Advanced steels for thermal power
– status, challenges and progress

Pertti Auerkari

VTT, Espoo, Finland

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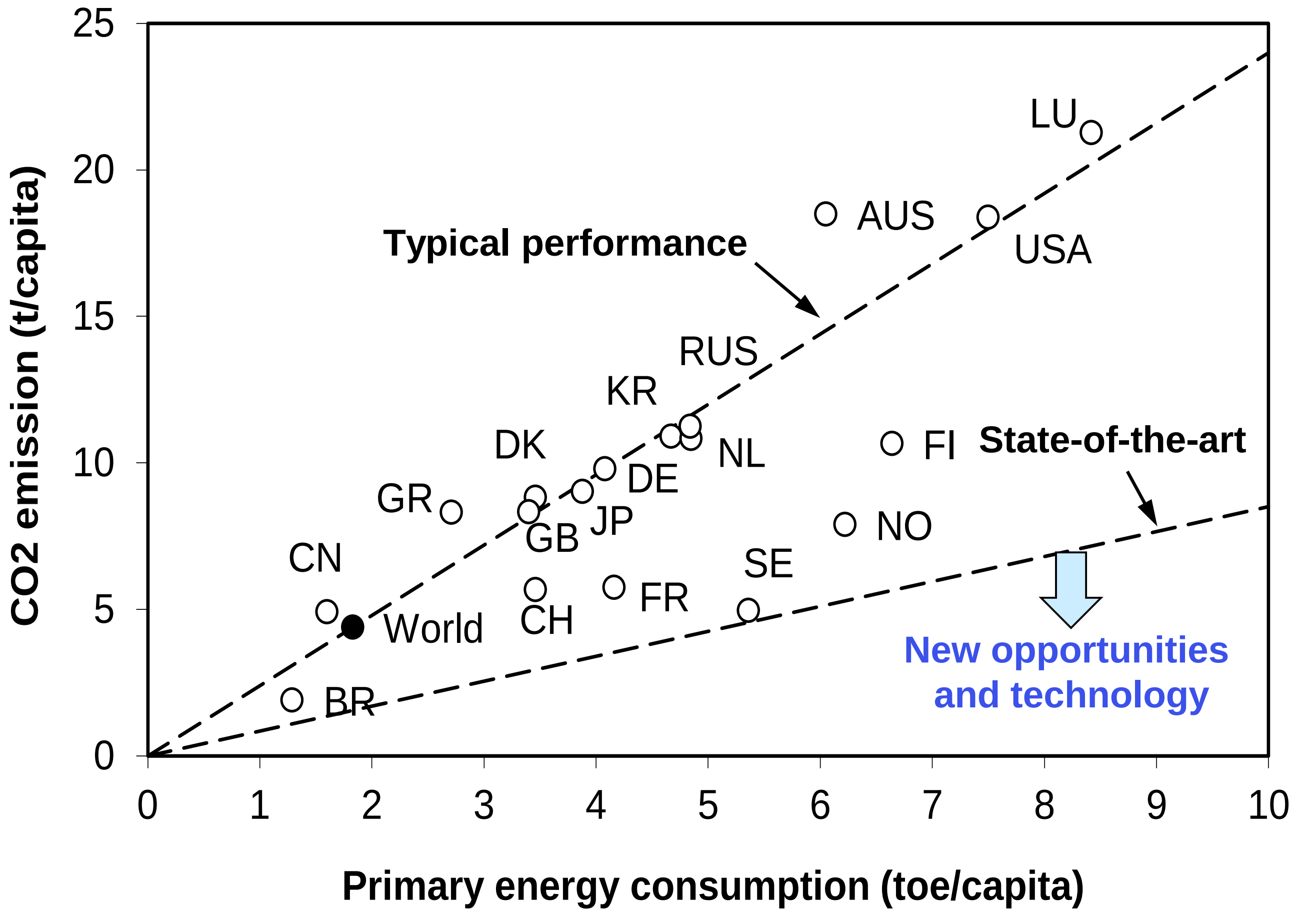
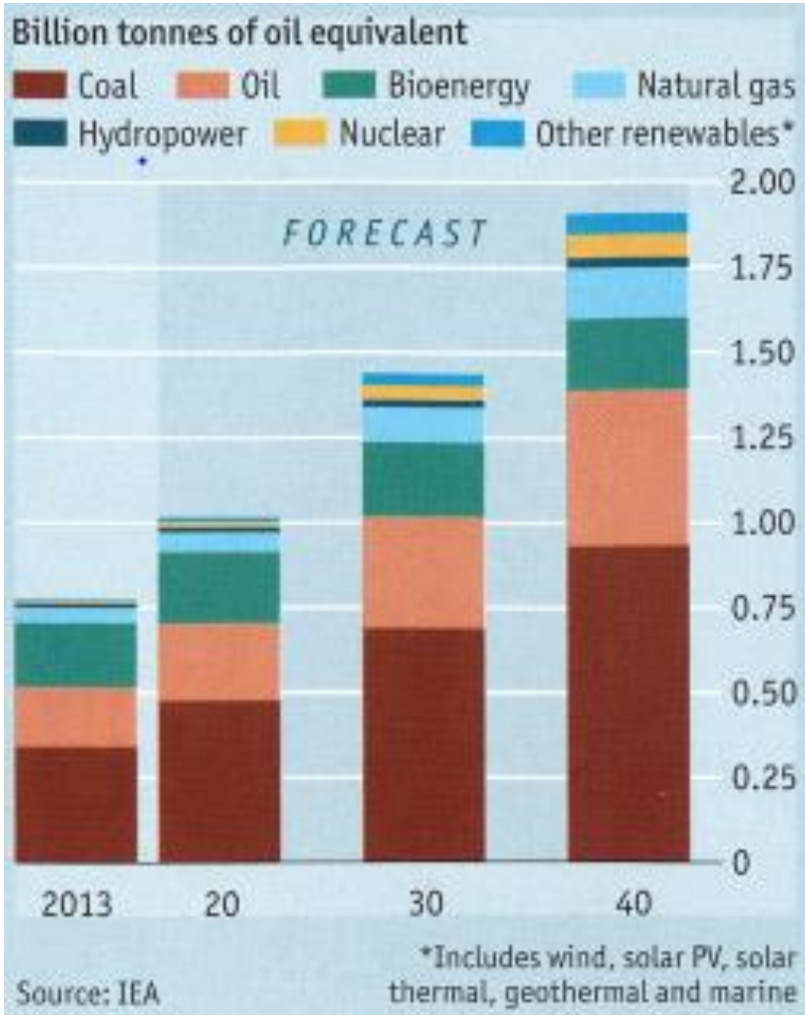
Introduction: drivers and trends



