CRUDE OIL SETTLING VESSEL FAILURE ANALYSIS –A CASE STUDY OF VESSELS IN AN OIL/GAS GATHERING FACILITY

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ABSTRACT

An analysis is performed to determine the cause(s) of failure of atmospheric, flat-fixed roof cylindrical vessels of vertical design used for transit storage (settling vessel) of hydrocarbon liquid (crude oil) in an oil and gas bearing facility. The vessel is fabricated with normalized low carbon steel (mild steel) plates designed as per API STD 650 and welded per ASME SECTION IX codes. Less than five (5) years in service, the vessels were noticed to be oozing out crude oil from and around the welded seams. This was less than the expected service life, it was designed for twenty-two and half ($22^1/_2$) years' service duration. The vessel characteristics, namely, material allowable stress, plate thickness were analyzed for ability to cope with the duty load imposed by the stored liquid. Further, sections were cut from the unfailed parts of the tanks and were subjected to mechanical tests and results compared with specifications. The failed weldment components were examined visually and metallurgically. The observed failures were due to design and welding errors: for instance, the service load on the vessel internal exceeded the maximum allowable static stress of the material. The welding procedure specification was inadequate for the duty as the mechanical properties obtained were lower than required. This led to weakening of the welded seams. To prevent these failures required choice of material (metal plates) with adequate thickness as well as use of assured welding procedure (including effective inter pass temperatures) during welding to achieve the specified mechanical strength.

Keywords: Circumferential Stress, Shell Plate Thickness, Tensile Strength, Fatigue, Porosities, Pitting.

1.0 INTRODUCTION

Crude oil settling (retainer) tanks for collection of oil in a terminal facility suddenly developed leakages (failure) around and on the welded areas of the seams. The design service life was for $22^1/_2$ years but the vessels (tanks) failed less than 5 years (60 months) in service. Typically, crude oil is received into the vessels through controlled run-in at a velocity of 4 m/s and the oil settles for hours before drain is effected via a centrifugal pump action. The normal operating conditions of the vessels are atmospheric pressure and 33ºC. The vessels are fabricated with carbon steel plates and welded to join. There are four (4) of such vessels installed and in service. All the four have shown signs of failure as they have leaked from and around the vertical and horizontal seams. The leaks occurred well below the design service life of the vessels. Thus there arose a need to do a study and establish the cause(s) of the failures.

The vessel characteristics, namely, material allowable stress, plate thickness were analysed for ability to cope with the duty load imposed by the stored liquid. Sections of some of the weldments were visually and metallurgically examined. The sections of the weldments were also subjected to tensile tests, impact tests and Nick-Break tests and the results matched with the design mechanical properties specified. The welding procedure specification was checked and compared with the requirements for such duty load.

The effects of the cycle of "Pressure and no-Pressure" the vessels were subjected to by the "fill and drain" cycle every forty-eight (48) hours are matched with the fatigue strength of the vessel.

1.1 Settling Vessel Description

Failed Weldment

Failed Weldment

Figure 1: Settling Tank with failed Seams

Figure 2: Settling Tanks with Failed Shells

The settling vessel is essentially a flat / fixed roof vertical cylindrical tank mounted atop a concrete foundation. Level, pressure and temperature gauges are installed on the vessel wall as shell appurtenances to indicate the corresponding parameters. The supply to the tank is located 50 mm below the weld seam of shell and top cover while the discharge is close to the concrete basement with an electric motor-driven centrifugal pump to evacuate the tank contents. The vessel internal is ambiented to the atmosphere by an elbow connection on the flat top thus qualifying the tank as atmospheric storage vessel.

The vessels essentially are subjected to static pressure when filled with crude oil and this pressure gradually reduces as the tank is emptied via a centrifugal pump system connected to the
bottom end of the tank. This cycle repeats every forty-eight (48) hours. In addition, the vessel is inadvertently subjected to vibration occasioned by the excursion in a 1200 cm diameter pipe of flare gas to the flare stack / burner facility adjacent to the vessels.
Vessels are field fabricated / erected with normalized low carbon steel and welded according to ASME SECTION IX code. The technical details of the vessel are listed in Table 1.

Table 1: Settling vessel technical data.

