SSRG International Journal of Mechanical Engineering
ISSN: 2348 – 8360/doi:10.14445/23488360/IJME-V6I8P103

Volume 6 Issue 8, 16-25, August 2019

Thermal Fatigue Stresses In Reinforcement Pads And Shell Wall Below, In An Un-Insulated Shut Down Vessel Operating At High Temperature

Ajay Mehta B.E.; M.Tech.; FIEAust Member, Engineers Australia

#*Team Leader Mechanical Engineering South.*
ALS Industrial, 450 Dynon Road, Victoria, 3005, Australia.

Abstract: *Un-insulated pressure vessels designed for higher temperature process fitted with reinforcement plates (re-pads) around the openings, operating under 'shutdown' conditions, develop very high induced stresses (approaching their yield limits and beyond) to differential thermal expansion, causing thermal fatigue. The reinforcement pads and corresponding patch of shell wall develop many fatigue stress cracks along the weld joints where the reinforcement pads are constrained to shell by fillet welds. The cracks initiate the blind side of the shell-reinforcement assembly (at the common interface), which cannot be easily detected by visual examination. An advanced non-destructive testing technique called Phased Array Ultrasonic Testing (PAUT) or Time of Flight Diffraction (ToFD) is required to be applied to detect the presence and extent of crack propagation. Australian pressure vessel design code identifies one of the design loads as 'Forces due to temperature conditions, including the effects of differential expansion of parts or attached piping.' However, there is no specific mandating guideline for steps to be taken when designing an un-insulated vessel operating at high temperatures and frequently shutting down. The author emphasizes to mandate insulation of shutdown vessels operating above ambient temperature or use a single heavy wall shell insert in place of reinforcement plate at the openings. There are chances of the fatigue cracks propagating un-detected, potentially causing catastrophic failure of the vessel.*

Keywords — *Shutdown Vessel – The pressure vessel that operates with batch processes and shuts down and starts up at batch frequency,*
Reinforcement Plate (Re-pad) – The doubling plate to compensate for the loss of shell wall when an opening is cut out Or compensation plate to take extra load due to external attachment, e.g., support legs, platforms above vessel, etc.,

Thermal Resistance; *Thermal fatigue stresses, Phased Array Ultrasonic Testing (PAUT), Time of Flight Diffraction (ToFD) inspection techniques.*

I. INTRODUCTION

During a routine inspection of a stainless-steel batch reactor vessel at a chemical plant in September 2017, the vessel inspector detected some cracks on the outer surface of reinforcement pads on the support legs. One year before that, in 2016, similar cracks were observed on a re-pad of the same vessel's lifting lug. The cracks detected in the lifting lug re-pads were leaking products (the cracks were in the shell and re-pad through the wall). The damaged segment of the shell was removed, and a shell-insert was welded to return the vessel to service. However, at the next inspection, more cracks were detected on support leg re-pads. The author of this paper visited the site and inspected the cracks. Vertical support re-pad of the vessel was under very low stress due to its orientation. The vessel was resting on the bottom part of the support leg and not on the support bracket's vertical part. Hence the chances of stress due to the weight of the vessel were meagre. The author observed that reinforcements (re-pads) at the leg supports and around all nozzle openings were very strong, and the vessel was not insulated. Hence chances of thermal fatigue stresses were assumed to be very high due to high operating temperature and frequent shutdown cycles in the batch process.

The author advised the client to carry out phased array ultrasonic testing (PAUT) of all re-pads (around 12 of them) to confirm if there were initiations of fatigue cracks between the re-pad and shell wall at the common interface (blindside). The PAUT inspection (ALS PAUT Inspection Report No. 44627.PA.01) detected cracks on all nozzle openings that had re-pads, along the periphery of the fillet welds joining shell and re-pad (see Figure #5).

The temperature distribution through the shell wall – re-pad assembly has been calculated concerning heat transfer theory published by Çengel and Ghajar (2011, 135–149).

II. THERMAL HEAT TRANSFER MODEL

The thermal heat transfer model was established, assuming steady-state heat flow from inside the shell outside in only one direction. There was no heat loss considered along the wall surface (through the edges). see figure 1.

If the Thermal Resistance (R) is determined under steady-state heat flow, the electrical circuit analogy can be applied, and various modes of heat transfer can be combined.

If the heat resistance of the shell plate is termed as R_{shell}

Heat transfer in terms of Resistance due to heat conduction can be expressed as:

$$Q' = (T_1 – T_2) / R_{cond}, \text{ where } R_{cond} = L/(kA) \quad (1)$$

Where k = Coefficient of thermal conductivity in W/(m*Δ ^{0}K),

Q' Heat flow per unit time in Watts W and,

L = thickness of medium conducting heat in meters.

Similarly, the thermal resistance of convection $R_{conv} = 1/(hA)$.

