Catastrophic Heat Exchanger Failures

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Guest Lecture, Cork Institute of Technology, 04-Oct-16

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Catastrophic Heat Exchanger Failures
Agenda

- **Key points**
- **Process safety**
- **Root cause analysis**
- **Shell-and-tube heat exchanger configurations**
- **Shell-and-tube heat exchanger parts**
- **Incident #1 (gas processing) - Gas Plant channel end rupture [Accident]**
- **Incident #2 (oil refining) - Naphtha Hydrotreater shell rupture [Accident]**
- **Incident #3 (oil refining) - Cat Reformer channel head failure [Near Miss]**
- **Summary (engineering issues, process safety management issues)**
- **References**
- **Questions**

Catastrophic Heat Exchanger Failures
Key Points

- **Most heat exchangers in gas processing and oil refining plant are constructed from carbon or low alloy steels**
- **Carbon and low alloy steels may be susceptible to brittle fracture**
- **Brittle fracture is low probability, high consequence failure scenario**
- **Brittle fracture requires low temperature and presence of flaw + stress**
- **Other factors increasing susceptibility of equipment to brittle fracture include metal degradation, metal quality (grain size) and metal thickness**
- **Abnormal (transient) operating conditions in heat exchangers (startup, fouling, shutdown etc) can create major process safety hazards**

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Process Safety

- **Process safety incidents can have catastrophic consequences including multiple injuries or fatalities, substantial damage to property and/or environment and major economic impacts (eg. lost production and fines)**
- **Important to learn lessons from previous incidents and near misses to raise awareness of potential hazards and minimise risk of or prevent a recurrence of similar incidents**
- **Near miss is an undesirable event which, under different circumstances, could have resulted in a process safety incident**
- **Incident investigation uses methodical examination of facts to identify root cause and recommends remedial actions to control the risks**

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Root Cause Analysis - Terminology

- **Root Cause Analysis (RCA) is a continuous improvement process to identify causes and make recommendations for the prevention of recurring and/or major failures to deliver safe, reliable and compliant operations and reduce long term costs to the business**
- **Immediate or Basic Cause is a sub-standard act or condition that led directly to the incident**
- **Critical Factor is an undesirable act or condition which if eliminated would have prevented occurrence or reduced severity of incident**
- **Root Cause or System Cause is an organisational failing that created circumstances or conditions enabling the incident to take place**

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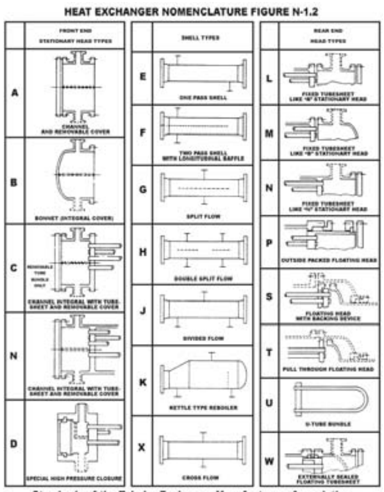
Tubular Exchanger Manufacturers Association (TEMA) Codes

- **TEMA is a trade association of leading manufacturers of shell and tube heat exchangers who produced design standard**
- **TEMA code describes overall configuration of exchanger**
- **Code is 3 letters representing front head, shell and rear head**
- **Type AES is most common:**
  - **A: channel + removable cover**
  - **E: single pass shell**
  - **S: floating head + backing device**



Standards of the Tubular Exchanger Manufacturers Association

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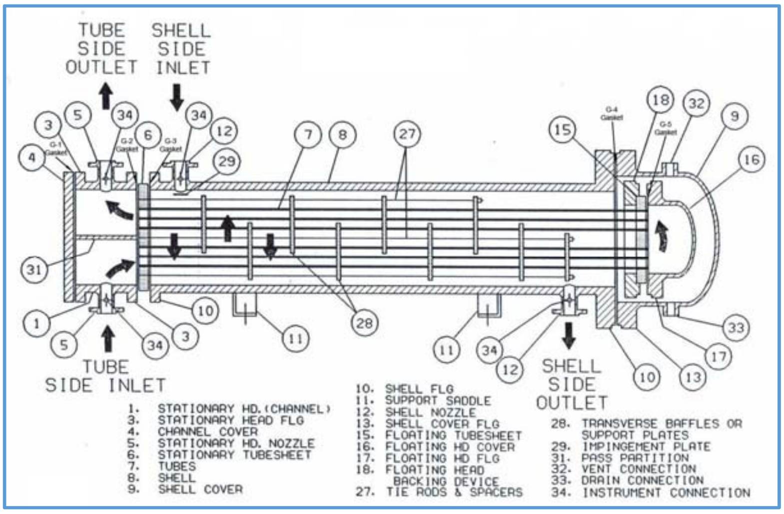
Typical Heat Exchanger Parts List (TEMA Type AES)



