THE "RUSTLESS" IRON PILLAR AT DELHI

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The 1600 years old forge-welded wrought iron pillar at Delhi, India (approximate average composition: 0·15% C, 0·25% P, 0·005% S, 0·05% Si, 0·02% N, 0·05% Mn, 0·03% Cu, 0·05% Ni, balance Fe) still shows but slight signs of rusting above ground. While the composition of the material, particularly its low S and high P contents, is conducive to a low corrosion rate in the atmosphere, the deciding factor is the dry and unpolluted climate of the area, the large mass of the pillar being a contributory factor. That part of the pillar that is below ground is covered by a rust layer, about 1 cm thick, and shows deep pitting. Above ground, the pillar is coated by a protective oxide film, 50—500 μm thick, whose analysis according to Ghosh is 67·0% Fe_3O_4, 13·1% FeO, 14·8% H_2O, 1·7% $FePO_4$, 3·1% SiO_2. Assuming a parabolic growth rate of the oxide film, its thickness is in accordance with present-day corrosion rate of carbon steel at Delhi, determined by Hudson, and corresponding to the formation of an oxide film, 5 μm thick in the first year.

In ancient Delhi, a huge ruin area about six miles south of New Delhi, capital in the Indian Union, there is a 1600 years old pillar of forge-welded wrought iron (0·15% C, 0·25% P), which does not rust and which has therefore since long fascinated both metallurgists and corrosionists. Since in the lapse of years many different explanations of this remarkable fact have been advanced, there is reason to review available data about the pillar in order to try thereby to create some clarity in the phenomenon. Such a discussion also proves to illustrate the most important both climatological and metallurgical aspects of the atmospheric corrosion of iron and steel.

The iron pillar is placed close to a minaret, called Qutab Minar, a 73 m high monument of victory, built from sandstone and marble in the 13th century A. D. The iron pillar is therefore sometimes also called the Qutab Pillar at Delhi. According to a Sanscrit inscription*

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* The English translation of the Sanscrit inscription reads: He, on whose arm fame was inscribed by the sword, when, in battle in the Vanca countries (Bangál), he kneaded (and turned) back with (his) breast the enemies who, uniting together, came against (him), - he, by whom,

(Fig 1*) on its surface, the iron pillar is also a token of victory or triumph, erected to the memory of a mighty king and conqueror, named Chandra, who is regarded as identical with Chandragupta II (375—413 A. D.). The pillar is supposed to have been placed in some other location earlier and is said to have been moved to its present position in the 12th century A. D. There are other, still existing examples which show that rajahs and other magnates in ancient India tried to preserve their names to posterity on just iron pillars. So did a Greek ambassador already before the beginning of our chronology. This must mean that under prevailing climatic conditions iron was considered to be a resistant material. For bibliographies of iron- and steelmaking in ancient India with numerous references to the Delhi pillar and other similar historical relics, see the handbooks[1,2]. Another interesting example, not mentioned there, is king Jarasandha's iron wall at Rajgir in the province of Bihar, India[3].

The pillar (see Figs 2 and 3) is totally 720 cm high, 50 cm of which stand below ground level and additional 45 cm are surrounded by a stone platform. The diameter of the pillar immediately above the platform is 49 cm. It is then tapered upwards to a smallest diameter of 30 cm just below the capital that tops the column. Its upper flat surface is provided with a rectangular hole, probably fitted for a flag-staff. The dimensions of the pillar allow its weight to be estimated to about 6 tons. Objects of iron or steel of this size were fabricated in the Occident only at the end of the 19th century.

Below ground level the pillar widens to a largest diameter of 62 cm. From its flat bottom face 8 short iron rods protrude and penetrate into a thick lead plate, which in turn rests on a flat rock. In this way, the pillar is so firmly anchored that it has even resisted firing with a cannon (by Nadir Shah in 1738), of which an indentation and a crack on its upper half still remind us.

