Discussion Meeting on

Delhi Iron Pillar

March 11, 2005

Indian National Science Academy, New Delhi

Organized by

Indian National Academy of Engineering (INAE) -
Engineering Heritage (Metallurgy)

Supported by

Department of Science and Technology
Department of Culture
Archaeological Survey of India
New Delhi

The Delhi iron pillar has long attracted the admiration of historians and curiosity of metallurgists mainly for its large size, manufacturing, and its excellent state of preservation. Several theories have been proposed in the past to explain the origin of the pillar, manufacturing technology and superior corrosion resistance of the Delhi Iron Pillar which has withstood corrosion for the last 1600 years. A consensus on these issues still eludes us in spite of a century long research investigations.

In this connection, the Engineering Heritage–Metallurgy Committee of Indian National Academy of Engineering (INAE), organized a Discussion Meeting on Delhi Iron Pillar on March 11, 2005 at Indian National Science Academy, New Delhi. The discussion meeting was attended by specialists/eminent personalities in the field of history, metallurgy and corrosion science to discuss the results of the investigations carried out so far and also chalk out the road map for further work. Dr. Baldev Raj, Chairman of the Committee, welcomed the gathering. Quoting from the Discovery of India by Pandit Jawaharlal Nehru, "Apparently ancient India had made great progress in the working of Iron. Near Delhi, there towers a great iron pillar which baffles contemporary scientists. They cannot determine the method of manufacture which prevented the iron from oxidation and other atmospheric methods". He added that the time has come for us to provide the answer. He also stressed the need for the consensus among the scientists for explaining the origin, manufacturing technology and corrosion resistance of the pillar. Dr. P. Rodriguez, Vice President, INAE chaired the meeting very effectively. He explained the role of various committees of INAE Engineering Heritage, and mentioned that the meeting should focus on the manufacturing technology and corrosion resistance of the pillar. The findings should help the conservation of the Pillar. Prof. V.S. Ramamurthy, Secretary, Department of Science and Technology (DST), in his remarks, emphasized that the participants should come out with recommendations for future work on Delhi Iron Pillar. He added that studies should also be made on the Konark iron beams and the Dhar iron pillar and also other ancient iron objects of similar age available elsewhere in the country. He also suggested INAE to come out with a handbook containing details of available iron ores in the country in a chronological manner. Eminent personalities like Prof. T.R. Anantharaman, Prof. S. Ranganathan, Dr. K. Elayaperumal, Prof. U.K. Chatterjee, Prof. E.S. Dwarakadasa, Prof. Vibha Tripathy, Prof. S.K. Seshadri and Dr. M.K. Totlani, participated in the meeting to form a collective opinion, after a detailed review of the current research and theories. The meeting had comprehensive presentations from Prof. T.R. Anantharaman, Ashram Atmadeep, Delhi on 'The Wonder that is Delhi Iron Pillar', Shri R.K. Sharma, Archaeological Society of India, Delhi on 'Issues Related to Conservation of the Iron Pillar, Delhi', Prof. R. Balasubramaniam, IIT Kanpur on 'A Perspective on Delhi Iron Pillar', Shri B. Venkatraman, IGCAR, Kalpakkam on 'NDE Investigations on Delhi Iron Pillar', Dr. T. Jayakumar, IGCAR, Kalpakkam on 'Microstructures and Manufacturing Technology of Delhi Iron Pillar, and Dr. U. Kamachi Mudali, IGCAR, Kalpakkam on 'In-situ Corrosion Investigations on Delhi Iron Pillar'. Dr. S. Varadarajan, Former Director General, CSIR and Former President, INAE and INSA, actively participated in the discussions and provided valuable comments and excellent suggestions. Smt. Nina Ranjan, Secretary, Department of Culture (DOC) participated in the concluding session that led to formulation of recommendations for future work. The following is the summary of the recommendations identified in the meeting:

