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A case study of high temperature reheater boiler tube failure

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Several investigations on the failure of boiler tubes of thermal power plant have been carried out. This paper presents the failure analysis of a reheater tube of 210 MW thermal power plant. The reheater tube got damaged after service exposure a life of 1,65,900 hrs. The failed tube has a slit type opening with minor circumferential expansion at the rupture section. Scale was observed on the inside and outside surface of the tube. The scale formed on the outside and in-side surface of the tube was analysed through EDX and XRD to know the constituents of the scale and in evaluating the cause of failure of the tube. The tube was observed through its cross-sectional for the wall thinning. The area around the failed reheater tube sample was prepared and studied for structural degradation; hardness mapping was also carried out on the tube to find the cause of failure.

Keywords: *Reheater Boiler tube, Hardness, Oxide scale layer, Wall thinning, Microstructure, EDX & XRD, 1.0*

1.0 INTRODUCTION

In the boiler of thermal power plant, water is converted into superheated steam at high pressure through heat energy and subsequently this superheated steam is used to run the turbine for electricity generation. The fuel such as fossil fuel like coal, oil or natural gas with preheated air is burnt in the furnace of the boiler. The combustion of fuel generates heat energy which flow up through the furnace and converts water into steam inside the tubes. The hot gases generated through combustion reach the roof of the furnace and this gas is forced to pass through horizontal bank of superheater and reheater tubes.

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It is evident that water is heated through heat transfer between flue gas and tube wall surface. During the process of heat transfer from flue gas, there is interaction with tube wall on the outside surface of the tube wall [1,2]. The flue gas with particulate matter (fly ash) attack on the outer side of the tube wall surface, along with formation of salt deposits like oxide of Na, K, Ca, Ti & Mg etc., [3,4]. Due to this, the outer side the tube surface gest corroded as revealed by the wall thinning of tube, while on the inner side,

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steam side reaction occurs between superheated steam and tube material, which are further accelerated by high temperature and pressure. Due to this reaction between steam and metal surface, there is a tendency of salt deposition on the inner surface of the tube also. This salt deposition is known as the formation of scale. Due to the formation of inside scale the heat transfer decreases from fire side to steam side, leading to an increase in the temperature of tube wall. Hence there is a large influence on the life of the tube component due to overheating. This overheating accelerates the damage mechanism and reduces the material life of boiler tube [5-9]. The oxide layer formed on the internal surface of low alloy steel tube exposed to the steam consists of a layer of different phases depending on the metal temperature, if metal temperature is below 560^0 C, the oxide layer consisting of magnetite (Fe_3O_4) and hematite (Fe_2O_3) is found. At higher temperature an additional layer of wustetite (FeO) may form [10-11]. The reaction below the temperature of 560^0 C is as follows:

$$Fe(s) + ½\ O_2(g) = FeO(s)$$

$$3\ FeO(s) + ½\ O_2(g) = Fe_3O_4(s)$$

$$2Fe_3O_4(s) +½\ O_2(g = 3Fe_2O_3(s)$$

While at temperature above 560^0 C an additional layer of wustite (FeO) may be formed by internal reaction between Fe_3O_4 and Fe.

$$Fe_3O_4(s) + Fe(s)\ \text{----}\ FeO(s)$$

FeO is formed due to destabilization of Fe_3O_4 at higher temperature.

2.0 OPERATIONAL HISTORY

A failure was reported in reheater tube of 210 MW thermal power station after serving a period of 1,65,900 hrs. At the time of failure, the reported parameter like temperature was 540^0C and pressure was 35- 40 $Kg/cm^2$and the grade of the material was SA213 T22.

3.0 VISUAL INSPECTION

Visual examination was carried out on the as received failed reheater tube which revealed the following:

i. The failed tube showed slit type opening with thick lip ductile edge.

ii. Minor swelling was observed around the failed section of the tube.

iii. Oxide scale deposition was observed (a) Inside the tube i.e., steam side of tube (b) Outside the tube, i.e., fire side of the tube

iv. Erosion of the tube was also observed.

v. Thinning of metal tube wall along the cross-section was observed.

