BUILDING A WORLD OF DIFFERENCE

2 March 2017

MATERIAL REQUIREMENTS AND SPECIFICATIONS FOR SUPERCRITICAL POWER PLANTS

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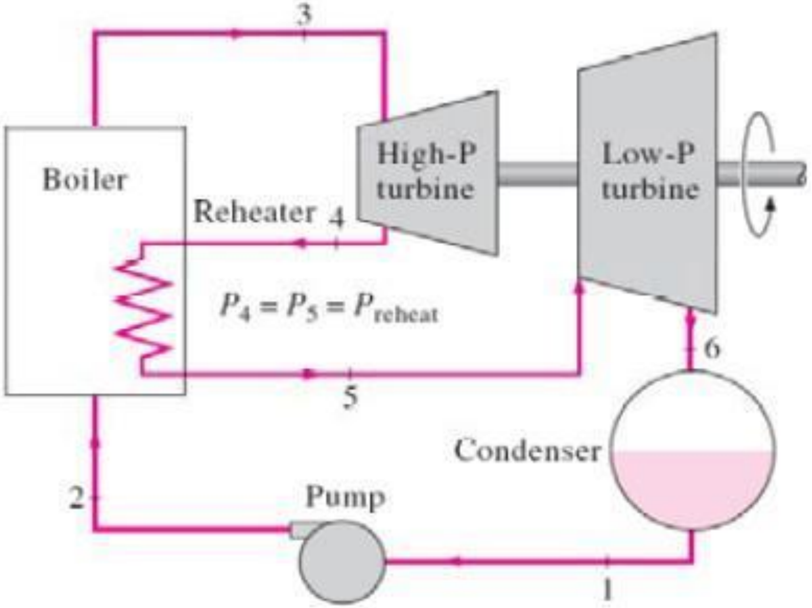
AGENDA

- **Background and Definitions**
  - What is a Supercritical Power Plant and How Are They Different Than Subcritical?
- **Material Issues**
  - Supercritical Impacts
  - Elevated Temperature
  - Flow Accelerated Corrosion
  - Cast vs. Forged Valves
- **Future Trends**
  - Market Trends and Regions
  - Emerging Materials
- **Discussion**

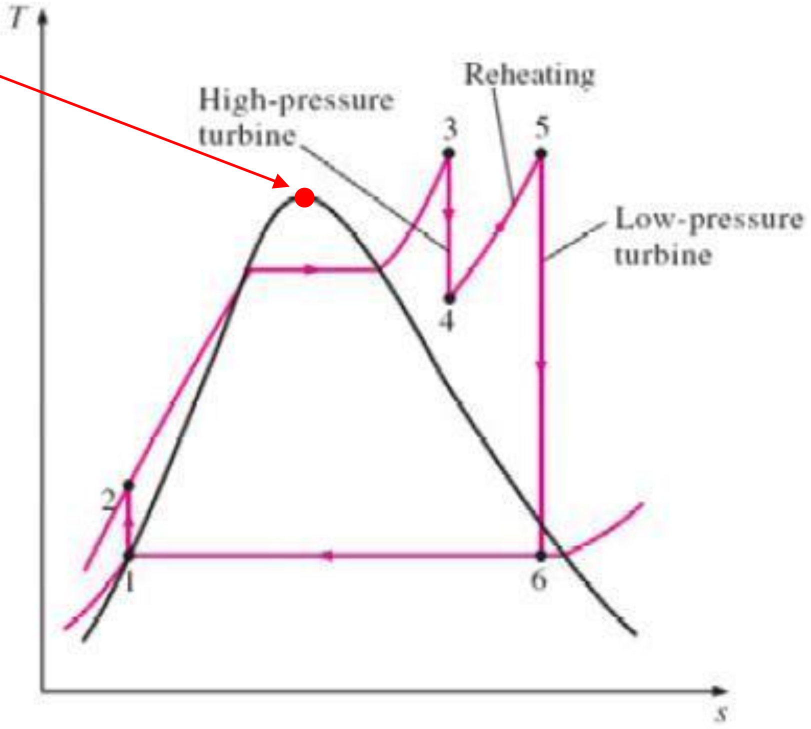
BACKGROUND AND DEFINITIONS

- Supercritical vs. Subcritical Power Plants
- Systems/Applications Unique to Supercritical Power Plants
- Piping Material Defines Valve Material

BASIC POWER PLANT STEAM CYCLE – (RANKIN CYCLE)

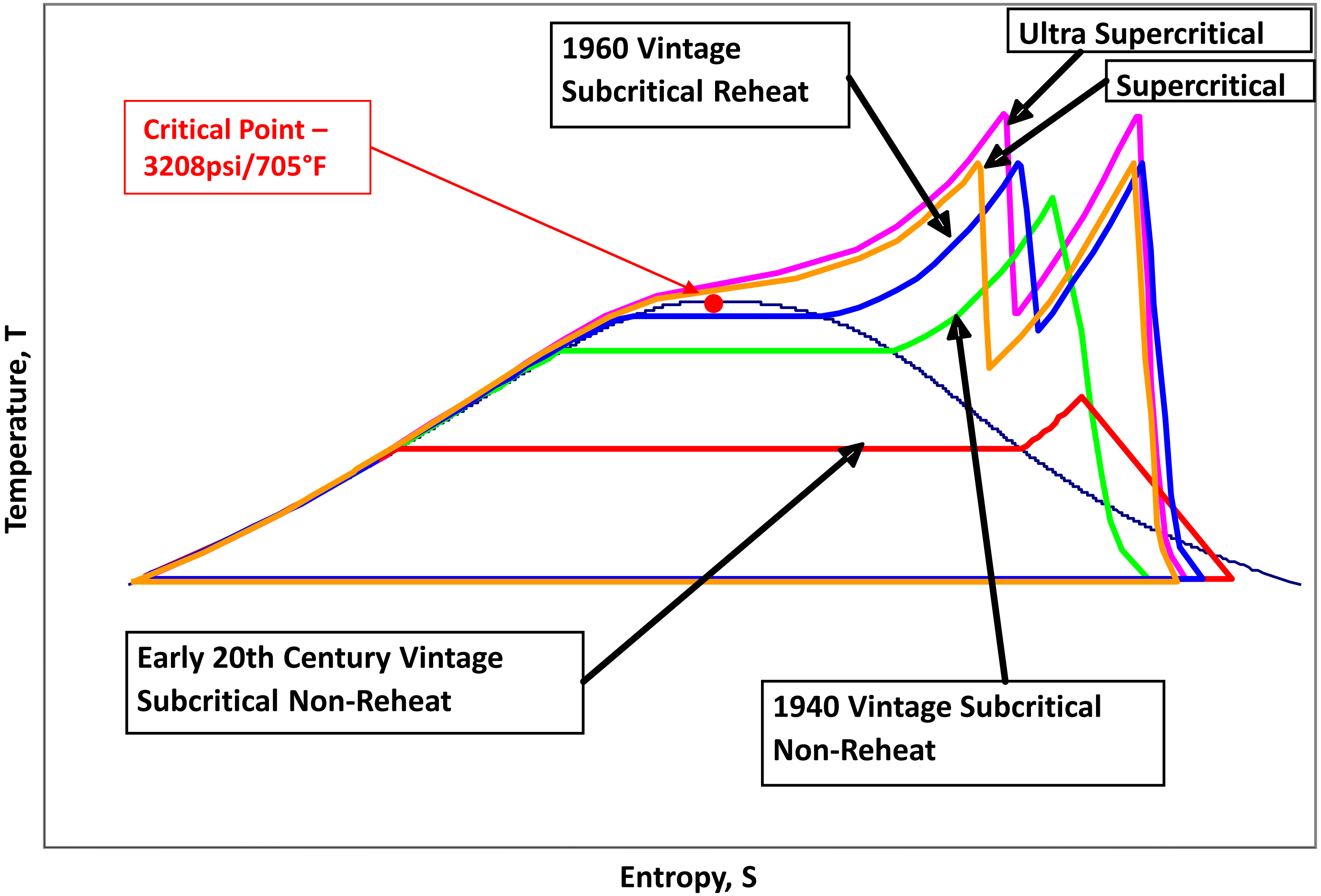


Critical Point – 3208psi/705°F



1 – Condensate
2 – Boiler Feedwater
3 – Main Steam
4 – Cold Reheat
5 – Hot Reheat

