Fitness for Service: Using NDT and Inspection

BS 7910, API 579 methodology

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What is Fitness for Service Assessment

- Quantitative engineering analysis performed to demonstrate Structural Integrity of an in-service item, due to:
  - Presence of a flaw by cracking mechanism or deterioration by thinning mechanism
  - Material properties change and / or metallurgical damage
  - Concerns on not meeting current design standards or best practices
  - Concerns on current operating conditions or fault scenarios
  - Changes in operating conditions which are more onerous than current
  - Operation under high temperature creep environment
  - Operation under mechanical or thermal fatigue environment
- FFS is carried out on static equipment
  - All types of pressure vessels such as reactors, distillation columns, absorbers, strippers, reformers, fired heaters, heat exchangers, Piping and Storage tanks, Utility plant items: e.g. furnace tubes, boiler drum, de-aerators, headers, economisers

Codes and Standards

- FFS assessment involve one or more codes and standards
  - BS 7910, API 579
  - Design codes such as ASME, British standard BS 5500 or European design codes
  - Guidance documents issued by recognized Associations or Authorities
  - Good engineering, Root Cause analysis & NDT practices recognized by the industry

Need for Fitness for Service

- ASME, API, BS 5500 & other recognized Design codes provide rules for design and fabrication of new items of plant
  - e.g. pressure vessels, piping & storage tanks
  - These codes do not address the fact that many items deteriorates during operation & that defects due to deterioration or from original fabrication, which are larger than allowed by the “Quality Control levels” found during in-service inspections.
    - The design codes do not address the fact that the mechanical properties and / or metallurgical status of some materials can change over time, under specific operating conditions.
- Acceptance of flaws found during construction is based on “Quality Control levels”.
  - Quality Control levels are usually both arbitrary and conservative, but are of considerable value as they provide a route to achieve reasonable consistency and confidence in the quality of the finished items.

FFS Assessment Technology

- When material deterioration exceeding the Quality Control levels are revealed or when material property changes / metallurgical degradation are suspected, rejection of the item is not necessarily automatic.

- The decisions on whether “run as is/ monitor, repair or replace” is based on the derivation of acceptance levels for defects larger than the “Quality Control levels” and / or the demonstration of suitability of materials under specific operating conditions.
  - This is the concept of Fitness-For-Service or FFS applications.
  - An item is considered to be fit for the intended service, provided it can be demonstrated (with acceptable safety margin) that the conditions to cause failure are not reached within a predetermined time period, giving due regard to the HSE and Business consequence of failure.

Multi-Angle Investigative Approach

- Depending on the complexity of an item & the problems, one or more expertise (multi-discipline) will be used
    - identify effects of process fluids, applied loads and external environment
    - Identify all damage mechanisms and any interdependency and effects
  - Stress analysis (can range from basic code calculations to Finite Element Analysis)
  - Metallurgical Investigations and Root Cause Analysis
  - Fracture Mechanics assessments
  - Remaining life calculations
  - Assessment of acceptable and optimized Inspection Interval & Inspection Methods based on risk & consequence of failure

Output of Fitness for Service Assessment

- Final output will include one or more of the following
  - Tolerable defect sizes and defect growth rates
  - Remaining life
  - Revised operating limits and/or other risk mitigating measures
  - Design improvements
  - Suitable NDT inspection methods and acceptable / optimized inspection interval

- Management can take important and timely decisions regarding:
  - To run item as is and at what inspection interval
  - To monitor defect and at what monitoring frequency
  - To repair or replace item and when should be carried out
  - To revise operating conditions
  - To modify design

Overview of API 579
General

- Applicable to pressurized components in pressure vessels, piping, and tankage (principles can also be applied to rotating equipment)
- Highly structured document with a modular system based on flaw type/damage condition to facilitate use and updates
- Multi-level assessment - higher levels are less conservative but require more detailed analysis/data
  - Level 1 - Inspector/Plant Engineer
  - Level 2 - Plant Engineer
  - Level 3 - Expert Engineer

Overview of API 579
General

- General FFS assessment procedure used in API 579 for all flaw types is provided in Section 2 that includes the following steps:
  - Step 1 - Flaw & damage mechanism identification
  - Step 2 - Applicability & limitations of FFS procedures
  - Step 3 - Data requirements
  - Step 4 - Assessment techniques & acceptance criteria
  - Step 5 - Remaining life evaluation
  - Step 6 - Remediation
  - Step 7 - In-service monitoring
  - Step 8 - Documentation
- Some of the steps shown above may not be necessary depending on the application and damage mechanism

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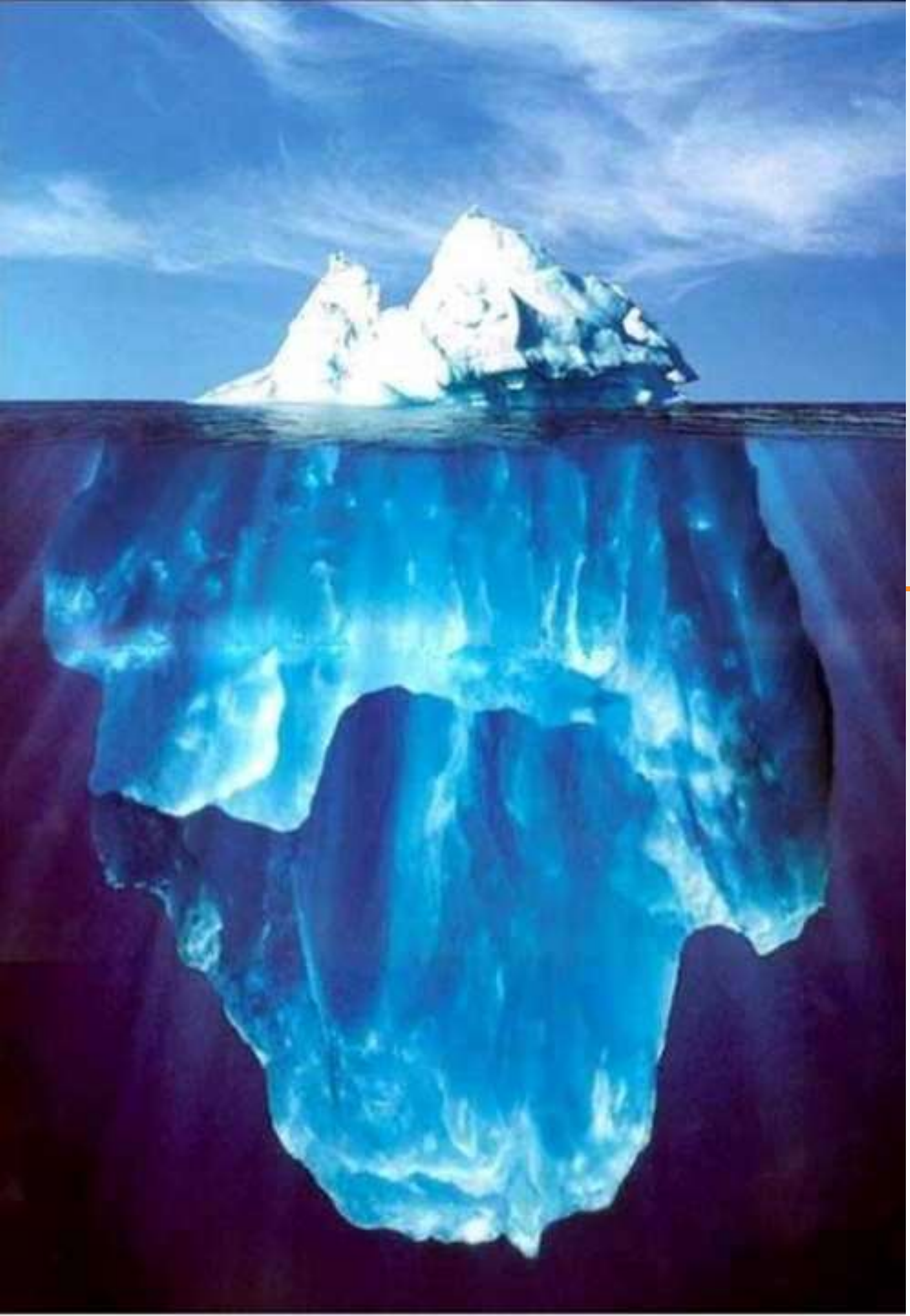
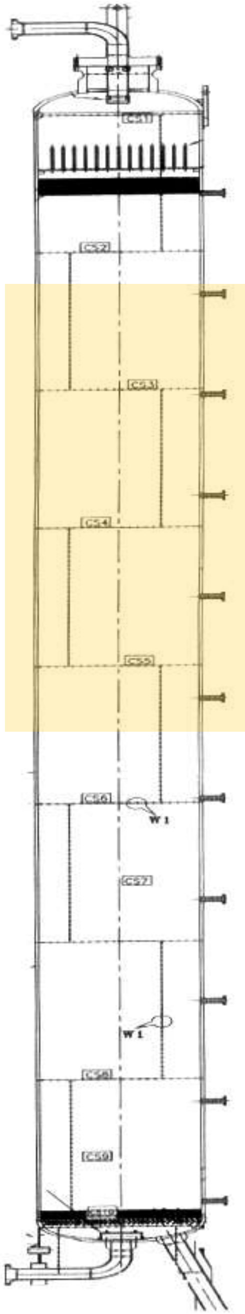


