# Study The Causes of Failure of Furnace Wall Tube In Thermal Power Plant (Part I)

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### *Abstract*

The failure of furnace wall tubes, boiler 6 –Najibia power station on March 2005 leading to plant shutdown was investigated. The present work deals with the experimental investigation to recognize the causes of failure. These included:1-Determination of scale density and its compositional analysis, 2-Spectrometric analysis of tube alloy material, 3-Mechanical testing of tubes material and 4-Examination of microstructure of the alloy.The results indicated that the recorded internal scale density ~ 45 $mg/cm^2$ may interfere with the heat transfer process leading to overheating. The loss of some alloying elements due to excessive heating reduces the strength of the alloy. An increase of hardness was detected to (720-800 HV) at the failed side which reflects the effect of metal hardening. Furthermore,the microstructural examination indicated the phase transformation of the pearlite to the martensite which confirmed the hardening effect leading to tube brittleness then rupture thereafter.The probable causes of tube failure were discussed.


# دراسة أسـباب فشـل انابيب جدار الفرن للمرجل في محطة الكهرباء الحرارية

**يوسف عبد الزهرة و نوال جاسم المدير و عبد الرزاق محمد حسين و عماد عبيد باجي**


### *الخلاصة*

اجريت دراسة اسباب فشل انابيب جدار الفرن للمرجل 6 – محطة كهرباء النجيبية التي حدثت في آذار 2004 .تضمن العمل البحثي اجراء الفحوصات العملية للتعرف على الاسباب التي ادت الى الفشـل ,اذ شملت : 1- تعيين كثافة القشرة الداخلية وتحليل مكوناتها 2- التحليل الطيفي لسبيكة الانابيب 3- الفحوصات الميكانيكية لمعدن الانبوب 4- اختبارات البنية التركيبية للمعدن .اشارت النتائج الى ان مقدار القشرة الداخلية 45 ملغم/سم$^2$ يؤثر في عملية النقل الحراري مسببا" التسخين المفرط. ان فقدان بعـض

العناصر السبائكية بسبب التراكم الحراري يختزل مقاومة السبيكة.وجد ان زيادة ملحوظة فـي صـلادة الجانب الساخن للانبوب المواجه للشعلة من ( 150- 185 ) الى (720- 800 فيكرز) الذي يدل على حدوث تصليد للمعدن .كما اشارت اختبارات البنية التركيبية الى حـدوث التحـول الطـوري للفـولاذ البيرلايتي الى المارتنسايت والذي يؤكد حدوث التصليد الذي ادى الى هشاشية الانبوب ثم التشقق. تمت مناقشة الاسباب المحتملة لحدوث الفشل.

## *Introduction*

The reoccurrence of tube rupture in the furnace wall tubes in high pressure boiler 6 (127 kg/cm$^2$,540 $^0$C) – Najibiya power station –Basra-Iraq led to frequent shutdowns.In general ,tube failure can occurr from improper operation including improper maintenance ( Ford ,2004).

It is possible for boiler tube to fail for a variety of reasons such as thermal stresses, structural changes in metal or alloy, distortion, thermal expansion effect (creep) and /or thermal fatigue .Poor chemical treatment and quality control introduce some complexity and interferences in tubes failure ( Raman & Petkovic ,1981) and (Zarrabi, 1997).

The factors that promoted tubes failure are : the presence of scale and deposits on the internal or external surfaces .Their effect on heat transfer surfaces had been comprehensively reported by several investigators (Charles, 2001),(Dewitt et al, 2002) and (Ford, 2004) .

The performance of burning system , atomization process, flame characteristics, physical and chemical properties of fuel, injection pressure ,flow rates of liquid or gas fuel were found markedly affecting the operating conditions and discussed by many authors ( Raman & Petkovic ,1981) and (Rupe ,1983).

The deviations and fluctuations of the thermal cycle of the boiler plant- firing system (especially the air heaters ) may create metallurgical changes in the tubes alloy material. These changes, if occur, usually associated with alteration in the mechanical properties of the alloy (Corr. Prog. Man.1989).

The present work is a case study which is aimed to identify the causes of furnace wall tubes failure and to have an approach to the problem of stress rupture through: local observation, scale density determination & its chemical composition, compositional analysis of tube alloy , testing the mechanical properties and metallurgical examination of the alloy.