EVOLUTION OF THE RANKIN CYCLE



SUB-CRITICAL VS SUPERCRITICAL CYCLES

Unit Type	Main Steam/Hot Reheat Conditions	Efficiency
Subcritical – Water boiling to steam with pressures below 'critical point'.	• 2,400 psig (165bar) • 1050°F/1050°F (566°C/566°C)	38%
Supercritical – Water to steam without boiling. Pressure above 'critical point'.	• 3,500 psig (241bar) • 1050°F/1080°F (566°C/582°C)	40%
Advanced Supercritical – Main Steam and Hot Reheat Steam temperatures above 1100°F (593°C).	• 4,710 psig (325bar) • 1130°F/1166°F/1166°F (610°C/630°C/630°C)	44%
Ultra Supercritical – Main Steam temperatures above 1200°F (649°C).	• 5,000 psig (345bar) • 1300°F (704°C)	46%

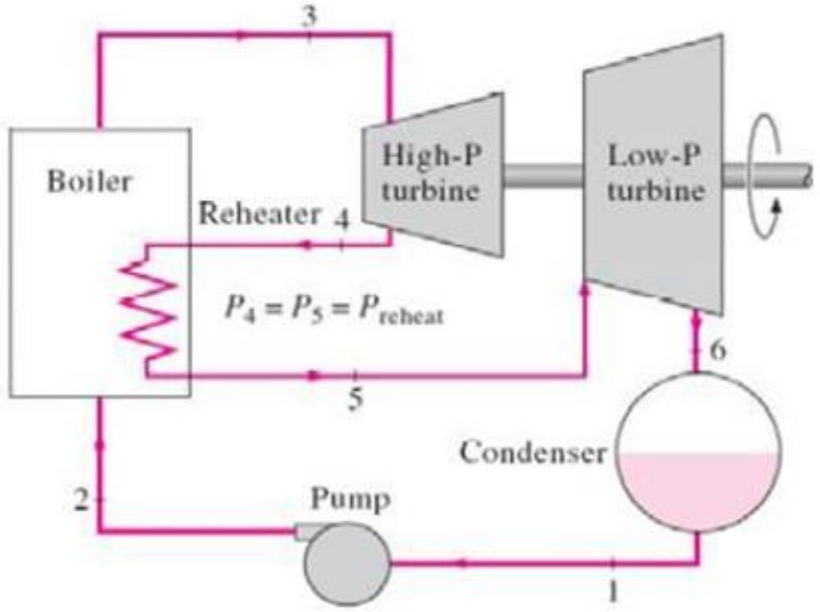
Temperature + Pressure = Higher Efficiency
Higher Efficiency = Less Emissions

HISTORY OF SUPERCRITICAL UNITS

- **First Supercritical Unit: AEP Philo Unit 6**
  - Initial Operation Date: 1957 (60 years ago)
  - 125 MW
  - Steam Conditions: 4500psi/1150F/1050F/1000F (double-reheat)
- **World-wide – Over 200 units**
  - Japan and South Korea largest capacity
- **Most Recent US Units**
  - John W. Turk and Sandy Creek– 2013
- **World Market (mainly Asia and sub-Sahara Africa)**
  - Ultrasupercritical coal
  - Indonesia, Vietnam, Philippines, Malaysia, Cambodia, India, South Africa

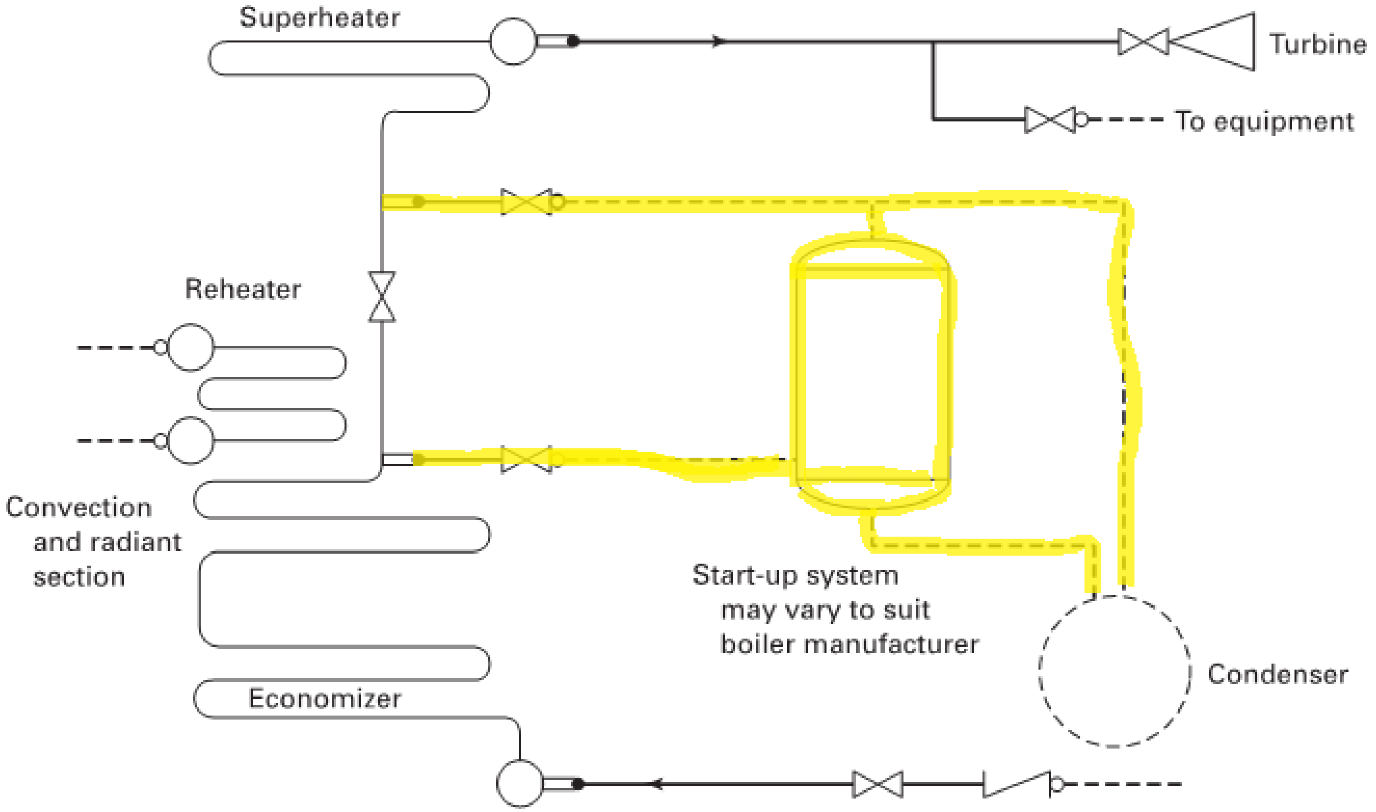
SYSTEMS/APPLICATIONS UNIQUE TO SUPERCRITICAL POWER PLANTS

- **Focus of this presentation is on four (4) major systems**
  - Boiler Feedwater – 2
  - Main Steam – 3
  - Hot Reheat – 5
  - Startup Systems
- **Most other systems are not unique to supercritical power plants and would be found in other subcritical power plant applications/systems**
  - Remaining power block
  - Balance of Plant
  - Air Quality Control Systems



STARTUP SYSTEMS

- No steam drum exists since water is converted to steam without boiling.
- During startup, a temporary drum is required to transition from subcritical conditions to supercritical conditions.



PIPING MATERIAL DEFINES VALVE MATERIAL

- Most designers are more familiar with piping materials than valve materials
- Piping materials are generally determined early in design process
- Piping material designations are often used to describe family of materials (i.e. P91)
- Material chemistry same but different product forms, i.e. A335 P91, A182 F91, A213 T91, A217 C12A, A387 91

MATERIALS

- Impact on Materials
    - Past and Present Materials Used
- Elevated Temperature Applications
    - Creep Strength Enhanced Ferritics
- Flow Accelerated Corrosion
    - Chrome Equivalent
- Cast vs. Forged Valves

SUPERCRITICAL IMPACT ON MATERIALS

- **Higher Operating Temperatures Require Improved Materials of Construction**
    - Higher Pressures Require Thicker Materials
    - Higher Stress Range
    - High Cyclic Fatigue Resistance
    - Increased Creep Resistance
    - Increased Fire Side Corrosion/Steam Side Oxidation Resistance
- **Cycles Have Traditionally Exceed Practical Limits of Some Materials**
    - Steam Systems: CS → P11 → P22 → P91 → P92
    - Feedwater: Grade B → Grade C → CrEq → P36

WHERE ARE WE TODAY?