- 1. A nationally coordinated committee comprising of leading research groups from the country is to be formed for identifying research programme for future work in order to further scientific understanding and information on history, fabrication, corrosion resistance and conservation of Delhi Iron Pillar
- 2. Accelerator based mass spectrometry study should be pursued to determine the date of the pillar by scooping a small amount of sample from the Pillar. However, the amount of sample needed should be established in consultation with Institute of Physics, Bhubaneswar. Also, studies with other ancient iron objects should be pursued for establishing the methodology of dating prior to scooping out sample from the Delhi iron pillar for this purpose.
- 3. Samples from other ancient iron objects like Dhar Pillar, Kodachadri Pillar and Konarak Beams shall be made available by ASI, New Delhi
- 4. A meeting should be organized with the participation of historians to deliberate about the history of the pillar (i.e. the King who made the pillar, and the original location of the pillar.)
- 5. ASI will make available the 1961 Excavation Report of the pillar. The confidential report by NPL, New Delhi on the NDE aspects of the pillar should also be made available.

- 6. One more R&D campaign to fully exploit the possible NDE testing methodologies shall be permitted for focused experiments such as X-ray tomography and laser Raman spectroscopy. In-situ metallography for 3D mapping of a section of the Pillar could be attempted to see finer details over a larger area of the Pillar. IGCAR, in collaboration with IIT Kanpur would be coordinating the work. Theories about manufacturing (horizontal, vertical, or both) and evidences of joints in the pillar should be evaluated through experimental simulation studies.
- 7. The Committee recommended scooping out small samples (5mm long, 3 mm breadth and 2 mm deep) from various parts of the pillar for careful analysis of scale, interface and pillar composition and microstructure; studies on iron objects of similar age should be pursued prior to this effort. Presently, the small chip of approximately 2mm found incidentally near the Pillar during the NDE campaign is being investigated to find out whether it belongs to Delhi iron Pillar, and if so, it would be examined for surface, interface and base iron to get further insight into the corrosion resistance. Studies to be undertaken on the material could be planned by the Co-ordination Committee.
- 8. Since more than 50 years passed after the conservation of the underground region of the pillar, the committee strongly recommended that part of the pillar may be dug out and the bottom portion reexamined for documenting the bottom portion. Actions for reexamining and conserving the underground region will be formulated.
- 9. Various methodologies for conserving the underground region were discussed. There is a need to formulate all possible protection measures in consultation with experts.
- 10. Engineering Heritage – Metallurgy Committee will lead the nationally coordinated project in collaboration with Department of Culture, Department of Science and Technology and Archaeological Survey of India, and assign the projects to individual groups and monitor the progress for periodically reporting to the above agencies

The following are the responses from the Secretary, Department of Culture:

- 1961 Excavation Report of the pillar and the confidential report by NPL, New Delhi on the NDE aspects of the pillar, will be made available
- New conservation techniques and methodologies should be established on iron objects of ancient period prior to plan about the digging out the pillar for conservation of the underground region
- Ancient iron objects of similar age shall be made available from elsewhere of the country for future work
- Holistic view of the Sanskrit literature with the support of Indira Gandhi Centre for Arts, Delhi and Manuscripts Division of Department of Culture shall be made in order to decide the origin and King who made the pillar
- ASI should take lead to study the soil properties at the pillar site and evolve methods to alter the soil conditions to minimize corrosion of underground portion of the Pillar

- Exhaust all methods of NDE prior to requesting for scooping out samples from pillar for microstructure and composition analysis.
- Exhaust all noninvasive techniques for assessing the underground portion of the Pillar to decide on the necessity for digging and the buried portion for direct assessment.
- The recommendations by the scientific community in the present meeting are well appreciated and DOC will provide all support in their endeavour.
- DOC will support the publication of books and documents related to ancient metallurgy, and can help to republish and subsidise the books already published
- All books of ancient metallurgy could be brought out as series, and DOC will support INAE for publication and distribution in this regard.

The meeting ended with Dr. Baldev Raj, Chairman, Engineering Heritage – Metallurgy of INAE thanking all the members for participating in the meeting and also for their excellent and stimulating interactions. All the participants thanked INAE for making excellent arrangements and were also appreciative of INAE and Dr Baldev Raj for organizing this first of its kind meeting. It was proposed to make a CD containing all the presentations and send the same along with the list of participants and recommendations to Department of Science and Technology, Department of Culture, Archaeological Survey of India and INAE.