Internal Diameter	D	25.00 m
Total Height of Tank	H	9.50 m
Height of Bottom Course	h1	1,000 mm
Nominal Tank Radius	r	12,500 mm
Vessel Shell Thickness	t	5.00 mm
Allowable Stress for Design	*Sd*	137 MPa
Allowable Stress for Testing	*St*	154 MPa
Number of courses		8
Vessel Material		Normalized Low Carbon Steel

Source: Facility Design Manual.

Table 2: Settling vessel service data.

Vessel	Duty Time (Months)	Duty History
1	48	Continuous in service, subjected to "Fill and Empty" cycle every 24 hours. Completely drained and flushed after 36 months duty.
2	55	Continuous in service, subjected to "Fill and Empty" cycle every 24 hours. Completely drained and flushed after 42 months duty.
3	59	Continuous in service, subjected to "Fill and Empty" cycle every 24

		hours. Completely drained and flushed after 49 months duty.
4	52	Continuous in service, subjected to "Fill and Empty" cycle every 24 hours. Completely drained and flushed after 39 months duty.

Source: Facility Daily Operations Log Book.

Table 3: Welding Conditions.

Welding process	Shielded Metal Arc Welding (SMAW)
Welding position	Vertical-Uphill
Joint configuration	Butt, Single V, 60^o, root face 2 mm
Electrode diameter	4.8 mm
Arc voltage	25 V
Welding current	175 A
Baking temperature	150^{o}C for 1 hr.
Inter-pass temperature	100 – 150^{o}C
Number of passes	4

2.0 TYPES OF STORAGE TANKS BY SHAPE

Above Ground:

Spheres - These are used for the storage of products at pressures above 35 kPa (ga).

Spheroids - For the storage of products above 35 kPa (ga). The tank is generally spherical but somewhat flattened. The shells of hemispheroidal tanks are cylindrical with curved roofs and bottoms. The noded spheroidal tanks are used in the larger size versions and as such their internals are supported with ties to keep shell stresses low.

Horizontal Cylindrical Tanks - The normal service pressures of these tanks range from 100 to 7000 kPa (ga), or even greater. The heads of these tanks are hemispherical.

Fixed Roof - The roofs are permanent on the shell, however the connection is fragile to serve as a relief for the vessel in case of over pressure of the internal. This is a special design feature. In this case, the equivalent pressure of the dead weight of the roof, including rafters shall be lower than the design pressure of the product.

Floating Roof - These are special tanks or storage vessels whereby the tank roof slides on the internal walls of the shell above the stored product. This is for near atmospheric pressure storage and is required to provide a constant minimum void or space between the roof and the product. The design can be adapted such that the floating roof is under a fixed roof and thus protected from the weather or exposed to the weather. The former design is in areas of heavy rainfall and snowfall; these interfere with the buoyancy of the floating roof. Generally floating roofs are used to reduce vapor losses and aid in conservation of stored fluids. There is also the environmental aspect to the use of floating roofs –in the area of vapour pressure recovery. Howbeit, for toxic or odoriferous materials, a better emission control measure or technique is needed than a floating roof can provide.

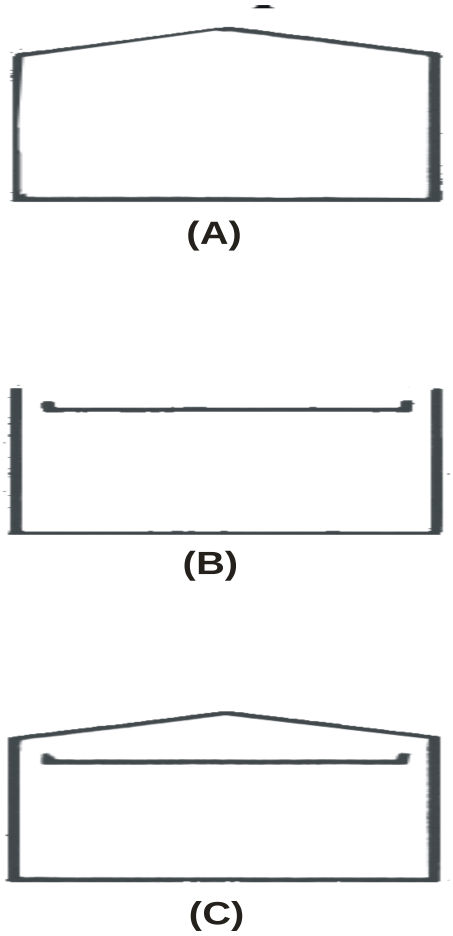

Figure 3: Atmospheric Storage Tanks (A) Cone Roof, (B) Floating Roof, (C) Internal Floating Roof.

