Superalloys for Advanced Power Systems

The long winding road to TRL 9

NETL Crosscutting Workshop on Developing a Domestic Supply Chain for High Temperature Steam Cycles

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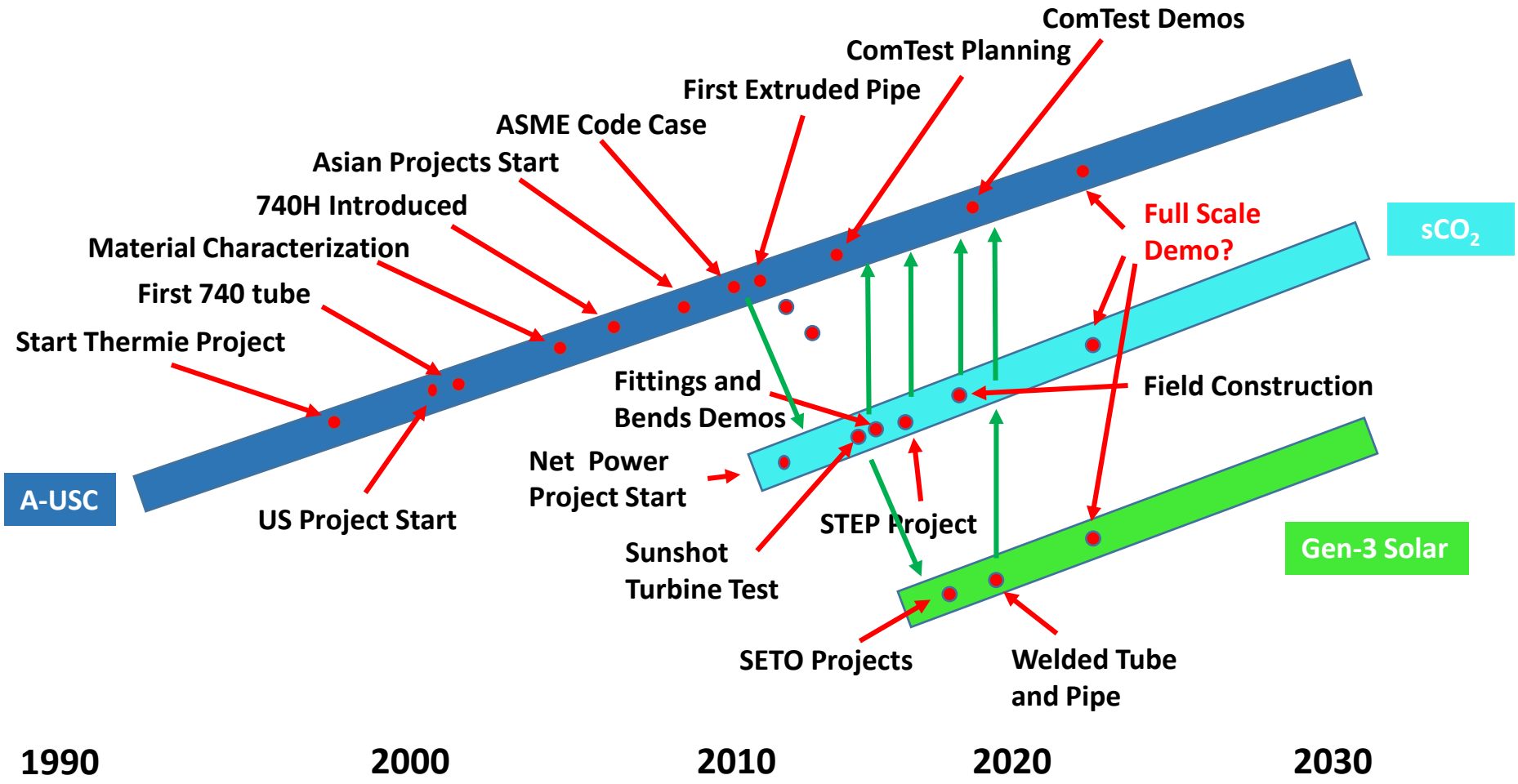
Special Metals