Case Study: FFS Assessment

Examples of Fitness-For-Service assessment work successfully carried out by TCR

Isomerization reactor



Location of temperature excursion

- First 4 shells from Top
- Highest temperature recorded at shell 2
- Maximum temperature recorded 710° C

Thermocouple	Thermocouple Location	Temperature (° C)	Duration
TW2	2^{ND} bed from top	710	1 min
		>700	9 min
		>600	44 min
	(Design limit)	>340	3h 10min
TW3	3^{RD} bed from top	616	1 min
		>600	9 min
	(Design limit)	>340	4h 24min
TW4	4^{TH} bed from top	465	1 min
		>400	5h 26min
	(Design limit)	>340	6h 55min

Operating and design parameters

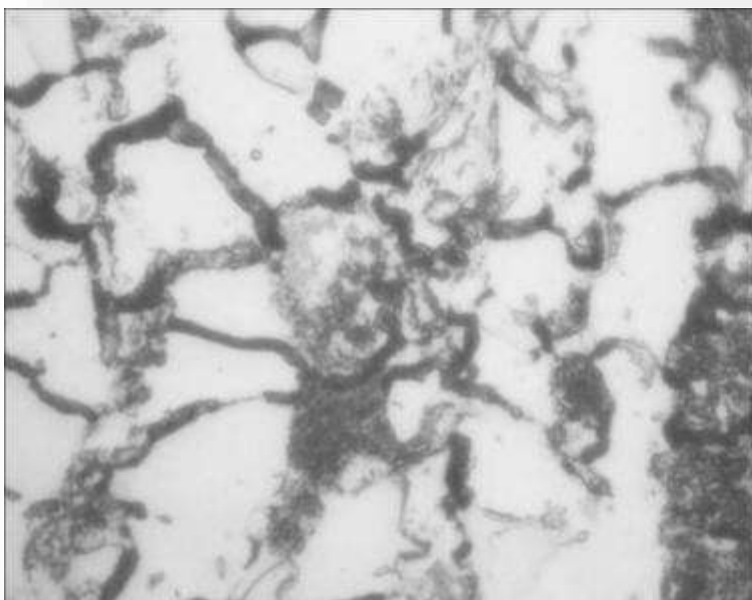
<table>
<tr><td>Normal operating service fluid</td><td colspan="2">C5 / C6 CUT + Hydrogen + Dry Hydro chloric acid</td></tr>
<tr><td>Operating temperature</td><td>165 °C</td><td rowspan="2">(End of run) operating parameters (reactor outlet temperature and reactor inlet pressure)</td></tr>
<tr><td>Operating pressure</td><td>35 kg/cm^2</td></tr>
<tr><td>Sulphur stripping operation</td><td colspan="2">Hydrogen + Hydrogen sulphide + Dry Hydro chloric acid</td></tr>
<tr><td>Operating temperature</td><td>310 °C</td><td></td></tr>
<tr><td>Operating pressure</td><td>23.7 kg/cm^2</td><td></td></tr>
<tr><td>Shell plate thickness</td><td colspan="2">36.0 mm</td></tr>
<tr><td>TL- TL Height</td><td colspan="2">20100 mm</td></tr>
<tr><td>Inside diameter</td><td colspan="2">1600 mm</td></tr>
</table>

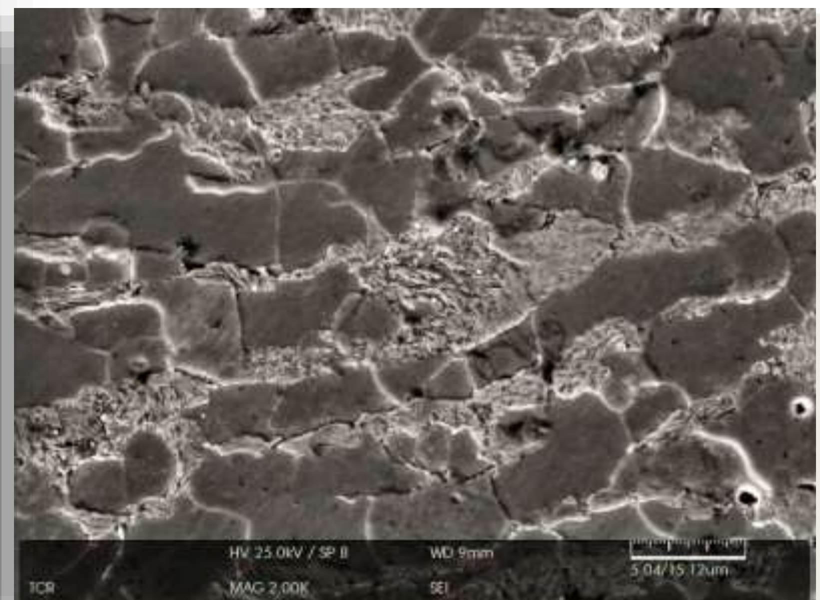
Damage mechanisms

- No operation induced damage- as it has run for 2 months.
- Anticipated damages due to accidental temperature rise :
  - High Temperature Hydrogen Attack (HTHA)
  - Metallurgical degradation of microstructure.
  - Mechanical structural distortion
  - Degradation of mechanical strength
  - High temperature corrosion
  - Integrity of weld joints

HTHA(High temperature hydrogen attack)

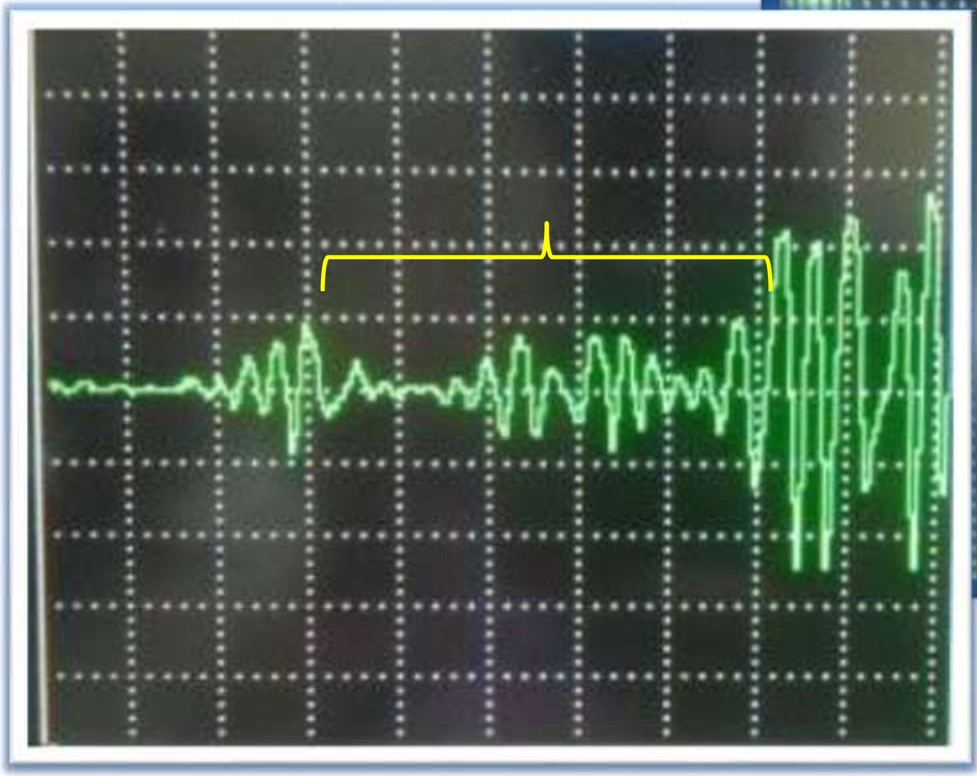
- Hydrogen can diffuse as nascent form in the steel
- Hydrogen reacts with cementite of pearlite in   steel microstructure.
- Carbides dissociate to form methane gas (CH_4)
- Accumulated CH_4 forms micro voids and fissures at grain boundaries