Flat-Sided Tanks - For space reasons, especially offshore structures, flat-sided vessels may be preferred to the general cylindrical shape tanks. Flat-sided or rectangular vessels are generally of the atmospheric type design. (Rajput, 2008).

2.2 WORKING PRESSURES

Generally, a design operating pressure can be calculated to prevent tank breathing, this prevents losses arising from idle storage (standing storage losses).

Atmospheric Tanks These are tanks designed and equipped for storage of contents at atmospheric pressure. The configuration of this type is of the vertical cylindrical shape. They are in sizes from shop-welded to field welded tanks. Bolted tanks, and occasionally rectangular welded tanks, may be employed for atmospheric storage services.

Low Pressure [0 to 17 kPa (ga)] The shape of this type is usually cylindrical with flat bottom and domed roof. They are generally of the welded design. The vessels are for storage of products that require internal gas pressure from near atmospheric to 17 kPa (ga).

Medium Pressure [17 to 100 kPa (ga)] For the storage of higher volatility products that cannot be stored in low pressure tanks. The conventional design is cylindrical with flat or dished bottoms. The roofs are domed shaped or sloped. Medium pressure tanks are usually of welded design, spheres that are welded may be employed in the service particularly for pressures close to 100 kPa (ga).

High Pressure [Above 100 kPa (ga)] For the storage of refined products at pressure above 100 kPa (ga). The configuration is the cylindrical or spherical welded design.

2.3 MATERIALS USED FOR STORAGE VESSELS FABRICATION

Metallic and non-metallic materials are used for tanks / vessels fabrication. Of recent, metallic materials have dominated. In some situations, due to the properties of the product stored, the internals of the metallic vessels fabricated with metals may be lined with plastics, etc.

In the metals regime, carbon steel is the material of common choice. The most common are A-36 structural steel and A-283 grade "C" structural quality carbon steel. Steel plates of gauge with a minimum tensile strength of 360 x 103 kPa is used. A-515, A-516 and A-612 mild low carbon steels are used for fabricating storage vessels for higher pressure services. These are common in such shapes as spheres and "bullets." (Fuchs and Stephens, 1980). The storage vessels are constructed to API 650 code; welding standards are taken from ASME Section IX code. These codes specify welding procedures, inspections testing requirements / procedures. Vessels for low temperature (cryogenic) service require materials from low alloys stainless steels, aluminium and some other specialized materials. (Blodbett and Omer, 1970)

3.0 DESIGN REQUIREMENTS FOR TANKS AND VESSELS

Design parameters to consider and include in the design equations are (Clifford, 1998),:

- design metal temperature (based on ambient temperatures).
- the design specific gravity.
- the corrosion allowance to be provided for each shell course, for the bottom, for the roof, and manholes and for structural members.
- the design wind velocity.
- external loads. The magnitude and direction of external loads or restraint the shell will be subjected to and as such designed for.
- Foundation considerations.

Service Conditions

The presence of hydrogen sulfide or other conditions that could promote hydrogen-activated cracking, notably near the bottom of the shell and particularly the joint between shell-to-bottom connections, care must be exercised to ensure that the materials chosen for the vessel fabrication as well as the details of construction are adequate to resist hydrogen-related cracking. The hardness of the welds, including the heat-affected zones that are in contact with this service state should be considered. There is the possibility of moisture being present on the inside metal surface, and thus the strength and hardness characteristics of the base metal and weld metal should equally be designed for.

Vessel Allowable Stress

The maximum allowable product design stress, *Sd*, The net plate thicknesses (i.e. the actual thicknesses minus the corrosion allowance) shall be the basis for the calculation. The design stress basis, *Sd*, shall be either two-thirds of the yield strength or two-fifths of the tensile strength of the material, whichever is less.

The maximum allowable hydrostatic test stress, *St*, The gross plate thicknesses, plus the corrosion allowance, shall be the basis for the calculation. The hydrostatic test basis shall be either three-fourths of the yield strength or three-sevenths of the tensile strength of the material, whichever is less. (API STD 650).