Organising Committee

Dr. Baldev Raj, Chairman, Indian Engineering Heritage – Metallurgy, INAE
Prof. T.R. Anantharaman, ASHRAM ATMADEEP, New Delhi
Dr. P. Rodriguez, IIT Madras
Prof. S. Ranganathan, IISc, Bangalore
Shri S.C. Marwaha, Deputy Executive Secretary, INAE
Dr. Rao Aiyagiri, DST, New Delhi
Dr. R.K. Sharma, ASI, New Delhi
Dr. R. Balasubramaniam, IIT Kanpur
Dr. U. Kamachi Mudali, IGCAR, Kalpakkam - Secretary

List of Participants

1. Prof. T.R. Anantharaman, New Delhi
2. Prof. S. Ranganathan, IISc, Bangalore
3. Prof. P. Ramachandra Rao, BHU, Varanasi
4. Dr. P. Rodriguez, Chennai
5. Prof. E.S. Dwarakadasa, Bangalore
6. Prof. B. Prakash, BHU, Varanasi
7. Prof. Vibha Tripathi, BHU, Varanasi
8. Prof. A.K. Biswas, Calcutta
9. Dr. K.Elayaperumal, Mumbai
10. Dr. M.K. Totlani, Mumbai
11. Prof. U.K. Chatterjee, IIT Kharagpur
12. Dr. Baldev Raj, IGCAR, Kalpakkam
13. Prof. S.K. Seshadri, IIT Madras
14. Dr. R.K. Sharma, NRLCCP, Lucknow
15. Dr. Rao Aiyagiri, DST, New Delhi
16. Dr. R. Balasubramaniam, IIT Kanpur
17. Dr. T. Jayakumar, IGCAR, Kalpakkam
18. Dr. B. Venkatraman, IGCAR, Kalpakkam
19. Dr. U. Kamachi Mudali, IGCAR, Kalpakkam

Discussion Meeting on "DELHI IRON PILLAR"
INSA, New Delhi
March 11, Friday, 2005

Technical Programme

9.00 h	Dr. Baldev Raj, Chairman Welcome and Opening Remarks
9.10 h	Presidential Address Dr. Placid Rodriguez, Vice President, INAE
9.20 h	Inaugural Address Dr. V.S. Ramamurthy, Secretary, DST, New Delhi
9.50 h	Keynote Address Smt. Nina Ranjan, Secretary, Department of Culture, New Delhi
10.05 h	Special Remarks Shri Babu Rajeev, Director General, ASI, New Delhi
10.15 h	Prof. T.R. Anantharaman, New Delhi The Wonder that is Delhi Iron Pillar
10.45 h	Dr. R.K. Sharma, ASI, New Delhi Issues Related to Conservation Problems of Iron Pillar, Delhi
11.15 h	Dr. R. Balasubramaniam, IIT, Kanpur A Perspective on Delhi Iron Pillar
12.00 h	Dr. B. Venkatraman, IGCAR, Kalpakkam Nondestructive Examination of Delhi Iron Pillar
12.45	End of Session
13.00 h	LUNCH
14.00 h	Dr. T. Jayakumar, IGCAR, Kalpakkam Microstructures and Manufacturing Technology of Delhi Iron Pillar
14.45 h	Dr. U. Kamachi Mudali, IGCAR, Kalpakkam Insitu Corrosion Investigations on Delhi Iron Pillar
15.30 h	Summary and Concluding Discussions (all participants)
17.30 h	Recommendations and Future Directions
18.00 h	Close of the Session

Indian National Science Academy, Bahadur Shah Zafar Marg, New Delhi - 110-002.
Phone Fax : 011- 3235648; 3231095 Web Site : http://www.insaindia.org

ISSUES RELATED TO CONSERVATION PROBLEMS OF IRON PILLAR, DELHI

R.K.Sharma
Archaeological Society of India
New Delhi

The iron pillar located in the courtyard of the Quawwat-ul-islam mosque, adjacent to the qutub minar is reported to have been built during the reign of Chandragupta II Vikramaditya (375-413) and moved to its current location in Delhi sometime in 11th or 12th cent. AD. This iron pillar for its exceptional resistance to atmospheric corrosion has attracted the attention of metallurgists and corrosion scientists as an object of unceasing interest and curiosity because of its remarkably well preserved condition.