4.0 DIMENSIONAL MEASUREMENT AND MATERIAL COMPOSITION

At different location, thickness of the failed tube was measured with DM 4DL Krautkramer™. This data revealed that there is wall thinning along the transverse direction of failed region. The reduction in thickness was observed in the range of 20 to 45%. The outer diameter was measured with Calliper (Mitutoyo™ make –Japan), and it showed that there was minor swelling along the ruptured section.

The tube was analysed for chemical composition through Spectromax™, Model- Jr CCD (Make-Germany), and the chemical composition of the tube analysed is as follow given in Table-I

TABLE 1

CHEMICAL COMPOSITION OF FAILED TUBE MATERIAL

Element	Wt (%)
C	0.13
Si	0.23
Mn	0.40
Cr	2.10
Mo	0.96
S	0.015
P	0.018

The material of tube shows the grade of T22 steel.

5.0 HARDNESS MEASUREMENT

Hardness measurement was carried out at different location of the reheater tube as shown in Figure 1 by using portable Hardness tester (Equotip2™ make- Switzerland), along the transverse direction of failed section, and the hardness value is found to be 96- 99 BHN at 10 inch away from the failed section while at the failed section hardness value was found 83-87 BHN. At180^0 opposite of the failed section, the hardness values were found in the range of 102-108 BHN, which are given in Table 2

TABLE-2

BRINELL HARDNESS NUMBER (BHN) OF FAILED TUBE AT DIFFERENT LOCATION

Near the failed section	**Away (5 inch) from failed section**	**Opposite (180^0) of the failed section**
83-87	96-99	102-108

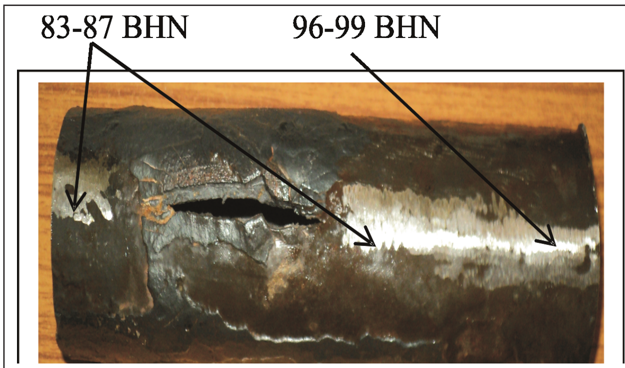

FIG. 1 FAILED TUBE SAMPLE

6.0 MICROSCOPIC EXAMINATION

For microscopic examination samples were taken from the tip of the failed region, polished with 1000 grade of emery paper followed by cloth polishing and the polished samples were etched with freshly prepared 2 wt.% Nital solution and the structures were observed under metallurgical microscope Rigaku™ (make –Japan). The microstructure is shown in Figure 2.

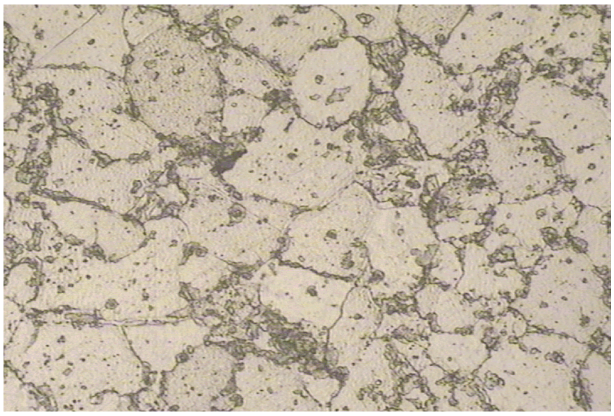

FIG. 2 500 X, MICROSTRUCTURE OF SAMPLE TAKEN FROM TIP OF FAILED SECTION.