Where h = Convection heat transfer coefficient in W/(m^2*Δ ^{0}K)

The heat transfer in terms of thermal Resistance is shown below, in Figure 1;

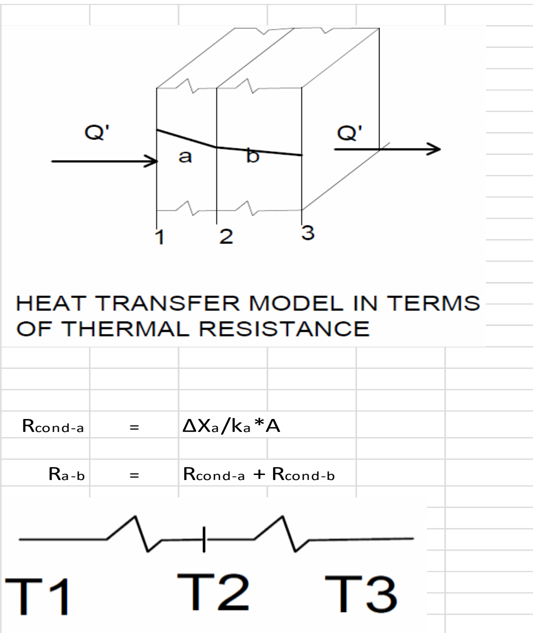

Figure 1 Thermal resistance through joining walls (Cengel-Ghajar. 2011, 135-149)

$R_{total} = R_{convection} + R_{conduction} +$

- The equivalent thermal Resistance of the shell _ re-pad combination can be modelled, as shown in Figure 2.

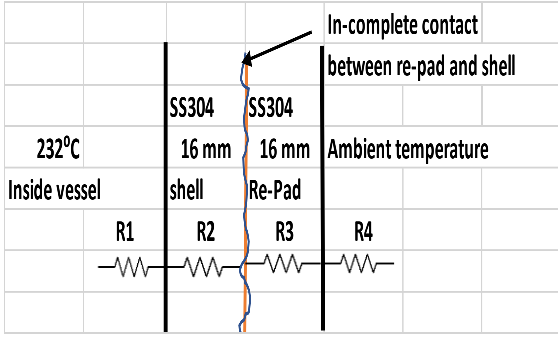

Figure 2 Thermal resistance model of shell and re-pad

The thermal Resistance can be derived as follows:

- $R_{total} = R_1 + R_2 + R_3 + R_4$ (2)

R1 and R4 are convective Resistance to heat flow at a shell inside the surface and re-pad outside surface. Similarly, R2 and R3 are conductive Resistance through the shell wall and re-pad plate, respectively.

This paper aims to determine the stresses induced due to the differential thermal expansion between shell and re-pad fitted around nozzle opening and where external structures are welded (support legs, lifting lugs, etc.) in an un-insulated pressure vessel operating at higher than ambient temperature and pressure.

It is observed that due to layered construction around reinforcements, infrequent shut down operating conditions, the inner (shell) and outer (re-pad) walls at the reinforcement experience very high induced stresses due to differential thermal expansion. Cracks develop on mating surfaces between shell wall and re-pad starting from inside, a common interface, to outwards. The cracks, originating on the blind side of the shell-reinforcement assembly, are not visible and cannot be inspected by commonly available inspection techniques. Advanced ultrasonic wave transmission technique called Phased Array Ultrasonic Testing (PAUT) method or Time of Flight Diffraction method (ToFD) requires to be applied to the area of reinforcement either from inside of the vessel, to detect and measure cracks on shell wall or, outside of the vessel, on re-pad, to detect cracks on the other side of re-pad.

The stainless-steel (SS) vessel mentioned above, used in batch reaction service, was studied to detect hidden and non-visible cracks after an incident of leak through shell behind re-pad of lifting lug was reported. Upon detecting more cracks in the re-pads of support legs, all re-pads at the nozzle openings (around 12 off them) were inspected by PAUT examination.

The vessel understudy has the following design parameters:

The vessel is called a 'Batch Reactor.'

DESIGN PRESSURE 1035 KPa & Full vacuum;

DESIGN TEMPERATURE 232^0 C.

POSITION Vertical

DIMENSIONS;
LENGTH (Tan to Tan) 10,140 MM (tan. to tan.)
INSIDE DIAMETER 3080 MM
SHELL / HEADS MATERIAL ASTM A-240-304, 16mm/19mm
REINFORCEMENT PADS ASTM A-240-304 – 16 mm

A typical example of a vertical pressure vessel is shown in Figure 3 below:

Figure 3 Typical Vertical Pressure vessel
(A re-pad can be seen around the inspection nozzle.)

In pressure vessel design, a compensation plate (re-pad) must reinforce the shell around the hole where the shell wall is cut out, and a nozzle is fitted.

A typical reinforcement is shown in Figure 4 below with a crossed hatched area showing the re-pad welded to the shell and nozzle (angular hatched area).