Since 1912, many scientific investigations have been carried out to understand its corrosion resistance behavior for such a long time. The chemical analysis carried out in the earlier years have indicated that it is made of pure wrought iron of 99.72 containing a high proportion of phosphorous and little sulphur. Subsequent investigations carried out by researchers using electron probe examination reported the presence of Cu (0.03%), Ni (0.05%) and Mn (0.07%).

In the year 1961, the Iron Pillar was dug out to understand the state of the buried portion of the pillar as it was observed that the iron in the region where the stone platform meets to ground was in more severely corroded condition. This buried portion having a lead sheet was noticed to have been covered with thick rust and there was a suggestion to replace lead coating with zinc so that the pillar no longer serves as the sacrificial anode. However, this scientific advice could not be implemented at the time of execution. Besides, rust formation has also been noticed at the capital part of the pillar. In view of these observations, it will be prudent to correlate all the scientific investigations and work out a proposal for the long-term conservation measures. The main related issues that may be considered are:

1. How to protect the protective film (Oxide in the form Limonite or Geothite or Magnetite as well as amorphous Phosphate layer) which is considered to be a passivating surface film on this structure. Are they permanent or feared to be damaged?
2. It is established that encapsulation or iron crystals with slag as well as its intermixing with iron is responsible for the corrosion resistance of iron pillar and that any break on surface may be dangerous. If so, does the pillar require any treatment so that breaks may be sealed to stop entry of water, oxygen etc?
3. It is reported that heat treatment using steam was given intentionally to develop oxide layer that acts as a protective cover. If this layer has been damaged, does the same treatment will help in any way to improve the protective action of the oxide film?
4. What type of materials were used to burnish the surface of Iron Pillar?
5. Does capital of the pillar requires any special treatment as it was not manufactured by the process of forging but was casted ?
6. If lead sheet is a requirement as a shield then does it need replacement by zinc or any other suitable metal in order to retard electrochemical corrosion of underground part of the pillar?

Some of the issues mentioned above may have to be considered through simulated laboratory studies.

A PERSPECTIVE ON THE DELHI IRON PILLAR

R. Balasubramaniam (bala@iitk.ac.in)
Department of Materials and Metallurgical Engineering
Indian Institute of Technology, Kanpur 208 016.

The Delhi Iron Pillar has attracted the attention of metallurgists and corrosion scientists for its excellent resistance to corrosion [1]. It is indeed a glowing symbol of Indian metallurgical heritage. The talk will summarize the studies conducted on the Delhi iron pillar based on the researches of the author. The presentation will be provided in chronological order of publications that have appeared on the Delhi Iron Pillar. The talk will first introduce and summarize the earlier work done on the Delhi Iron Pillar. The Delhi Iron Pillar has been one of subjects of research of the author since 1993. After a careful analysis of the existing literature, the corrosion of the pillar was first addressed based on the mixed potential theory [2,3]. The salient feature of the work was to provide theoretical framework for the possible polarization nature of the iron of the Delhi pillar. The dimensions of the pillar were critically analyzed next. The relationship of the burial depth and decorative bell capital height to the overall pillar dimensions was set forth [4]. At the same time, the corrosion of the pillar in the buried underground region was also addressed [4]. The decorative bell capital of the pillar was described in detail in 1998, with detailed descriptions of the various components that make up the capital and the critical discussion on the possible fitting methodology of the capital to the pillar mail body [5]. The presence of lead at several locations has been analyzed [6,7]. Special attention was focused on the lead coating in the buried underground region and the deleterious nature of the lead coating to the pillar in the buried underground region was experimentally verified [7]. The use of lead-based solders in manufacturing the bell capital was confirmed [7].