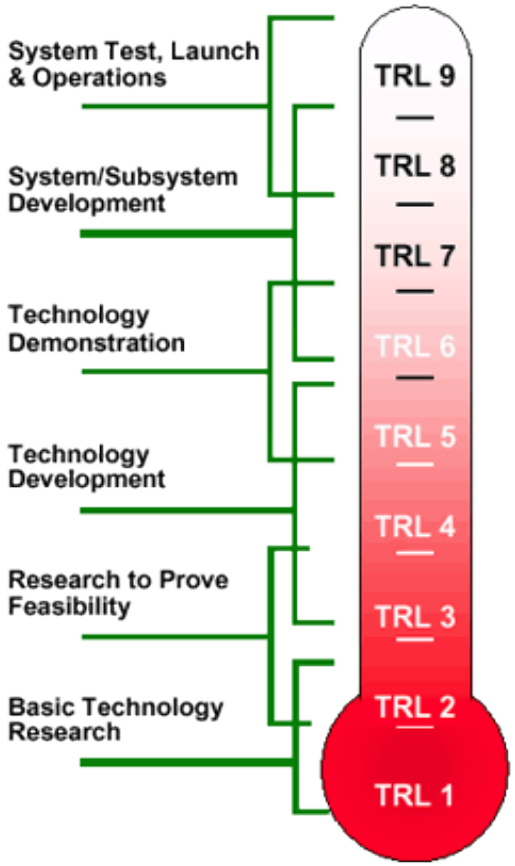
November 14, 2018

A Brief History of 740/740H



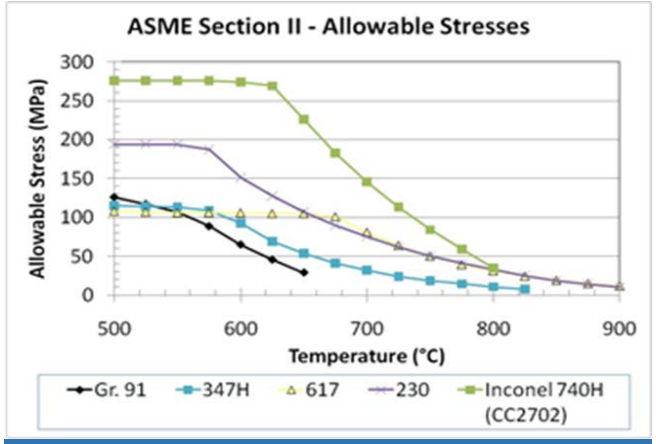
Where are we now ?

- NASA definition of mature technology
  - "Actual system proven through successful mission operations"
- A-USC materials readiness is really a hierarchy of elements
  - Materials production
  - Component production
  - Shop fabrication
  - Field erection
  - Operation and repair
- Step through these as they relate to 740H usage in advanced power systems
- Other considerations for success of the technology