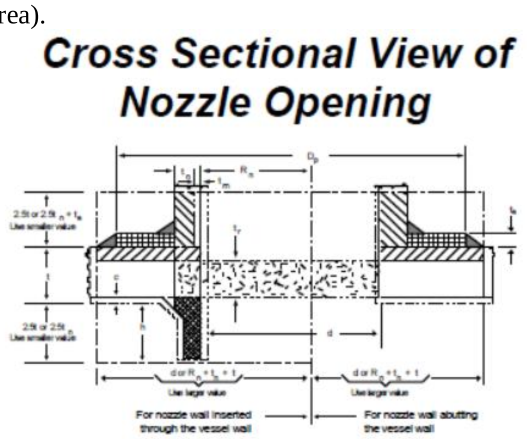

Figure 4 Crossed hatch area is shell reinforcement (ref. AS 1210-2010)

One of the nozzles in the reactor vessel is shown below, with a reinforcement pad welded to the shell. Figure 5, below, is re-drawn from the construction drawing of the ship under study.

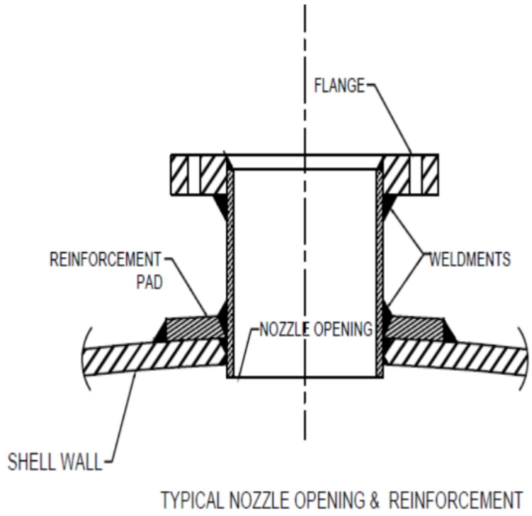

Figure 5 Typical nozzle weld joint with reinforcement

A typical support leg reinforcement is shown below in Figures 6, 7, and 8. The leg support structure is also heavily reinforced.

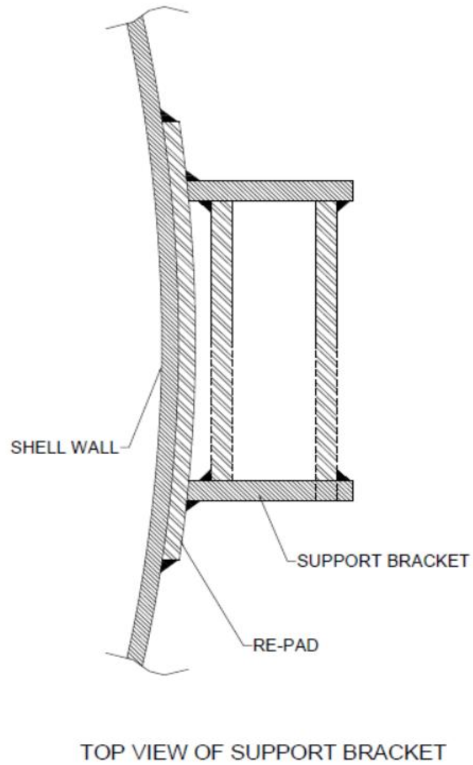

Figure 6 Support leg construction details plan view

The Reactor support leg photo and side view with structural details are shown in Figure 7 and Figure 8 below.

Figure 7 Support leg re-pad weldment

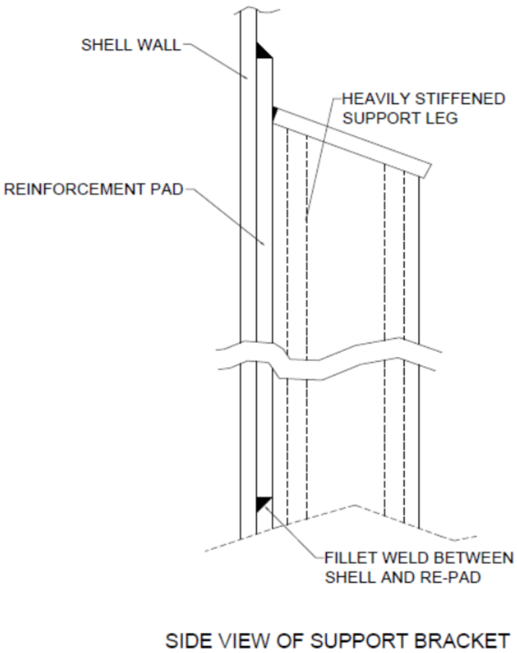

Figure 8 Support leg construction details side view

III. THERMAL STRESSES CALCULATIONS

As shown above, in the vessel design data, the vessel operates at an elevated 232 deg temperature. C (505 ºK) while the outside ambient temperature can be varied from 0 deg. C (273 ºK) to 50 deg. C (323 ºK).