Materials and Means of Manufacture

The first who studied the material in the pillar scientifically by means of chemical analysis and metallographic investigation, was Hadfield[4-7]. Later, a more thorough investigation was presented by Ghosh[8]. The material in the pillar is so-called wrought (*i.e.* worked) iron, which means that, in contrast to modern steel, it has never been molten. In ancient times, wrought iron was manufactured directly from iron ore, in this case probably weathered magnetite, obtained by surface quarrying. The ore was bedded intermittently with charcoal in a charcoal-fired small furnace with a foot-driven hide-bellow. The reduction temperature was probably[9] about 1 000°C. The lumps of iron sponge thus obtained were then hammer-forged in order to squeeze out most of the slag. At the same time, most of the carbon still remaining in the iron was oxidized. Judging from weld-lines on its surface, the Delhi pillar seems to have been built up from a great many lumps, weighing 20—30 kg, which have been successively forge-welded together under firing

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having crossed in warfare the seven mouths of the river Sindhu, the Váhlikas were conquered; - he, by the breezes of whose prowess the southern ocean is still perfumed; - he, the remnant of the great zeal of whose energy, which utterly destroyed (his) enemies like (the remnant of the great glowing heat) of a burned-out fire in a great forest, even now leaves not the earth; though he, the king, as if wearied, has quitted the earth, and gone to the other world, moving in (bodily) form to the land (of paradise) won by (the merit of his) actions (but) remaining on (this) earth by (the memory of his) fame; - by him, the king, - who attained sole supreme sovereignty in the world, acquired by his own arm and (enjoyed) for a very long time; (and) who, having the name of Chandra, carried a beauty of countenance like (the beauty of) the full-moon, - having in faith fixed his mind upon (the god) Vishnu, this lofty standard of divine Vishnu was set up on the hill (called) Vishnupada.

* See insert facing p. 624.

FIG. 1

Detail of Surface of the Iron Pillar at Delhi, Showing its Metallic Lustre and the Excellent State of Preservation of the Sanscrit Inscription

Photo: Mr J. F. H. van Eijnsbergen, Stichting Doelmatig Verzinken, The Hague, Holland.

with a charcoal blast[4,10]. The surface of the pillar shows marks of hammer-blows. The original inscription is still sharp and in excellent condition. *Cf.* Fig. 1. Even before the beginning of our chronology, the old Hindus are said to have mastered the art of melting wrought iron in small crucibles to actual steel, from which they prepared surgical instruments and stone-cutting tools, imported and highly cherished by both Alexander the Great and the Egyptian pharaos[1].

Factors Causing "Rustlessness"

Regarding the remarkable freedom from rusting of the Delhi pillar, European investigators[11-13] have stressed climatic conditions whereas Indian metallurgists wish to see its resistance to corrosion as a result of the composition of the iron[8] or of its high slag content[14,15].