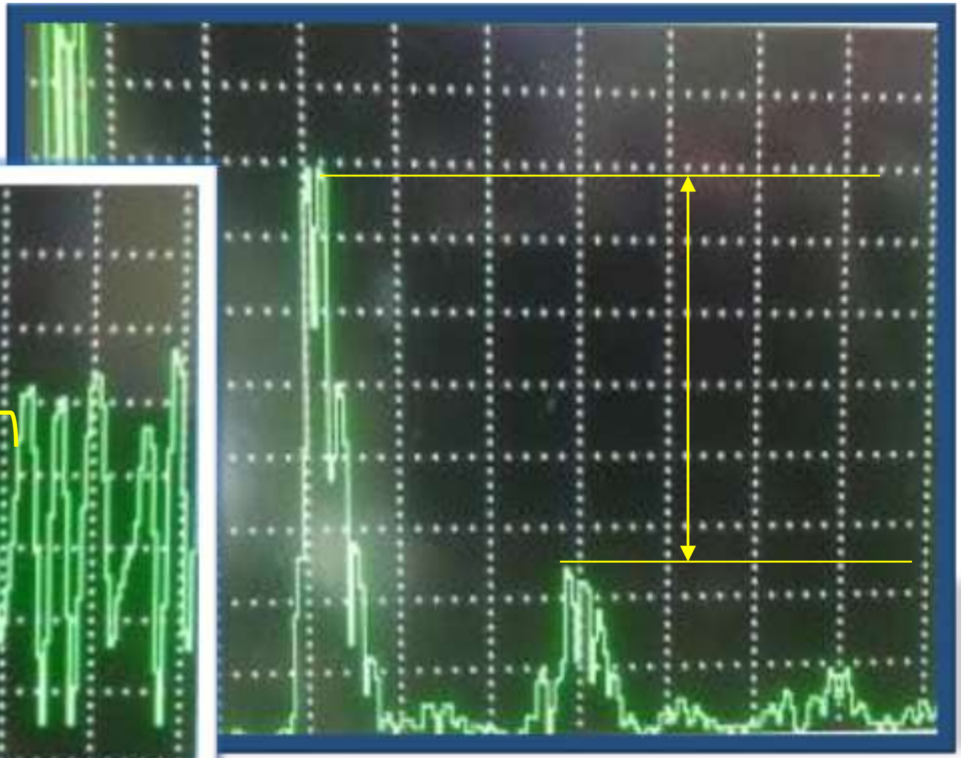




HTHA

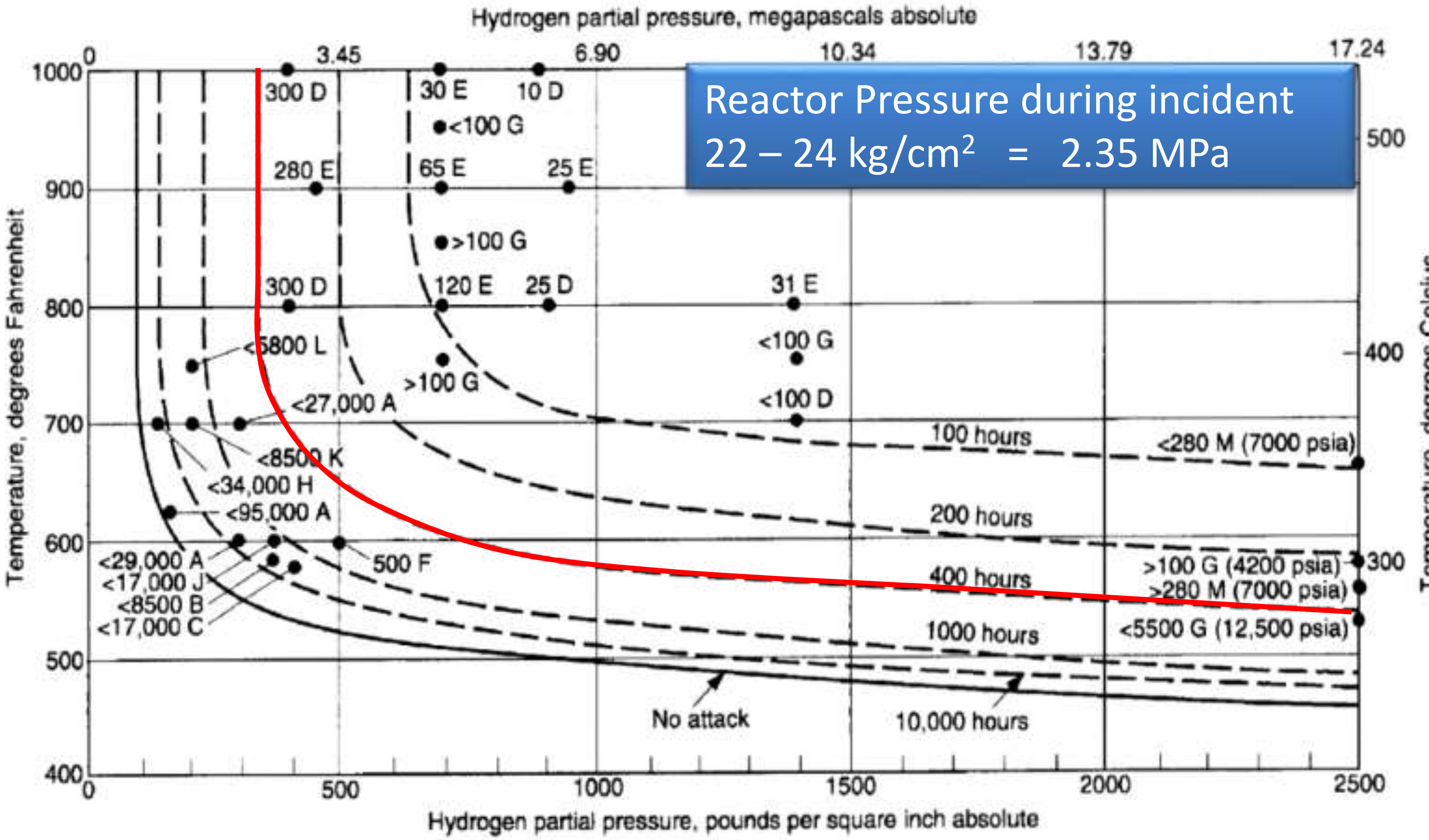
- Detection of HTHA by Advanced Ultrasonic Backscatter Test
- Attenuation Measurements





HTHA

- Probability of HTHA based on nelson curve- API 941



Nelson's Curve : *Guideline API 941*

HTHA

Theoretical Probability of HTHA

Reactor Pressure during incident
$22 – 24\ kg/cm^2 = 341.4$ PSI

The theoretical incubation period $t = C \times P^{-3} \times e^{[Q/(R \times T)]}$

Where, t: Incubation time in hours

C: constant: 1.39×10^6

P: Partial pressure of hydrogen (PSI) = 24 kg/cm^2 or 341.4 PSI

Q: Activation energy 14.6 kcal / mol

R: Gas constant

T: Absolute temperature of exposure (°K) = 710°C or 983°K

Gas constant for hydrogen 'R' = R_U / M_{gas}

Where, R_U : universal gas constant = 1.9858×10^{-3}

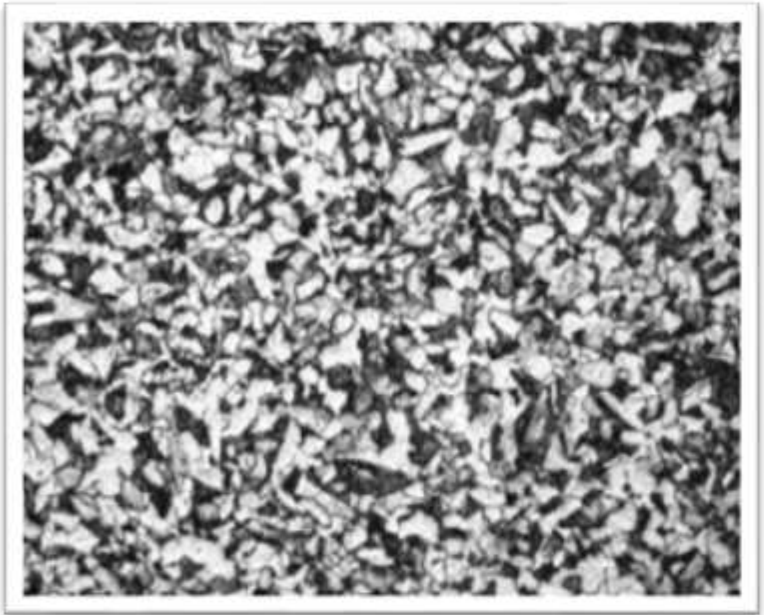
M_{Gas}: Molecular weight of H_2 (1.0079),