The thermal resistance model of the Shell – Re-pad can be written, as shown below in Figure 9:

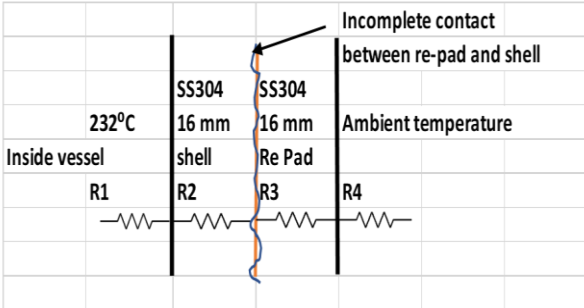

Figure 9 Thermal resistance model: Shell - re-pad assembly

Since the surface contact between the shell and the re-pad is not a full 100% surface contact due to inherent rolled plate roughness, the gap can be represented as a value of thermal Contact Resistance arrived at experimentally in laboratory conditions. As documented by Çengel and Ghajar (2011, 135–149), the thermal contact conductance of a pair of stainless steel AISI 304 ground plates under 4 to 7 MPa contact pressure is measured to be hc = 1900 W/(m2 K). In the vessel consideration, the contact conductance can be less than 1900 W/(m2 K) because the mating plates are not under 4 to 7 MPa contact pressure. The surface finish is not ground, but it is as rolled.

Hence the thermal resistance model can be re-defined, as shown in Figure 10 below:

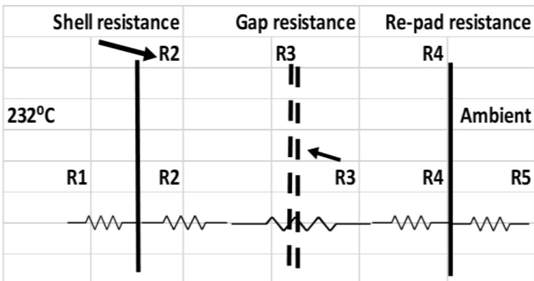

Figure 10 Thermal resistance model accounting for the gap between shell and re-pad (Gap resistance R3)

In the model above, thermal resistances' values are defined as Table 1 below with 25W/(m2*K) contact conductance between shell and re-pad.

Table 1

R1 =	Convective resistance of Shell inside surface	1.25E-02	sq.m*T/W
R2=	Conductive resistance of shell wall SS304	9.64E-04	sq.m*T/W
R3=	Conductive resistance of shell-re-pad interface	4.00E-02	sq.m*T/W
R4=	Conductive resistance of 19 mm Re-pad SS304	9.64E-04	sq.m*T/W
R5=	Convective resistance of Re-pad outside surface	1.00E-01	sq.m*T/W

The thermal contact conductance between shell and re-pad is considered to be 25 W/(sq.m*K).
Hence R_3 = 1/ h_c = 4.00E-02 sq.m*T/W (various values of Contact Conductance (h_c) from 300 to 1800 W/(sq.m*T) were considered to cover a wide range of contact characteristics as the exact value of thermal contact conductance of mating SS plates of shell and re-pad was not available).
Table 1: Values of resistances due to convection, conduction, and conductance of the gap between shell and re-pad (resistance R3)

(The units of convective Resistance and conduction resistance are shown earlier).

Equivalent Resistance of the whole shell & Re-pad assembly per unit area is found to be:

$R_{total} = R1+R2+R3+R4+R5 = 1.54E\text{-}01\ ^0K/W$ 3

From the above values, total Resistance to the heat flow is calculated for different ambient temperatures.

Heat Flow $Q' = (Tk\ in - Tk\ out)$ *in Kelvin* $/ R_{total}$ 4

From an established heat flow at a particular ambient temperature, the corresponding temperatures are calculated in the middle of the shell and re-pad thicknesses.

$T_{shell} = (Q' \times R_{shell}) - T_{inside}$ 5

The thermal contact conductance between shell and re-pad is considered to be 25 W/(sq.m*K).

Hence R_3 = 1/ h_c = 4.00E-02 sq.m*T/W (various values of Contact Conductance (h_c) from 300 to 1800 W/(sq.m*T) were considered to cover a wide range of contact characteristics as the exact value of thermal contact conductance of mating SS plates of shell and re-pad was not available).

The shell and re-pad are assumed to have uniform temperatures through their thicknesses, found in the thickness's middle.

From the above calculations, it was observed that at 10 deg. C ambient, the middle of the shell has T_{shell} = 486 °K and at the middle of re-pad thickness $T_{re\text{-}pad}$ = 391.5 °K

For a two-dimensional structure (shell and re-pad plates are assumed to be two-dimensional), heat transfer media thickness is too small concerning the area.

Thermal stresses in structural members are caused by temperature changes, accompanying dimensional changes, and restraint to structural changes.

When restraints are in x-and y-directions, Bednar (1986, 241–256) has published formulae to calculate stresses induced between shell and re-pad due to differential thermal expansion as given below.

$\sigma\text{-}x = \sigma\text{-}y = \alpha E (T1 - T2) / (1\text{-}v)$, *where*: 6

$\sigma\text{-}x$ & $\sigma\text{-}y$ are stresses induced in respective directions.