## *Experimental*

**Local observation**

General Inspection of the furnace wall tubes boiler 6 –Najibiya power station during March ,2005 showed that tube rupture was concentrated on the left side of the furnace i.e. the salt section of the boiler drum. Twelve tubes were found ruptured. The failed tubes observed in the side A of the salt section No.( 12-15) and (19- 26) located at the furnace front wall were labeled and cut for partial replacement .

A sample of the failed tubes showed buldging with a fracture of 3-4 cm length and a wide opening of 2 cm length, thick- edged , with numerous cracks . Slight swelling in the region adjacent to the tube rupture of about ($\Theta$=30°).The macroscopic direction of the fracture is normal to the tube surface and parallel to the tube axis .The tube internal surface was covered with a layer of scale and deposit 1-2 mm thickness. Mechanical scrubbing showed a roughened surface under laminated scale layer. Intensive pitting corrosion were observed under the scale layer .The appearance and the nature of the rupture are probably similar to the over heat rupture resulting from excessive thermal effects. This has necessitated a metallurgical justification.

**Sample preparation**: Tube samples were obtained from the failed regions 10 cm length,5 cm diameter and 4 mm thickness .The samples were sectioned axially into two longitudinal parts to produce a coupon representing the hot and cold sides of the tube.The hot side is the surface facing the flame and the cold is the opposite side. Then the tube samples were subjected to the following investigations.

**1- Scale density determination**

a. Mechanical method: the amount of scale and deposits adhered to the internal surface area of tube samples were determined by weighing method according to ASTM (Annual Book 1990).The amount of the collected scale per unit area estimated in $mg/cm^2$ is presented in **Table 1**. However, this method was considered as approximate since there has been some of the unremovable scale remained adhered to the metal substrate. Hence, the chemical method has necessarily to be adapted.

**b.** Chemical method: the tube samples were conditioned and treated by chemical cleaning solution (5% inhibited HCl) according to the standard method given by ASTM (Annual Book 1990). The samples weighed prior to and after subsequent cleaning .The amount of scale per unit area in $mg/cm^2$ was determined and also listed in **Table 1.**

**c.**

**Table1-Scale density determination on internal surface of tubes-boiler 6**

| Method | Mechanical method | | | Chemical method | | |
|---|---|---|---|---|---|---|
| **Sample No.** | **1** | **2** | **3** | **1** | **2** | **3** |
| **Scale density $mg/cm^2$** | 21 | 24 | 28 | 45 | 44 | 48 |
| **Average layer thickness mm** | 1 | 1.5 | 1.5 | 2 | 2 | 2.2 |

**2-Spectrometric analysis of scale and deposits**

Quantitative analytical methods were followed using U.V.visible spectrometer (U.V.160A,Shimadzu,Japan), the composition of scale and deposits present on the tube interiors are shown in **Table 2.**

**Table2-Compositional analysis(%w/w)of tube internal scale–boiler 6.**

| Scale thickness* mm | Silica as $SiO_2$ | Iron oxide as $Fe_2O_3$ | Calcium as CaO | Magnesium as MgO | $PO_4$ |
|---|---|---|---|---|---|
| 1.2 | 2.53 | 51.05 | 15.32 | 30.48 | 0.62 |
| 2.1 | 2.84 | 50.56 | 18.82 | 27.33 | 0.45 |

*****the results represent the average of three samples.

**3- Spectrometric analysis of tube alloy material**

A specimen of tube alloy sample was subjected to spectrometric analysis using spectrometer IRL 34000, Swiss.The results are presented on **Table3**compared to the new tube specifications (Tech. Pr. Ex.2004).

**Table 3-Compositional analysis(%w/w)of the failed tube alloy–boiler 6.**

| Fe | C | Mn | Si | P | S | Cr | Ni | Cu |
|---|---|---|---|---|---|---|---|---|
| **Balance(1)** | 0.26 | 0.60 | 0.38 | 0.018 | 0.025 | 0.22 | 0.23 | 0.24 |
| **Balance(2)** | 0.18 | 0.45 | - | - | 0.016 | <0.01 | 0.0 | <0.05 |

(1) composition of new tube sample.

(2) composition of failed tube sample.