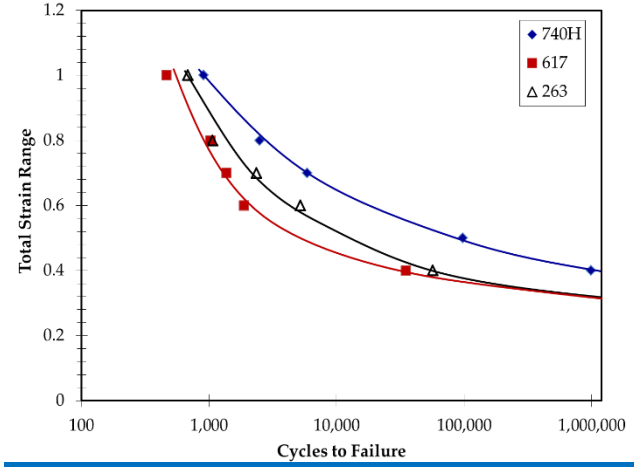


Material Characterization

- Alloy meets original design criteria
  - Primary (100,000 hr creep life, coal ash and steam corrosion resistance)
  - Secondary (weldability, formability, microstructure stability)
- A-USC consortium developed comprehensive data package for ASME code case 2702
- Microstructure has been extensively studied and documented
- Properties of small and intermediate scale components meet code and ASTM spec requirements
- Strain aging is a consideration in various situations
- Alloy has good fatigue properties in limited testing. More detailed HCF/LCF, hold-time fatigue and thermal fatigue testing is needed for specific applications
- Remnant properties and creep damage effects have not been characterized
- 740H strongly auto-ages in sections thicker than 4"… what consequences for final properties?



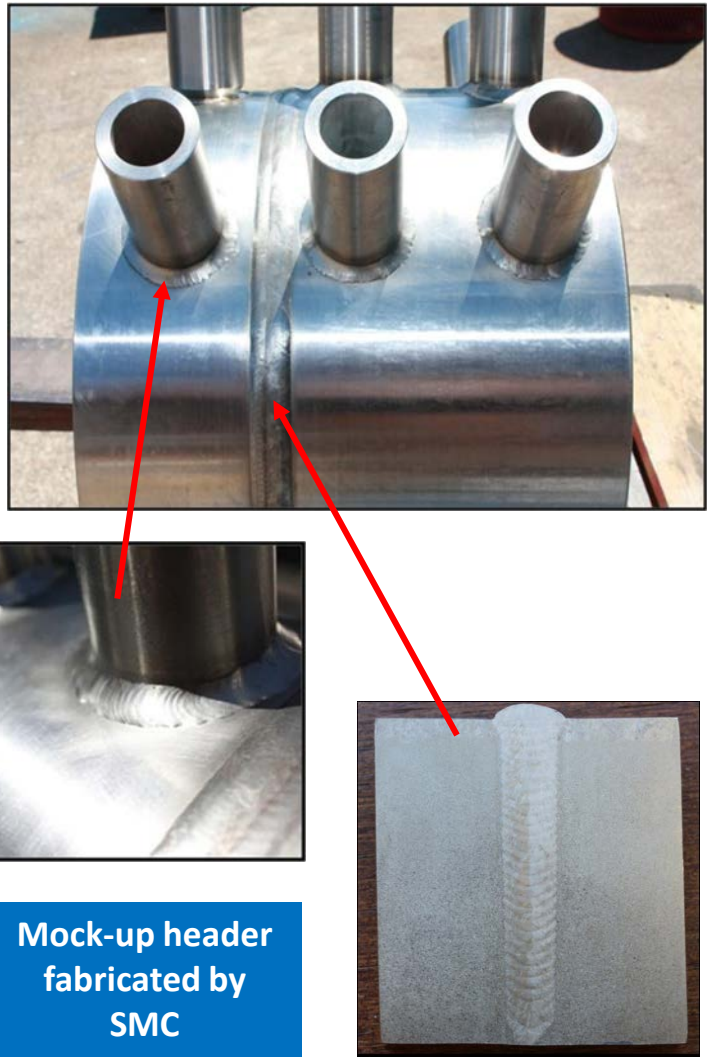
Comparison of age hardened alloy 740H with solid solution alloys



Representative fatigue test data, 725°C, R=0, Zhang et al - IHI

Welding

- Critical to successful use of the alloy
- Work by Sanders, Siefert at B&W defined basics for ASME code rules
  - Same alloy filler
  - GTAW, GMAW
  - PWHT mandatory
  - Weld qualification procedures
- WJSRF – 70%
- Dissimilar metal welding required
- ORNL creep testing to qualify SMAW using Bohler Therminit 263 electrode nearly complete (repair)
- Solution annealed welds (improve WJSRF)
- Ongoing quantification and modeling of stress relief/relaxation cracking: Lehigh, OSU, INL