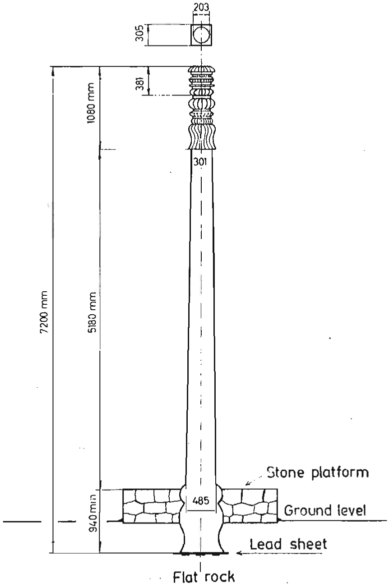

FIG. 2

Sketch, Showing Dimensions and Anchoring of the Pillar

It should be observed, though, that the "rustlessness" of the pillar is not complete. The lowest part of the pillar, which is buried in the ground, a moister environment than the atmosphere, is covered by a rust layer more than one cm thick and shows corrosion pits up to 10 cm deep. This is a first indication that climate rather than composition is the deciding factor for the good resistance of the pillar above ground. Immediately above the surrounding platform, the surface of the pillar is very rough, apparently due to defects in the forge-welding, which seem to have been made worse by corrosion, resulting in deep pits. A band of the circumference of the pillar at a height between 1 and 1·5 m above the stone platform is very bright, as if polished (See Fig. 3*). The latter is due to the custom of visitors to stand with their backs towards the pillar, trying to clasp their hands around it "for luck". The whole pillar is covered by an oxide film of metallic lustre but varying colour (black-blue-brown). According to magnetic measurements[12], the oxide film on the bright, polished section is less than 50 μm, immediately above 500–600 μm and higher up thinner again. It should also be noticed that if the oxide film is scraped off on some spot, the exposed iron starts to rust as usual[8]. After a week or so a normal rust spot is observed, which, however, is gradually converted to a darker oxide. After a few years the newly formed oxide cannot be distinguished from the main oxide of the pillar. This shows that the good state of preservation of the pillar is due to a protective film of corrosion products, formed also in present-day Delhi climate, and not to some inherent slag or oxide coating or some surface treatment carried out during the early history of the pillar, as has occasionally been suggested[16]. Such a coating would certainly have been damaged and made ineffective, at least locally, in the course of the ages.

In this and other similar cases where unprotected iron has been preserved in the atmosphere for many centuries, at least two cooperating factors have to be considered:

Favourable climatic conditions: Delhi has a dry and clean atmosphere, which furthermore, particularly in the beginning of the exposure, has been alkaline (ammoniacal) and hence passivating rather than sulphurous and corroding. This has allowed the initial corrosion to proceed at a very low rate and hence result in a protective coating.

A favourable composition with regard to corrosion in the atmosphere: In the present case this means a low sulphur and a high phosphorus content, which has also promoted the formation of a protective coating.

In this particular case, one additional factor may have contributed to the good state of preservation of the pillar, *viz*:

Large mass and hence large heat capacity. This means that the heating due to sunshine in day-time counteracts dew precipitation during the night and results in rapid

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* See insert facing p. 626.

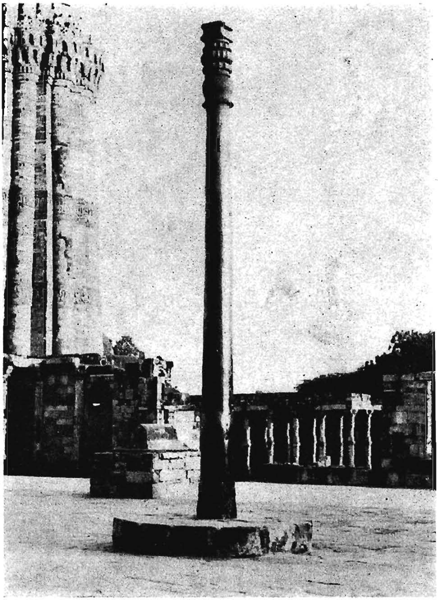

FIG. 3

View of the Pillar

Note the Polished Area, 1—1·5 m above the Stone Platform, and the Scar and Crack at about Middle Height of the Pillar. Photo: Archaeological Survey of India.

drying after rain-fall. While moisture and dew may occasionally be observed on cars in the early morning at Delhi, this probably occurs to a much lesser degree on the pillar.

On the bright band on the lower part of the pillar the polishing and greasing effect of the touching by clothes and human hands have contributed to the preservation of a surface of metallic lustre, on which, however, a fatty layer may be observed at close range[17]. This favourable effect of handling is known in some other cases of atmospheric corrosion. Along a mountain path in Ceylon there are some 2000 years old iron chains, provided to facilitate the visit of Indian pilgrims to a shrine on Adam's Peak[18,19]. Apart from the favourable climate, the repeated polishing and greasing of the oxide film on the links by the contact with human hands have practically prevented rusting. It is well known, on the other hand, that finger-prints *etc.* often exert a very detrimental influence on otherwise clean and polished and not oxide-coated metallic objects, stored indoors, in which case the salt content rather than the fat of the prints is of deciding importance.

Composition of the Delhi Pillar

Regarding the composition of the iron in the Delhi pillar, several analyses have been published according to the summary in Table I.