- **Cost / economy**
- **Environment**
  - reduce emissions
  - give up fossil
- **Technical opportunities**
- **Opinion climate**

Data IEA 2008

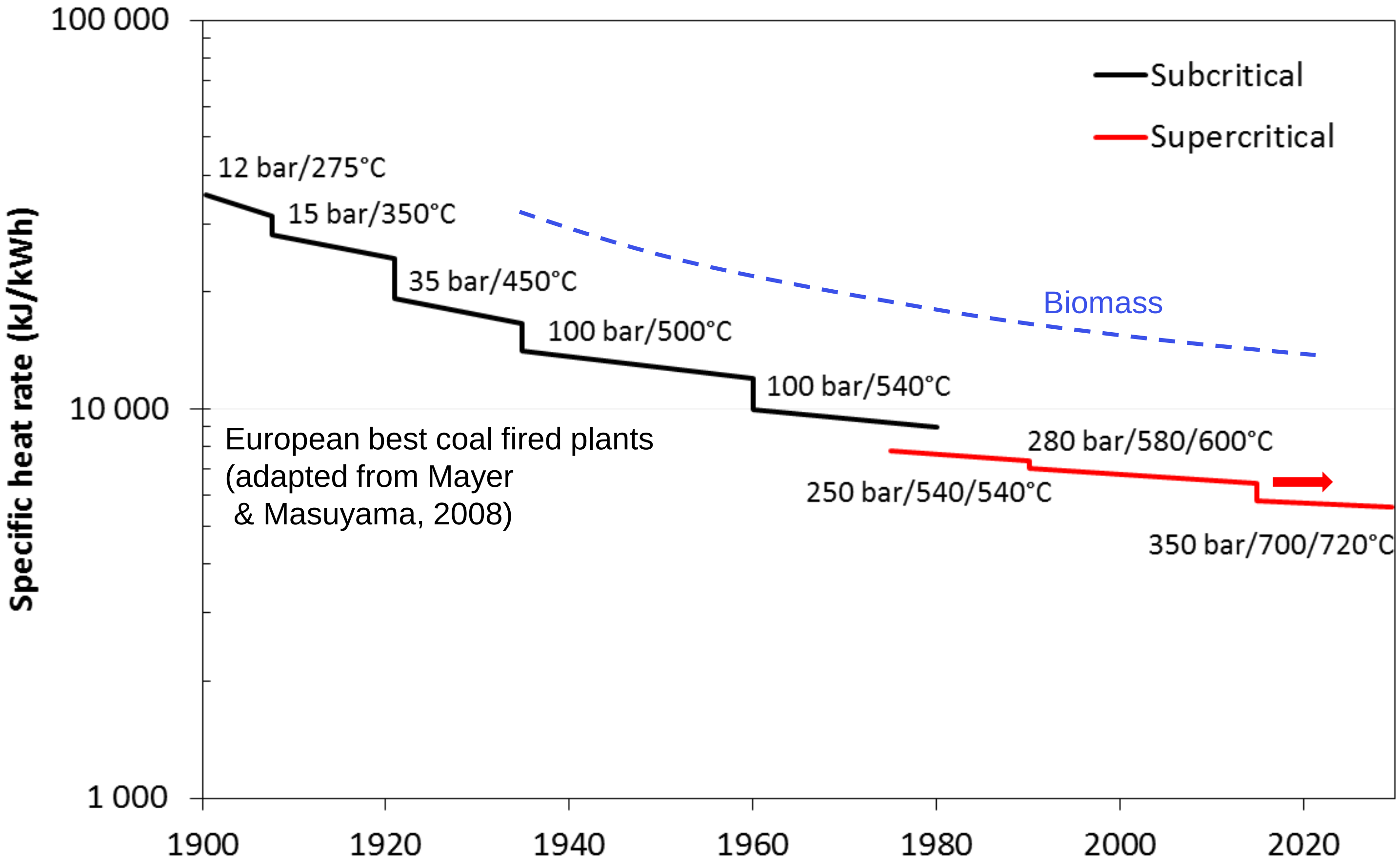


The Economist 14-20.11.2015

Example: India

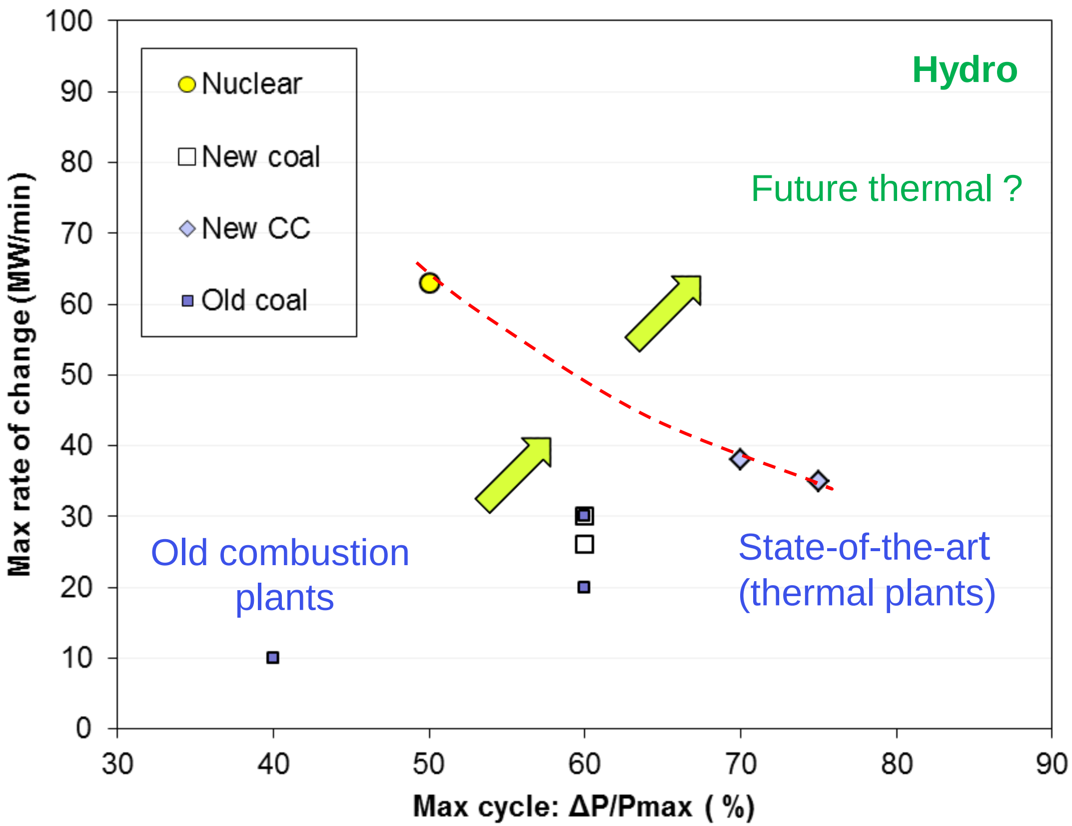
- **Significant growth**
  - coal, oil, gas
  - large now and in future
- **Modest growth**
  - nuclear, hydro
  - other renewables
  - remain small to 2040
- **Almost no growth**
  - biomass
  - large but stagnant
- **Cf. Europe, China, …**

Advanced steels for thermal power : what is new?