Mock-up header fabricated by SMC

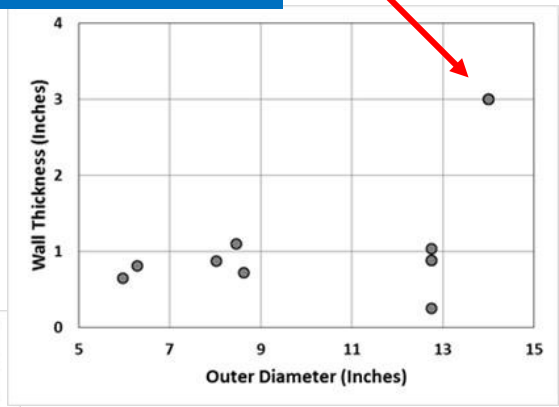
Primary Mill Product Forms

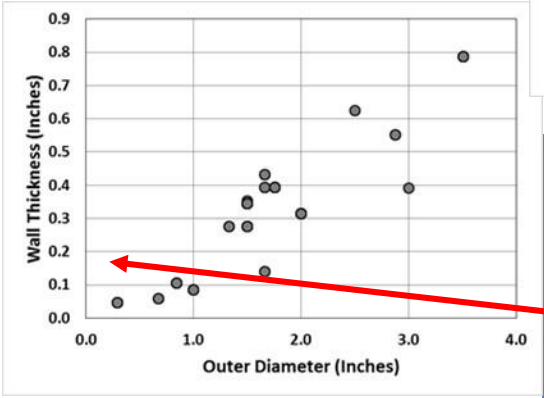
- First mill product in 2005 at SMC UK from 20” x 6,000lb VIM/ESR ingots
- Scaled to bigger VIM/VAR ingots in SMC US - 36” x 30,000 lb
- Tube: Horizontal extrude and cold pilger/draw
- Pipe: Vertical extrude at Wyman-Gordon
  - Prototype header extruded 2011
  - A-USC ComTest trial to establish size limits (22” OD x 3.7” W and 28” OD x 1.5” W)
- Welding wire
- Forging/Machining quality bar
- Sheet and Plate

TRL 8 except large pipe TRL 6

14.9” OD x 3.5” W pipe extruded at Wyman-Gordon

Tube and pipe sizes made to date

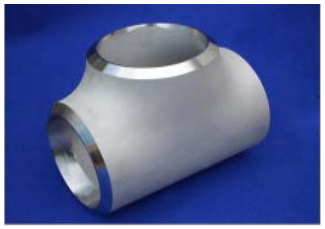


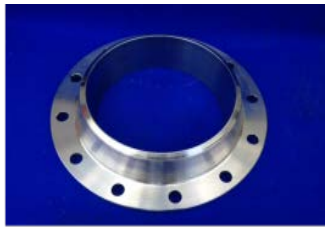


0.29” OD x 0.045” W tube

Fittings and Shapes

- Small Parts
  - Flange (Maass Flange)
  - Elbow (McDermott)
  - Concentric reducer (McDermott)
  - Cold hydro-formed tee (McDermott)
- Ring Products
- Made on existing tooling in various commercial shops, Met ASTM min properties
- Process optimization needed to reduce microstructure variability
- Large parts to be made in A-USC ComTest
  - Valve body and parts
  - Wye
  - Tee
- Machinability testing