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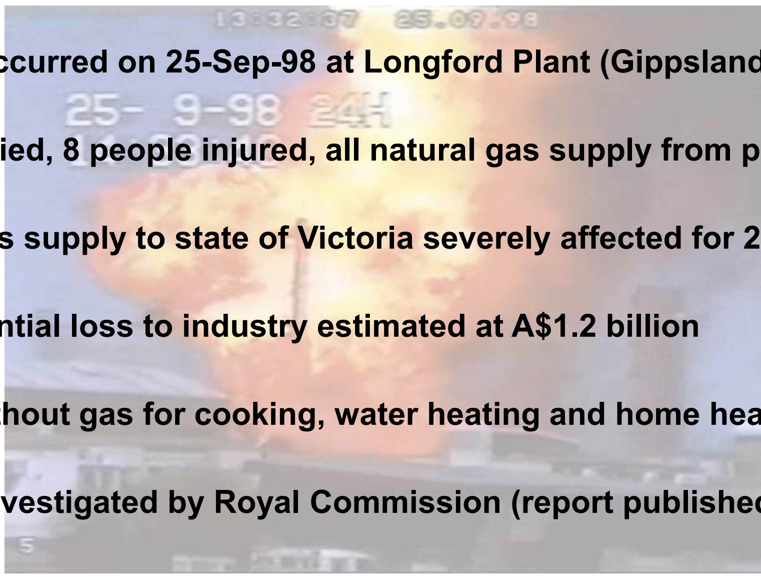
Incident #1 - Longford Gas Plant Explosion



- **Incident occurred on 25-Sep-98 at Longford Plant (Gippsland, Victoria)**
- **2 people died, 8 people injured, all natural gas supply from plant ceased**
- **Natural gas supply to state of Victoria severely affected for 2 weeks**
- **Consequential loss to industry estimated at A$1.2 billion**
- **Homes without gas for cooking, water heating and home heating**
- **Incident investigated by Royal Commission (report published June 1999)**

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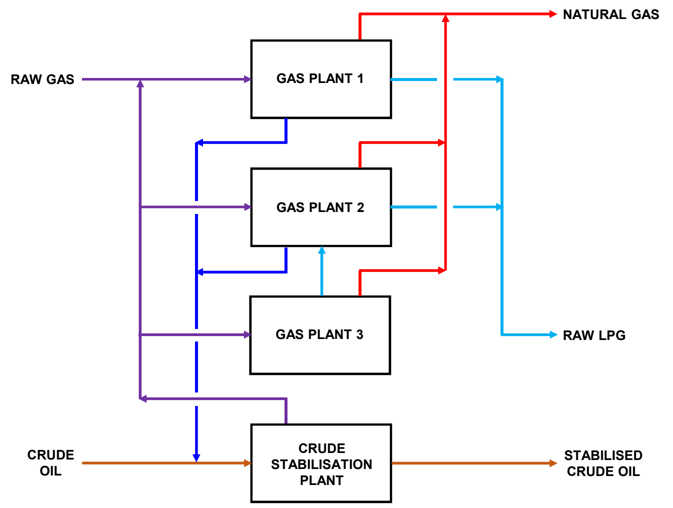
Incident #1 - Site Overview



- **Processes crude oil and raw gas from Bass Strait offshore oilfields**
- **Site comprised:**
  - **Crude Stabilisation Plant (CSP)**
  - **3 x Gas Plants (GP1/2/3)**
- **Gas plants separate and purify incoming gas to make natural gas**
- **GP1 (started 1969) is refrigerated lean oil absorption plant**
- **GP2 (1976) and GP3 (1983) are cryogenic separation plants**