According to the analyses, the average composition of the material in the pillar may be given as: 0·15% C, 0·25% P, 0·005% S, 0·05% Si, 0·02% N, 0·05% Mn, 0·03% Cu, 0·05% Ni, balance Fe.

TABLE I

Analyses of Samples (%) Taken from the Delhi Pillar According to Different Authors

Element	Ref.[4–7]	Ref.[8,14]	Ref.[8]		Ref.[12]
			sample taken above ground	sample taken below ground	
C	0·080	0·28	0·23	0·03	—
P*	0·114	0·155	0·28	0·48	—
S	0·006	0·003	Trace	0·008	—
Si	0·046	0·056	0·066	0·004	—
N	0·032	—	0·0065	—	—
Mn	0	0	0	0	0·07
Cu	0·034	—	—	—	0·03
Ni	—	—	—	—	0·05
Cr	—	—	0	—	0

* Partly in solid solution in the ferrite, partly as iron phosphate slags, particularly in the oxidized, decarburized parts and visible as yellow speck on the surface.

It is obvious, however, that the composition of different samples is strongly varying. On the whole, this is characteristic of wrought iron as a result of the method of manufacture. Furthermore, the Delhi pillar has been forge-welded together from a great many sponge iron lumps of different composition. In accordance, the microstructure of the material is strongly varying and its slag content is very high[8,12,14]. The slag probably consists mainly of magnetite, Fe_3O_4, but part of it is iron phosphate, $FePO_4$, particularly in the more strongly oxidized surface layers.

The carbon content shows considerable variations. Its average value is not particularly low. The content of carbon and hence of pearlite is very low in the surface layer, determining the corrosion characteristics, but increases inwards, apparently a result of surface decarburization during hammer forging.

The phosphorus content is very high according to all analyses and is less varying. Segregation of P may be disclosed by the preferential etching of areas, rich in P, in hydrochloric acid or still more clearly by Stead's etchant (an aqueous solution of hydrochloric acid and cupric chloride), which gives Cu deposition on areas, low in P, since these are inactive and hence act as cathodes[8,20]. While P in steel exclusively occurs as a solid solution in the ferrite, which may dissolve up to c. 1% P, a considerable part (30–60%) of the P content in wrought iron may appear as slag inclusions of iron phosphate[21,22]. Naturally, the phosphate content tends to be higher in the more strongly oxidized parts, depleted in C, and particularly in the surface layer. In good accordance, Ghosh[8] found that out of totally 0·28% P in a sample from the Delhi pillar, 0·18% occurred as elementary P, whereas the rest or 0·10% appeared as phosphate slag.

The sulphur content is very low according to all determinations, a result of the use of charcoal in reducing the ore. Considering the very low Mn content, S probably appears as finely dispersed MnS or as solid solution in the ferrite[23]. In contrast to modern steels, the wrought iron of the Delhi pillar does not seem to contain any larger, microscopically visible inclusions of sulphides, as is clearly visible from a so-called sulphur print[24]. This test is carried out by pressing a photographic paper, soaked in dilute H_2SO_4, against the polished surface of the sample. The paper is then immediately transferred to the fixation bath, after which sulphide inclusions show up as black spots. Such spots did not appear on a sulphur print of a sample from the Delhi pillar[8]. This is in accordance with the invariably even values of the S content in the chemical analyses, whereas elements occurring as separate phases (C) or larger slag precipitates (P, Si) show strong segregation.

The silicon content is rather low. It is probably present mainly as iron silicate slags, explaining the varying analytical values.

Low contents of both Mn and Cu are typical of old Indian wrought irons as of most ancient wrought irons, obtained directly from the ore[9,25]. So-called puddled wrought iron, manufactured during the 19th century from pig iron, usually contained more Cu. This was lucky, since Cu to a certain extent neutralizes the corrosion stimulating effect of S which occurred to a much higher content in puddled wrought irons than in ancient, directly produced wrought irons. Finally, the material in the Delhi pillar shows negligible contents of Ni and Cr, important constituents not only in stainless steels but also in many low-alloyed, slowly rusting (so-called weathering) steels.