- **Carbon Steel For Applications Up To 800°F (427°C)**
  - CrEq carbon steel or P36 for applications where flow accelerated corrosion (FAC) is of concern
  - P11/P22/P5/3xx for 2-phase erosion is of concern
- **P11/P22 Materials For Applications From 800°F to 1025°F (427°C to 552°C)**
- **Creep Strength Enhanced Ferritic Steels (CSEF) Have Emerged As the Most Common Material For High Temperature Steam**
  - P91 – 1025°F to 1100°F (552°C to 593°C)
  - P92 – 1100°F to 1200°F (593°C to 649°C)
- **Nonmetallics for Lower Temperature, Corrosion/Erosion Applications**
  - Most Commonly in Air Quality Control Systems

CREEP STRENGTH ENHANCE FERRITIC (CSEF) STEELS

- **High alloy steels that contain between 9 and 12% Cr, small amounts of Mo, V, Nb, and varying additions of W, Co, B, N, and Ni.**
- **Normalization and tempering heat treatments produce a microstructure of tempered martensite.**
  - Provides an optimal combination of creep resistance and toughness.
- **Primary application is boiler superheaters, pipes, and headers**
- **Most commonly material is Grade 91 (C12A).**

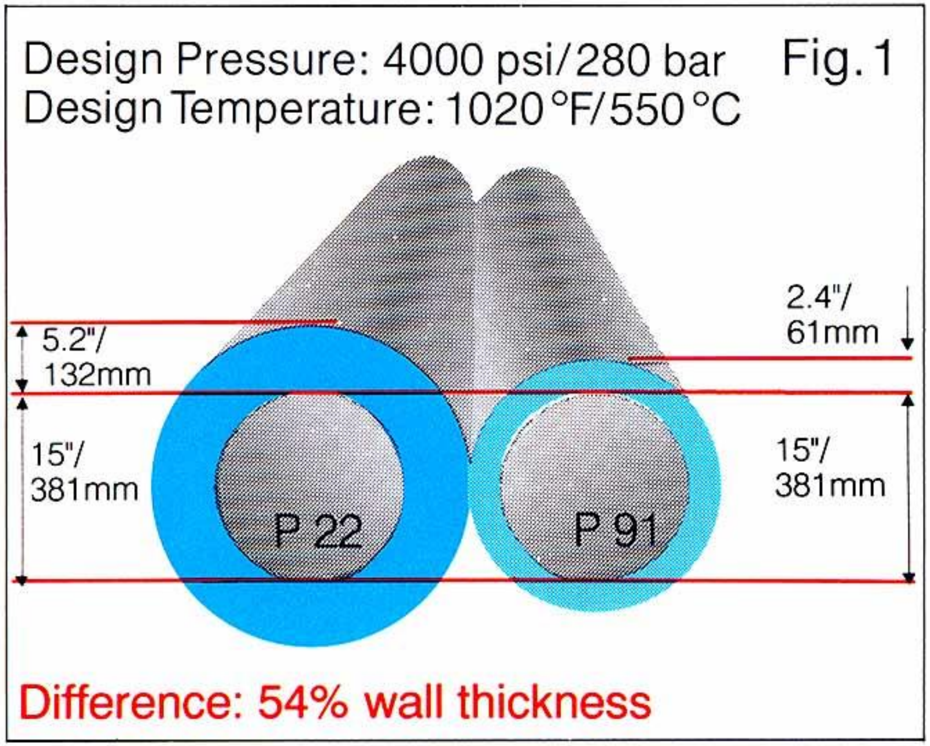
CS VS. P11 VS. P22 VS. P91

	Base Material Specifications			
	A106 Gr. B	**P11**	**P22**	**P91**
C	0.30 max.	0.05 - 0.15	0.05 - 0.15	0.08 - 0.12
Mn	0.29 - 1.06	0.30 - 0.60	0.30 - 0.60	0.30 - 0.60
P	0.035 max.	0.025 max.	0.025 max.	0.020 max.
S	0.035 max.	0.025 max.	0.025 max.	0.010 max.
Si	0.10 min.	0.50 - 1.00	0.50 max.	0.20 - 0.50
Cr	0.40 max.	1.00 - 1.50	1.90 - 2.60	8.00 - 9.50
Mo	0.15 max.	0.44 - 0.65	0.87 - 1.13	0.85 - 1.05
V	0.08 max.	-	-	0.18 - 0.25
N	-	-	-	0.03 - 0.07
Ni	0.40 max.	-	-	0.40 max.
Al	-	-	-	0.04 max.
Cb	-	-	-	0.06 - 0.10
Cu	0.40 max.	-	-	-

Grade 91’s Strength is Obtained Through Chemistry and Heat Treatments (N&T)

ADVANTAGES OF CSEF STEELS

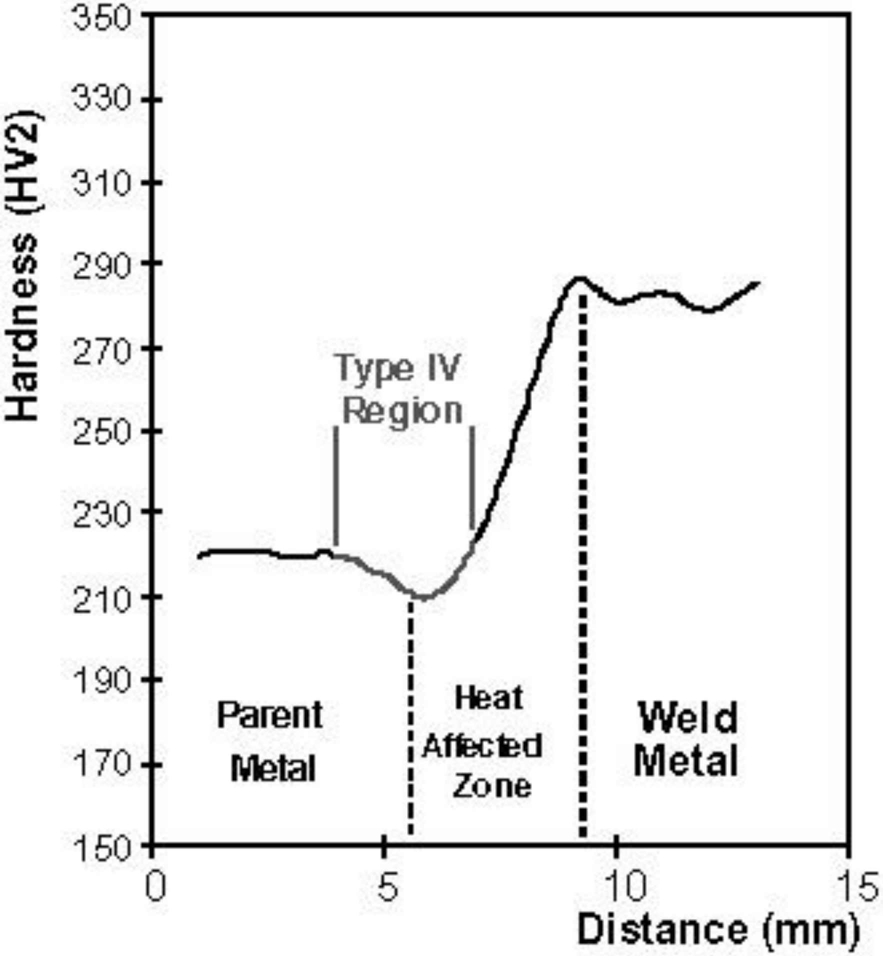
- Over Twice as Strong as P22 (2.25%Cr – 1Mo) at High Temperatures
- Excellent Resistance to Creep
- Reduces System Weight
- Improves System Flexibility
- Excellent Oxidation Characteristics



DISADVANTAGES OF CSEF STEELS

- **Martensitic Steel**
  - Strength is obtained through chemistry and heat treatments
- **Welding requires strict controls in order to maintain martensite grain structure, i.e. controlled preheat and interpass temperatures**
- **Listed as a P15E Weld Code by ASME, i.e. mandatory postweld heat treatment**
- **Weld HAZ's are Likely Failure Locations – Type IV Cracking**
- **Susceptible to Carbon Migration and Hydrogen Embrittlement, i.e. postweld bakeout**

EXAMPLE OF TYPE IV CRACKING



OTHER CSEF STEELS – 92, 911, 122

- **P92 - ASME Code Case 2179**
  - Developed by Nippon Steel as NF616
  - Similar to P91 but with 0.5% Mo – 1.7%W
  - 30% Reduction in Wall Thickness to P91
- **P911 - ASME Code Case 2327**
  - Developed by V&M in Europe
  - Similar to P91 but 1% W
  - Creep Strength Falls Short of P92
- **P122 - ASME Code Case 2180**
  - Developed in Japan as HCM12A
  - Similar to P92 but with 11% Cr and 1% Cu
  - Increased Chromium Improves Steam and Fire Side Corrosion Resistance