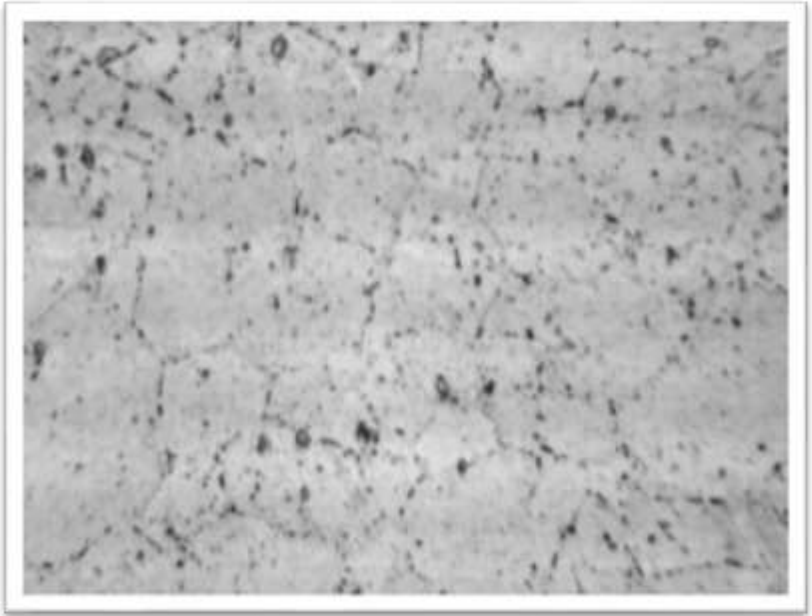
i.e. $t = 1.39 \times 10^6 \times 341.4^{-3} \times Exp\ [14.6 / (1.9702 \times 10^{-3} \times 983)]$

$= 65.6$ h

Metallurgical degradation

- SA516 Grade 70 in normalized conditions has of ferrite and pearlite
- Reactor shell may undergo transformation of phases if the local temperature excursion exceeds 723°C
- Pearlite gets spherodized resulting in reduction of strength





Normal structure Spherodized pearlite

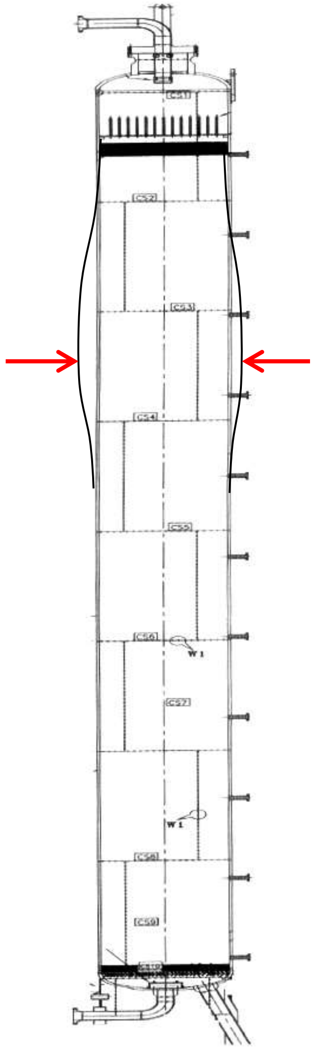
Possible structural distortion

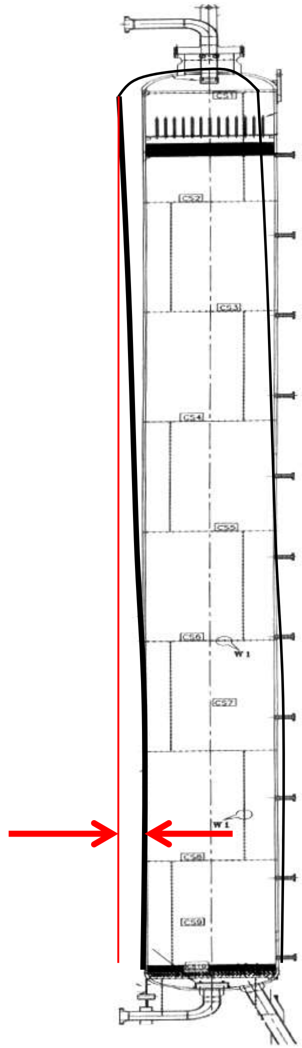
Generally observed as

- Overall or localized bulging of reactor shell
- Leaning / out of verticality of reactor.

Dimensional verification methods:

- Change in outer diameter through circumference measurement
- Plumb measurement at 4 orientations





Other Damage Mechanisms

High temperature corrosion:

- High temperature corrosion in dry hydrochloric acid environment can cause internal damage.
- Can affect effective wall thickness and strength of material in long use
- Can be detected by ultrasonic thickness mapping.

Presence of weld flaws:

- Sudden heat excursion followed by cooling may exert high stresses at the welding joints
- At locations of high stress concentrations, internal defects like crack may occur.
- Presence of internal weld flaws can be detected through
  - Time of Flight Defraction (TOFD) ultrasonic flaw detection
  - ‘A’ scan angle beam ultrasonic method

On-site NDT

Date of inspection	23 to 29 June 2012
Extent of coverage	All shells of reactor, all thermowell and manhole nozzles
Access for inspection	External only
Inspection techniques	Visual examination
	Outside diameter measurement
	Dimension profile of verticality
	Ultrasonic thickness measurements
	Wet Fluorescent Magnetic Particle Inspection
	TOFD Flaw Detection
	AUBT and HTHA detection
	'A' Scan – angle beaming ultrasonic flaw detection
	In-situ Metallographic Replication
	Hardness Measurements

Dimension measurement

	Outer Diameter	Tower Verticality	Shell Thickness
Total points of measurement	3 elevations on each shell	4 elevations on each shell (N, E, S, W)	2 elevations on each shell (N, E, S, W)
Observed minimum value	Circ: 5264 mm OD: 1676 mm (CS1)	6.4 mm (W)	36.6 mm (CS9)
Observed maximum value	Circ: 5275 mm OD: 1680 mm (CS8)	9.3 mm (N)	38.6 mm (W : CS3-CS4)
Maximum deviation	+4 mm Design: 1600	2.1 mm	+0.6 mm Design: 36.0 mm

No structural distortion

No effect of high temperature corrosion

Wfmpi and UT

Wet Fluorescent Magnetic Particle Inspection:

- All weld joints were subjected to 100% inspection, including the nozzles of thermowell and other insulation support clit joints
- **Result: No significant linear indication observed anywhere**

'A' Scan Ultrasonic Flaw Detection:

- Extent of coverage: Weld joint of CS1 and weld joints of top nozzle 'N1'
- Probe angles : 45°, 60°
- Probe frequency: 4 MHz
- Reference :

  V2 Block,

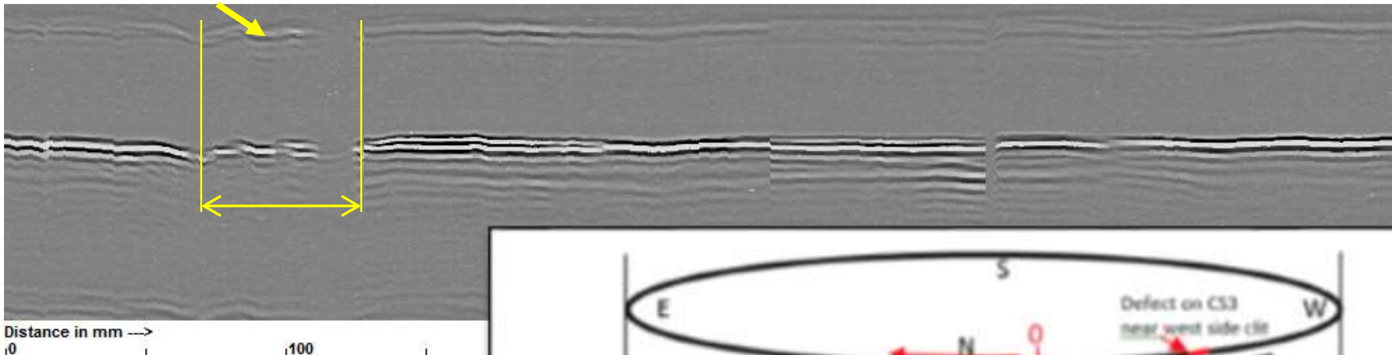
  Distance Amplitude Correction on Ø4mm SDH of similar material
- **Result** : **No significant defect indication was observed**