**4- Mechanical testing of tube alloy**

The hardness test was adapted to evaluate the hardness of the failed and intact regions of tube alloy by using Vickers hardness (HV)tester ,as the change of hardness is associated with the structural deformation of tube alloy .The results of testing are shown in **Table 4**.

**Table 4- Hardness testing results of the failed tube- boiler 6.**

| Specimen No. | Location Tube No. | Hardness HV | | |
|---|---|---|---|---|
| | | Hot side | Cold side | Intact Tube |
| 1 | 12 | 720 | 136 | 150 |
| 2 | 14 | 750 | 138 | 175 |
| 3 | 20 | 785 | 141 | 180 |
| 4 | 22 | 760 | 145 | 170 |
| 5 | 24 | 794 | 147 | 185 |
| 6 | 25 | 800 | 138 | 165 |

It can be noticed that the hot side showed a remarkable increase of the hardness from a range of 150- 185 HV for the intact tube to 720- 800 HV for the failed region , whereas the cold side exhibited 136 -147 HV. Thus, the hot sides experience unexpected hardening effect possibly because of the drastic thermal changes induced during abnormal operational cycle.

**5-Metallographic Examination**

The microstructure of the tube alloy was examined according to ASTM (Annual Book 1990) by means of an optical microscope (Olympus,Japan) which is provided with a microprocessor (Pentium 3) , photographic system and printer to assign the different features of the failed tubes .The deformed microstructure can be identified so that an approach to the actual causes would be then possible .The observed metallographic features of the hot and cold sides of the ruptured regions compared to the intact ones are shown in **Plates 1-4.**

## *Results And Discussion*

***Scale density determination:*** By referring to the results listed on **Table1**, the amount and thickness of the scale of about 45 gm/cm$^2$ & 1.2-2.1 mm present on the internal surface were considered to be unacceptable according to the USSR-STD specifications (Tech. Pr. Ex.,1978-2004).In addition, the internal scale consisted of laminated layers of ~0.5 mm each within the overall thickness of (2.2 mm) which were beyond the allowable scale thickness (0.15-0.2 mm).The presence of scale and deposits would interfere with the heat transfer process and would lead to overheating (Reid and Merrigan ,1995).

Moreover, structural deformation of tube alloy material was expected when high scale density 90-110 mg/cm$^2$ was obtained. Hence, chemical cleaning of boiler tubes may be required as the boiler operated under reduced load (Dewitt 2002) and (Sheikh,2003) .

***Scale compositional analysis:*** The analysis results **(Table2)** indicated that the laminated scale consisted mainly of (51%) $Fe_2O_3$ (hematite) and 47% of total hardness (TH) salts of Ca & Mg . The hematite should be present in a form of magnetite to about 99% . The TH value should be zero.The source of TH in feed water was derived from the accidental huge condenser tube leakage caused by a piece of cracked turbine blade (occurred in March 2004). However, phosphate treatment for boiler water was considered as trap for hardness salts and and have to be used continuosly (Columbus1998) (Charles,2001).

***Corrosion under scale:*** The presence of scale layer on tube internal surface hidden crevice corrosion underneath **(Plate1)**. These crevices are concentrated on the cold sides more than that on the hot sides. This could be related to the thinner scale layer of the cold side compared to that of the hot side . Such layer may permit diffusion of the aggressive ions from boiler water to the metal surface which resulted in crevice corrosion (Ateya et al,2000). Moreover, some of the crevices merged together and aligned themselves at the crack root. These crevices act as stress-raisers and serve as crack initiators.

***Tube alloy material:***A significant reduction of some constituents were found in the failed region **(Table 3)**, the loss of alloying elements such as C, Ni ,Cr can be attributed to the oxidation during burning process. The departure of alloying elements from the alloy matrix leads to deterioration of mechanical properties of the alloy steel ( Al-Mudeer et al , 1999 & 2003).

***Metallurgical Examination:*** Undoubtedly, there is a remarkable correlation between the mechanical properties and the alloy composition in terms the allotropic forms (Raman and Petkovic 1981).It was found that the hardness increased in the buldged-ruptured region of the fire side (hot) of the tube wall to higher values of 720-800 HV compared to the hardness values of 136-147 HV observed in the opposite side (cold region). The hardness of the intact tube was in the range of 150-185 HV **(see Table 4).** For instance , the new tube showed normal hardness values of 150- 230 HV with the normal structure of pearlitic steel **(Plate 2).**

In the meanwhile, the the cold-side of the failed region showed no significant alteration of hardness and with normal structure of the pearlitic steel **(Plate 3).** The microstructural examination of the failed region at the buldged area revealed a phase transformation of the pearlitic steel to the martensite i.e. the hardest phase of steel **(Plate 4).** These observations were found in good agreement with the actual values of the hardness of martensite that was reported within the range of 680- 820 HV (Pollack ,1981).