- **Increasing efficiency = decreasing heat rate**
- **Development of technology**
- **Reduce fossil fuels - then what?**

New requirement: more flexibility & storage



Data from Timpf & Fuchs 2012; and
Jeschke, Henning & Schreier 2012

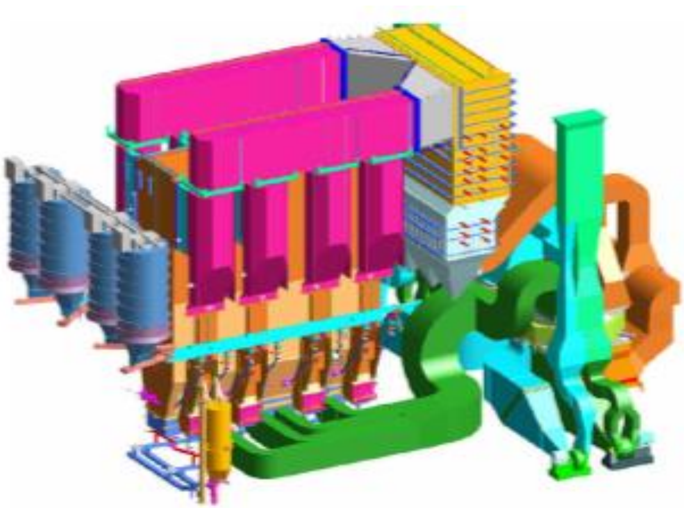
- **Increasing renewables**
  → more cycling & ramping
  → need for more storage
- **Need for improved technology:**
  - process
  - design
  - materials

Advanced steels for thermal power: what is new?

- New processes and equipment
- New materials (steels/alloys, consumables…)
- New fabrication & related technology
- New experience (from new to established)

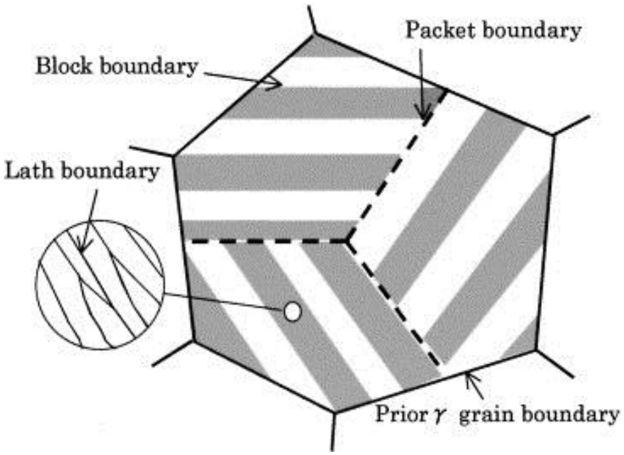
Drivers:
- policies < climate change, taxation etc.
- competitive options in trading, production, fuels,…
- grid connections/capacity (local, regional, wider)
- new opportunities

New processes and plant types: example



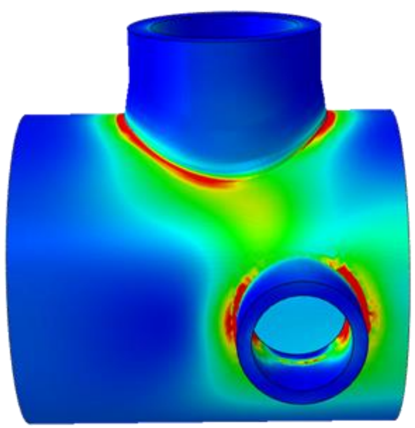
- **Conventional thermal (steam) plant**
  - pulverised fuel (coal, lignite) firing at ~1250ºC
  - up to ~1100 MWe
  - efficiency ~38 to 44%
  - conventional to newer materials
- **New steam plant** (CFB as an example)
  - flexible fuels incl. biomass, firing at ~900ºC
  - up to ~500 MWe
  - similar efficiency with comparable fuels
  - conventional to newer materials
- **Process** matters less than operating environment: e.g. P91 widely used in steam plants, gas turbines and chemical industry

New materials: e.g. 9-12% Cr steels



Multiscale microstructure of tempered martensitic steel
(Hayakawa 2000, Kimura et al. 2006)