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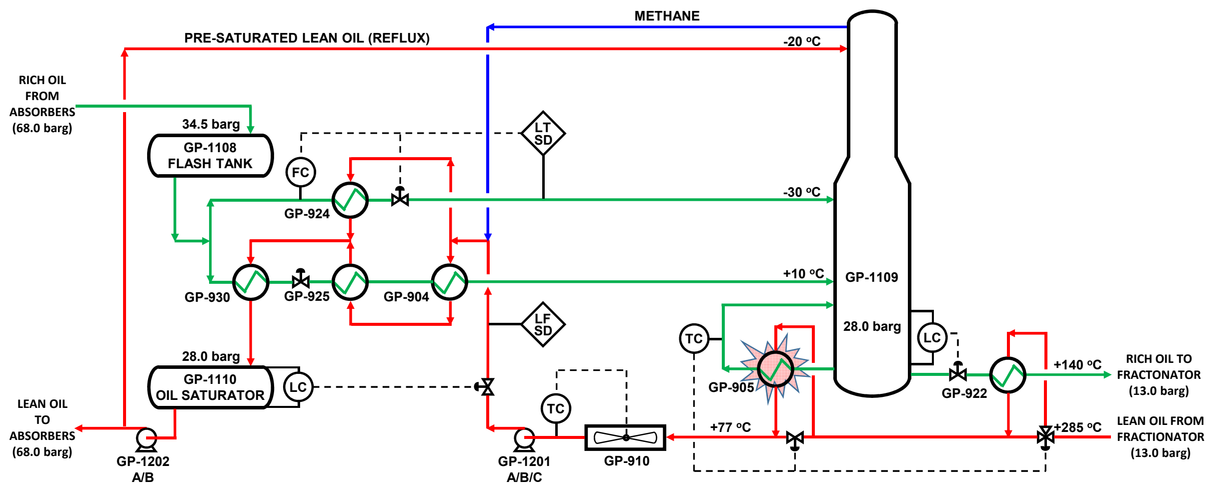
Incident #1 - Rich Oil Deethaniser Process Flow Diagram



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Incident #1 - Sequence of Events

- Upset caused increase in flow and molecular weight of GP1 raw gas feed and condensate began to accumulate in 1 of 2 parallel lean oil absorbers
- Rich oil deethaniser began to flood and puked liquid to saturator tank
- Saturator tank high level caused GP-1201A/B/C lean oil pumps to trip
- GP-1202A/B lean oil booster pumps tripped on saturator tank low level
- Loss of lean oil flow for several hours and ongoing buildup of condensate in lean oil absorber caused condensate carryover to rich oil system
- Pressure letdown from lean oil absorbers to rich oil flash tank caused condensate to flash and chill equipment to abnormally low temperatures

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Incident #1 - Sequence of Events (cont.)

- Deethaniser reboiler (GP-905) shell temperature fell from 100 °C (212 °F) to -48 °C (-54 °F) and ice formed on uninsulated surfaces
- GP-1201 pump restarted and warm lean oil flow resumed to GP-905
- GP-905 steel had become brittle and thermal stress generated by radial expansion of the tubesheet created stress that resulted in brittle fracture
- Vapour cloud containing > 10 tonnes of flammable gas ignited resulting in an intense jet fire beneath elevated piperack junction (“Kings Cross”)
- Unable to isolate leak and flame impingement caused 3 more leaks
- Entire plant inventory was lost and fire burned for more than 2 days

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Incident #1 - Fire Damage

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Incident #1 - Root Cause Analysis

- **Immediate (basic) cause of loss of primary containment (LOPC) was brittle fracture of deethaniser reboiler shell**
- **Critical factors were:**
  - **Intense low temperature of shell due to loss of warm lean oil flow for extended period**
  - **Absence of remote isolation valves to isolate interconnected gas plants**
- **Root (system) causes included**
  - **Inadequate hazard identification (HAZOP not done)**
  - **Inadequate procedures (cold metal embrittlement hazard not recognised)**
  - **Inadequate training (how to deal with loss of warm lean oil flow)**
  - **Inadequate alarm management (alarm flood)**
  - **Inadequate risk assessment (relocation of experienced engineers to remote head office)**
  - **Ineffective incident reporting system (escalation potential of process upsets not considered)**
  - **Inadequate safety management system (inadequate auditing by parent company)**

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Incident #2 - Anacortes Feed/Effluent Exchanger Shell Rupture