α = Coefficient of thermal expansion in mm/mm/°K

For SS304, α = 1.73 E-05 mm/mm/°K

E = Modulus of elasticity = 2.00 E+05 MPa

v = Poisson's ratio = 0.3

With above values substituted in formula (6), the thermal stresses due to differential thermal expansion between shell and re-pad with T_{shell} = 486 °K and $T_{re\text{-}pad}$ = 391.5 °K can be found as shown in equation (7) below.

The induced thermal stresses in x- and y-directions are

$\sigma\text{-}x = \sigma\text{-}y = 269\ MPa$. 7

Above exercise was carried out with the ambient temperature assumed to be between 10 deg. C and 50 deg. C at an interval of 10 degrees.

The following graph in Figure 11 shows the induced stresses against various ambient temperatures with vessel operating temperature at 232 deg. C.

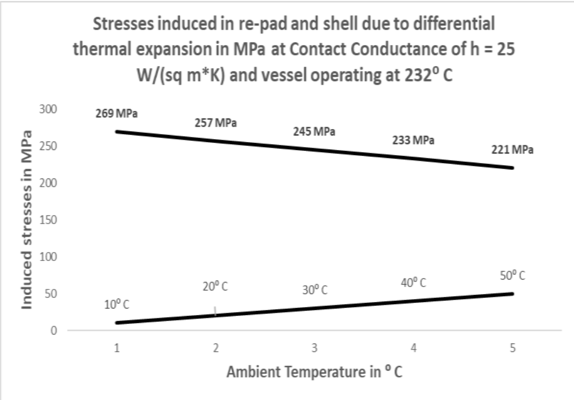

Figure 11 Stresses induced in shell and corresponding re-pad at 232 deg. C process temp.

From the above graphical presentation, as the ambient temperature rises, the stresses induced due to differential thermal expansion are reduced.

Suppose the internal process temperature is reduced from 232 deg. C to 140 deg. C (client was advised to reduce the operating temperature to a minimum that the process allows, which was 140^0C), the induced stresses also reduce further as shown in the graph in Figure 12 below:

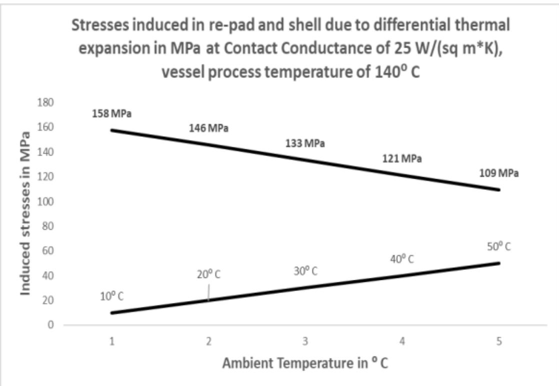

Figure 12 Stresses induced at a process temperature of 140 deg. C

It was also observed that when the thermal contact conductance was changed between 300 and 1800 W/(sq.m*K), the induced stresses varied from 321 MPa to 329 MPa. Figure 13 below shows the increase in contact conductance and change in the stresses induced.

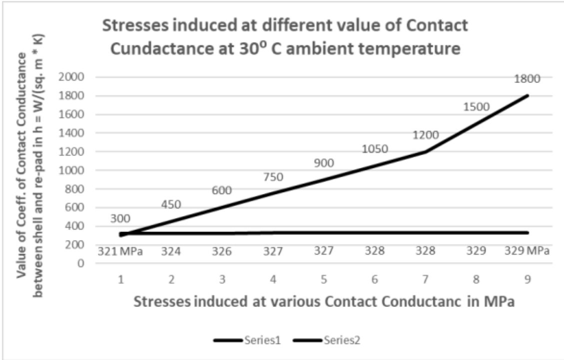

Figure 13 Stresses induced at different values of contact conductance

To confirm potential initiation and presence of thermal fatigue stresses in the mating surfaces of shell and re-pads (on the blind side of vessel shell when seen from inside of vessel or outside of re-pads) phased array ultrasonic testing (ALS PAUT Inspection Report No. 44627.PA.01) was carried out on all locations where re-pads were welded to the shell.

The PAUT inspection of the nozzles with re-pads invariably detected cracks initiated from inside surface propagating perpendicular to the surface. Figure 14 and Figure 15 below show photos of typical circular and rectangular re-pads with white marks showing the blindside's crack locations.

Figure 14 Cracks detected on the outer shell surface-initiated on the blind side of the shell and corresponding re-pad (photo taken from inside of vessel)

The cracks induced are perpendicular to the direction of fatigue stresses. It can be seen that the circular re-pad – shell assembly tries to stretch the peripheral length; hence the cracks are found to be parallel to the periphery. The rectangular re-pad – shell assembly has stresses induced in X and Y direction, and cracks are parallel to fillet welds (Figure 15 below shows cracks along the fillet weld line).

Figures 6, 7, and 8 earlier showed the rectangular pad's position and weldment on the vessel. Figure 15, below, shows the crack locations detected on the re-pad and shell from inside the vessel (at rectangular leg support reinforcement and bracket).