If we wish to compare the material of the Delhi pillar with a modern steel, we find that its C and Si contents roughly correspond to an ordinary constructional steel of the type En 3 (AISI 1015) of semi-killed quality. The Delhi iron is different from the steel in three important aspects, however, *viz*:

1. low Mn content, as compared to ca 0·5% in the steel, *2*. high P content, about 5 times as high as in the steel, *3*. low S content, an order of magnitude lower than in the steel.

To this should be added the high slag content and the strong heterogeneity in composition as well as structure of the wrought iron which are consequences of its primitive mode of manufacture.

Without being particularly remarkable, the composition of the iron of the pillar is favourable for a good corrosion resistance in the atmosphere. Hence, the low S content and its homogeneous distribution are conducive to a low corrosion probability[26] since sulphide inclusions are often effective local cathodes and are known to stimulate corrosion also in the atmosphere[27]. Corrosion attacks usually start close to certain Mn-sulphides[28], often resulting in pitting. In addition, any sulphide ions entering the corrosive solution act catalysing on both the cathode and the anode process[29]. Regarding the content of P, that part of the P which occurs in solid solution in the ferrite acts strongly catalysing on the dissolution of iron in acids in much the same way as S does. While S preserves its detrimental influence also in oxygen consuming corrosion, as in water and in the atmosphere, a high P content actually exerts a beneficial influence under these conditions, probably because P in the ferrite is then oxidized to phosphate which as an inhibitor promotes the formation of protective oxide films. It should be observed that modern slow-rusting (weathering) steels of the type Cor-Ten have high P contents (besides Cu, Si and Cr).

The composition of the material of the pillar can only be of secondary importance, however, whereas the favourable climate of Delhi is the deciding factor. Some wrought iron beams at the well-known temple ruin at Konarak situated close to the coast, some 300 miles from Calcutta are still preserved but are badly rusted although the rust on some beams is repeatedly worn away by sand storms[30]. Samples taken from the Delhi pillar and from other ancient wrought iron constructions of similar composition[4,18,19,31], which have been cleaned from protective oxide films and exposed together with samples of modern steel, are found to corrode in much the same way as the latter. General corrosion during total immersion in water usually occurs at just the same rate, determined by the diffusion of dissolved oxygen. In present-day atmospheres, small differences corresponding to the differences in composition and structure are observed. Hence, Lahiri and coworkers[14] found a corrosion loss of 5 μm/year after exposure of a small sample from the Delhi pillar for 3·5 years at Jamshedpur. This is about twice the rusting rate that Hudson[11] found for copper-containing, slowly rusting steel at Delhi (considering the fact that the latter case concerned test plates, exposed on both sides.) Trägårdh[32] found, furthermore, that a steel, specially prepared with a composition corresponding to Hadfield's analytical figures for the composition of the Delhi pillar, did not rust less than normal carbon steels in Swedish climate.

Composition of the Protective Film of the Pillar

It has been suggested that the protective film on the surface of the pillar might be due to the presence of phosphate slags in the iron. This seems less likely, however, in view of the low solubility of iron phosphate and the uneven distribution of the phosphate slags. According to another theory, the surface of the pillar is supposed to be covered by a protective silicate layer, formed during forge welding of the pillar on a flat rock as would seem likely. Although there is evidence to show that layers of silicate slags may temporarily halt corrosion attacks on old specimens of wrought iron, this effect is probably not of importance in this case. The protective film, with which the pillar is covered, probably consists of corrosion products, in which P and Si have become enriched in various ways.