COMPARISON OF COMPOSITION

	Base Material Specifications			
	P91	**P92**	**E911**	**P122**
C	0.08 - 0.12	0.07 - 0.13	0.10 - 0.13	0.07 - 0.14
Mn	0.30 - 0.60	0.30 - 0.60	0.30 - 0.60	0.70 max.
P	0.020 max.	0.020 max.	0.020 max.	0.020 max.
S	0.010 max.	0.010 max.	0.010 max.	0.010 max.
Si	0.20 - 0.50	0.50 max.	0.10 - 0.30	0.50 max.
Cr	8.00 - 9.50	8.50 - 9.50	8.50 - 9.50	10.00 - 12.50
Mo	0.85 - 1.05	0.30 - 0.60	0.90 - 1.10	0.25 - 0.60
V	0.18 - 0.25	0.15 - 0.25	0.15 - 0.25	0.15 - 0.30
N	0.03 - 0.07	0.03 - 0.07	0.05 - 0.08	0.04 - 0.10
Ni	0.40 max.	0.40 max.	0.40 max.	0.50 max.
Al	0.04 max.	0.04 max.	-	0.04 max.
Cb	0.06 - 0.10	0.04 - 0.09	0.04 - 0.09	0.04 - 0.10
W	-	1.50 - 2.00	0.90 - 1.10	1.50 - 2.50
B	-	0.001 - 0.006	0.001 - 0.006	0.0005 - 0.005
Cu	-	-	-	0.30 - 1.70

EROSION VS. CORROSION

- **Erosion is the damage of materials caused by physical processes such as high-speed, impinging flows or solid impacts on the surface.**
  - Cavitation erosion
  - Flashing erosion
  - Droplet impingement
  - Solid particle erosion
- **Corrosion may be defined as material attack which is chemical or electrochemical in nature.**
  - Widespread attack - General corrosion, Flow-Accelerated Corrosion (FAC)
  - Localized attack - Galvanic corrosion (between dissimilar metals), Crevice corrosion, Cracking Pitting

FLOW-ACCELERATED CORROSION

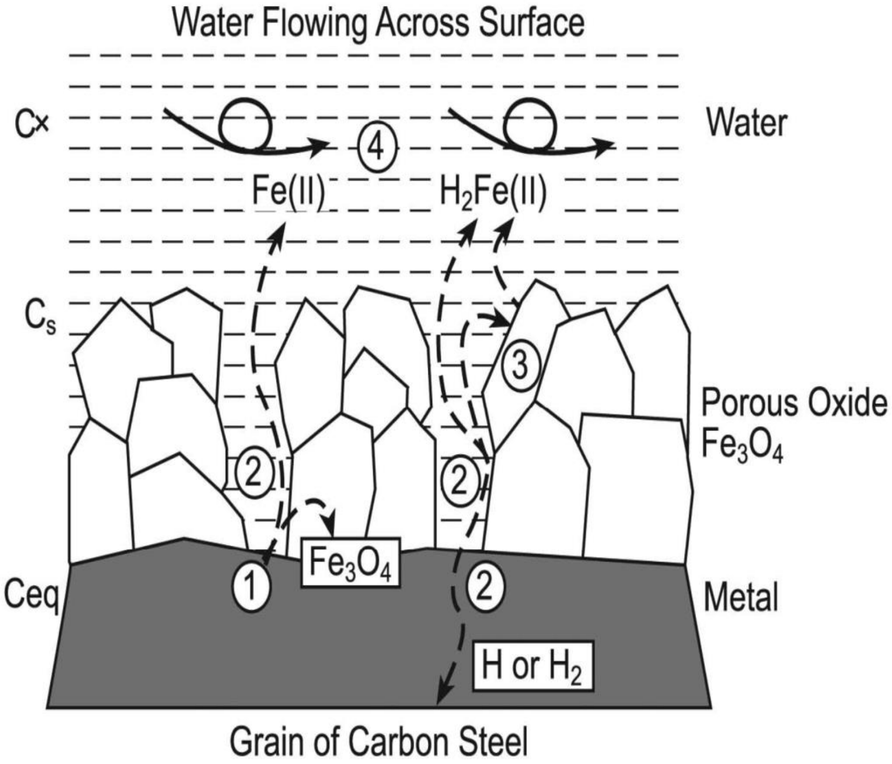
- **Nuclear**
  - 1986 – Surry Nuclear Power Station – Condensate System
- **Fossil**
  - Later 1980's – FAC Identified in Feedwater Systems
  - 1995 – Pleasant Prairie Plant – Feedwater System
- **Flow- Accelerated Corrosion (FAC) is a corrosion process that degrades carbon steel material**
- **Degradation occurs under certain temperatures and specific chemistry conditions**
- **FAC requires that flowing water or water/steam be present**
- **FAC is normally related to turbulence especially near fittings, e.g., elbows, tees, orifices, valves.**

DESCRIPTION OF FAC

FAC occurs when the normally protective iron-oxides dissolve into the flowing stream

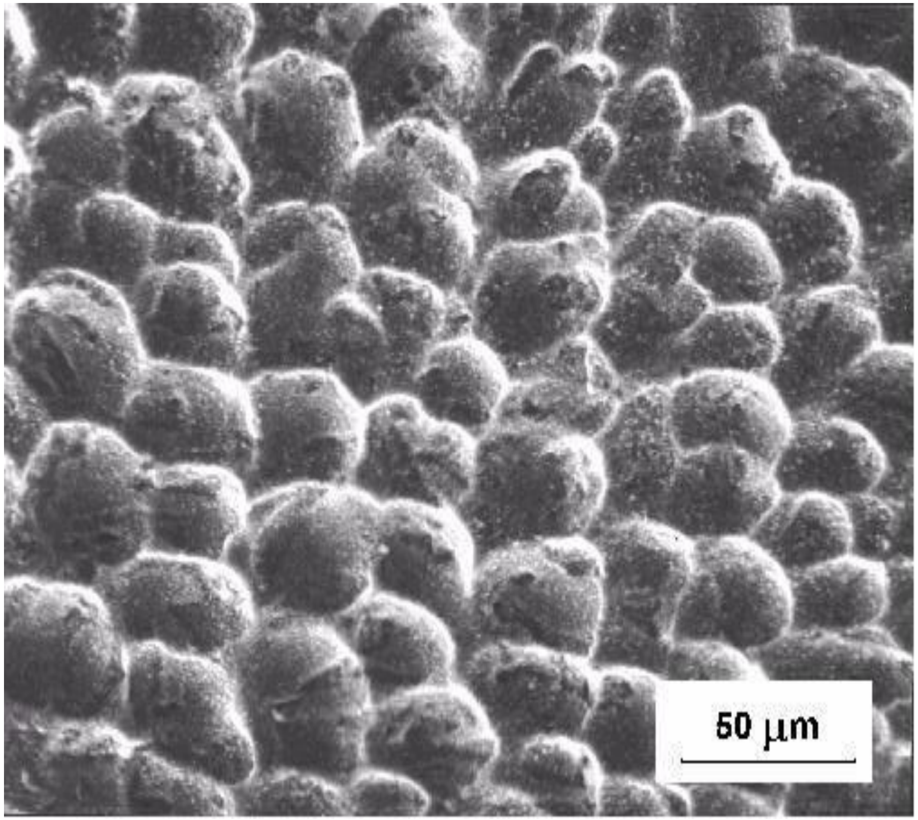
FAC is a global attack on piping (i.e., widespread thinning) rather than local attack (i.e., pitting or cracking)