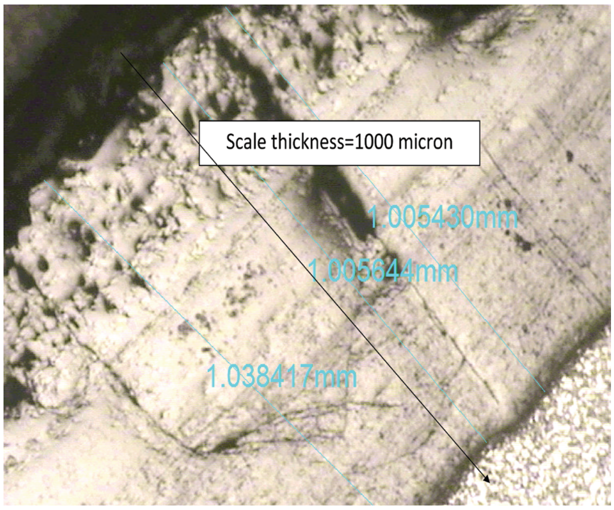

FIG. 3 50X, OXIDE SCALE AT THE INNER SURFACE, THE SAMPLE TAKEN NEAR FAILED SECTION.

The microstructure of the sample taken from the tip of failed section of reheater tube shows ferrite with precipitated carbide, the pearlite has been fully decomposed. The precipitation of carbide is due to long term overheating [1, 12-13]. Oxide scale thickness was measured in the microscope and the values were found in the range of 1000 micron along the failed section as shown in Figure 3.

7.0 OXIDE SCALE MEASURMENT & WALL THINNING

Figure 4 showed scale deposition on inside and outside surface of the failed tube. Inside oxide scale was measured by the thickness instrument 37 DL plus (Olympus make) on the failed tube at different location.

FIG. 4 INSIDE AND OUTSIDE SCALE ON THE FAILED TUBE

Oxide scale was measured at different position on the failed tube sample; the oxide scale measured was in the range of 800 to 1100 micron along the failed section i.e., 12 O' Clock position while it was in the range of 500 to 800 micron at 180 degree opposite of the failed section.

FIG. 5 INSIDE AND OUTSIDE SCALE ON THE FAILED TUBE

The Figure 5 shows the cross-sectional view of the failed tube showing non-uniform scaling on the inner side of the tube.

Diagrams showing thinning of tube

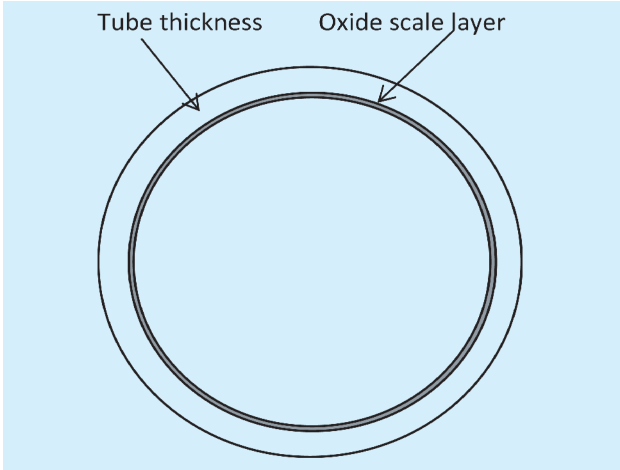

FIG. 6 UNIFORM LAYER OF OXIDE SCALE THICKNESS (AT X RUNNING HOURS OF TUBE/PLANT).

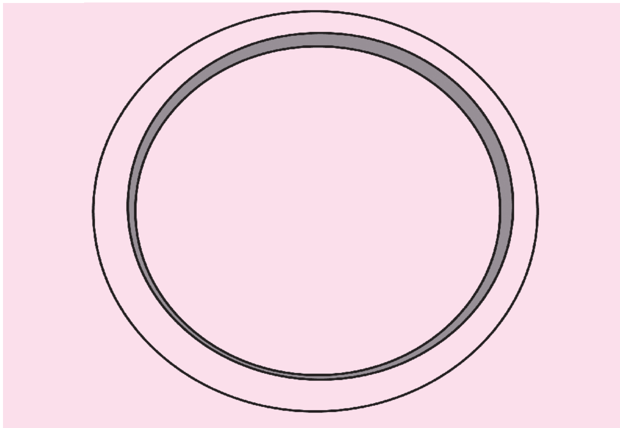

FIG. 7 NON-UNIFORM LAYER OF OXIDE SCALE THICKNESS (Y RUNNING HOURS OF TUBE/PLANT, Y > X).