According to optical[12], X-ray[8] and chemical[8] investigations, the oxide film seems to consist mainly of magnetite, Fe_3O_4, possibly with some limonite, $Fe_2O_3.H_2O$, on the surface. Ghosh[8] hence reports a chemical analysis of the surface oxide, which may be recalculated as follows: 67·0% Fe_3O_4, 13·1% FeO, 14·8% H_2O, 1·7% $FePO_4$, 3·1% SiO_2, 0·2% MgO, 0·1% CaO, in total 100%. The content of phosphate in the surface oxide corresponds to 0·35% P in the iron, which is within the variation of the P values of the analyses of the material of the pillar. Normally, however, there occurs an enrichment of P in rust, as compared to the substrate[8,9]. That part of the P content of the basis material which is evenly distributed as a solid solution in the ferrite has probably contributed more to the formation of the protective surface film than the heterogeneously distributed inclusions of phosphate slags. The SiO_2 content of the surface oxide, on the other hand, is much higher than what corresponds to the Si content of the iron. Since, furthermore, X-ray diffraction analysis of the surface oxide shows the presence of quartz, it is farily obvious that the SiO_2 content is mainly derived not from silicate slags but from occluded dust, a consequence of the sand storms that are quite common in the area. The same is apparently true of the reported contents of MgO and CaO. The thick rust layer below ground, on the other hand, has a composition, closely corresponding to Fe_2O_3, H_2O.

TABLE II

Corrosion Rate of Carbon Steel at Some Different Locations, Including Delhi

Location	Type of climate	Thickness loss of test plates μm/year	Relative corrosion rate
Khartoum, Soudan	rural, desert-like	2	1
Delhi, India	rural, dry	5	3
Abisko, Sweden	rural, arctic	6	3
Berlin, Germany	urban	60	30
Kure Beach, USA	marine	80	40
Pittsburgh, USA	industrial	130	65
Frodingham, England	industrial	200	100

The Corrosion Climate at Delhi

Regarding the relative importance of various corrosion factors, it seems *a priori* probable that the climate at Delhi should be mentioned first for the simple reason that the rate of rusting of un-alloyed or low-alloyed iron and steel varies much more strongly with climatic conditions than with composition. While the rate of rusting of one and the same steel varies as 1 to 100, or more, in different climates, different unalloyed or low-alloyed steels, exposed in the same location, show much smaller variations, perhaps as 1 to 5 or as 1 to 10 at the most.

As regards atmospheric corrosion, a table is often reproduced, showing the weight or thickness losses of one and the same carbon steel, exposed at some 20 locations on the earth with widely varying climate. If Delhi is included in this series, based on exposure tests with carbon steel plates, carried out by Hudson[11] at Delhi in 1950 to 52, we find a sequence according to Table II, in which just a few test stations are included.

While the rate of rusting at Delhi was determined for exposure times of just one year, tests at the other locations lasted about 10 years. This means that the value for Delhi is, relatively, too high, since the rate of rusting in slightly corrosive climates follows a parabolic rather than a linear function. For zinc test plates, exposed along with the steel plates, Hudson observed an even smaller corrosion rate at Delhi than at Khartoum. The atmospheric corrosion of zinc is known to follow a linear time function.

The climatic conditions at Delhi are summarized in the diagrams in Fig. 4. The main cause of the low corrosion rate at Delhi, as at other hot and dry places, is the low relative humidity (R. H.) of the air. It is only in the morning hours during the monsoon rains in July, August and September and also in January that the R. H.

exceeds the critical 70%, above which noticeable rusting starts. In the afternoon, the R. H. never exceeds this critical limit and, except in the monsoon period, it is then very low (20–40%). The amount of rain, on the other hand, is considerable; the area is not a desert. The yearly rainfall, amounting to about 700 mm, of which 3/4 are the monsoon rains, is about the same as in Europe, but it is small for Indian conditions. Surrounding mountains, where the yearly rainfall may be 10 times as high, liberate the main part of the monsoon rains. The relatively small rainfall in conjunction with the high temperature constitutes the dry climate. This also means that rain moisture rapidly dries up. This is particularly true of a large, freely exposed object of large heat capacity such as the iron pillar. It is also known that heavy rains exert a rinsing and cleansing effect.

Hudson's data involve a thickness loss of 2·5 μm/year at one-sided exposure of a specimen for 1 year. If the oxidation is assumed to proceed to magnetite, Fe_3O_4, which remains on the surface, this means that during the first year of exposure a magnetite film, about 5 μm thick, is formed. It is now known that during slow rusting in a rural climate a protective film is formed whose thickness increases according to the parabolic law, $y^2 = kt$. With $y = 5$ μm for 1 year we obtain for 1 600 years $y = 200$ μm in excellent agreement with measurements by Bardgett and Stanners[12].