The manufacturing methodology of the main body of the iron pillar by forge welding methodology was elucidated in 1999, by critically analyzing various aspects of forge welding technology. Based on a careful and detailed observation of the condition of the surface of the pillar, it was proposed that the pillar was manufactured by sideway addition of iron pancakes with the pillar lying in the horizontal direction [8].

Rust samples obtained from the topmost region of the iron pillar body, just below the decorative capital was analyzed by X-ray diffraction [9], Fourier transform infrared spectroscopy [10] and Mössbauer spectroscopy [11] and the nature of the rust was characterized [12]. Based on the rust analysis and observations of earlier researchers on the pillar, a possible scheme for the excellent corrosion resistance of the Delhi Iron Pillar by the formation of a protective passive film was proposed [13]. The qualities of the protective passive film were also explained [14].

The identity of *Chandra* and *Vishnupadagiri* (which appear in the oldest Sanskrit inscription on the Pillar) was addressed [15]. It was shown that *Chandra* could be unambiguously identified based on a detailed analysis of the archer type gold coins of the Imperial Guptas. Further, Udayagiri in Central India was identified as *Vishnupadagiri* based on geographical, historical and archaeological evidences. The status of the research was reviewed in 2001 [16] and the presence of special marks on the capital region was described. During the summer of 2001, a book was written summarizing all the features of the research conducted on the Delhi Iron Pillar and this appeared in print in early 2002 [17]. The historical aspects of the pillar were explored in great depth in this publication and the movement of the pillar from the original location to its current location in the Quwwat-ul-Islam mosque by Iltutmish was described [17].

The kinetic scheme for the protective passive film formation on the Pillar was first presented as a keynote lecture at an international workshop [18] and explained in detail in a research communication [19]. The relevance of the Delhi Iron Pillar to modern technology was indicated in 2003 based on ideas obtained from studies on the pillar [20]. The effect of material inhomogeneity on the protective passive film formation was addressed by providing a detailed description of earlier work on etching studies on the pillar iron [21]. The available microstructures of the Delhi pillar iron were also critically analyzed [21]. The development of electrochemical potentials on the Delhi iron pillar was also hypothesized in 2003 [22] and the hypothesis tested with a Gupta-period iron. The influence of forge welding on the corrosion resistance of the pillar was also elucidated with special reference to surface compressive stresses, nature of distribution of entrapped slag particles and the arrangement of lump-lump interfaces [23,24]. The role of the environmental conditions on the corrosion resistance was addressed in 2004 [25]. The total wetting time due to rainfall and moisture condensation was evaluated and the thickness of surface rust for these conditions evaluated. It was concluded that the environment was only a contributory factor in the pillar's corrosion resistance [25].

The original erection site of the Delhi Iron Pillar at Udayagiri was addressed [26] in association with Dr. Meera I. Dass, whose doctoral thesis was on the Udayagiri archaeological site. The original image that was atop the pillar (i.e. *chakra)* was deduced based on archaeological evidence and art historical analysis [27]. The identification of the capital of the stone pillar that was on the top of Udayagiri was relevant. Professor Ellen M. Raven of the Kern Indological Institute at Netherlands assisted in the art historical analysis. Some astronomical functions of the Delhi Iron Pillar at its original erection site at Udayagiri have been described [28]. Udayagiri is situated on the Tropic of Cancer and it was a location for astronomical observations even in the period prior to the Guptas. The direction of shadow of the pillar due to early morning sun during summer solstice was shown to be significant [28]. The status of the work of the author has been recently presented in a review article [29,30].

The presentation will conclude by providing some thoughts for possible future work on the Delhi Iron Pillar. The lead coating in the buried underground region has to be addressed. Material characterization issues need to be also undertaken. Excavations at Udayagiri will help throw further insights on the original erection site of the pillar. This calls for a concentrated collaborative effort between archaeologists, technologists and scientists.