4.0 CALCULATION OF SHELL PLATE THICKNESS BY THE 0.3 m (1-FOOT) METHOD

The 0.3 m method calculates the thicknesses required at design points 0.3 m (1 ft) above the bottom of each shell course. (Normally this method is for tanks not larger than 60 m in diameter).

The required minimum thickness of shell plates shall be the greater of the values computed by the following formula (Zick and McGrath, 1968):

$$td = \frac{4.9D(H-0.3)G}{Sd} + CA \quad (1)$$

$$tt = \frac{4.9D(H-0.3)}{St} \quad (2)$$

Where:
td = design shell thickness, in mm,
tt = hydrostatic test shell thickness, in mm,
D = nominal tank diameter, in m,
H = design liquid level, in m, = height from the bottom of the course under consideration to the top of the shell including the top angle, if any,
G = design specific gravity of the liquid to be stored,
CA = corrosion allowance, in mm,
Sd = allowable stress for the design condition, in MPa,
St = allowable stress for the hydrostatic test condition, in MPa.

For both the design condition and the hydrostatic test condition, the minimum shell plate thickness shall be determined. The required shell thickness for each course shall be the greater of the two in addition to any corrosion allowance specified.

The bottom-course thicknesses T1*d* and T1*t* for the design and hydrostatic test conditions are governed by the following formulas:

$$T1d = \left(1.06 - \frac{0.463D}{H}\sqrt{\frac{HG}{Sd}}\right)\left(\frac{2.6HDG}{Sd}\right) + CA \quad (3)$$

$$T1t = \left(1.06 - \frac{0.463D}{H}\sqrt{\frac{H}{St}}\right)\left(\frac{2.6HD}{St}\right) \quad (4)$$

where the letters and symbols have the already stated meanings

To calculate the second-course thicknesses for both the design condition and the hydrostatic test condition, the value of the following ratio shall be calculated and interpreted as per the steps listed below:

$$\frac{h1}{(rt1)^{0.5}} \quad (5)$$

where
*h*1 = height of the bottom shell course, in mm,
r = nominal tank radius, in mm,
*t*1 = actual thickness of the bottom shell course, less any thickness added for corrosion allowance, in mm, used to calculate *t*2 (design).

If the value of the ratio is less than or equal to 1.375,

$$t2 = t1 \quad (6)$$

If the value of the ratio is greater than or equal to 2.625,

$$t2 = t2a \quad (7)$$

where

$$t2a = \frac{3.49D(H - 2/12)G}{Sd} + CA \quad (8)$$

But if the value of the ratio is greater than 1.375 but less than 2.625, then:

$$t2 = t2a + (t1 - t2a)\left[2.1 - \frac{h1}{1.25(rt1)^{0.5}}\right] \quad (9)$$

CALCULATIONS

Technical Data:

Specific gravity of liquid, *G*:	1.0
Corrosion allowance:	0.0 mm
Tank diameter, *D*:	25.00 m
Total height of tank, *H*:	9.50 m
Number of courses:	8
Allowable stress for design, *Sd*:	137 MPa
Allowable stress for testing, *St*:	154 MPa
Height of bottom course, *h*1:	1,000 mm
Nominal tank radius, *r*:	12,500 mm

The values of thickness of shell plates obtained for the design condition is usually greater than that obtained for hydrostatic test conditions. This is because the value of the allowable stress for hydrostatic test condition is greater. We shall do the required computations based on design condition.

First Course (t1)

For the design condition, the applicable equation is eqn. (1): i.e.

$$td = \frac{4.9D(H - 0.3)G}{Sd} + CA$$

Substituting the values, we have:

$$td = \frac{4.9 \, x \, 25(9.5 - 0.3)1}{137} + 0.0$$

= 8.226 mm

Using equation (2) for the hydrostatic test condition for checks, i.e.,

$$tt = \frac{4.9D(H - 0.3)}{St}$$

Substituting the values, we have:

$$tt = \frac{4.9 \, x \, 25(9.5 - 0.3)}{154}$$

= 7.318 mm

td > tt. We shall use the value of td for the shell plate thickness.

The applicable thickness for the shell plate from the calculations is 8.226 mm, rounded up to 8.5 mm.

The thickness of shell plate used for the tanks is 5 mm. This is inadequate for the service load.