FAC caused failures are often sudden and catastrophic



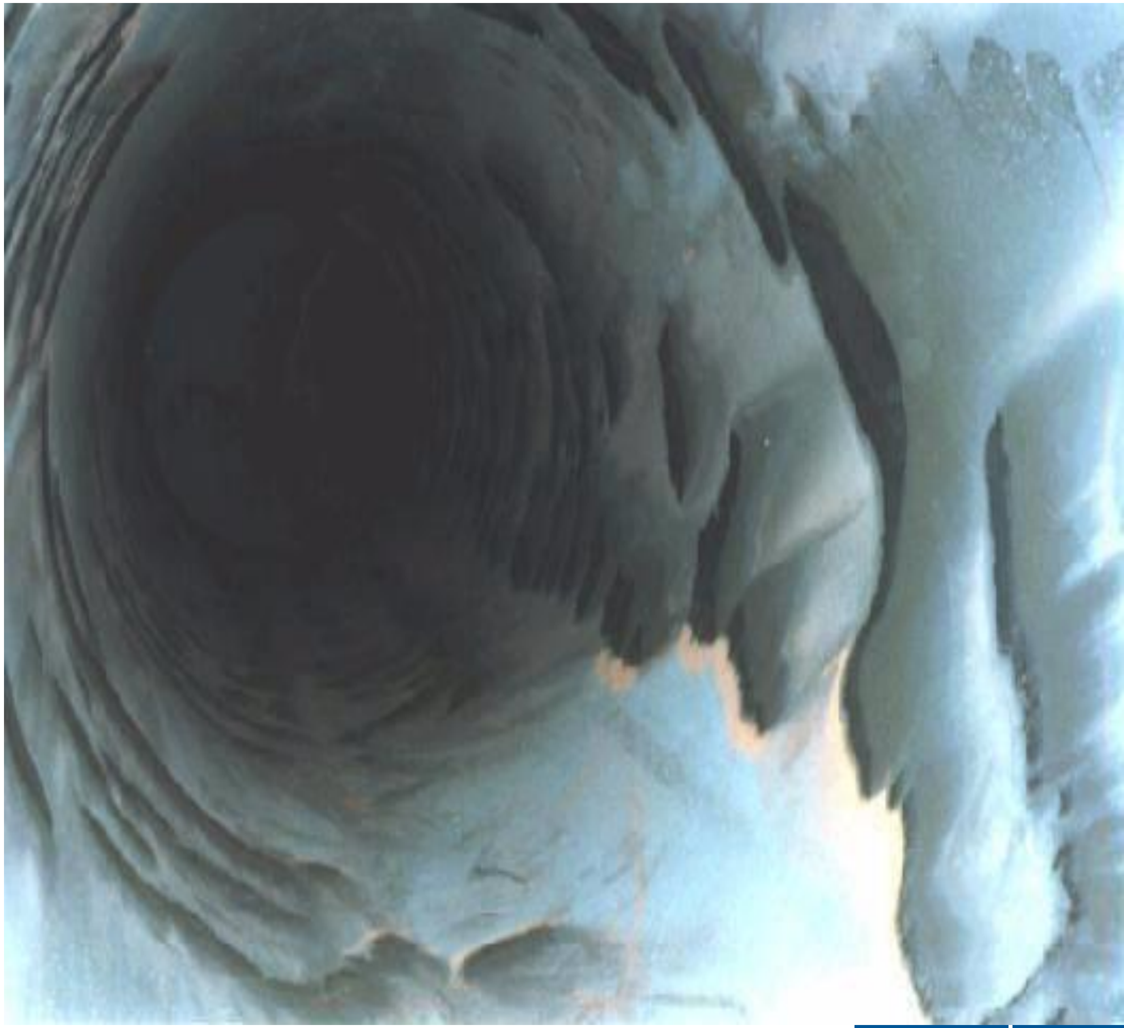
WHAT DOES FAC DAMAGE LOOK LIKE?

- Under single-phase (i.e., water only) conditions, the damaged surface displays a “scalloped” or “orange-peel” surface
- This type of surface is conclusive evidence that the damage is caused by FAC
- Depending on the conditions, magnification may be required to view the scalloping



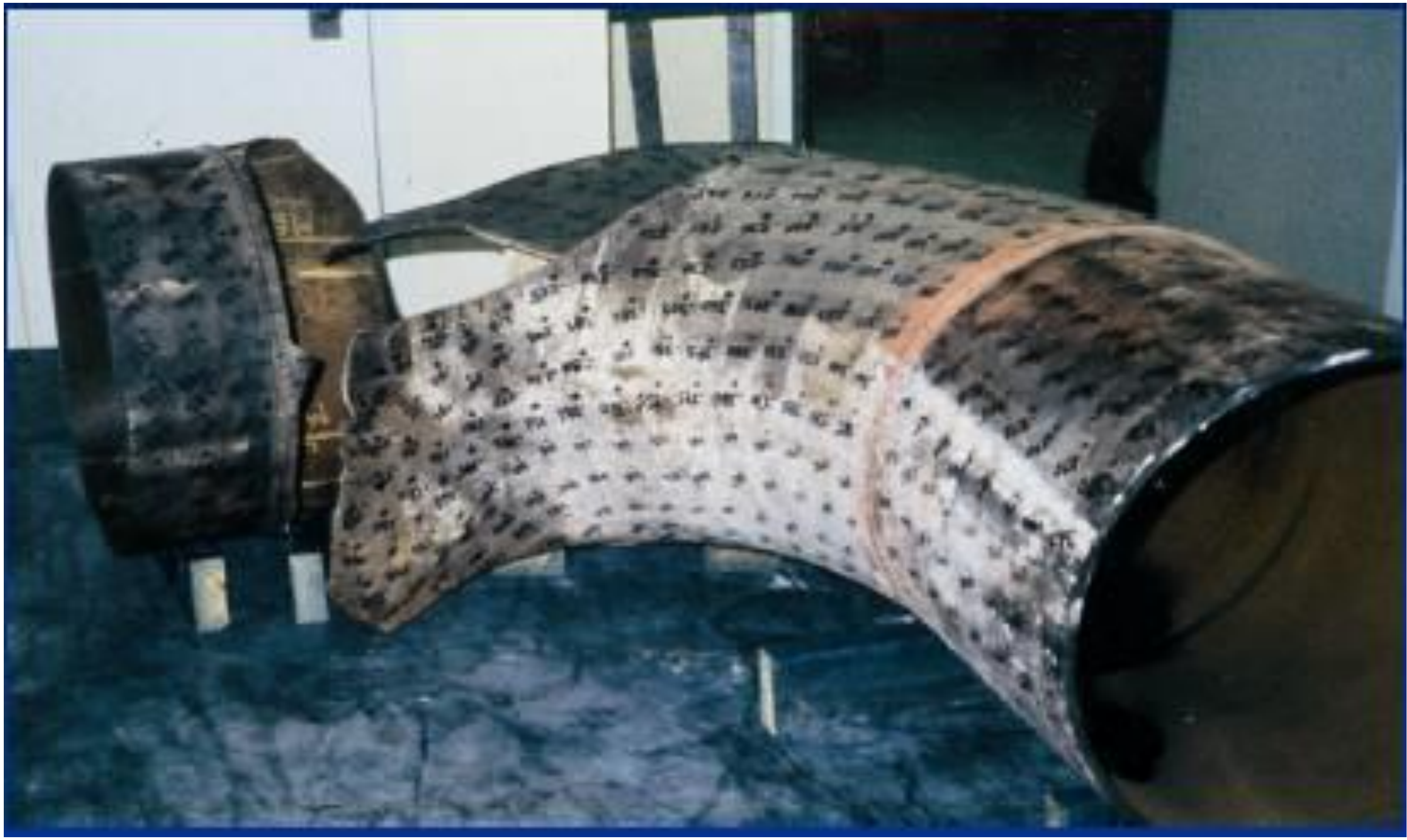
WHAT DOES FAC DAMAGE LOOK LIKE?

- Under high quality, two-phase conditions, the surface may show a pattern of dark and light areas known as “tiger stripping”
- Tiger-striping is also conclusive evidence of FAC



SURRY UNIT 2 - 1986

- 18” Elbow in a Condensate Line
- Four Fatalities and Several Injuries Resulted



DUKOVANY (CZECH REPUBLIC) - 2001

- 12” High Pressure Extraction Line

MIHAMA UNIT 3 - 2004

- A 22” Condensate Line Downstream of an Orifice
- Five Fatalities and Several Injuries Resulted