Small parts TRL 7,
Large parts TRL 4

As-forged ring, Carlton Forge

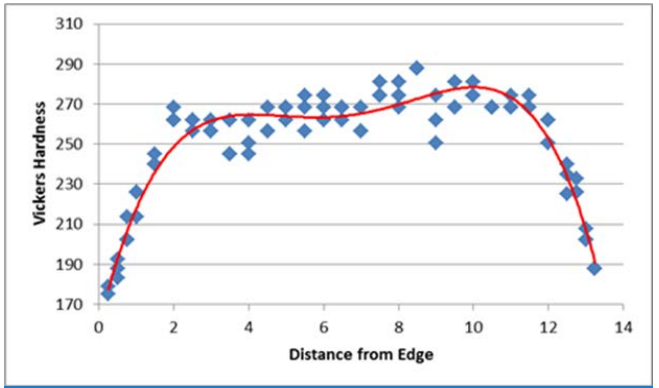


Illustration of auto-aging in annealed 13” dia. 740H bar

Bending Tube and Pipe

- Tube
  - Has been studied intensively in US and Japan
  - Cold bending can be done with conventional equipment and procedures
  - For cold strain >5%, tube must be annealed
  - Some potential for strain-age cracking
  - Thar heater for SwRI turbine test contained hundreds of tube bends
- Pipe
  - McDermott hot induction bends for Net Power
  - Solution annealed and aged properties acceptable
  - **Header and reheater pipe bends planned for AUSC ComTest**

Tube and small pipe TRL 8,
Large pipe TRL 6

Cold bends and welds, B&W

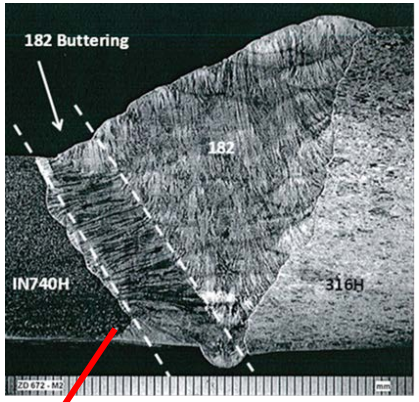
Induction Bending – McDermott

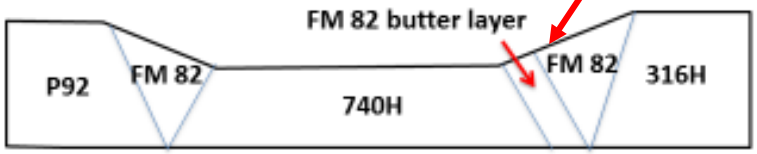
Welded pipe section – McDermott

First Use in USC Plant

- Doosan-Babcock led project
- Problem: Coefficient of expansion mismatch between 316H header and P92 steam pipe with potential for fatigue cracking
- 30” VIM/VAR ingots melted at SMC
- 12.74” OD X 0.88” W Pipes extruded at W-G (First commercial production)
- Extensive weldability studies to select filler (FM82), weld parameters and PWHT
- Went into service in 2017

Extruded pipe



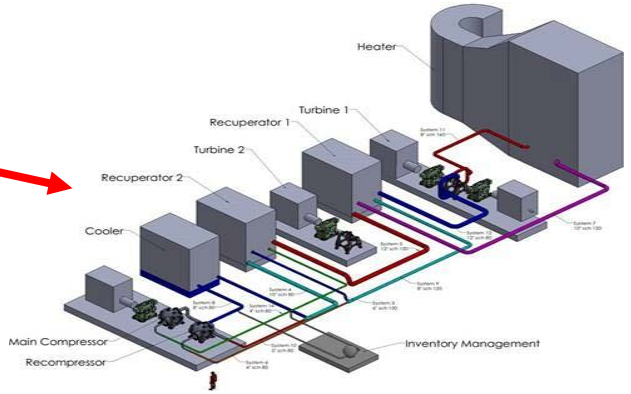


Schematic of joint

Welded Assembly

sCO_2 Driving Fabrication Experience

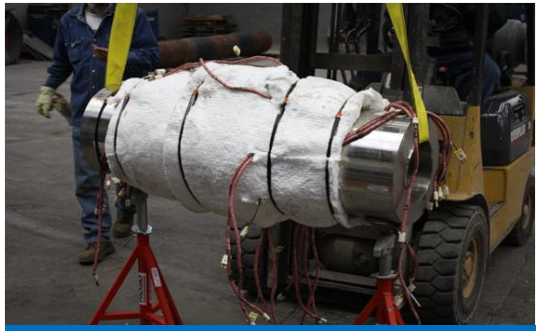
- **Providing critical design and fabrication experience**
- **SwRI sCO_2 Turbine Demo Sunshot (Operating in start-up mode)**
  - **Thar Heater (fully heat treated after fabrication)**
  - **Pipe connections (first system fabrication)**
- **Net Power Pilot Plant (Components tested, system ready to go)**
  - **Transfer piping**
  - **Bends and Tees**
- **STEP (in final design, procurement and tube production)**
  - **Gas fired heater**
  - **Transfer piping**
  - **Turbine housing**