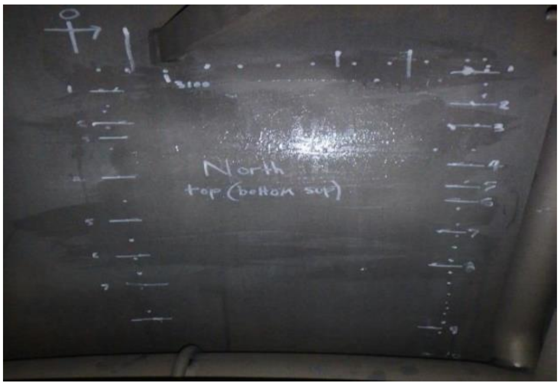

Figure 15 The cracks are perpendicular to X and Y directions following the fillet weld line of rectangular re-pad welded between shell and support legs.

Figure 16, (a) and (b) below show the shell and rectangular re-pad (see the photo in Figure 7) when the vessel fires up and reaches from ambient to operating temperature. It can be seen that the re-pad gets distorted (b). The re-pad surface in contact with the shell elongates due to a rigid fillet weld connection with the shell wall. The cracks are detected along the fillet weld line positioned parallel to the weld line. Cracks originate at the common interface and progress outward in shell and re-pad (b).

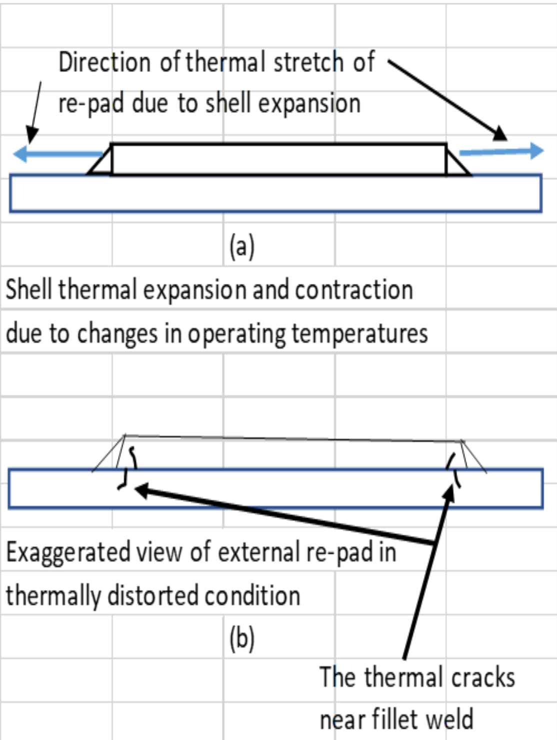

Figure 16 The stretching of re-pad and detected cracks

The cracks were found along the fillet weld near the edge of the re-pad and shell wall, as shown in Figure 17 below.

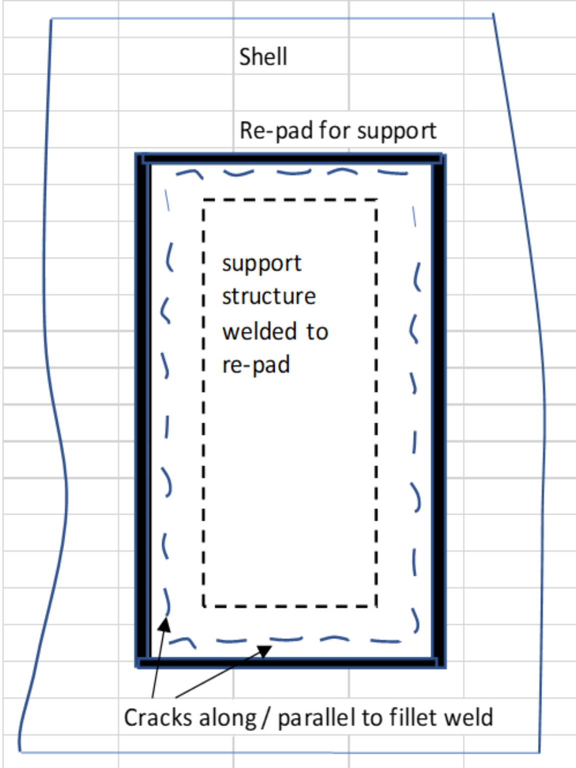

Figure 17 The cracks detected on the support leg re-pad

IV. EXPERIMENTAL ANALYSIS TO SUPPORT THERMAL STRESS ANALYSIS

There was no opportunity to carry out experimental analysis to measure induced stresses on the vessel. The vessel was a part of a critical batch process, and the client could not offer the vessel for experimental analysis. The client allowed the phased array UT to measure the extent of damage incurred to the re-pad – shell assembly. The cracks detected in Figures 14 and 15 provide evidence of cracks following the heavy fillet weld line along the periphery. The direction of crack initiation and propagation confirms the cracks being induced due to thermal fatigue stresses. The client understood the damage done due to a high temperature shut down operation of the un-insulated vessel. The client could not take the vessel offline, and so, it continued to operate the Reactor vessel at reduced capacity, low temperature, and pressure.