- Incident occurred on 02-Apr-10 at Naphtha Hydrotreating unit at Anacortes Refinery (Washington)
- 7 people died (6 operators and 1 shift supervisor)
- Refinery remained shut down for more than 6 months
- Incident occurred during non-routine startup activity (restreaming bank of 3 shell-and-tube heat exchangers after off-line cleaning)
- Incident investigated by US Chemical Safety Board (CSB)
- CSB incident report published in May 2014

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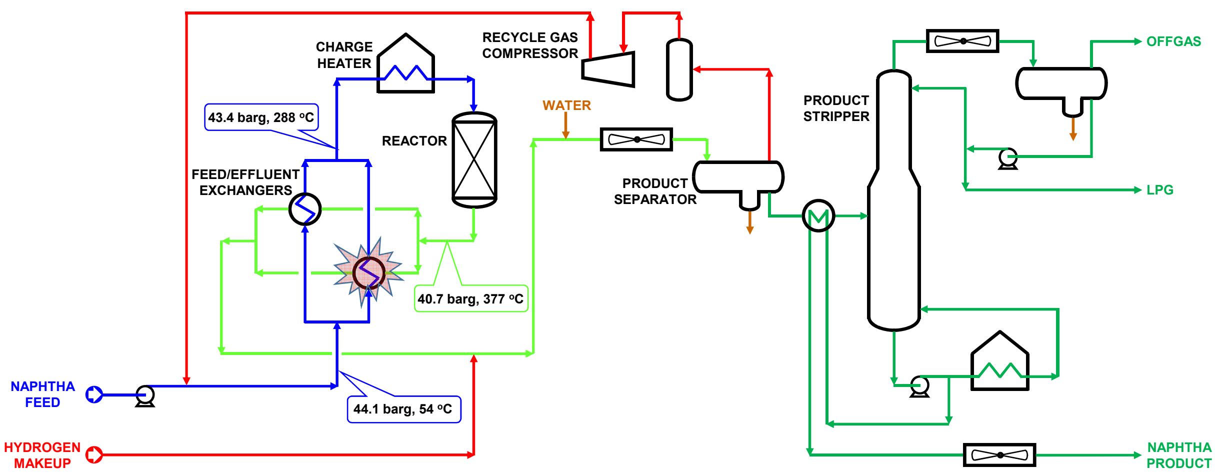
Incident #2 - Typical Naphtha Hydrotreater Flow Diagram



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Incident #2 - Feed/Effluent Exchanger Fire Damage

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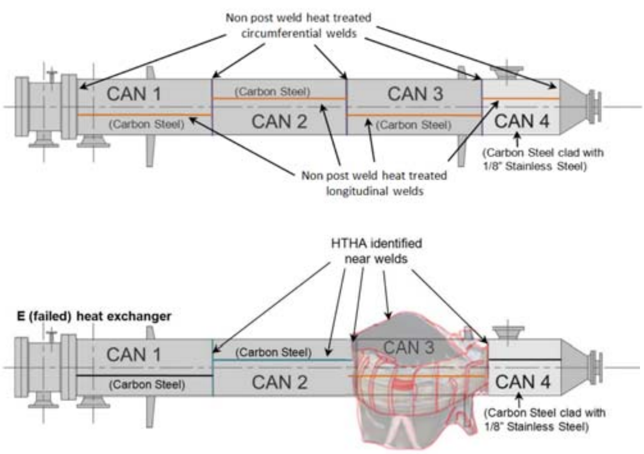
Incident #2 - Exchanger Construction



- **Failed shell (and twin) were fabricated from carbon steel and partially clad with 316 SS**
- **Longitudinal & circumferential seam welds had not been post-weld heat treated**
- **Metallurgical analysis showed shell rupture caused by high temperature hydrogen attack**
- **Shell had been in service for 38 years when it failed**

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Incident #2 - High Temperature Hydrogen Attack

- **High temperature hydrogen attack (HTHA) occurs when carbon and low alloy steels are exposed to high hydrogen partial pressures at high operating temperatures for extended period (exposure time cumulative)**
- **Atomic hydrogen reacts with carbides in the steel to form methane (CH_4) which cannot diffuse through the steel**
- **Loss of carbides weakens the steel and accumulation of CH_4 pressure in the steel creates cavities and fissures which combine to form cracks**
- **HTHA most likely to occur in heat affected zones (HAZs) around welds**
- **Inspecting for HTHA damage is extremely difficult (microscopic and localised) and is therefore not reliable enough to ensure integrity**