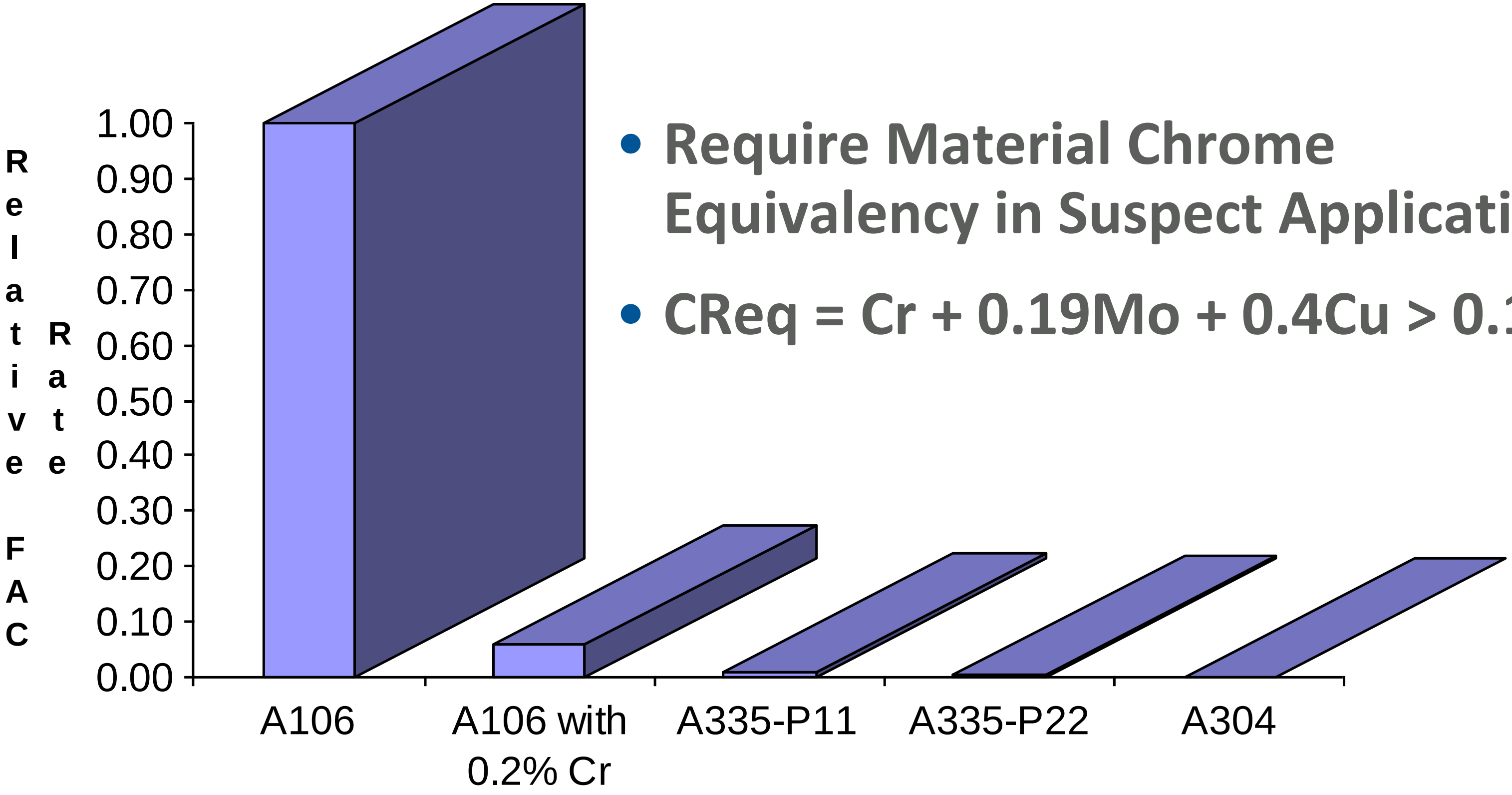
IATAN UNIT 1 - 2007

- 4” Boiler Feedwater to Desuperheater
- Two Fatalities and One Injury

SUSCEPTIBLE CONSIDERATIONS

- **Piping is susceptible to FAC if:**
  - The material is carbon steel
  - There is water or wet steam flowing in the pipes
  - Temperature conditions are within band 200°F to 500°F
  - The water is deoxygenated (i.e., service water systems do not experience FAC)
- **Systems which are of concern:**
  - Generally all of the secondary side in PWRs and the equivalent BWR systems are susceptible to damage
  - Some BWR auxiliary systems (e.g., RHR) may also be susceptible
  - In fossil plants, condensate and boiler feed systems are susceptible as well as some extraction steam lines
  - Auxiliary systems such as building steam may also be susceptible

FAC RESISTANT - MATERIAL VS. WEAR RATE



- **Require Material Chrome Equivalency in Suspect Applications**
- **CReq = Cr + 0.19Mo + 0.4Cu > 0.16%**

ALTERNATE MATERIALS – P36

- **Developed by Vallourec & Mannesmann**
  - Copper-Nickel-Molybdenum-Alloyed Carbon Steel
  - Standard in India and China for Super-Critical Applications
- **ASME Code Case 2353 for Section I**
  - Approved Material B31.1
  - Used in 30+ Plants since 1972
- **Advantages**
  - 35% Reduction in Wall Thickness over A106 Grade C
  - High Resistance to FAC
- **Disadvantages**
  - No Casting Equivalent Currently Exists – Use Transition Pieces or Forged Valves

A106 GRADE B/C VS. P36

	Base Material Specifications		
	A106 Gr. B	**A106 Gr. C**	**P36**
C	0.30 max.	0.35 max.	0.10 - 0.17
Mn	0.29 - 1.06	0.29 - 1.06	0.80 - 1.20
P	0.035 max.	0.035 max.	0.030 max.
S	0.035 max.	0.035 max.	0.025 max.
Si	0.10 min.	0.10 min.	0.25 - 0.50
Cr	0.40 max.	0.40 max.	0.30 max.
Mo	0.15 max.	0.15 max.	0.25 - 0.50
V	0.08 max.	0.08 max.	0.02 max.
N	-	-	0.02 max.
Ni	0.40 max.	0.40 max.	1.00 - 1.30
Al	-	-	0.05 max.
Cb	-	-	0.015 - 0.045
Cu	0.40 max.	0.40 max.	0.50 - 0.80

FORGED VS. CAST STEEL

- **Trend over the last few years for forged valves being quoted as alternative to cast steel valves, especially for high pressure applications**
  - Forged valves have traditionally been used for small bore applications (≤2” NPS) and cast for large bore applications.
- **Both can provide acceptable performance for most power applications**
  - Perception by some is that forged valves are superior in quality but cast is lower cost.
  - Decision to go with cast or forged valves depends on several factors, but cost is often the determining one.
- **Code requirements such as ASME’s quality factor can cause design challenges with regards to transitions between pipe and valve**

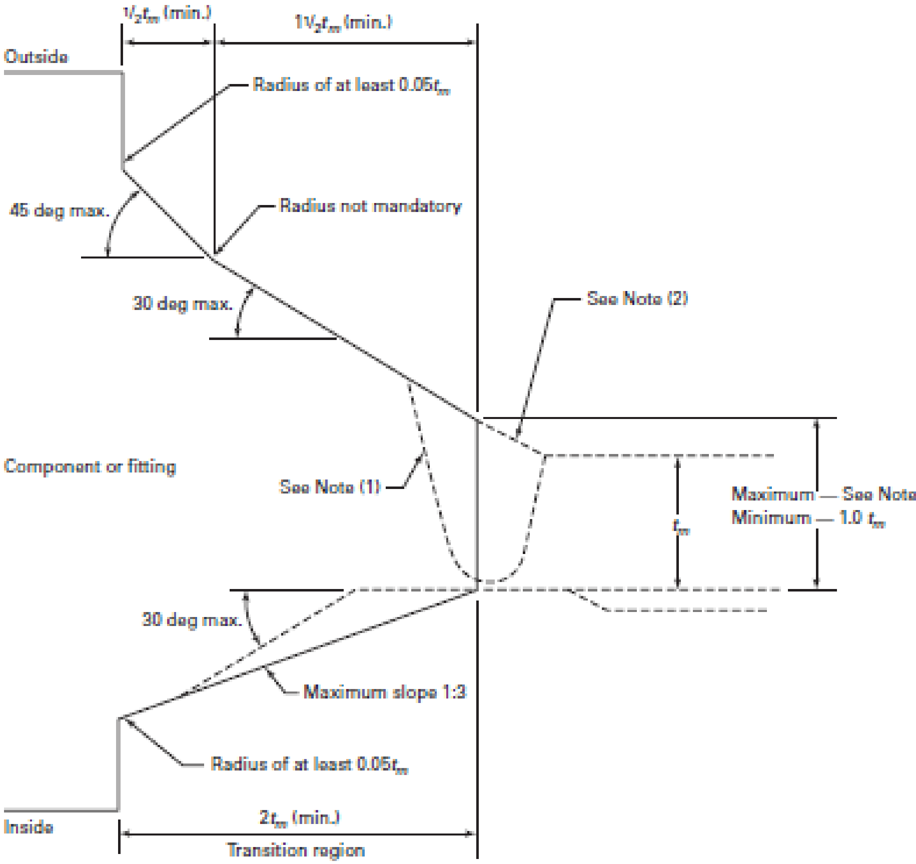
FORGED VS. CAST STEEL – CONT'D

- **With new materials, cast grades often lag in development and forged valves provide more direct use of advance materials.**
  - Designer forced to specify a lower strength material and transitions are required for difference in strengths in addition to dissimilar metal welding.
  - Example is how long C12A was introduced after Grade 91 pipe and forgings. Designers specified WC9 valves with transition pieces between pipe and valve.
  - Has caused a delay in utilization of P92 and P36 materials in US market
  - India and Chinese markets and developers generally use forged valves in lieu of cast grades with transitions.