ToFD

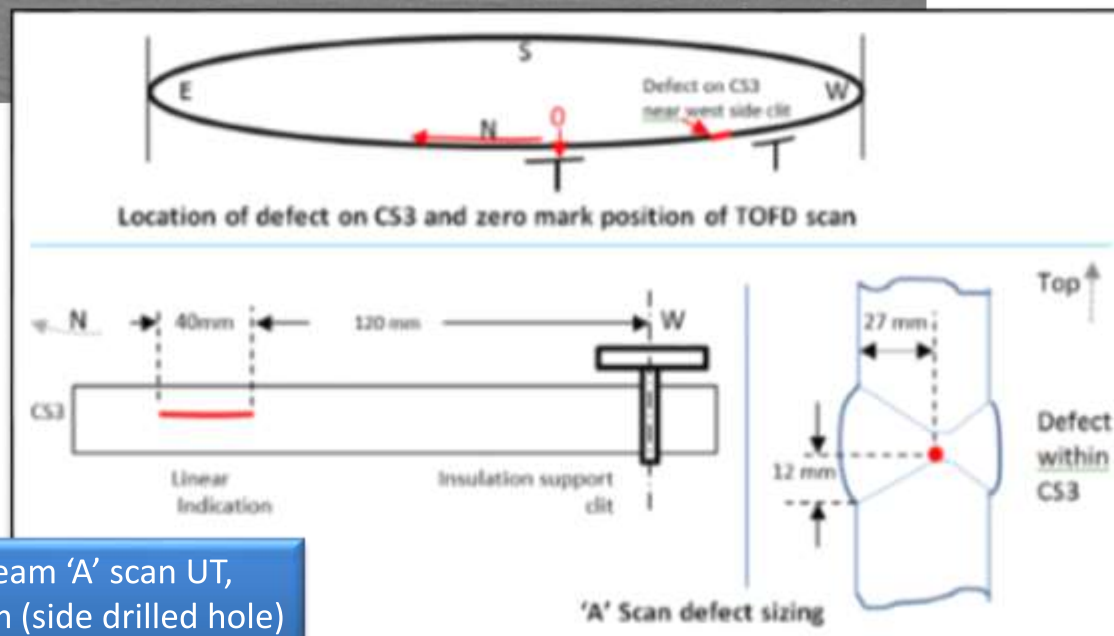
Time of Flight Diffraction (TOFD) Flaw Detection:

Extent of coverage: CS2 – CS5, LS1 – LS3, All Tee Joints

Probes: 2 MHz, Wedge Angle: 60°, Reference: ASME calibration blocks Fig 11.1 - 11.3



Drop in back wall echo with indication of flaw

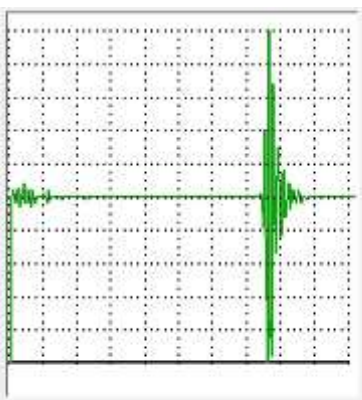
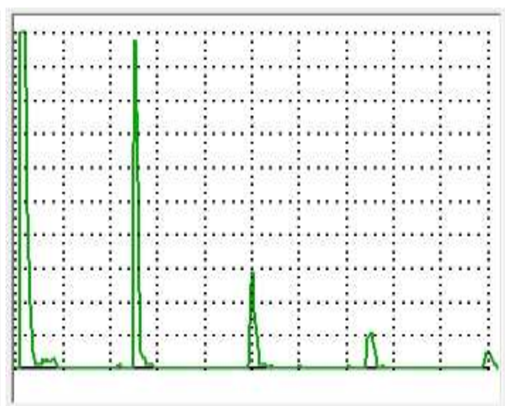
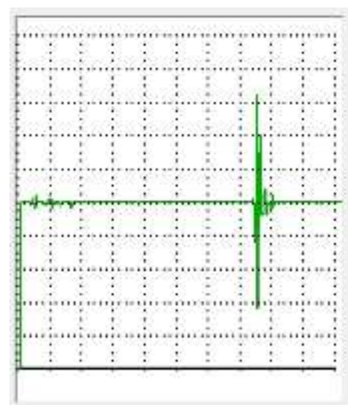
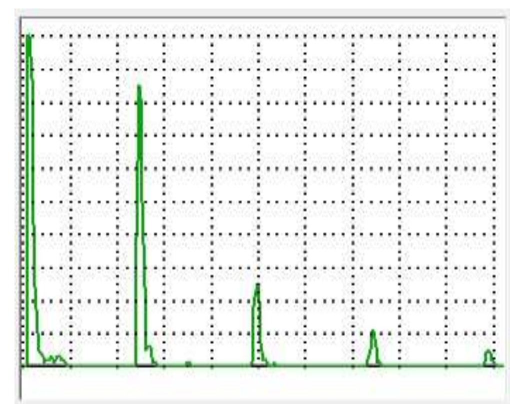


Defect sizing by angle beam 'A' scan UT, size equivalent to Ø4mm (side drilled hole) and 40 mm length

AUBT as per API 941

AUBT : HTHA assessment:

- Extent of coverage: First four shells: 100% scanned with 10% probe overlapping method
- Probes: 10 MHz
- References: (1) Guideline from API 941 (2) Comparison with away region
- No indication of HTHA observed anywhere

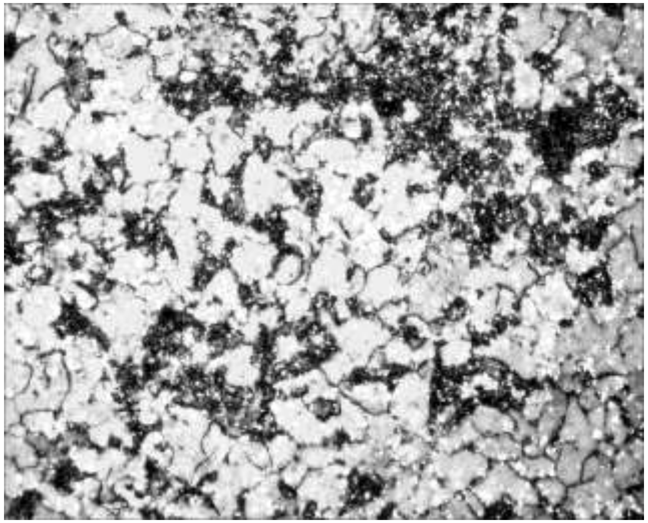
AUBT Attenuation AUBT Attenuation

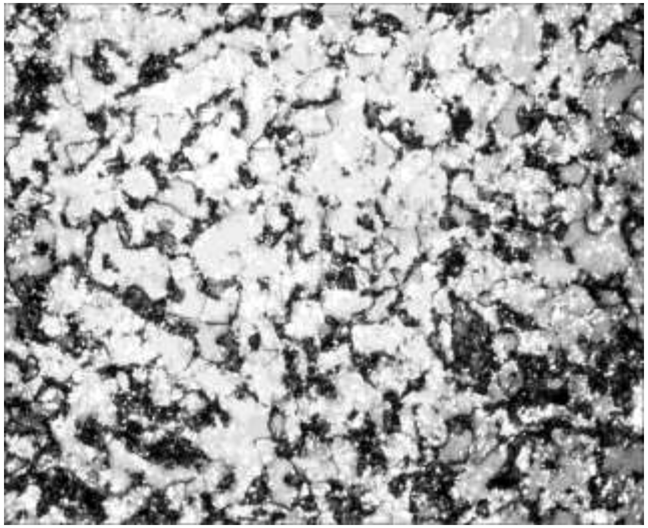
Echo pattern at Shell 2 Echo pattern Shell 8

In situ metallography

In-situ metallographic replication:

- Extent of coverage: Total 60 Locations *(Shell 2 : 16 locations)*
- Method: ASTM E1351 "Practice for production and evaluation of field metallographic replicas"
- Etching technique: Manual swabbing with 2% nital
- No significant change in microstructure is observed, microstructures show ferrite and pearlite structure. ASTM Grain size 9 to 10. No indication of pearlite degradation.
- **Heat excursion on external surface of shell is insignificant**