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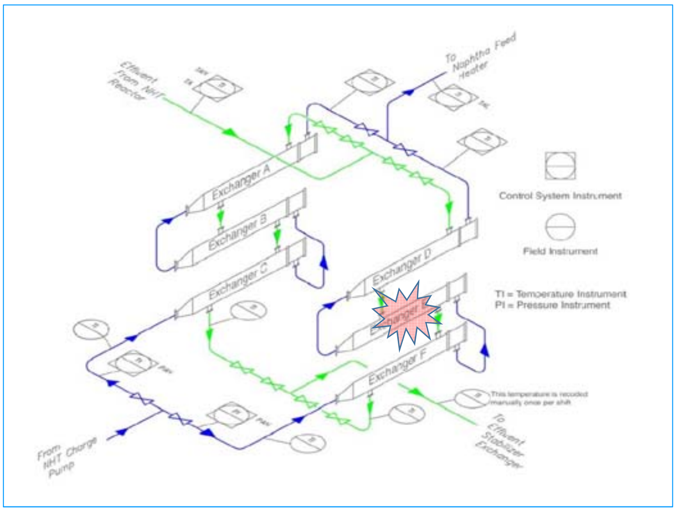
Incident #2 - Piping Isometric Diagram



- **Isometric shows inlet and outlet temperature and pressure sensors**
- **Some measurements displayed at control panel via distributed control system (DCS)**
- **Some measurements displayed in field only**
- **No instrumentation on inlet or outlet streams of intermediate shells**

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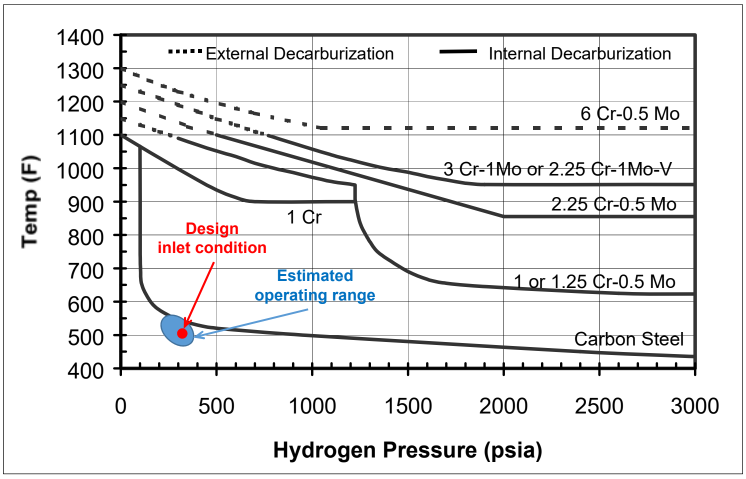
Incident #2 - API RP 941 Nelson Curves



- Nelson curves provide limits on temperature and hydrogen partial pressure for carbon and alloy steels
- Curves are empirical based on experience
- Apply safety margin for both parameters;
  28 °C (50 °F)
  3.5 bar (50 psi)

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Incident #2 - Root Cause Analysis

- Immediate (basic) cause of loss of primary containment (LOPC) was high temperature hydrogen attack (HTHA)
- Tubeside fouling was a contributing factor (higher shell temperature)
- Critical factors were:
  - Design conditions used to evaluate susceptibility to HTHA (should use actual conditions)
  - High residual stresses in seam welds of shell (no post-weld heat treatment)
  - Presence of additional personnel (multiple large manual block valves at different locations)
- Root (system) causes included
  - Inadequate hazard identification (proof of danger rather than effective safety implementation)
  - Inaccurate Nelson curve for carbon steel
  - Inadequate process monitoring (inadequate thermometry)
  - Failure to apply inherently safer design principles (Cr-Mo steels less susceptible to HTHA)

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Incident #3 - Combined Feed Exchanger Channel Head Failure

- Semi-regen catalytic reformer combined feed exchanger
- Channel head failed during hydrostatic testing at well below intended test pressure
- Fortunately no injuries but restart delayed by 20 days
- Reactor feed on shellside, reactor effluent on tubeside
- Tube inlet service conditions ca 25.5 barg and 480 - 530 °C