For the second course plate thickness, we test the ratio of eqn. (5), i.e.

$$\frac{h1}{(rt1)^{0.5}}$$

Substituting values, we have:

$$\frac{1000}{(12500 \, x \, 8.5)^{0.5}}$$

= 3.068

The value of the ratio is greater than 2.625, hence t2 = t2a and the value of t2a is obtained from eqn. (8), i.e.:

$$t2a = \frac{3.49D(H - 2/12)G}{Sd} + CA$$

Substituting values, we have:

$$t2a = \frac{3.49 \, x \, 25 \, (9.5 - 2/12) \, x \, 1}{137} + 0.0$$

= 5.944 mm

This is rounded up to 6.0 mm

The shell plate thickness used for the second course is 5.0 mm as against the required design value of 6.0 mm for the service.

Tensile Test

The tensile strength of the weld, including the fusion zone of the specimen shall be greater than or equal to the specified minimum tensile strength of the vessel or pipe material but need not be greater than or equal to the actual tensile strength of the material See Table 4. (API 1104, 2000).

Table 4: Result of Tensile Strength Tests of the Tank Weldments.

Tank	Test Specimen	Tensile Strength MPa	Tensile Strength (Average of 2 Specimens) MPa	Specified Tensile Strength for weldment MPa	Tank Material Actual Tensile Strength MPa	Comments
1	1	290	**295**	**325**	360	Tensile strength of weldment lower than specification. Indication of weldment possessing lower mechanical properties than required for the service. (Allowable design stress is 137 MPa).
	2	300		**325**	360	
2	1	295	**287.5**	**325**	360	As in Tank 1.
	2	280		**325**	360	
3	1	300	**295**	**325**	360	As in Tank 1.
	2	290		**325**	360	
4	1	285	**287.5**	**325**	360	Tensile strength of weldment lower than specification. Indication of weldment possessing lower mechanical properties than required for the service. (Allowable design stress is 137 MPa).
	2	290		**325**	360	

Nick-Break Test

The results of the Nick-Break tests (exposed surfaces of each fractured specimen x 8 specimens) showed evidence of lack of complete penetration and fusion in the weldments, there were gas pockets in excess of 1.6 mm in the weldment. The acceptance limit for gas pockets in the weldments is less than 1.6 mm (API 1104, 2000).

Impact Test

Specimens were cut from the unfailed sections of the vessel weldments. These were prepared, etched and subjected to impact tests in accordance with ASTM E 23, ASTM A 370 and AWS B4.0. The results in Table 5 showed the weldments do not possess the mechanical properties required by the design. By extension, this implies that the **Welding Procedure Specification** was faulty.

Table 5: Result of Impact (Charpy) Test on the Vessel Weldments.

Tank	Test Specimen	Test Specimen Temp. °C	Energy Absorbed J	Energy Absorbed (Average of 3 Specimens) J	Required Absorbed Energy J	Comments
1	1	25	17	**17**	**20**	Weldment and Fusion zone possess lower mechanical properties required for the service. Welding procedure specification inadequate.
	2	25	16.5			
	3	25	17.5			
2	1	25	16.5	**16.5**	**20**	As in Tank 1.
	2	25	17			
	3	25	16			
3	1	25	17	**16.5**	**20**	As in Tank 1.
	2	25	16			
	3	25	16.5			
4	1	25	16.5	**16.67**	**20**	Weldment and Fusion zone possess lower mechanical properties required for the service. Welding procedure specification inadequate.
	2	25	16.5			
	3	25	17			

Visual and Metallurgical Examinations of Weldments

Sections were cut from the unfailed weldments of the vessels and subjected to visual and metallurgical examinations.

Visual Examination

- Dye-penetrant examination of cut sections of the weldments revealed cracks.
- The weldments revealed deep cuts. These are usually effects of poor surface- grinding after welding.
- The unfailed sections of the base metal and weldments showed pitting corrosion attack. See Figures 4 and 5. The depths of pits are within acceptable limits for such environment. This is normal for the metal in the exposed environment.

Metallurgical Examination

- A chemical composition analysis (see Table 6) showed that the vessel material is not different from that specified (Low Carbon Steel). This is acceptable within the industry standards.
- Metallurgical examination of a section of the failed vessel identified fatigue cracks, which extended into the bulk of the material. This is traceable to the vibration load imposed by the adjacent pipeline escorting gas (gas excursion) to the flare stack.