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NON-DESTRUCTIVE EXAMINATION OF DELHI IRON PILLAR

B.Venkatraman and Baldev Raj
Indira Gandhi Centre for Atomic Research
Kalpakkam – 603 102

As part of the Department of Science and Technology (DST) project on Investigations on Delhi Iron Pillar, a comprehensive study on the Iron Pillar using Non-Destructive Test Techniques was undertaken by the Indira Gandhi Centre for Atomic Research, Kalpakkam during the period 1999 - 2002. The NDE techniques chosen for investigations include ultrasonics, impact echo, radiography, radiation gaging, in-situ metallography and electrochemical analysis. Of these, impact echo, radiography and radiation gaging are techniques which have not been attempted by any of the earlier investigators. This talk focuses on three NDE methods low frequency ultrasound, impact echo and radiography used for the investigations on the iron pillar.

Low frequency ultrasonic velocity measurements were made using low frequency transducers (250 kHz) in through transmission mode at various cross sections and elevations on the Pillar. The ultrasonic velocities measured in the cylindrical region were almost similar in the radial direction at all the elevations, indicating the similar structure of the pillar.

Impact echo testing was carried out in grids of 250 mm height and 45º sectors, covering the whole cylindrical portion (except the bottom rough portion) of the pillar and the decorated portion (flower) on top of the pillar. Testing was also carried out at 50 mm intervals in the vertical direction at two locations, 90º apart at each elevation. Impact echo testing also revealed uniform ultrasonic velocity in the cylindrical portion in all the radial directions. The decorative portion however exhibited a high velocity compared to that in the cylindrical portion, which was attributed to the presence of acicular slag.

In both low frequency ultrasound and impact echo techniques, additional peaks were noticed in different sections and at different depths which was attributed to the presence of the random voids.

Radiography revealed the presence of voids in the top cylindrical region. Radiography carried out on the same area in two perpendicular orientations revealed voids typically 200 mm in length with a narrow width of a few mm. The second orientation indicated the same voids but the images were diffused indicating a very small thickness in the direction of the X-ray beam. The nature and shape of the void suggest that the pillar was forged radially and the defects formed during the forging process got elongated in axial direction. Radiography also confirmed the presence of voids in the locations where additional peaks were both by low frequency and impact echo techniques.

A total of 3 campaigns were undertaken during the period 1999-2002. In this talk we outline the procedures developed and the challenges faced during the NDE investigations. The results of the present investigations and the possible future investigations including application of newer techniques such as tomography and Raman Spectroscopy will also be presented.

MICROSTRUCTURES AND FABRICATION METHODOLOGY OF THE DELHI IRON PILLAR

T. Jayakumar and Baldev Raj
Indira Gandhi Centre for Atomic Research
Kalpakkam – 603 102

The microstructures obtained through in-situ metallography studies on Delhi iron pillar is discussed after presenting a brief review of the earlier investigations on chemical composition and microstructure of the Iron Pillar. A possible mode of fabrication of the pillar is also proposed after analyzing the earlier proposed modes of fabrication, in view of the non-destructive evaluation results obtained on the pillar.

The in-situ metallography studies on Delhi Iron Pillar indicated that, at all the locations in the smooth portion of the main pillar, microstructure consists of ferrite grain with intragranular elongated precipitates and a few globular precipitates. These elongated precipitates are found to have a specific orientation relationship with the matrix. The recent in-depth analysis of the orientation relationship of these precipitates with the matrix, by comparing the orientation relationship of the precipitates observed in Adivasi steel and cementite in ferritic stainless steel, revealed that these elongated precipitates should be carbide (cementite) and the globular precipitates should be phosphides. Further, the microstructure in the top square platform is similar to 'as-cast' and 'over-heated' structures. If it is indeed as-cast, this part would have been added at a later period or local melting due to lightening strike is another possibility. However, we may tend to believe more that this is also a wrought structure in overheated condition, as reported by the earlier investigators. The studies carried out by us so far, also revealed that in the smooth region of the Pillar, the ferrite grains are not covered with slag and the surface of the pillar appears to be free from any large size slag entrapment, at least in the regions where in-situ metallography has been carried out. Further detailed studies are planned to confirm this.