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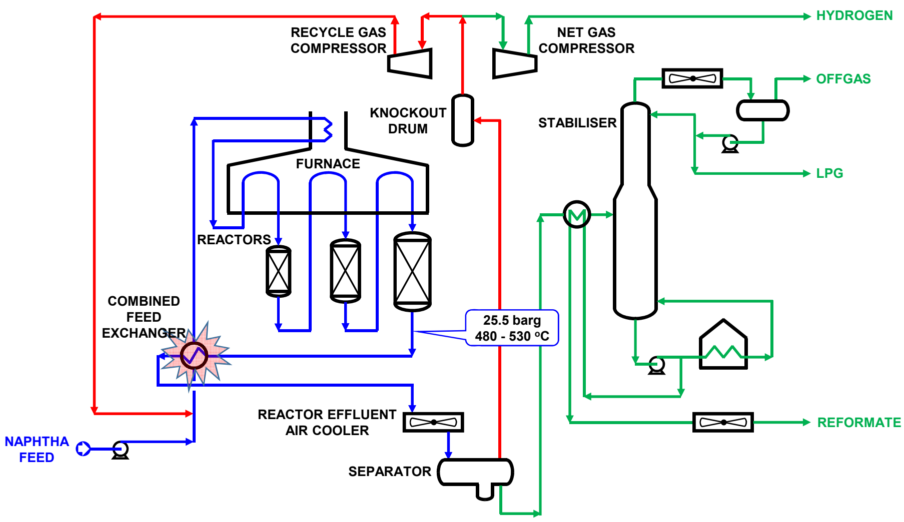
Incident #3 - Typical Catalytic Reformer Flow Diagram



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Incident #3 - Combined Feed Exchanger Fabrication Details

- **Exchanger built in 1980**
- **Designed to ASME VIII Div. 1 (1977), API RP 660 2nd Edition**
- **TEMA Handbook 6th Edition, Class R (1978)**
- **Channel head fabricated from 40 mm thick 2.25 Cr/0.5 Mo steel plate**
- **Channel flange fabricated from 195 mm thick 1.25 Cr/0.5 Mo forged steel**

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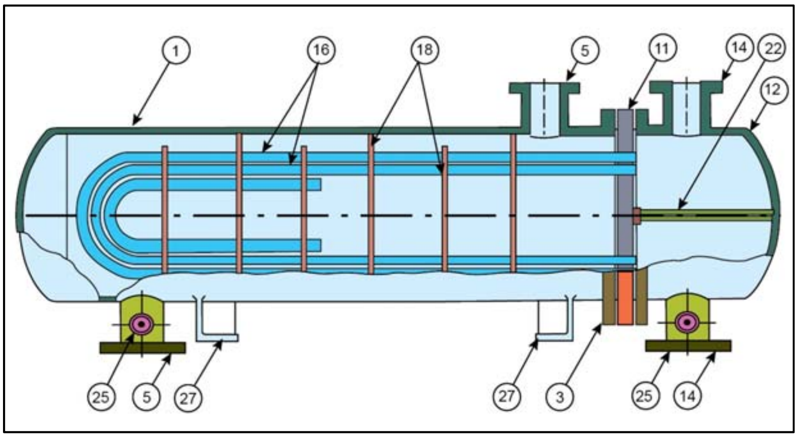
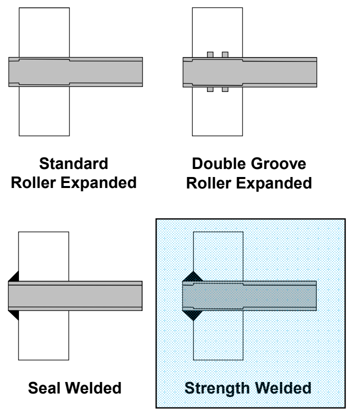
Incident #3 - Combined Feed Exchanger Construction

- **Exchanger was specified as TEMA Type BEU with strength-welded tubes**





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Incident #3 - What Is Hydrostatic Testing?