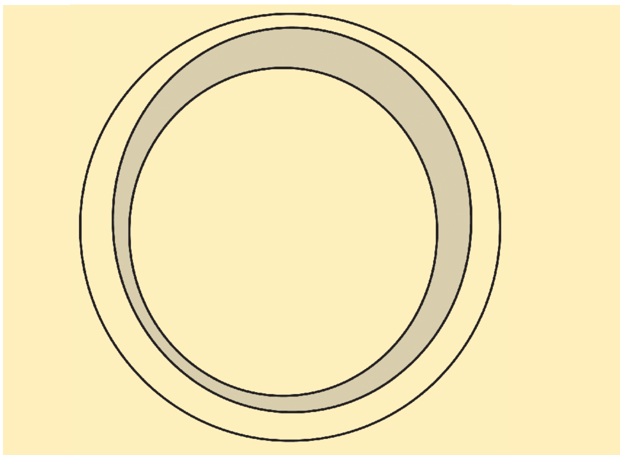

FIG. 8 NON-UNIFORM LAYER OF OXIDE SCALE THICKNESS (Z RUNNING HOURS OF TUBE/PLANT, Z > Y).

(i) EDX of inside scale:

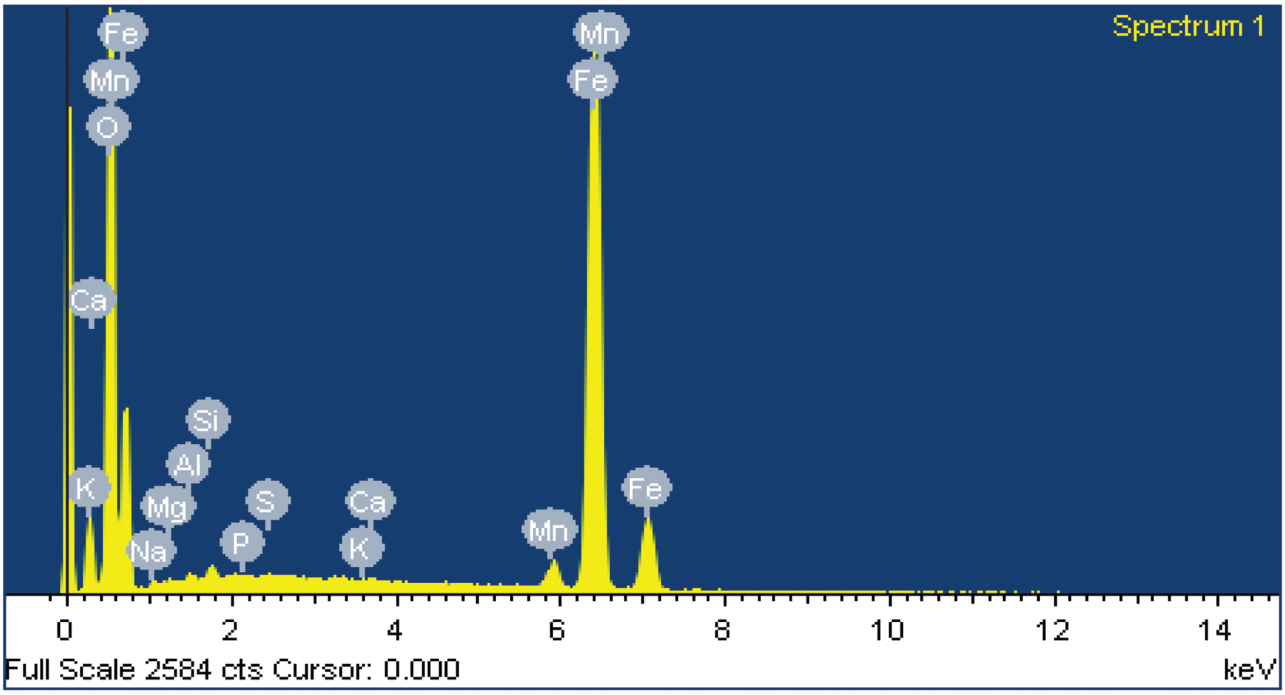

FIG. 9 EDX SPECTRUM OF SCALE FORMED INSIDE SURFACE OF THE FAILED TUBE.