Structure at Shell 2 | Structure at Shell 8

Hardness

Hardness Measurements:

- Extent of coverage: 60 locations of metallographic replication
- Instrument used:, MIC20-Krautkramer
- Minimum Hardness: Required 147 BHN Measured : 147 BHN

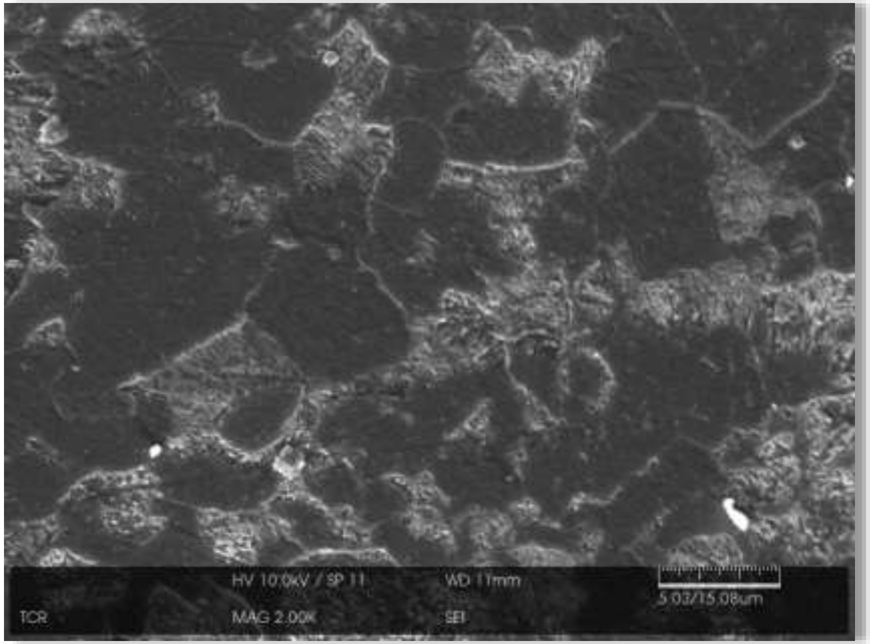
Location	Minimum (BHN)	Maximum (BHN)
Overall Shell hardness range	147	188
Shell 1	148	177
Shell 2	147	170
Shell 3	150	186
Shell 4	156	188
Shell 5	155	172
Shell 6	148	168
Shell 7	151	181
Shell 8	151	169
Overall weld hardness range	162	218

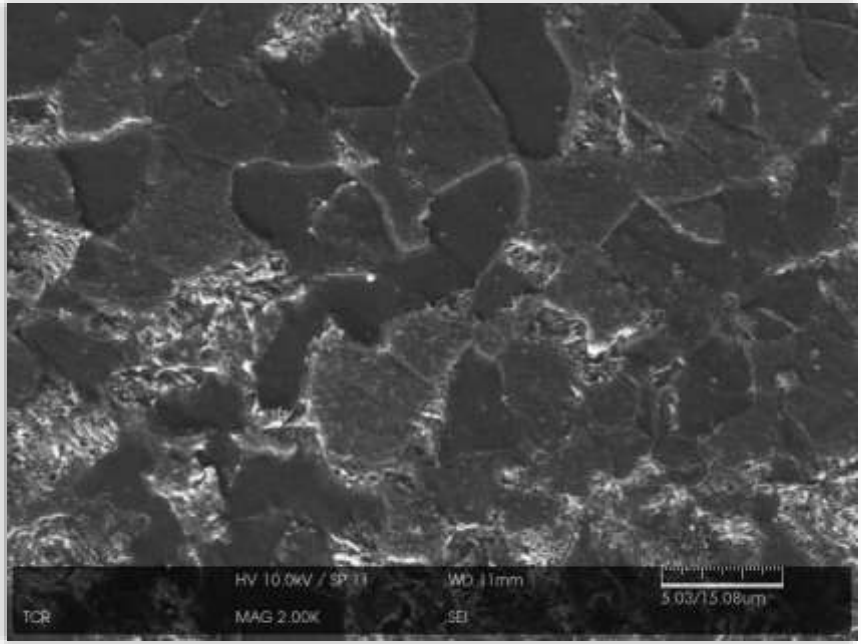
Laboratory finding

Scanning Electron Microscopy (SEM) Observations:

- Extent of coverage: 15% of replicated structures
- Magnification up to 3500X after Gold coating of replica
- Finding: Fine grained ferrite and pearlite structures

  No significant difference in structures



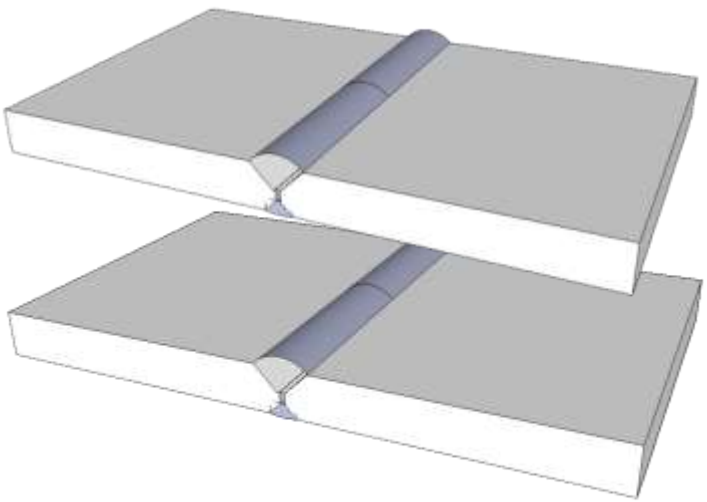


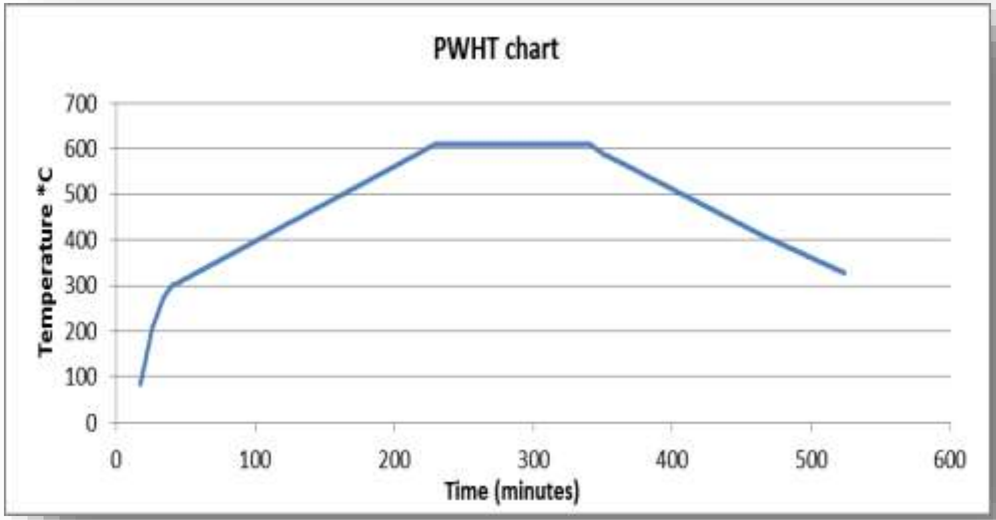
Structure from Shell 2 | Structure from Shell 7

Laboratory simulation experiment

- Two 36mm thick coupon plates were prepared as per WPS given for the equipment
- Two sets of such welded pieces were fabricated at laboratory.
- Both the coupons were Post weld heat treated

  soaking for 2h at 610°C.