X20 header section



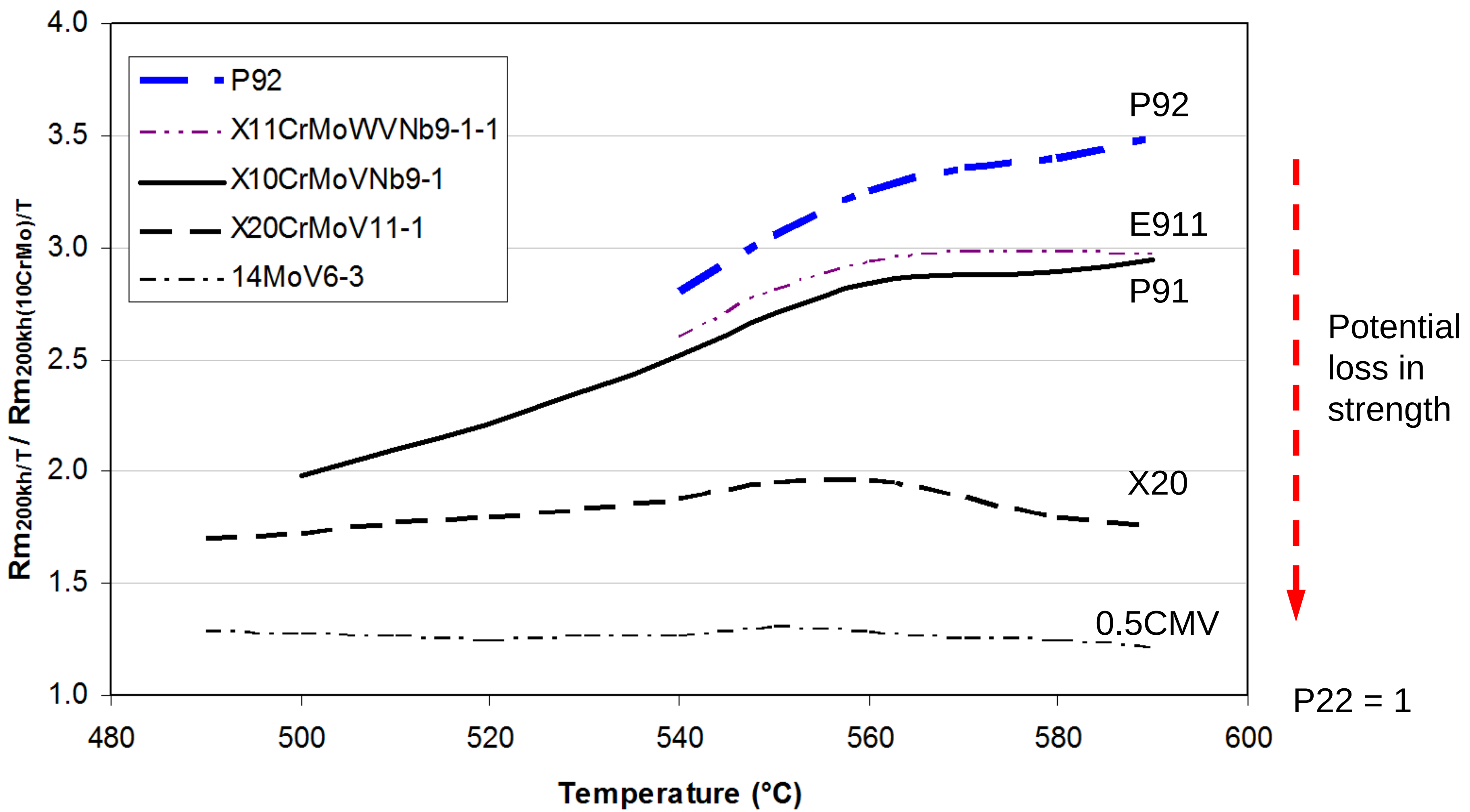
Steels for tubes & pipes:

- 1960’s - : X20 (DE), not so new anymore
- 80’s to ‘90’s- : P91 (US), P92 (JP)
- 2016? - : P93
- Numerous predecessors & sidesteps, parallel alloys for castings, forgings, …

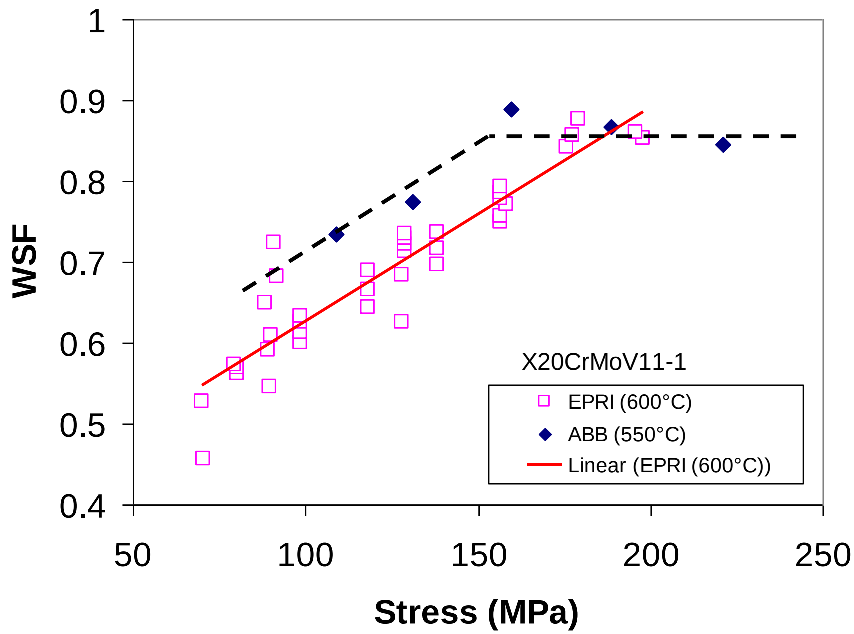
Characteristics:

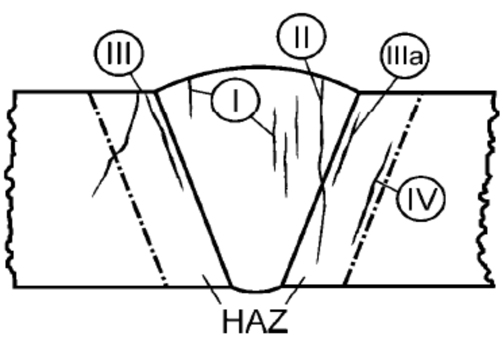
- tempered martensitic microstructure
- multiscale internal boundaries, precipitates, solid solution elements $\rightarrow$ strength, ductility
- fair oxidation resistance (Cr), compatibility in thermal cycles of operation
- strong influence by errors in heat treatments
- *new until full range of service experience*

Creep strength (EN 10216-2, 200 kh) compared to 10CrMo9-10 (P22)



Fabrication & related technology





Processing & heat treatments

- Casting, forging, rolling, drawing, …
- PM heat treatment (aust. + tempering)
- Welding & PWHT, incl. DMW's
- Repairs: weld repair & PWHT

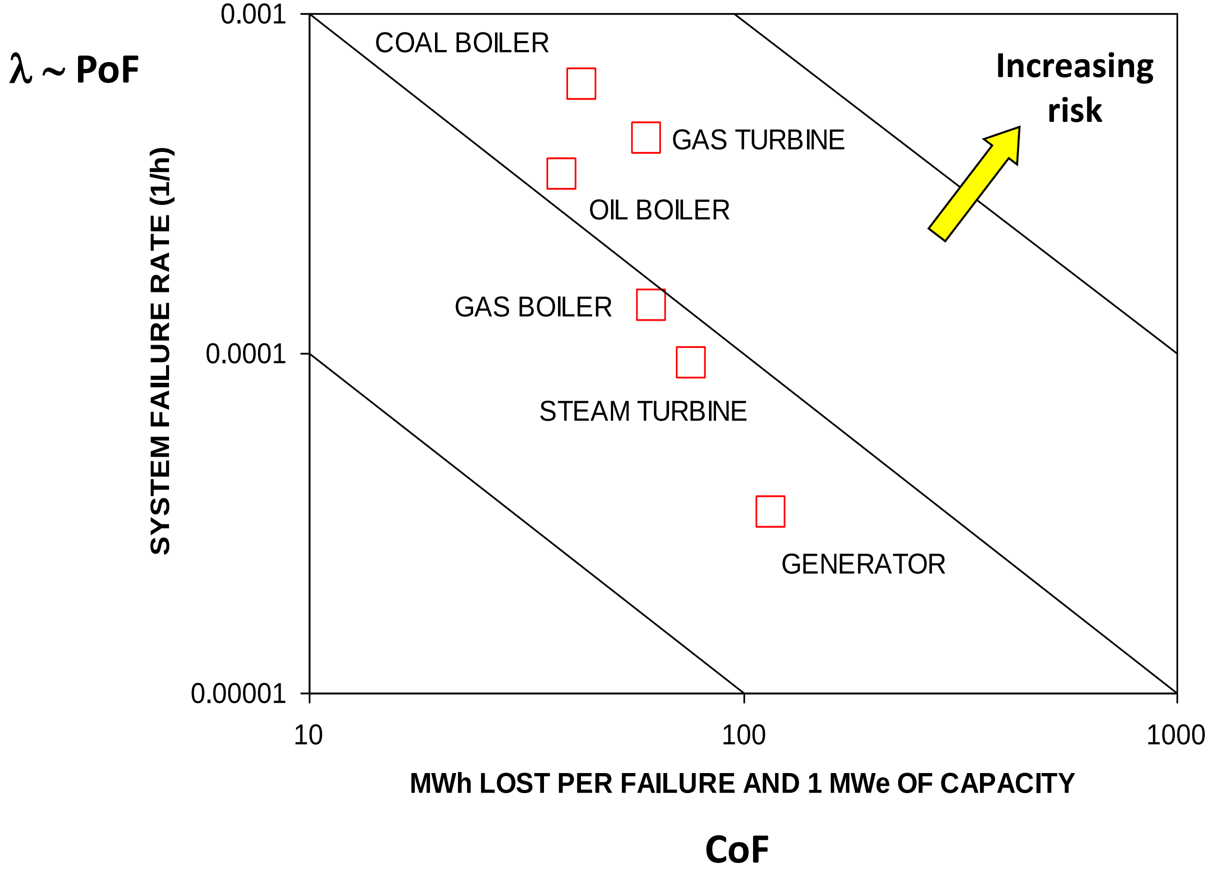
Most common deviations in:

- temperature / time / env. of treatment
- material / material combination
(- chemical composition)

Welds:

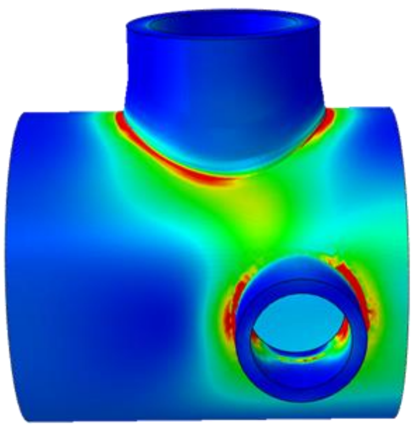
- potential weak links ☹
- mechanical fuses ☺

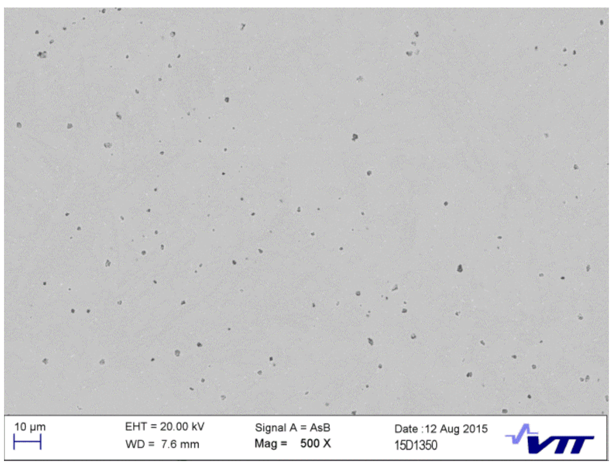
Risk of failures – power equipment



- **Risk of failures**
  - depend on application
  - shift in time?
- **Material impact**
  - only conventional
  - mixed with all sources

