5.2.4 - 9 shows the rain erosion protection systems investigated by Rieger and Boche.

TABLE 7.5.2.4 - 9  
Rain Erosion Protection Systems from Rieger and Boche<sup>290</sup>

| Bonded systems    | Examples                                             | Applications                          |
|-------------------|------------------------------------------------------|---------------------------------------|
| Plastic / plastic | Polyurethane / Glass fiber reinforced plastic (GFRP) | Protection of radomes                 |
| Metal / plastic   | Titanium / GFRP                                      | Leading edges of helicopter blades    |
|                   | Steel / GFRP                                         |                                       |
| Metal / metal     | Nickel / CFRP                                        | Engine air intakes                    |
|                   | Nickel / steel                                       | Protection of parts against erosion   |
|                   | Stellite / steel                                     | Leading edges of steam turbine blades |

In metallic coatings, the bonding of a sheet of metal involves a triple layer system; damage may arise as a result of erosion, separation or tearing of the metallic coating. The adhesive layer separating the coating from the substrate is of primary importance. Various tests can be summarised as follows.

Except for the soft aluminium coatings and the medium hardness Cu-Be alloy coatings, the other protection methods are better with a polyurethane glue than with an epoxy resin glue. The difference in the erosion resistance due to the adhesive cannot be explained by its shear strength, since the shear strength of polyurethane ( $6 \text{ MN/m}^2$ ) is lower than that of the epoxy resin ( $25 \text{ MN/m}^2$ ). This difference seems to be due to the shear stress  $\tau_s$ . An approximate calculation has been made by considering a two-layer system in the two cases of stress:  $\tau_{s12}$  for the coating/adhesive case and  $\tau_{s23}$  for the adhesive/support case. Table 7.5.2.4 - 10 contains the mechanical characteristics of the metals investigated and Table 7.5.2.4 - 11 gives the values of the shear stresses  $\tau_{s12}$  and  $\tau_{s23}$ , as well as the length of the test before rain erosion damage occurred in identical conditions of impact velocity ( $V = 410 \text{ m/s}$ ), droplet diameter ( $1.2 \text{ mm}$ ) and rain density ( $\rho_{w/a} = 0.25 \times 10^{-6}$ ).

A comparison can be made between the metallic coatings, the silica carbide and the tungsten carbide coatings obtained by transfer, by electron bombardment, from a cathode to the cold surface of an anode, investigated by Gentner<sup>201</sup> (see paragraph 7.5.1.1 - b).

TABLE 7.5.2.4 - 10

Strength and Elasticity Data on the Metal Coatings Investigated by Rieger and Boche<sup>290</sup>

| Material                             | Ultimate strength<br>$\text{MN/m}^2$ | Young modulus, E<br>$\text{MN/m}^2$ | Coulomb modulus, G<br>$\text{MN/m}^2$ | Poisson's ratio, $\nu$ |
|--------------------------------------|--------------------------------------|-------------------------------------|---------------------------------------|------------------------|
| 17-7 Cr-Ni steel (German 1.4310 X12) | 690 - 880                            | 196,000                             | 74,500                                | 0.32                   |
| 18-9 Cr-Ni steel (1.4301 X5)         | 490 - 690                            | "                                   | "                                     | "                      |
| Alloys                               |                                      |                                     |                                       |                        |
| Ti Al 6 V 4                          | 980-1230                             | 108,000                             | 38,750                                | 0.395                  |
| Cu-Be soft                           | 660                                  |                                     |                                       |                        |
| mean                                 | 834                                  | 127,500                             | 49,000                                | 0.3                    |
| hard                                 | 1210                                 |                                     |                                       |                        |
| 5052 Al Mg 3                         | 225-245                              | 68,670                              | 24,500                                | 0.32                   |

TABLE 7.5.2.4 - 11

Correlation Between Erosion Life Before Damage and Erosion Shear Stresses, from Rieger and Boche<sup>290</sup>

| Systems<br>Coating / glue / substrate | Computed shear stresses, $\text{MN/m}^2$ |     | Erosion life before damage, minutes : |
|---------------------------------------|------------------------------------------|-----|---------------------------------------|
|                                       | s12                                      | s23 |                                       |
| Steel / Polyurethane / Steel          | 15                                       | 15  | 93                                    |
| Steel / Epoxy / Steel                 | 330                                      | 110 | 16                                    |
| Steel / Polyurethane / GFRP           | 15                                       | 15  | 91                                    |
| Steel / Epoxy / GFRP                  | 330                                      | 42  | 29                                    |
| Ti-Al6-V4 / Polyurethane / GFRP       | 470                                      | 74  | 13                                    |

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| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                                                                                                                                                          |                                            |                                                               |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|---------------------------------------------------------------|
| 1. Recipient's Reference                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 2. Originator's Reference<br>AGARD-MAN-10<br>(ENG.)                                                                                                      | 3. Further Reference<br>ISBN 92-835-1389-4 | 4. Security Classification<br>of Document<br><br>UNCLASSIFIED |
| 5. Originator                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Advisory Group for Aerospace Research and Development<br>North Atlantic Treaty Organization<br>7 rue Ancelle, 92200 Neuilly sur Seine, France            |                                            |                                                               |
| 6. Title                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | MANUAL ON THE FATIGUE OF STRUCTURES                                                                                                                      |                                            |                                                               |
| 7. Presented at                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                                                                                          |                                            |                                                               |
| 8. Author(s)/Editor(s)<br>W.G.Barrois                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | 9. Date<br>June 1981                                                                                                                                     |                                            |                                                               |
| 10. Author's/Editor's Address<br>Ingénieur en Chef Militaire Honoraire<br>de l'Armement (Air)<br>42 rue Larmeroux, 92170 Vanves, France                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              | 11. Pages<br>140                                                                                                                                         |                                            |                                                               |
| 12. Distribution Statement                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications. |                                            |                                                               |
| 13. Keywords/Descriptors<br><br>Fatigue<br>Mechanical damage<br>Corrosion<br>Plastic deformation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |                                                                                                                                                          |                                            |                                                               |
| 14. Abstract<br><br>The present publication (AGARD-MAN-10 (Eng.)) contains Chapter 7 which deals with mechanical surface damage. This concerns surface damage arising from wheel grinding, wear, rolling fatigue, contact fatigue, fretting fatigue and erosion by solid or liquid particles. Such damage is often the origin of fatigue cracks. An attempt is made to summarize those aspects of scientific knowledge in the field which are particularly relevant to the structural design process. It is hoped that full appreciation of this information and its careful use by designers will improve significantly the environmental resistance of our future vehicles and will thus produce important benefits in cost and maintenance reduction and in aircraft availability.<br><br>This Manual was prepared at the request of the Structures and Materials Panel of AGARD. |                                                                                                                                                          |                                            |                                                               |

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