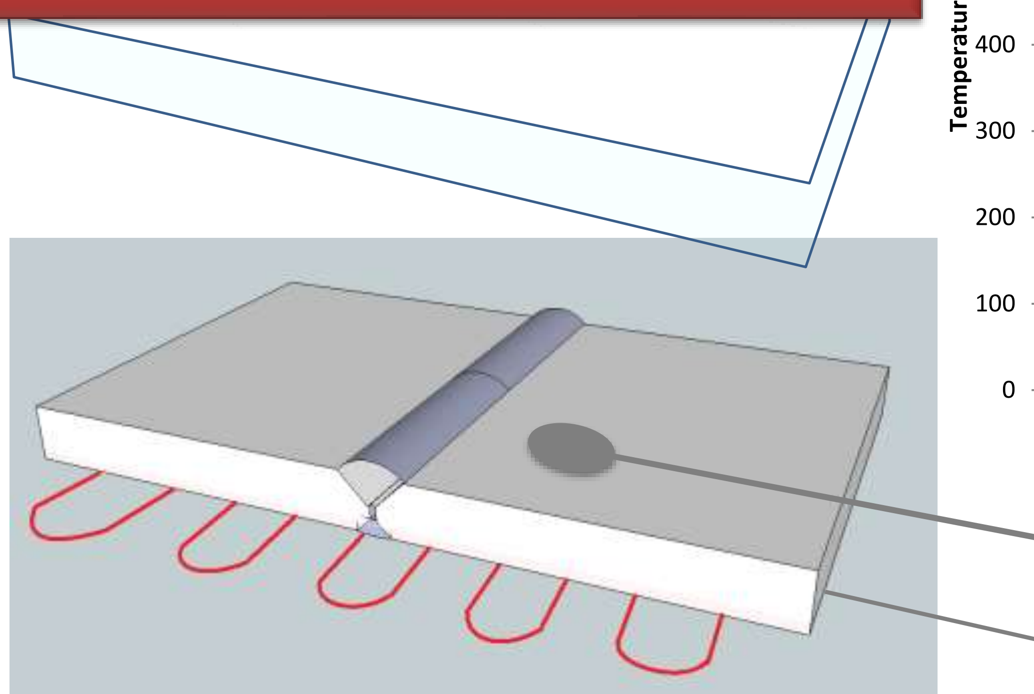


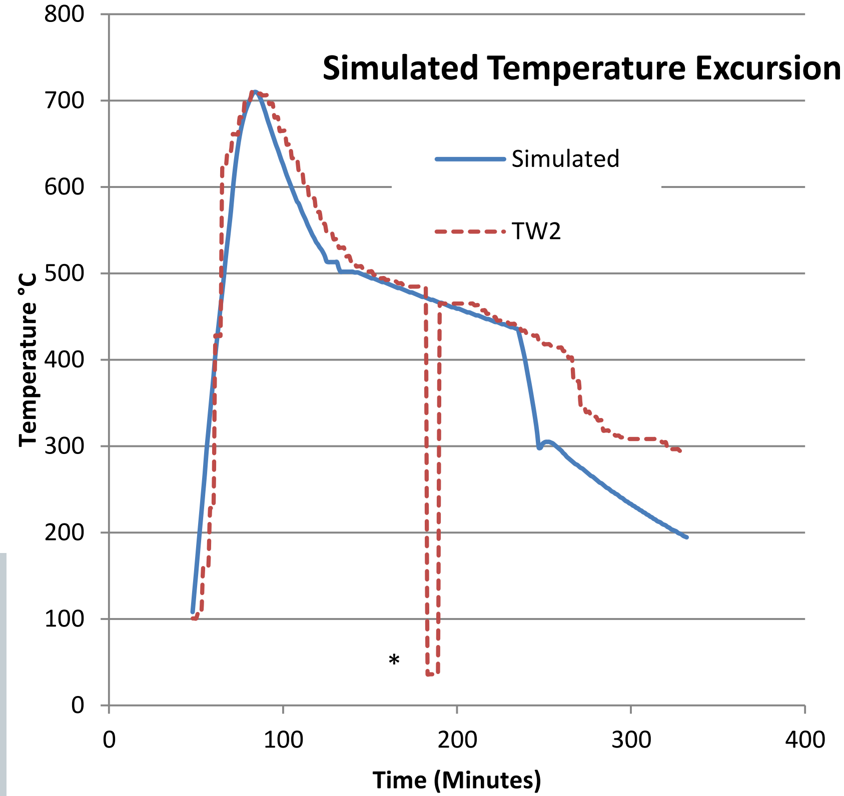
Heat excursion simulation

Welded coupon placed on heater coil

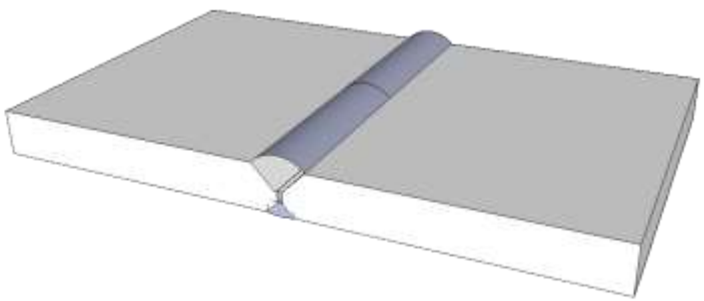
Covered with 45mm thick hot insulation

Control cooling to simulate actual heat excursion



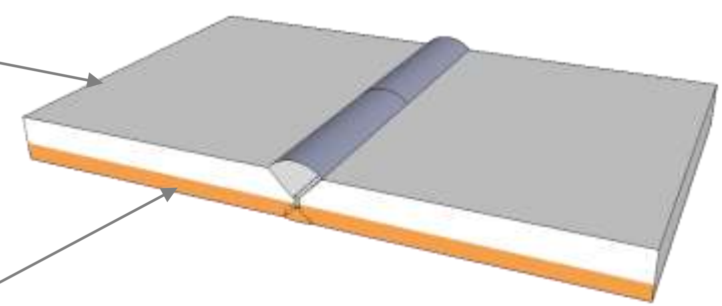


Mechanical tests

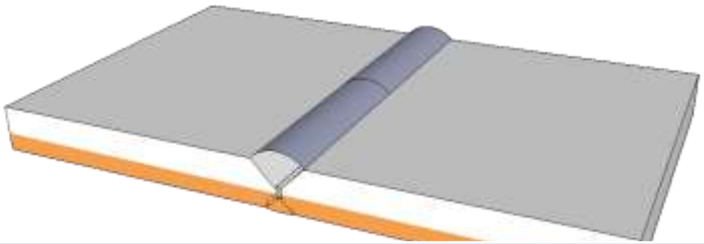


PWHT coupon test result					
	P.M.	Req.	HAZ	Weld	Req.
Y.S. (N/mm^2)	420	260	-	458	400
U.T.S. (N/mm^2)	530	485	-	535	490
E (%)	31	21	-	27.6	22
CVN (Joule)	21	20	23	146	20

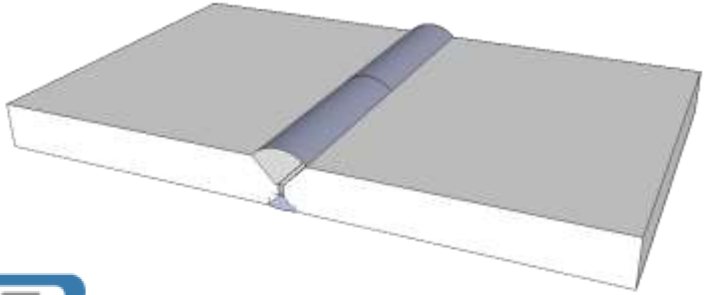
PWHT + Heat Simulated coupon test result			
	P.M.	HAZ	Weld
Y.S. (N/mm^2)	441	-	446
U.T.S. (N/mm^2)	551	-	544
E (%)	35.18	-	26.89
CVN (Joule)	67	21	113
Y.S. (N/mm^2)	**429**	**-**	**373**
U.T.S. (N/mm^2)	558	-	474
E (%)	36.06	-	36.54
CVN (Joule)	179	28	53

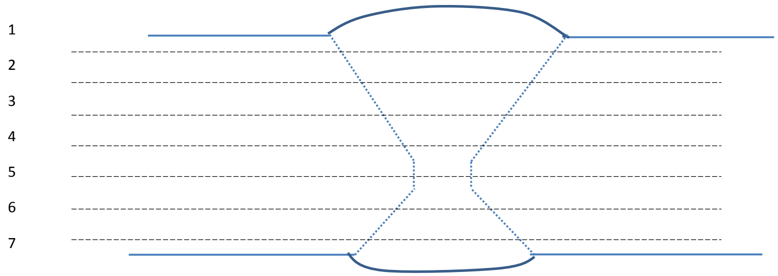


Hardness (BHN)



	PWHT coupon					PWHT + Heat simulated coupon				
	PM	HAZ	WELD	HAZ	PM	PM	HAZ	WELD	HAZ	PM
1	147	148	166	148	166	162	161	171	157	166
2	153	151	169	151	162	169	159	158	150	160
3	147	159	163	156	160	162	161	157	162	166
4	-	161	-	162	-	-	153	-	156	-
5	158	147	165	149	166	154	159	163	159	166
6	164	153	150	153	169	167	159	167	148	167
7	160	149	156	148	158	157	154	161	155	164
Max. Difference			10					10		