Experience on materials in service



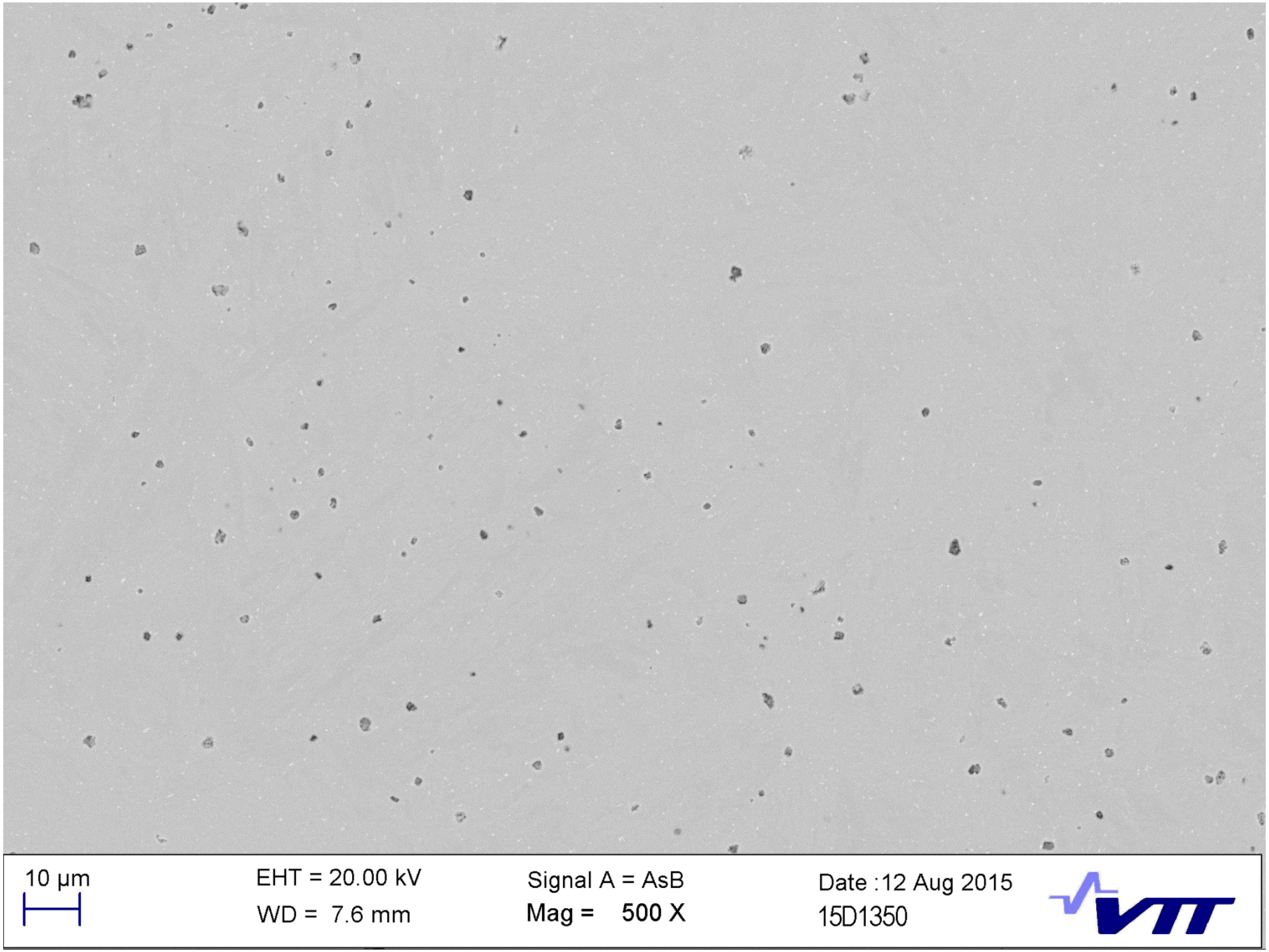