(ii) EDX of outside scale:

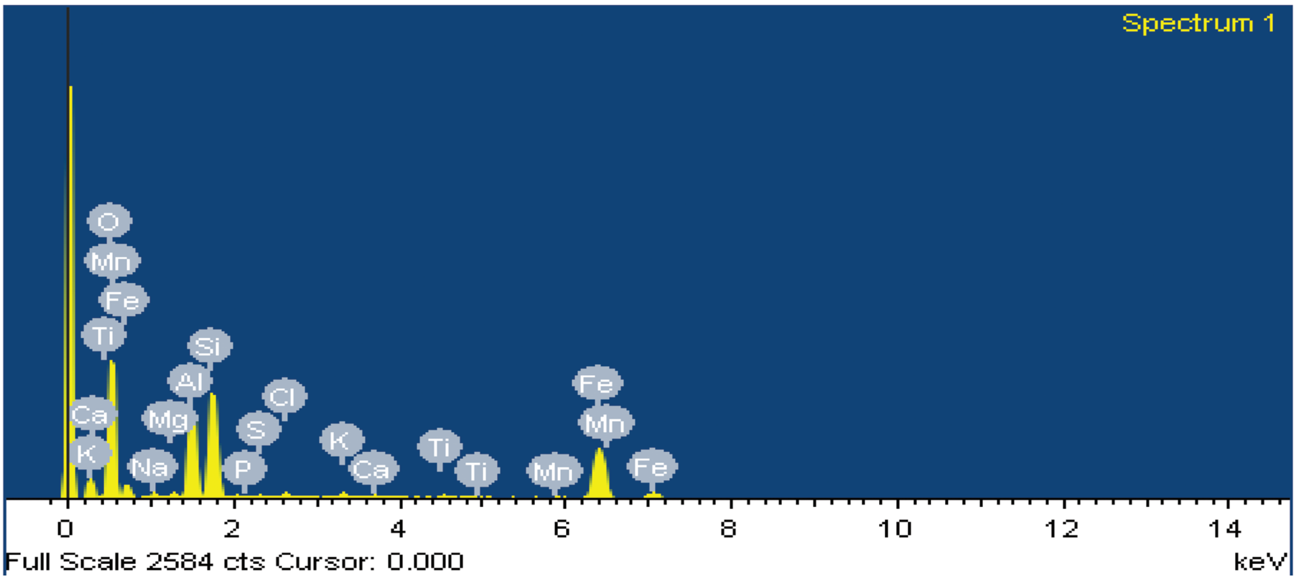

FIG. 10 EDX SPECTRUM OF SCALE FORMED OUTSIDE SURFACE OF THE FAILED TUBE

TABLE 3

EDX ANALYSIS OF OXIDES SAMPLES

Wt (%)	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	MnO	Fe_3O_4	TiO_2
Inside scale	0.81	0.65	0.48	0.92	0	0	0	0.32	2.15	94.40	-
Outside scale	1.61	0.94	20.66	30.46	0	0.23	0.87	0.72	0	42.71	1.23

Figure 6 to 8 showed the schematic growth of inside oxide scale deposition along the cross-sectional area with different running time of the plant. Initially, the formation of inside oxide scale is uniform; as running hour of plant increases the growth of oxide scale is more in a particular direction i.e., along the direction of flue gas interaction with the tube metal wall surface. This is also confirmed from the observation on the cross-sectional of the failed tube shown in Figure 5.

8.0 ANALYSIS OF OXIDE SCALE

Oxide scale formed on inside and outside surface of the failed tube was analysed through Energy Dispersive Spectrum X-ray (EDX) and X-ray diffraction pattern.

(iii) XRD Analysis of inside scale:

To established the phases of the scale inside surface of the failed tube X-ray Diffraction (XRD) pattern of the inside scale was taken