An important piece of feedback was received from the client during the author's discussion for the repair strategy. When the author advised replacing re-pads with a single heavier plate shell insert at nozzle opening, the client informed that they replaced reinforcement pads with a single-piece shell insert as part of their repair at one site in Europe strategy.

Further work on a model pressure vessel in a laboratory environment can help establish the effects of thermal fatigue stress failures of re-pad – shell material and measure induced stresses at various temperatures to confirm theoretical calculations performed above.

V. ANALYSIS AND DISCUSSIONS

The purpose of this section is to highlight the fact that design guidelines have identified the initiation of fatigue stresses due to differential thermal expansion at reinforcement plates when the vessel operates above ambient temperature and shuts down frequently. The author's concern is that the thermal fatigue stresses develop on the blind side of the re-pad – shell assembly. This can go unnoticed if the right inspection techniques are not applied. This can lead to a catastrophic failure of the vessel under operating conditions. Even if it leaks, to start with, too many reinforced openings can demand a very expensive repair plan, potentially writing off the vessel.

There is no mandating guideline to insulate the pressure vessels designed to operate at high temperatures under shutdown conditions. From the above thermal fatigue stress calculations and real-life findings, it is observed that the induced thermal fatigue stresses are extremely high, in the vicinity, of yield strength of the material or exceeding it. The nature of crack orientation observed suggests that the damage mechanism acting on the re-pad – shell assembly is fatigue due to differential thermal expansion between shell and re-pad.

The technical guidelines reproduced from various design standards and textbooks provide strong arguments in favour of insulating the vessel or eliminating reinforcement pads favouring thicker, single-piece shell insert where reinforcement is required when operating at higher than ambient temperature.

WHAT FOLLOWS ARE RELEVANT QUOTES FROM STANDARDS OR HANDBOOKS AS LISTED BELOW

1. **The Australian standard for pressure vessel design (AS 1210-2010) Section 3:**
   - *3.2.3 Design loadings*

(l) Forces due to temperature conditions, including the effects of differential expansion of parts or attached piping.

(n) Forces due to fluctuating pressure or temperature.

- *3.18.4 Size of openings*

In cylindrical, conical, and spherical shells.

(i) the reinforcement provided, be distributed close to the junction (a provision of about two-thirds of the required reinforcement within a distance of 0.25d on each side of the finished opening is suggested);

(iii) reinforcement often may be advantageously obtained using a more massive shell plate for a vessel course or inserted locally around the opening.

2. **The American standard for boiler and pressure vessel (ASME Section VIII Div. 1-2017):**
   - UG-22 - LOADINGS

(h) temperature gradients and differential thermal expansion;

3. **American Petroleum Institute standard (API.571 2003)**

Para 4:
Thermal fatigue
Description of damage

Critical factors.

c) Start-up and shutdown of equipment increase the susceptibility to thermal fatigue. There is no set limit on temperature swings; however, cracking may be suspected if the temperature swing exceeds about 200 degrees as a practical rule. F (93 deg. C).

d) Damage is also promoted by rapid changes in surface temperature that result in a thermal gradient through the thickness or along the length of a component, for example, cold water on a hot tube (thermal shock); *rigid attachments and a smaller temperature differential; inflexibility to accommodate differential expansion.*

Appearance or morphology of damage.

a) Thermal fatigue cracks usually initiate on the surface of the component. They are generally wide and often filled with oxides due to elevated temperature exposure. Damages may occur as single or multiple cracks.

b) Thermal fatigue cracks propagate transverse to the stress, and they are usually dagger-shaped, trans-granular, and oxide filled. However, cracking may be axial or circumferential, or both, at the same location.

4. **American Petroleum Institute standard (API.579-1 2007)**

I.93 Thermal Stress – A self-balancing stress produced by a nonuniform distribution of temperature or differing thermal coefficients of expansion. Thermal stress is developed in a solid body whenever a volume of material is prevented from assuming the size and shape that it normally should under a change in temperature. To establish allowable stresses, two types of thermal stress are recognized, depending on the volume or area in which distortion takes place. General thermal stress that is associated with the distortion of the structure in which it occurs. Suppose the stress of this type, neglecting stress concentrations, exceeds twice the yield strength of the material. In that case, the elastic analysis may be invalid, and successive thermal cycles may produce incremental distortion. Therefore, this type is classified as secondary stress. Examples of general thermal stress are the stress produced by an axial temperature distribution in a cylindrical shell, the stress produced by the temperature difference between a nozzle and the shell to which it is attached, and the equivalent linear stress produced by radial temperature distribution in a cylindrical shell. Local thermal stress is associated with almost complete suppression of the differential expansion and thus produces no significant distortion. Such stresses shall be considered only from the fatigue standpoint and are therefore classified as local stresses.

- ***ANNEX B4***

B4.2.2 Local Thermal Stress – Local thermal stress is associated with almost complete suppression of the differential expansion and produces no significant distortion. Such stresses shall be considered only from the fatigue standpoint and are therefore classified as peak stresses. Examples of local thermal stresses are the stress in a small hot spot in a vessel wall, the non-linear portion of a through-wall temperature gradient in a cylindrical shell, and the thermal stress in a cladding material a coefficient of expansion different from that of the base metal. Local thermal stresses are characterized by having two principal stresses that are approximately equal.

