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ASME BPVC CODE-COMPLIANT HEATER DESIGN & FABRICATION USING INCONEL 740H

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Background & Experience

- Founded in 1987 in Tulsa, OK w/ manufacturing located in Chanute, KS.
- More than 30 years of experience in boiler & pressure vessel design and manufacturing:
  - Superheater, reheater, & economizer elements & headers
  - HRSG coils & harps
  - +170 combined cycle projects
  - +1700 pressure part modules
  - Thousands of ASME code welds
    - Carbon steel
    - Low chrome allows (1¼-Cr & 2¼-Cr)
    - 9 Chrome: T9 & T91
    - AWS G-Classified T21
    - 300-series, 400-series, & Duplex stainless steels
    - Inconel™ & Hastalloy™

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Quality Assurance

- Shop Qualifications
  - ASME Section I – Power Boilers
  - ASME Section VIII, Div. 1 – Pressure Vessels
  - ASME B31.1 – Power Piping
- Quality system based in ISO 9001 elements
- CWI & Level II Inspectors
- Non-Destructive Examinations
  - Radiography (RT, X-ray), Liquid Penetrant Testing (PT), Ultrasonic Testing (UT), Magnetic Particle Testing (MT), Fluoroscopic
  - PMI
  - Helium Leak Detection
  - Hydrostatic & Pneumatic testing

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Heater Coil Design

- Design Conditions:
  - MAWP = 4000-psig / 275.8 barg
  - Design Temps = 1,125°F – 1,375°F / 607.2°C – 746.1°C
- 1.5” (38.1mm) OD tubes w/ spiral wound, 304SS & 409SS welded fins
- 4”, 8”, 12” Pipe headers w/ Grayloc (clamp style) connections to supply/return piping
- Headers, end plates, tubes, & flanges are all 740H material
- Total # of Welds:
  - 1,296 tube-tube (butt, thin) welds
  - 288 tube-header set-on style (corner, thin-thick) welds
  - 4 header end plate (corner, thick) welds
  - 4 vent/drain set-on nozzle (corner, thin-thick) welds
  - 2 flange-header (butt, thick) welds

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Heater Coil Design, cont'd

- Floating coil design to minimize thermal expansion stress in tubes and headers
- Cast tubesheets (Nickel-Chrome alloy) support coil at even intervals, allow tubes to freely slide through supports
- Welded fin parameters (height, pitch, style (solid vs. serrated) & material) used to control tube metal temperature at various sections through the coil: balance heat absorption & tube metal temperature.
- Optimus / Special Metals developed and tested continuous fin welding procedures to ensure effective bonding of stainless fin strip to 740H tube.

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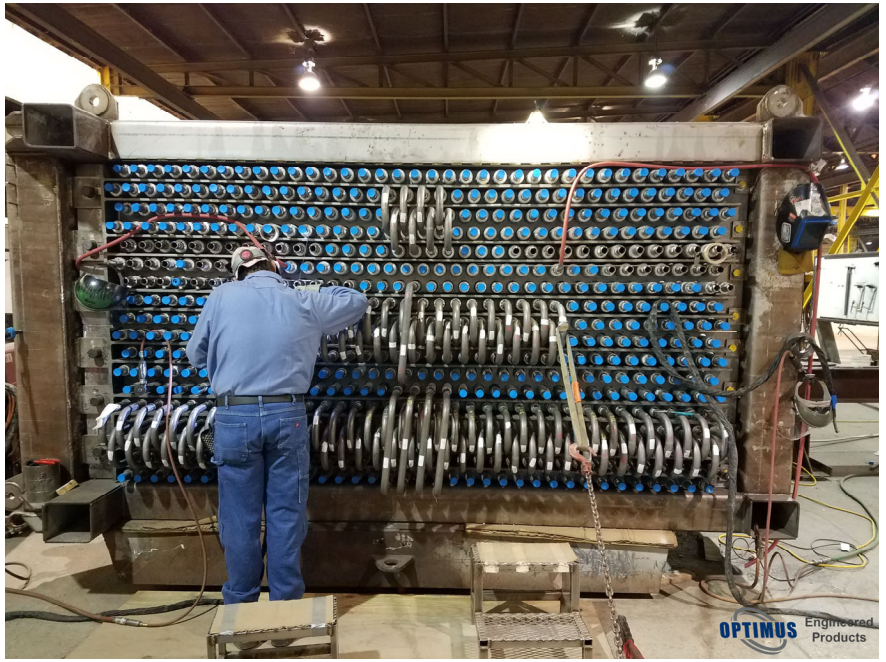
Header Coil – Weld Joint Examples

- Tube to Tube butt welds (thin wall)



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Header Coil – Weld Joint Examples

- Tube to Header set-on style corner joint welds (thin-thick wall)

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Header Coil – Weld Joint Examples

- Header End Plate set-in corner joint welds (thick wall)

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Header Coil – Weld Joint Examples

- Vent/Drain Nozzle Set-on style corner welds (thin-thick wall)

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Header Coil – Weld Joint Examples

- Flange to Header butt welds (thick wall)

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Welding Procedures (WPS)

- Weld procedures developed in accordance with ASME Code Case 2702-3
  - Applicable version at time of order origination
- Types of Weld Procedures
  - 740H-740H
  - 740H-dissimilar (P8, P43, P45)
- Welding Process: GTAW
  - Pulsed MIG not used in coil fab
- Inert gas purge required (He-Ar mixture) of coil internal volume
  - Coil opening closures critical to establishing a complete and thoroughly purged environment