Two methodologies have been proposed earlier for the fabrication of Delhi Iron Pillar, i.e. horizontal and vertical forging. The NDE results obtained on the Iron Pillar could not be correlated completely with either of these fabrication methodologies. A plausible new methodology has been proposed that involves a combination of axial and radial forging, but building the Pillar in the vertical direction. This mode of fabrication explains the NDE results and horizontal weld lines seen on the surface of the pillar.

INSITU CORROSION INVESTIGATIONS ON DELHI IRON PILLAR

U. Kamachi Mudali and Baldev Raj
Indira Gandhi Centre for Atomic Research
Kalpakkam – 603 102.

Insitu electrochemical investigations were conducted for two different campaigns with the iron pillar for studying the corrosion behaviour with respect to electrochemical potential and polarization measurements. Attaching a specially devised electrochemical cell on the iron pillar electrochemical experiments were carried out, and the solution employed was distilled water added with traces of sodium sulphate (0.001 M). Experiments were conducted at six different locations over rust layers, and five different locations over as-polished surfaces, from the bottom of the pillar to the crown of the decorated bell top.

The corrosion behaviour of the as-polished locations varied depending on the location of the measurement; for example, the crown of the decorated bell top showed the most noble potential while the polished location at 4.88 m from bottom showed the least corrosion resistance. Corresponding with this, the polished specimens also exhibited polarization behaviour. The surface appearance of the tested regions showed differences in the pattern of corrosion attack for each region.

The corrosion behaviour of the rust layers varied depending on the nature of the rust; the rust developed after 10 months and 25 months showed improved performance with time while the thick rust layers of green and brown in appearance exhibited true passive behaviour. The rust layer developed over 4.88 m and over the crown surface also exhibited noble behaviour with a wide passive region. The rust collected at different regions of the pillar showed mainly the presence of various oxides of iron, and Laser Raman Spectroscopic study revealed similar findings of the rust from the pillar.

The corrosion resistance of the pillar has been a subject of discussion for many years. There are several theories postulated based on both hypotheses, and experiments conducted with iron objects presumed to be of similar age of the pillar. The present study, with insitu experiments conducted on the pillar, revealed that several locations of the pillar corroded actively after the corrosion potential during polarization irrespective of the surface microstructure, except for a minor variation in their corrosion rates. The appearance of the post corroded surface showed, however, significant variations in their appearance. It should be mentioned here that the present day pure iron (Armco Iron) exhibited better corrosion resistance under simulated testing in laboratory.

The striking evidence obtained in the present work is the significant passive behaviour of the oxide scale developed over the surface which is also similar to the 'rust' scale developed on pure iron exposed for long period to atmosphere. However, depending on the locations and the nature of the rust the 'passiveness' of the scale varied. An interesting observation was the not so 'passive' behaviour of the scale developed within short period, say up to two years. This indicated that the scale developed after prolonged exposure to atmosphere exhibited better corrosion resistance.

The initial corrosion of the Pillar is similar to any pure iron object exposed to atmosphere. The forge hammering of the pillar would have helped in the redistribution of the slag/oxide scale formed during hot forging, creation of heavily distributed active anodic sites under heavy deformation, and depletion of carbon at the surface, all of which resulting in the uniform corrosion of the surface to produce a thin scale of high integrity during the initial stages. However, over the long period of alternate wet and dry cycles of atmospheric exposure below 70% relative humidity 'ageing' of the scale results in the formation of stable and noble scale on the surface resulting in excellent corrosion resistance. The minor alloying elements, like P, Cu, Si and Ni help in transforming the initially formed thin oxide film containing γ-FeOOH into finely distributed α-FeOOH oxides at the interface of iron and Fe_3O_4 at the outer surface. The purity of the iron with low S and Mn helps in avoiding the formation of deleterious MnS inclusions that would give site for the pitting attack to take place. Thus, one can attribute the excellent corrosion resistance of the Pillar to the formation of a protective scale with an interface of α-FeOOH providing resistance for further corrosion, the presence of minor alloying elements like P, Cu, Si, Ni, and the purity of the iron with low S and Mn content.