WELD END TRANSITIONS

- Weld end transitions are common and required on most cast and some forged products due to differences in wall thickness
- Outside-to-Inside of component was traditionally minimized
- On forged components made by machining operations, Outside-to-Inside may not be minimized

Fig. 127.4.2 Welding End Transition — Maximum Envelope



On high temperature applications, transition region needs to be lengthened

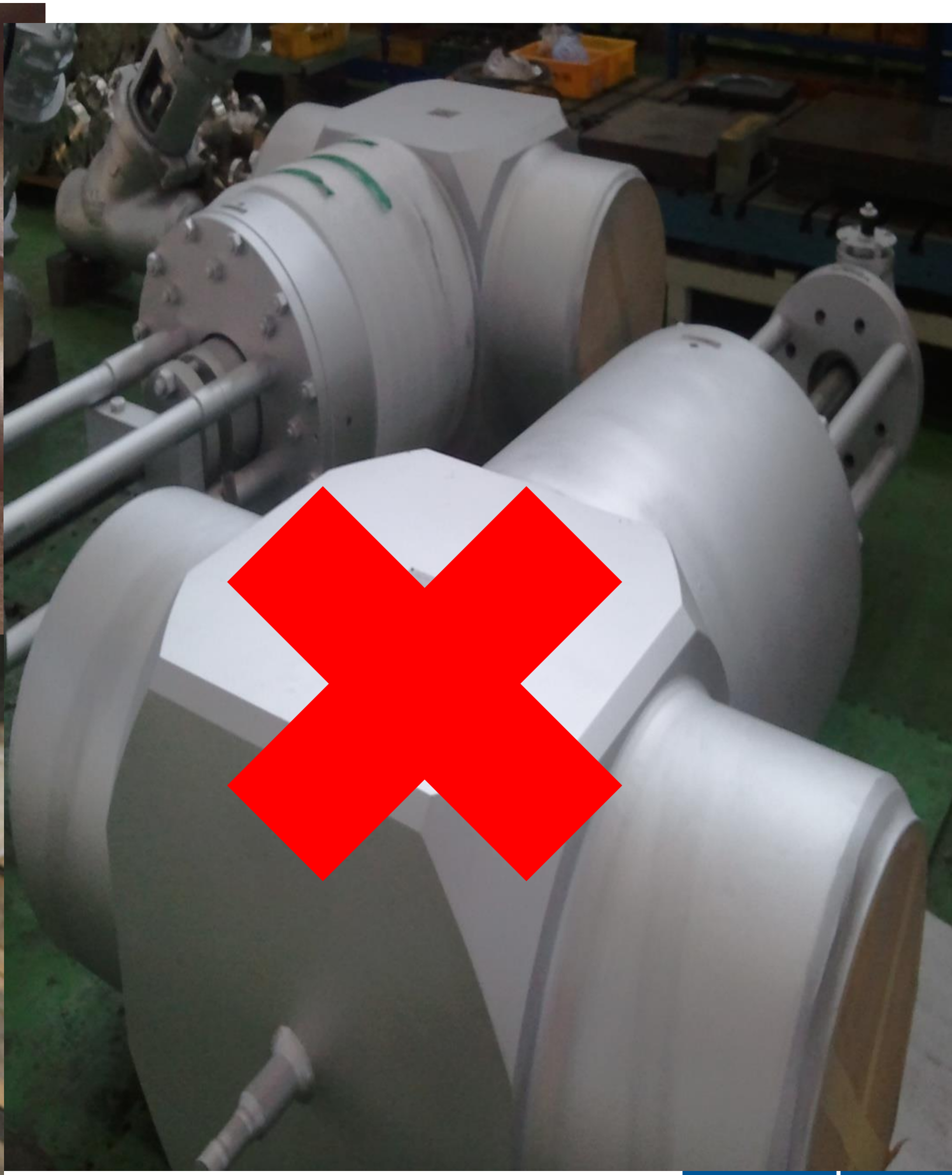
LESSONS LEARNED FROM WYE FORGINGS

REVISED SPECIFICATIONS

- **ASME Codes do not define component design to this level of detail**
  - May actually be acceptable for some applications
- **Revised piping specifications to require machining to “partially contoured” or “fully contoured”**
  - Exterior surfaces of wye and lateral fittings shall be machined to remove as much excess metal as possible.
  - The principle of material removal shall be to make all wall sections as uniform as possible, consistent with any required pressure reinforcement.
  - Radii to eliminate block corners shall be, at a minimum, one half of the respective outside radius of the branch header.

Question: Do similar requirements need to be included in valve specifications where forged steel valves can be substituted for cast valves

EXAMPLES OF FORGED VALVES



FUTURE TRENDS

- Future Market for Supercritical Units
- Emerging Materials
  - Designing over 1200°F (649°C)
- What it means for valve industry

FUTURE MARKET FOR SUPERCRITICAL UNITS

- **Election on November 8th Created Significant Uncertainty in the Coal Generation Market**
- **New Generation Coal Market**
  - B&V currently involved in over a dozen supercritical units
    - Developing Countries in Asia
    - India
    - Sub-Sahara Africa
    - Limited Parts of South America
- **North America and Europe**
  - New renewable capacity additions
  - New natural gas-fueled generation
  - Significant portion of coal fired generation fleet (>50%) will be retired due to age or cost of compliance with the pending air quality regulations

ESTIMATED COSTS AND THERMAL EFFICIENCIES OF VARIOUS PLANT TYPES

Unit Type	Average Efficiency	CO2 Emissions, g/kWh	Power Generation Costs, US¢/kw	Total Plant Capital Cost US$/kw	Time to Build Plant, months
Subcritical	36-40%	766-789	4.0-4.5	2,900-3,300	48-60
Supercritical	40-44%	722	3.5-3.7	3,500-4,500	48-72
Ultrasupercritical	44-46%	<722	4.2-4.7	4,700-5,200	48-72
IGCC	42-44%	710-750	3.9-5.0	3,800-6,600	84-120
NGCC	50%	344-430	3.4-6.8	600-1,000	30

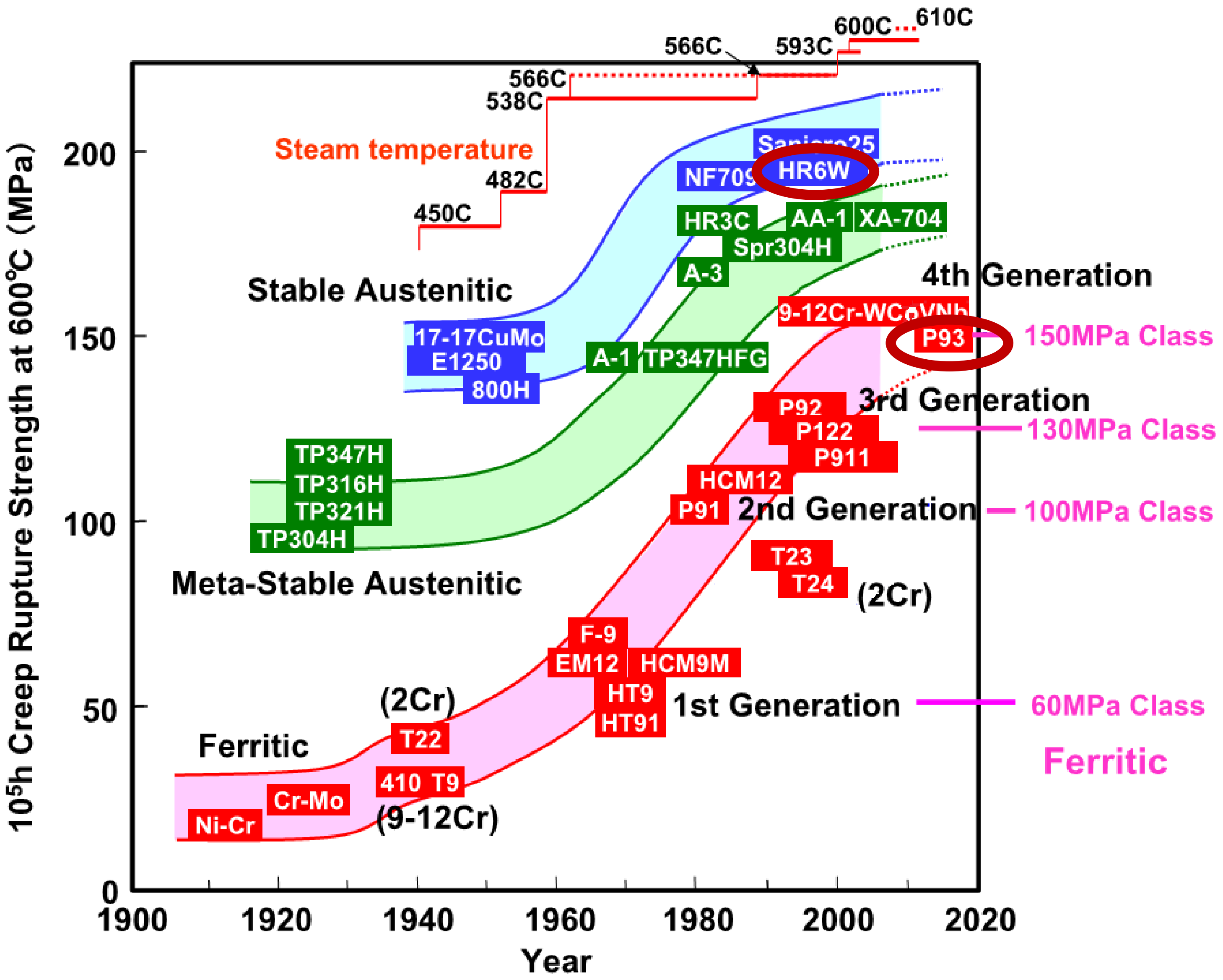
There are sound reasons why natural gas combined cycle power plants continue to be the primary unit built in the US market.