The causes of tube failure on the basis of the present findings and observations is differ from that observed in previous reportation (Al-Mudeer et al , 1999 & 2003). Usually the plastic deformation of the buldged regions associated with loss of hardness and increase of ductility i.e.creep rupture. But , in the present case the buldged region showed a remarkable increase of the hardness of the tube hot-side.

However ,the plastic deformation obviously resulted from excessive firing to a higher temperature than tolerated values . While the metal hardening possibly resulted from rapid cooling rates of the overheated tubes from (50°C above the critical hypoeutectiod temperature,723°C) to about 200°C within a very short time interval which favored the formation of the martensite (Askeland 2003).

Practically, flame impingement on tube metal due to asymmetrical flame distribution observed at the furnace wall tube definitely would be the main cause of overheating.

While rapid cooling rates might be due to : a)sudden replenishment of the boiler water by relatively cold make-up water during leakage from a failed tube and/or b)sudden exposure of the overheated tubes to a water splash produced from a leakage of one of the failed tubes. However, all findings revealed that tube rupture is a complex case of plastic deformation (buldging) arose from overheating followed by quenching or sudden cooling leading to the hardest phase transformation i.e. to the martensite. The net result that the metal would not be able to withstand the nominal operating pressure leading to"brittle fracture".

## Conclusion

The results of investigation clearly demonstrated that the causes of tube failure throughout the followings:

1-The presence of scale density of about 45 $mg/cm^2$ in tube interior interfere with the heat transfer process and accelerate the corrosion under deposit or "crevice corrosion".

2-Plastic deformation( buldging)of tube alloy was proceeded under the effect of overheating imposed by improper burning process.

3-Metal hardening (increase of hardness) associated with a phase transformation of the pearlitic steel to martensitic in the hot sides indicated the great risk of rapid cooling rates of the overheated alloy .

## Recommendations

The following recommendations should be fulfilled according to the standard operation instruction given by the instructor:

1-Avoid scale formation inside furnace wall tubes by elimination of condensers leakage and other contamination sources.

2-Treatment by trisodium phosphate solution continuously to prevent scale formation in tubes interiors.

3-Control and monitor the combustion process including air heaters, burners and other auxiliaries.

4-Avoid flame impingement at the furnace wall tube to overcome the problem of overheating.

5-Avoid rapid cooling rates during plant operation and shutdowns.

6-Chemical cleaning of the boiler is necessary in the next maintenance.

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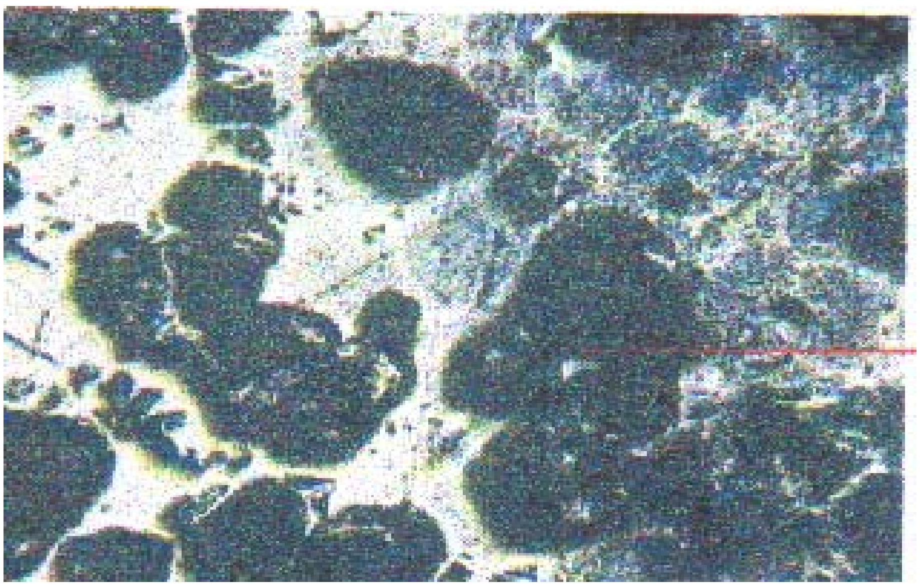

**Plate 1** -Surface feature of the failed tube ( steel 20 )boiler 6 as received–before cleaning ,showing the deposition,200x .