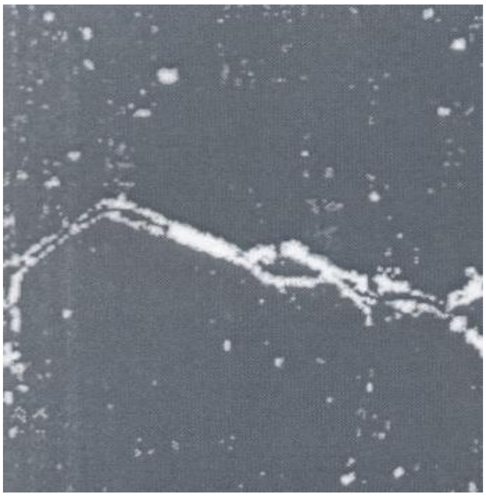

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Figure 4: Pitting Corrosion and Cracks in Weldment.

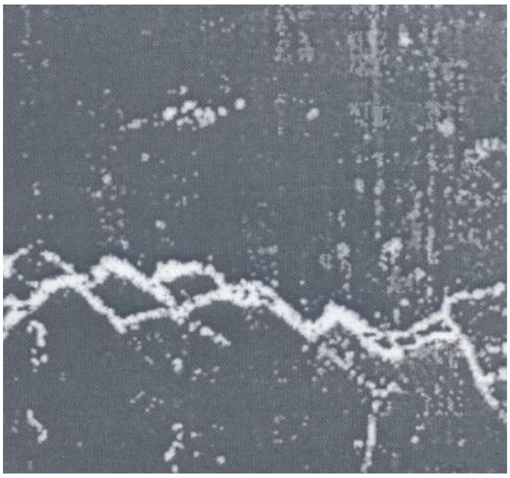

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Figure 5: Pitting Corrosion and Cracks in Weldment.

Table 6: Chemical Composition of Settling Tank Material.

Element	Settling Tank Material (% by mass)	Low Carbon Steel (% by mass)
Carbon	0.25	0.30
Silicon	0.20	0.30
Manganese	0.90	1.00
Sulphur	0.04	0.05
Phosphorus	-	0.05
Iron	remainder	remainder

Table 7: Typical Results for Storage Tanks Units 1 to 4.

Storage Tank Parameter	Measured Shell Plate Thickness (mm)	Minimum Required Design Shell Plate Thickness (mm)	Comments
First Course: Shell Plate Thickness	5	8.5	Plate thickness inadequate for the service load. Inefficient design.
Second Course: Shell Plate Thickness	5	6	Plate thickness inadequate for the service load. Inefficient design.
Shell Material	NA	NA	Low Carbon Steel. Within acceptable industry standard.
The weldments revealed deep cuts.	NA	NA	These are usually effects of poor surface- grinding after welding.
Results of Nick-Break tests showed evidence of lack of complete penetration and fusion in the weldments, there were	NA	NA	The acceptance limit for gas pockets in the weldments is less than 1.6 mm (API 1104, 2000).

gas pockets in excess of 1.6 mm in the weldment.			
Results of Tensile and Impact tests produced values lower than specified for the weldments	NA	NA	Weldment and Fusion zone possess lower mechanical properties required for the service. Welding procedure specification inadequate.

CONCLUSION

- Design errors were responsible for the premature failure of the settling tanks: 1) The choice of shell plate material thickness was inadequate to bear the service loads imposed on the vessels. 2.) The welding procedure specification used did not produce the specified mechanical properties required to withstand the service stress. The tensile tests, Nick-Breaks and impact tests results of the cut-out weldments provide confirmations.
- The same plate thickness was used for all the courses of the shell –there should be different plate thickness for the different shell courses.
- The welding workmanship was responsible for the porosities and cracks detected in the weldments. These porosities and cracks served as spots of weakness, the weakness was exaggerated on exposure to the circumferential stresses in the vessels induced by the stored product.
- Visual examination of the weldments revealed deep cuts. These are usually effects of poor surface-grinding after welding.
- The vessel was subjected to vibrations and the effects of fatigue were not considered in the design.
- The result of the chemical compositional analysis (shown in Table 6) of the vessel material was not different from the grade specified, i.e., low carbon steel. Generally this grade is within the industry standard.

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