POWER PLANT INNOVATIONS

- On 3 June 2014, the Australian government's research organization CSIRO announced that they had generated 'supercritical steam' at a pressure of 23.5 MPa (3,410 psi) and 570°C (1,060°F) in what it claims is a world record for solar thermal energy.
- The Cottam combined-cycle power plant in the central part of England is supercritical heat-recovery steam generator (HRSG).

It is no longer limited to coal-fired power plants.

HISTORICAL IMPROVEMENT OF CREEP RUPTURE STRENGTH STEELS



SAVE12AD (GRADE 93)

- **A normalized and tempered steel, 9Cr-3W-3Co-Nd-B, developed by Nippon Steel & Sumitomo Metal (NSSMC), Japan**
  - 30% stronger in creep than P92 at 1200°F (649°C)
  - Improved creep rupture ductility
  - Type IV-free or less-degradation welds
- **ASME Section I Code Case 2839 approved on October 15, 2015 and ready for publication**
  - Proposed designation to be P93 for pipe, T93 for tube and F93 for forgings in ASTM and ASME
  - Property Data to 1200°F (649°C)
  - Built to ASME Standards SA-182, SA-213, SA-335

HR6W (UNS N06674)

- **A solution annealed Nickel alloy, 47Ni-23Cr-23Fe-7W, developed by Nippon Steel & Sumitomo Metal (NSSMC), Japan**
  - Stability of long term creep rupture strength and superior creep rupture ductility
  - Much better corrosion resistance than 18Cr-8Ni austenitic stainless steels
  - Microstructural phase stability at elevated temperature, which contributes to superior stress relaxation and fatigue properties
  - Better formability, wider available size range and better weldability than other nickel based alloys
- **ASME Section I Code Case 2684 approved on November 14, 2014**
  - Property Data to 1500°F (816°C)
  - Built to ASTM Standard B167 and B564

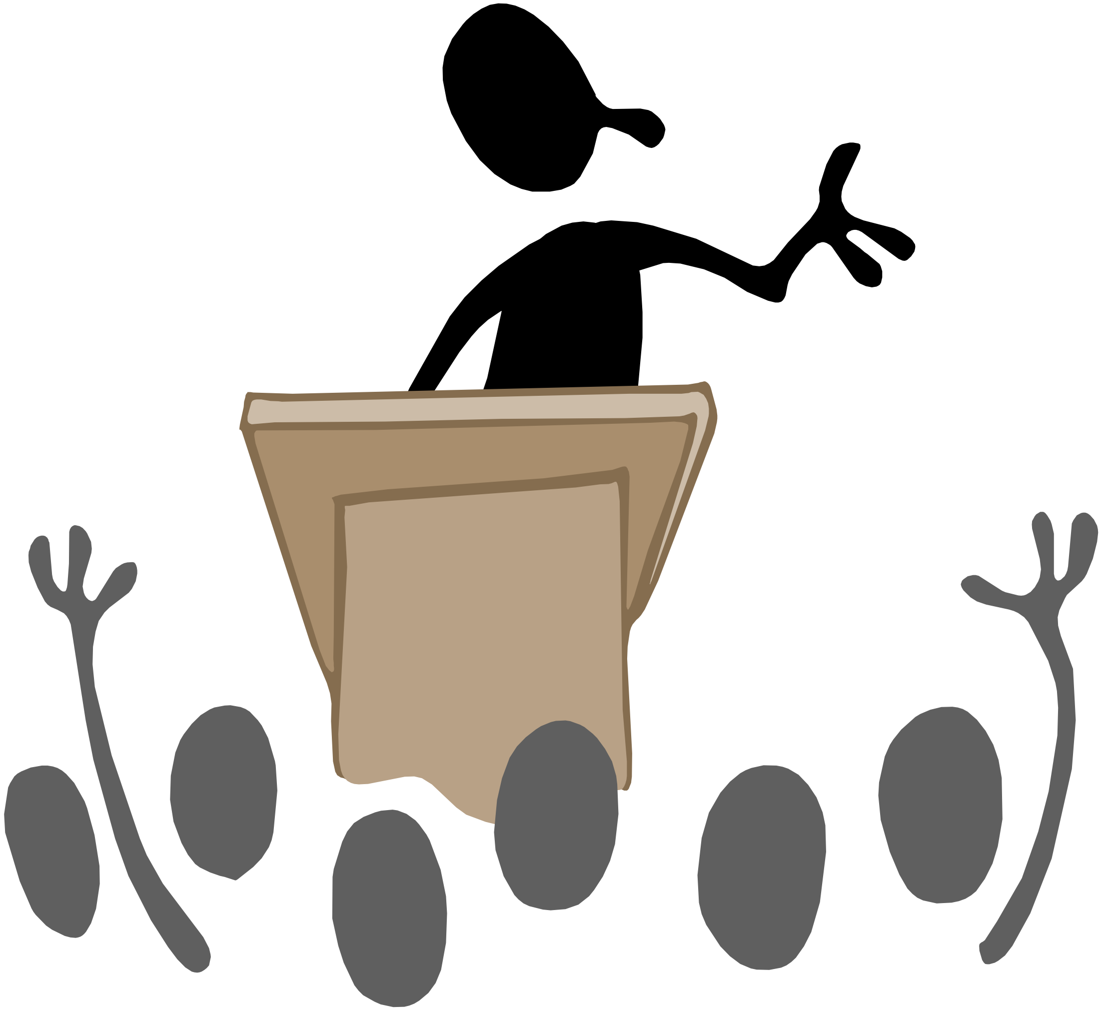
COMPARISON OF COMPOSITION

	Base Material Specifications			
	P91	**P92**	**P93**	**HR6W**
Fe	Remainder	Remainder	Remainder	20.0 - 27.0
C	0.08 - 0.12	0.07 - 0.13	0.05 - 0.10	0.10 max.
Mn	0.30 - 0.60	0.30 - 0.60	0.20 - 0.70	1.5 max.
P	0.020 max.	0.020 max.	0.020 max.	0.030 max.
S	0.010 max.	0.010 max.	0.008 max.	0.015 max.
Si	0.20 - 0.50	0.50 max.	0.05 - 0.50	1.0 max.
Cr	8.00 - 9.50	8.50 - 9.50	8.50 - 9.50	21.5 – 24.5
Mo	0.85 - 1.05	0.30 - 0.60	0.90 - 1.10	-
V	0.18 - 0.25	0.15 - 0.25	0.15 - 0.30	-
N	0.03 - 0.07	0.03 - 0.07	0.005 - 0.015	.02 max.
Ni	0.40 max.	0.40 max.	0.20 max.	Remainder
Al	0.04 max.	0.04 max.	.030 max.	-
Cb	0.06 - 0.10	0.04 - 0.09	0.04 - 0.09	-
W	-	1.50 - 2.00	2.5 – 3.5	6.0-8.0
B	-	0.001 - 0.006	0.007 - 0.015	0.0005 - 0.005
Co	-	-	2.5 - 3.5	-

WHAT IT MEANS FOR VALVE INDUSTRY

- **Traditional mid to high-alloy steels will be utilized for supercritical units operating below 1200°F (649°C).**
  - Higher fatigue cycle resistance required for fast responding assets as renewables come to market
- **Nickel based materials will be used for supercritical applications greater than 1200°F (649°C), but this will most likely be limited in markets outside the US and Europe.**
- **FAC greater concern for aging fleet built with standard carbon steels.**
- **Duplex and nickel alloys as well as nonmetallic components will be utilized in AQCS applications on remaining US coal fleet as well as international markets.**
- **International supply chain will introduce unexpected issues.**

QUESTIONS AND COMMENTS



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