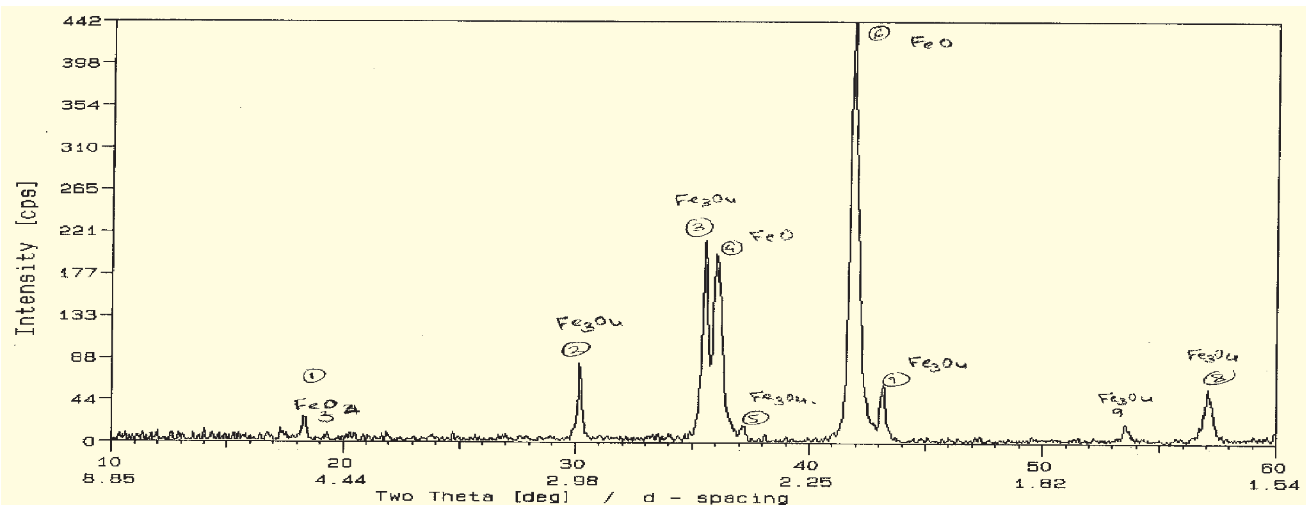

FIG. 11 XRD PATTERN OF INSIDE SCALE DEPOSITED ON FAILED TUBE

The XRD pattern confirms that oxide scale on the inner surface of the reheater tube consists of only Fe_3O_4 and FeO, which is also confirmed by literature and that at temperature above 560 ^{0}C an additional layer of wustite (FeO) may be formed by internal reaction between Fe_3O_4 and Fe.

$Fe_3O_4(s)$ + Fe(s) ---- FeO(s).

9.0 RESULT & DISCUSSION

The microstructure reveals ferrite and accumulation of precipitated carbide throughout the matrix. The structure also shows that the tube has undergone high temperature oxidation. Due to precipitation and accumulation of carbide the strength of the material has deteriorated. The microstructure analysis of oxide layer indicated that the layer is formed at the expense of tube wall. Thus by oxide scale deposition the tube suffered thinning by oxide conversion of wall metal. The microstructure analysis also reveals different layers of oxide scale deposition and presence of voids in the tube wall. Due to oxide scale deposition inside the tube, it acts as thermal barrier for heat transfer thus increasing metal temperature and making the tube softer by decreasing the strength. The effective metal wall temperature calculated for the oxide layer of 1000 micron was 607^0 C, which is much higher than the safe operating temperature of the material is due to higher temperature, and hence the microstructural and mechanical property got degraded [11].

The metal temperature is calculated by the equation [6]

$$\log X = -6.8398 + 2.83\times 10^{-4}\ T\ (13.62 + \log t) \quad ....(1)$$

Where X= Oxide scale thickness in (mils), T= Expected metal temperature in ^{0}R, t= running hours of tube/boiler.

The received failed tube has also undergone thinning as a result of fire side corrosion, which is in turn due to high temperature and attack of fly ash particle. The EDX analysis of fireside scale confirms the presence of higher percentage of silicon, aluminium, sodium, potassium and titanium, which are the source from the fly ash.

10.0 CONCLUSION

Tube metal is consumed from both the sides by forming of oxide scale

i. Steam side (inner diameter side) it is consumed by forming Fe_3O_4 and FeO.

ii. Fire side (outside diameter) flue gas with ash attacking tube by forming oxides, silicates, and due to erosion from OD.

Due to oxide scale deposition inside the tube, metal temperature increased which resulted in microstructural changes and change in mechanical property leading to structural degradation of the tube material.

Because of excess thinning in the cross-sectional area of the tube (due to oxide scale formation inside and outside of the tube), the reheater tube couldn't withstand the designed temperature and pressure and lead to rupture of the tube.

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