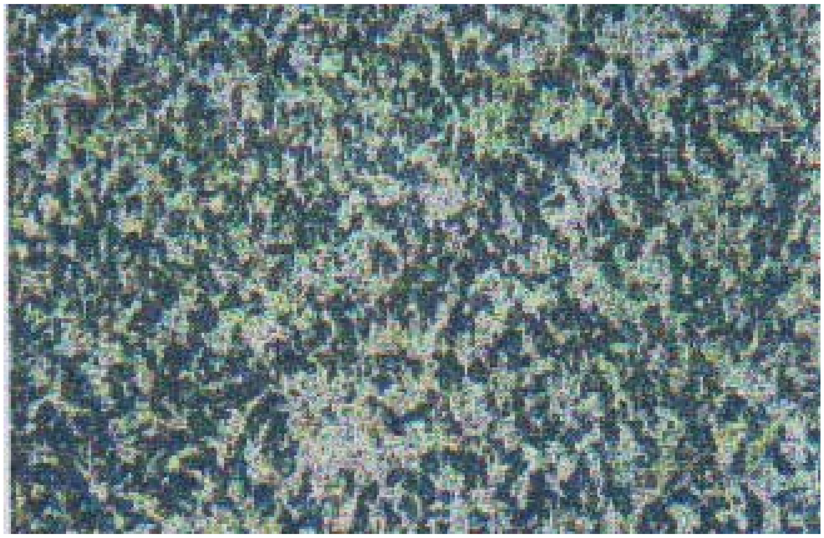

**Plate 2**- Normal microstructure of the intact new tube ( Steel 20), boiler 6 showing the two phases of ferrite and pearlite ( HV 175 ), etched by nital,200x .

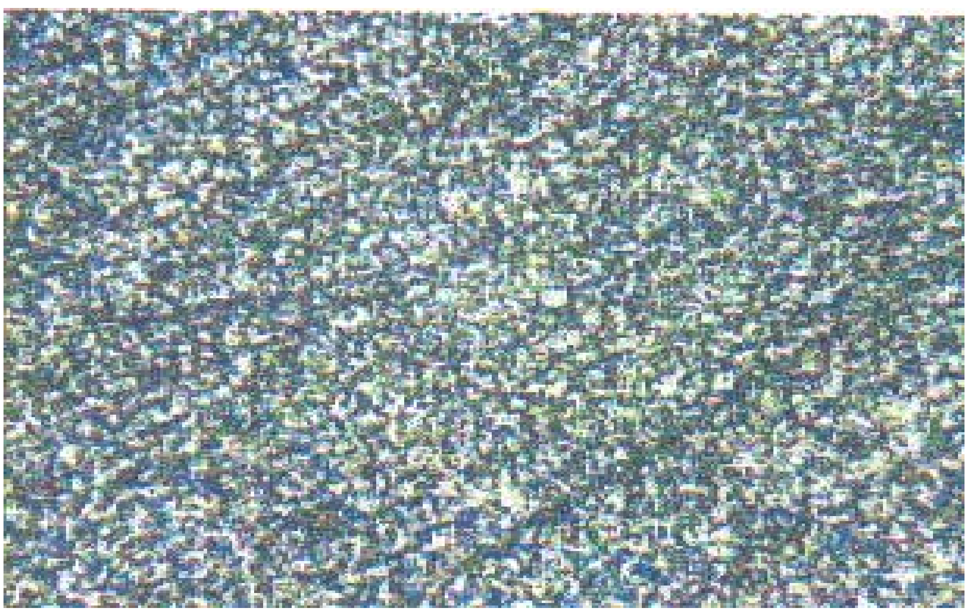

**Plate 3**- Microstructure of the failed tube ( steel 20 ) boiler 6 hot-side showing phase transformation to martensite ( HV 720 ), etched by nital , 200x .

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