- **Hydrostatic testing ("hydrotest") is mandatory test procedure carried out at specified intervals to verify strength/integrity of process equipment**
- **Test pressure >> operating pressure to provide safety margin**
- **Test fluid normally incompressible liquid because easy to develop high pressure and only releases small amount of energy in case of failure (high pressure gas would rapidly expand risking injury and damage)**
- **Water typically used as test fluid because cheap, easily available and harmless in most test applications**
- **Test water has quality spec. (pH, Cl- etc) and temperature limitation**

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Incident #3 - Combined Feed Exchanger Hydrostatic Testing

- **Tubeside design pressure was 32.8 barg (475 psig) @ 552 °C (1026 °F)**
- **Tubeside hydrotest pressure specified as 140 barg (2036 psig)**
- **Minimum allowable hydrotest temperature specified as 6 °C (43 °F)**
- **Rupture occurred at ~ 93 barg (1350 psig) with water at 20 °C (68 °F)**
- **Exchanger had been in service for approximately 23 years**
- **Metallurgical analysis showed failure mechanism was brittle fracture**

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Incident #3 - Temper Embrittlement

- **Temper embrittlement causes loss of toughness in low alloy Cr-Mo steels after long exposure to temperatures in range 327 - 593 °C (621 - 1100 °F)**
- **Effect most pronounced in range 427 - 510 °C (801 °F - 950 °F)**
- **Loss of toughness only affects material when exposed to relatively low temperature (eg. startup, shutdown or hydrostatic test)**
- **Temper embrittlement caused by segregation of tramp elements and alloying elements along grain boundaries**
- **Composition of steel, metal temperature, exposure time (thermal history) are all critical factors**

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Incident #3 - Was 140 barg Test Pressure Really Necessary?

- **Two pressure envelope integrity concerns;**
  - external pressure envelope (leakage to atmosphere resulting in fire)
  - internal pressure envelope (leakage of reactor feed to reactor effluent)
- **Tube rupture exempted as credible failure scenario if tubeside hydrotest pressure ≥ shellside maximum allowable working pressure (MAWP)**
- **ASME code mandated use of "2/3rd design rule" so minimum acceptable hydrotest pressure would have been 150% of MAWP**
- **Tubeside hydrotest pressure based on 2/3rd rule is 49.2 barg (714 psig)**
- **Shellside design pressure was 33.4 barg (485 psig) @ 427 °C (801 °F) so failure of shell due to tube rupture is not credible scenario**

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Incident #3 - Root Cause Analysis

- Near miss; failure at startup could have caused personnel injury or fire
- Immediate (basic) cause of channel head failure was brittle fracture due to temper embrittlement
- Uneven bolt torque and flange misalignment were contributing factors
- Critical factors were:
  - age, composition of steel and operating temperature (temper embrittlement susceptibility)
  - tubeside hydrotest pressure (excessive stress)
- Root (system) causes included
  - Inadequate job knowledge (full hydrotest pressure not required to verify tube joint integrity)

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Summary - Engineering Issues

- Most pressure equipment in gas processing/oil refining is constructed from carbon or low alloy steels
- Carbon and low alloy steels are susceptible to cold metal embrittlement when exposed to low temperatures (depressurisation/auto-refrigeration)
- Carbon and low alloy steels lose strength when exposed to hydrogen at elevated temperatures and pressures (high temperature hydrogen attack)
- Some low alloy Cr/Mo steels are susceptible to temper embrittlement after extended exposure to high temperatures but effect only evident when cool (startup, shutdown or hydrostatic test conditions)
- Gradual changes to operating conditions due to equipment fouling or catalyst deactivation may lead to accidental breach of operating limits

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Summary - Process Safety Management Issues

- Systematic process hazard analysis (PHA) vital for accident prevention
- Procedures and gun drills essential for abnormal operating conditions
- Startup, shutdown and emergency procedures to be rigorously enforced
- Alarm review important to avoid too many alarms, poorly prioritised
- Remote-operated isolation (shutoff) valves can reduce magnitude of leak
- Safety Case agreed with regulator includes details of safety management system, risk assessment studies and emergency response (audit basis!)

Catastrophic Heat Exchanger Failures
References

- "Standards of the Tubular Exchanger Manufacturers Association"
  Tubular Exchanger Manufacturers Inc (9^{th} Edition, 2007)
- "The Esso Longford Gas Plant Accident"
  Report of the Longford Royal Commission, Parliament of Victoria (1999)
- "Lessons from Esso's Gas Plant Explosion at Longford"
  Andrew Hopkins PhD, CCH Australia (2000)
- "API RP 941 Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants" (2016)
- "Catastrophic Rupture of Heat Exchanger (Tesoro Anacortes Refinery)"
  Report of the US Chemical Safety and Hazard Investigation Board (2014)

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Questions