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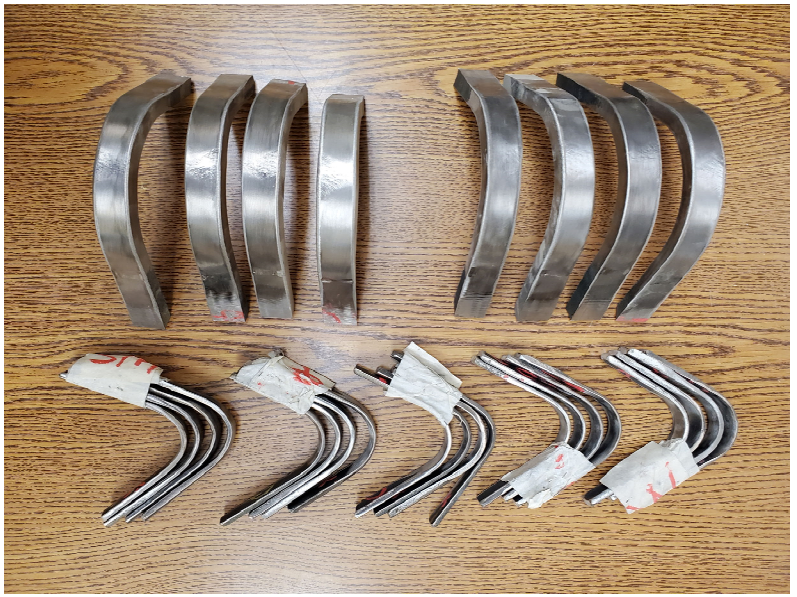
Welder Qualification Testing (PQR)

- Testing per ASME Code Case 2702-3 and all applicable reference spec's
- Destructive testing performed
- 2 welders qualified for headers welding
- 6 welders qualified for tube welding



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Non-Destructive Examination (NDE) of Welded Joints

- All NDE performed in accordance with ASME Section V
- Types of NDE performed:
  - Visual: Internal root checks on tube to header & tube butt welds
  - Liquid Penetrant Testing (PT) on finished welds
  - Radiograph Testing (RT) of all butt welds
  - Phased Array Ultrasonic Testing (PAUT) of all tube butt welds (supplementary test to RT)

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Non-Destructive Examination (NDE) of Welded Joints

- Hydrostatic test per ASME Section I
  - Test performed after coil completion
  - Minimum test pressure = 1.5 x MAWP = 6000 psig
  - Alternate test pressure = 7,299 psig
    - Pressure calculated to simulated equivalent stress ratios on material at test temperature (ambient) vs. operating temperatures

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Heat Treatment during Fabrication

- Requirements per Code Case 2702 – “all material must be supplied in solution heat treated and aged condition”
- After cold-forming strains exceed 5%, solution annealing must be performed to entire parts (tube bends)
- Material may only be welded in aged condition.
- Tubes to be finned were delivered in aged condition
- Tubes to be cut up for bends and header pipe were delivered in solution annealed condition
  - Reduces strain and wear on cutting, bending, and drilling operations to cold work tubes and drill headers in non-aged condition
  - Following tube bending and header drilling, tubes were re-annealed and aged. Headers did not required re-annealing, just aging.
- Once all components had been heat treated to aged condition, coil welding assembly could begin
- After completion of all 740H coil welding, entire coil needed PWHT
  - *See pictures on following slide*

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740H Completed Coil PWHT

- PWHT performed per Code Case 2702
- 1,400°F – 1,500°F (760°C – 815°C)
- Min. 4 hour soak up to 2 inch (50 mm) thickness
  - Add 1-hour per add'l 1 inch (25 mm) of thickness

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Linear Indications (Cracks) in 740H Production Welds

- Following PWHT, several tube welds were found to contain small cracks
- PT, air test w/ soap bubbles, RT used to confirm crack locations
- Repairs to cracked welds made per developed procedure (see next slide)
- Cracks could not simply be ground out and remade as per typical with carbon or stainless steels due to tube ID contaminants

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Weld Repair Procedure

- Following PWHT, several cracks in tube butt welds were discovered
- Repair procedure developed per following:
  - Cut tube on either side of bad weld (allows for tube ID cleaning) & prep tube ends
  - Weld new tube “pup” piece in per applicable WPS
  - PT/RT new welds
  - PWHT new welds per Code Case 2702 (local PWHT acceptable in this instance)
  - PT/RT welds following PWHT

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Challenges with 740H Fabrication

- Material toughness (cutting, drilling, bending)
- Welder qualification
- Intricate welding & inter-pass cleaning procedure
- Delayed cracking in thin-walled tube butt welds

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Success with Inconel 740H Fabrication

- 1st large scale application of an age hardenability alloy in a pressure vessel/heater in the world
- Demonstration of large-scale manual welding of Inconel 740H in compliance with ASME Boiler & Pressure Vessel Code
  - Successful welder qualification testing of multiple ASME Code welders
  - More than 1,600 ASME BPVC code compliant welds made and inspected
  - **ZERO** inspection or cracking issues with thick-walled welds (4 end plates and 2 flanges to headers)
  - **ZERO** inspection or cracking issues with thin/thick-walled tube/nozzle to header welds (292 welds)
  - **ZERO** inspection or cracking issues with dissimilar metal welds, i.e. 740H to 347H stainless (4 welds)
  - Delayed/Post-PWHT cracking accounts for only **3%** of all tube butt welds made (39/1312 welds)