In a discussion of the influence of climatic factors on corrosion the pollution of the atmosphere must be included. Due to small industrialization and little use of fossil

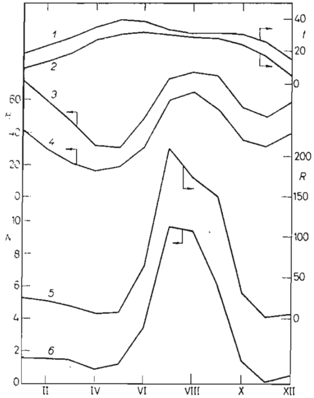

FIG. 4

Diagrams, Showing Details of the Climate at Delhi (Safdarjang, Lat. 28°35′ N, Long. 77°12′ E). Height above M. S. L. 216 metres. Means, Based on Observations from 1931 to 1960

The year's course of temperature t (in °C) at *1* 17·30, *2* 8·30, relative humidity H (in %) at *3* 8·30, *4* 17·30; *5* rainfall R (in mm), *6* number of rainy days N.

fuels, the concentration of sulphur dioxide in the air is probably low in India. Accumulation in a hot and densely populated country like India of waste products from animals and men, generating ammonia, will presumably mean that the atmosphere is alkaline rather than acid and hence conducive to a good corrosion resistance of iron and steel. This was probably still more true during the first 1 500 years of the life of the pillar. Copper alloys, particularly brass, on the other hand do not fare well in atmospheres containing ammonia, which tend to cause stress corrosion cracking (so-called season cracking) of copper alloys. It is characteristic that whereas the corrosion of steeel, *e.g.* on railway cars, is remarkably small in all India[33], stress corrosion cracking of brass, *viz.* in cartridge-cases was first observed just in India and was named after its seasonal dependence on the monsoon rains.

The Rate of Rusting in the Middle Ages and Today

When we sometimes observe and wonder that very old iron, deriving from Antiquity or the Middle Ages, has rusted much more slowly than steel, manufactured by modern technology, does today, two things must be remembered, as was particularly stressed by Evans[22,26,34].

1. That the atmosphere under the rural, not to say Arcadian conditions prevailing during the first exposure was much less corrosive than now and maybe even acted passivating on iron and steel due to an excess of ammonia (from dunghills, cowhouses, stables *etc.*) rather than of sulphurous compounds from fossil fuels. The conditions in the beginning of an exposure are often deciding for the life of a metallic object in the atmosphere, however. Under favourable conditions, a protective layer of corrosion products is then formed which to a certain limit protects the metal also when the atmosphere is by and by being polluted. Hence, Daeves[25] investigated some construction details of wrought iron, high in P but low in S, from the cathedral at Cologne which during ca five centuries had not rusted more than what unprotected carbon steel does in as many years in some of our worst industrial climates today.

2. That only those objects which have had the most favourable composition remain. One may speak of a "survival of the fittest" here too. Materials of high corrodibility were apparently produced in ancient times also. This is evident from an ancient method for treating iron used by the old Celts in Spain and described by J. Webster[35]. "Lastly, as to this point I shall onely mind the Worker in this metal of a passage in *Diodorus Siculus*, an ancient Author, who tells us: That the Celtiberians did thus prepare Iron to make their weapons of War of. For they hiding Iron plates in the earth, did suffer them to be there so long, until the weaker part of the Iron wasted, and the stronger remained. Then of that they made Swords, and other Arms for the use of the War. To these, thus made, all things or Arms would yield, that neither shield nor helmet, nor any other Armour could resist them."

According to this description it seems probable that rusting in the earth removed parts of the plates particularly high in embrittling impurities, such as sulphides. This ancient method is a unique example of a corrosion process used as a metallurgical refining operation. Materials of a composition more sensitive to corrosion have since long disappeared, however, and are hence not availalbe for a comparison which is therefore not quite fair.

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