5. Pressure vessel design handbook (Bednar 1986). Para 1.3. DESIGN TEMPERATURE

For shutdown conditions, the maximum design temperature for an un-insulated vessel and connecting piping will be the equilibrium temperature for metal objects, approximately 230 deg. F (110 deg. C) for torrid zone, 190 deg.F (88 deg.C) for temperate zone and 150 deg.F (66 deg.C) for frigid zone where:

- The Torrid Zone refers to the Earth's area between the Tropic of Cancer and the Tropic of Capricorn. Geographically, the Torrid Zone is defined by 23.5 degrees North latitude and 23.5 degrees South latitude. The tropical zone is another name for the Torrid Zone. For **Torrid Zone**, **the vessel to be insulated above the design temperature of 110 deg. C**.
- The North Temperate Zone extends from the Tropic of Cancer (approximately 23.5 deg. North latitude) to the Arctic Circle (approximately 66.5 deg. north latitude). The South Temperate Zone extends from the Tropic of Capricorn (approximately 23.5 deg South latitude) to the Antarctic Circle (at approximately 66.5 deg. south latitude). **For Temperate Zone, the vessel to be insulated above design temperature 88 deg. C.**
- Either of the two zones of the Earth of extreme latitude, the North Frigid Zone, extending north of the Arctic Circle, or the South Frigid Zone, extending south of the Antarctic Circle. For **Frigid Zone, the vessel to be insulated above the design temperature of 66 deg. C.**

VI. CONCLUSIONS AND RECOMMENDATIONS

The cracks induced in re-pads and corresponding shell area due to thermal fatigue initiate the surfaces that are on the blind side of the vessel shell and re-pad (mating faces between re-pad and shell). These cracks are not visible until they progress through the thickness of the wall and cause leakage. Hence the situation can become catastrophic if not detected earlier.

The Australian design standard for 'Pressure Vessels' (AS 1210) and American design standard for pressure vessel (ASME Section VIII Div. 1) do not mandate insulation of vessel or a single piece thick shell to the vessel at nozzle opening where reinforcement is required by design calculations and vessel operates above ambient temperature and under shut down conditions. Reinforcement can be either by a doubling pad or thicker shell area where the nozzle opening is to be cut out. If the vessel is not insulated and operates at higher temperatures under shutdown conditions, the author recommends a single thicker wall shell or insulation of the vessel.

Advanced inspection techniques such as Phased Array Ultrasonic Testing (PAUT) or Time of Flight Diffraction (ToFD) are required to be used to detect the cracks behind the visible side of the wall.

These techniques can detect planar defects below the surface in the metal.

The following steps are recommended to eliminate chances of thermal fatigue cracks and potentially catastrophic failure of the vessel when the vessel design temperature is approximately 60 degrees C or more above ambient temperature, the vessel is un-insulated and operates as a shutdown vessel (frequently shutting down and starting up):

(1) At nozzle opening or where a reinforcement pad is required, use of single thicker shell insert or heavier nozzle to be welded instead of reinforcement pad.

(2) If a reinforcement pad is used at nozzle opening, insulate the vessel if the design temperature is 60 degrees or more, above ambient temperature and vessel shuts down frequently.

(3) Apply slow heating or cooling process during start-up or shut down to allow a slow temperature gradient.

(4) If the vessel is already operating above ambient temperature, not insulated, and frequently shuts down, carry out PAUT/ToFD techniques to scan the re-pads and the shell wall (from inside) near the weld joint. This inspection technique can detect the potential presence of cracks on the other side of the plate being inspected.

ACKNOWLEDGEMENTS

The author acknowledges his employer ALS Industrial for getting Phased Array Ultrasonic Testing (PAUT) of the shell area directly under the re-pads, reviewing the PAUT inspection reports, and

allowing various clarification with the reporting technicians as a part of the investigation.

REFERENCES

[1] API (American Petroleum Institute). 2003. API RP 571: Damage mechanisms affecting fixed equipment in the refining industry.

[2] API (American Petroleum Institute). 2007. API 579-1/ASME FFS-1- Fitness-for-service.

[3] AS 1210–2010: Australian standard for the design of unfired pressure vessels. Published by SAI Global Limited under license from Standards Australia Limited, GPO Box 476, Sydney, NSW 2001, Australia

[4] ASME (American Society of Mechanical Engineers). 2017. ASME VIII: Boiler and Pressure Vessel Code DIV 1.

[5] Bednar, Henry H., 1986. Pressure vessel design handbook. 2nd ed.

[6] Çengel, Yunus A., and Afshin J. Ghajar. 2011. Heat and mass transfer: fundamentals and applications. 4th ed. New York: McGraw-Hill.

[7] PAUT Inspection Report No. 44627.PA.01 - Phased Array Ultrasonic Testing of Reactor Vessel Dated 27/05/2017