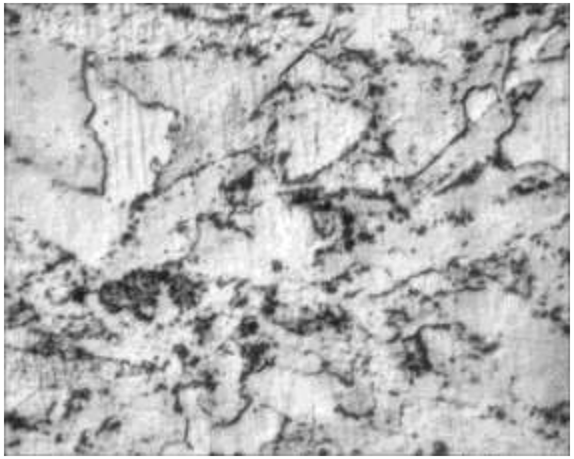


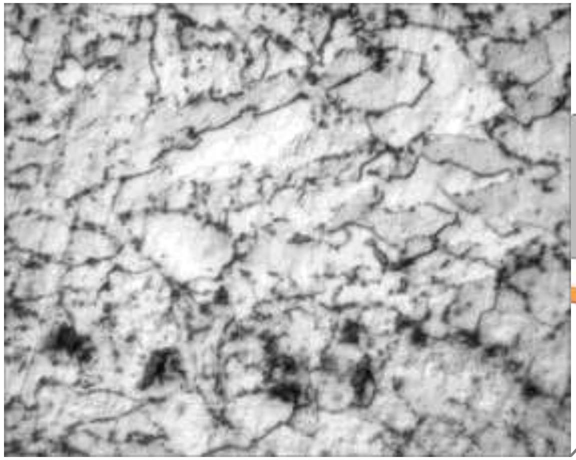


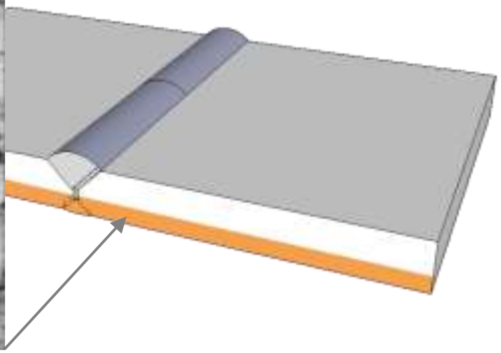
Microstructure

Between PWHT and PWHT + Heat simulated coupons

- Microstructure are of ferrite and pearlite.
- No significant change in grain size after simulated heat excursion.
- Minor effect of spherodization of pearlite.
- No significant change in microstructural properties after short period temperature excursion up to 710°C







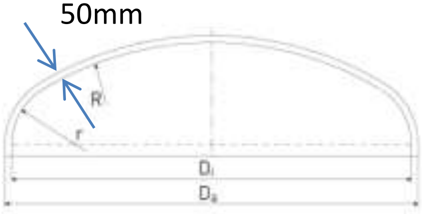
PWHT Coupon

PWHT + Heat simulated coupon (*Bottom*)

Design calculations

Elliptical head design:

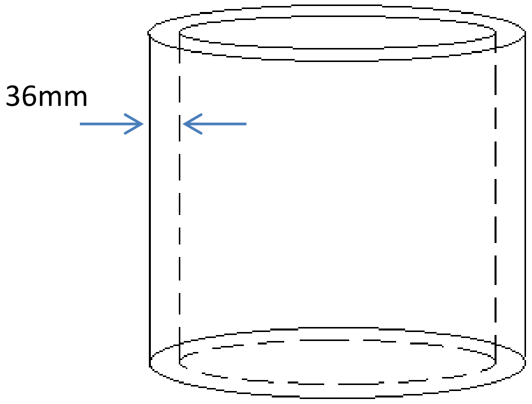
- Thickness Due to Internal Pressure [Tr]:
- = (P*(D+2*CA)*K)/(2*S*E-0.2*P) Appendix 1-4(c)
- = (44.600*(1600.0 + 2*3.0)*1.00)/(2*1406.14*1.0 - 0.2*44.6)
- = 25.55 + 3.0 = 28.55 mm



The available thickness of elliptical head of 50 mm is higher than the minimum required thickness of 28.55 mm.

Cylindrical shell design:

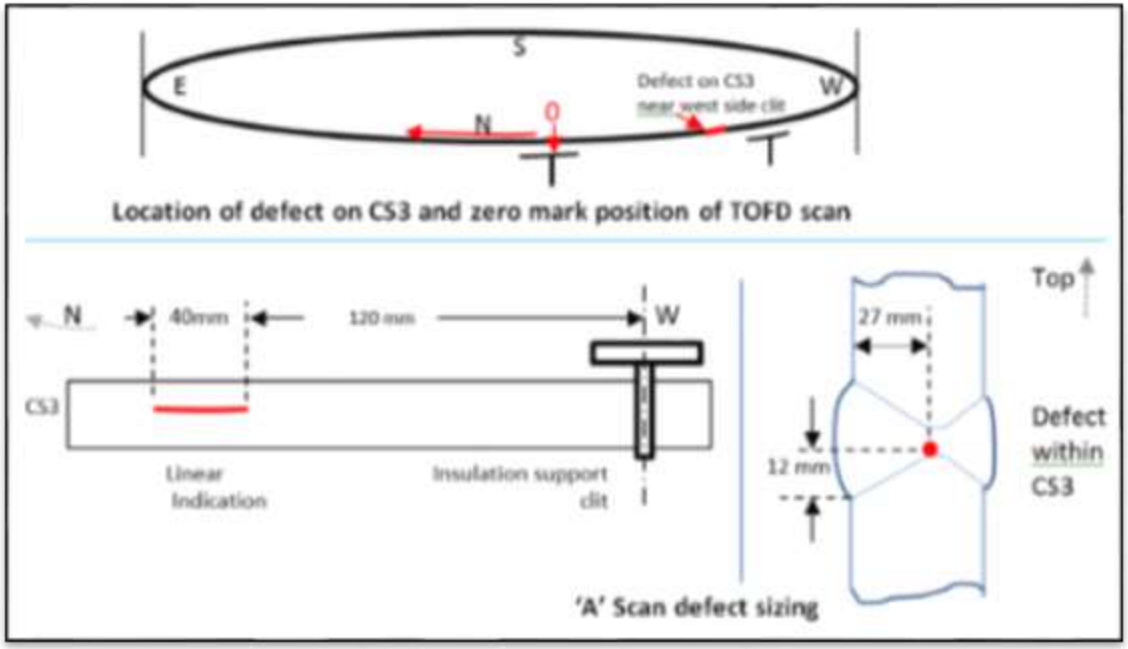
- Thickness Due to Internal Pressure [Tr]:
- = (P*(D/2+Ca))/(S*E-0.6*P) per UG-27 (c)(1)
- = (44.600*(1600.0000/2+3.0000))/(1406.14*1.00-0.6*44.600)
- = 25.9637 + 3.0000 = 28.9637 mm



The available thickness of shell wall of 36.6 mm is higher than the minimum required thickness of 28.96 mm.

Fracture toughness calculation for assessment of crack like flaw in weld

- Any flaw of less than 11mm x 220mm is Safe
- Flaw existing at CS3 has size of SDH Ø4mm x 40mm
- The existing flaw size is less than critical flaw size
- The defect located at CS3 is innocuous to continued safe operation of the reactor



Summary

All anticipated damage mechanisms	
Visual abnormality	No significant visual abnormality
Structural distortion	No significant bulging No change in verticality
HTHA	Did not show significant damage.
High temp. corrosion	No reduction in thickness
Microstructural properties	No significant degradation is observed from external surface. Grain size ASTM 9 to 10 everywhere
Weld joints	No defect observed in WFMPI Defect at CS3 has dimensions less than critical size
Simulation study	Heat simulation indicated the overall strength as acceptable as per minimum requirement of SA 516 gr 70
FFS calculations	The flaw at CS3 is acceptable considering FFS calculations

Judgment of FFS

- From the accessible inspection and simulation studies it is concluded that the reactor has not been affected due to short term exposure to 710° C temperature to an extent that it is of immediate concern. The condition of reactor vessel is considered fit-for-service, for further operation as per OEM design and operation guidelines. Monitoring of flaw size at CS3 weld joint is to be done within next 2 years of operation.
- Considering the limitation of the inspection which excludes internal side of the reactor, regarding distributors, support trays or fittings, no judgment on their internal condition could be provided.

Questions?