Shop and Field Welding

- 740H is very weldable…..but it is a superalloy and requires strict adherence to detail to obtain an acceptable weld
- Observations
  - Contract construction welders have no experience with superalloys
  - Weld qualification procedures do not represent actual conditions
  - Detailed information may not be available at the plant site
  - Manual out-of-position welds are often necessary
  - Critical equipment may not be available
  - Inspection and PWHT of complex joints difficult
  - Tight construction schedules can lead to unrecorded process deviations
- Critical issues
  - Joint design, purge gas purity, root pass heat input, PWHT heating rate, torch practice, inter-pass grinding, etc
- SMC welding assistance
- SMC Practical Welding Guide

Weld in 3” 740H pipe showing ceramic heating elements used for PWHT



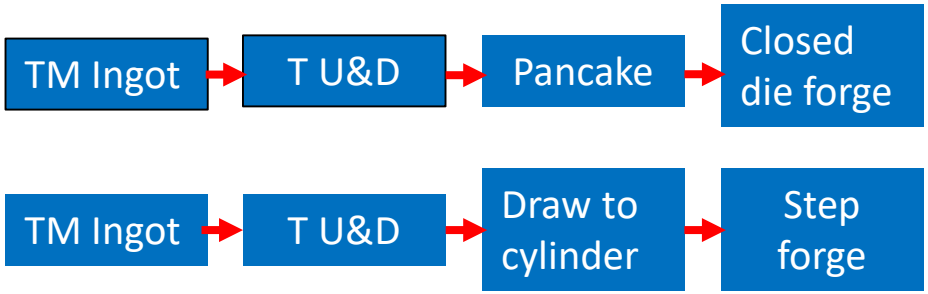
With insulation

Field welding TRL 6

Haynes® alloy 282® Rotor Forging

- **A-USC First Trial (GE Design)**
  - Triple melt VIM/ESR/VAR, 24” dia. ingot, 8,500 lb
  - Triple upset and draw forge to 22”, GS ASTM 3
  - Pancake forge to 49.5” x 9.5”, GS ASTM 8-9
  - Final weight 4,830 lb
  - Testing GE & ORNL
- **A-USC New Trial (Alstom Design)**
  - Triple Melt to 36” dia. Ingot, 36,000 lb
  - Triple upset and draw then step forge to 26”, 42” and 19” dia at Shultz Steel
  - Final weight ~30,000 lb
  - Machine to drawing
  - Testing EPRI
- **Potential issues**
  - Ingot cracking
  - Segregation (freckle)
  - Forge cracking
  - Grain size
  - Machinability

Pancake forging – Wyman-Gordon



Disk forging TRL 6, Shaft forging TRL 3

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Final Comments

- 740H capable for all mill product forms and sizes of “hard” nickel alloys such as 617 and 625 & meets properties
- Cost of raw materials
  - Cobalt volatility
- Production capacity
  - Melting
  - Seamless tube manufacture
  - Welded tube for DOE SETO Gen-3 Solar Project
  - 740/740H Patents expire 2021-2029
- All products except weld wire are “made to order”, no supplier or distributor stock, translates to long lead times
- Many small forgings made by forgers with nickel experience
- Large forgings not yet demo, ~36,000 lb ingot envelope, auto-aging is potential issue
- Full-scale header and re-heater pipe not yet demo, size limit unknown
- Code enhancements underway
- Field erection has been demonstrated on limited scale
- Operating experience, test loops only

Recent history of cobalt price

2” x 0.065” Welded Tube

Seam weld

Burst Test