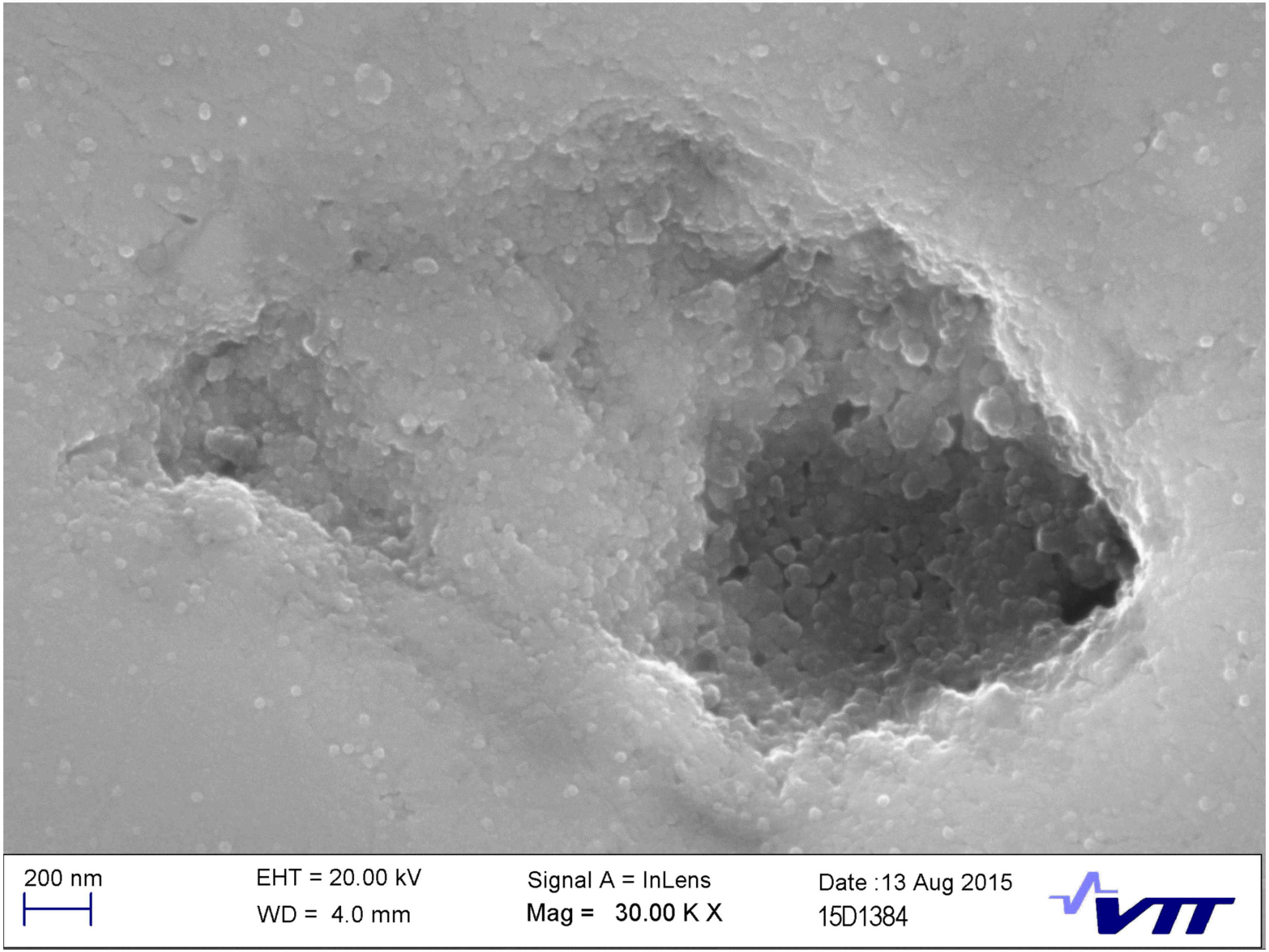
X20CrMoV11-1 (EN 10216-2):

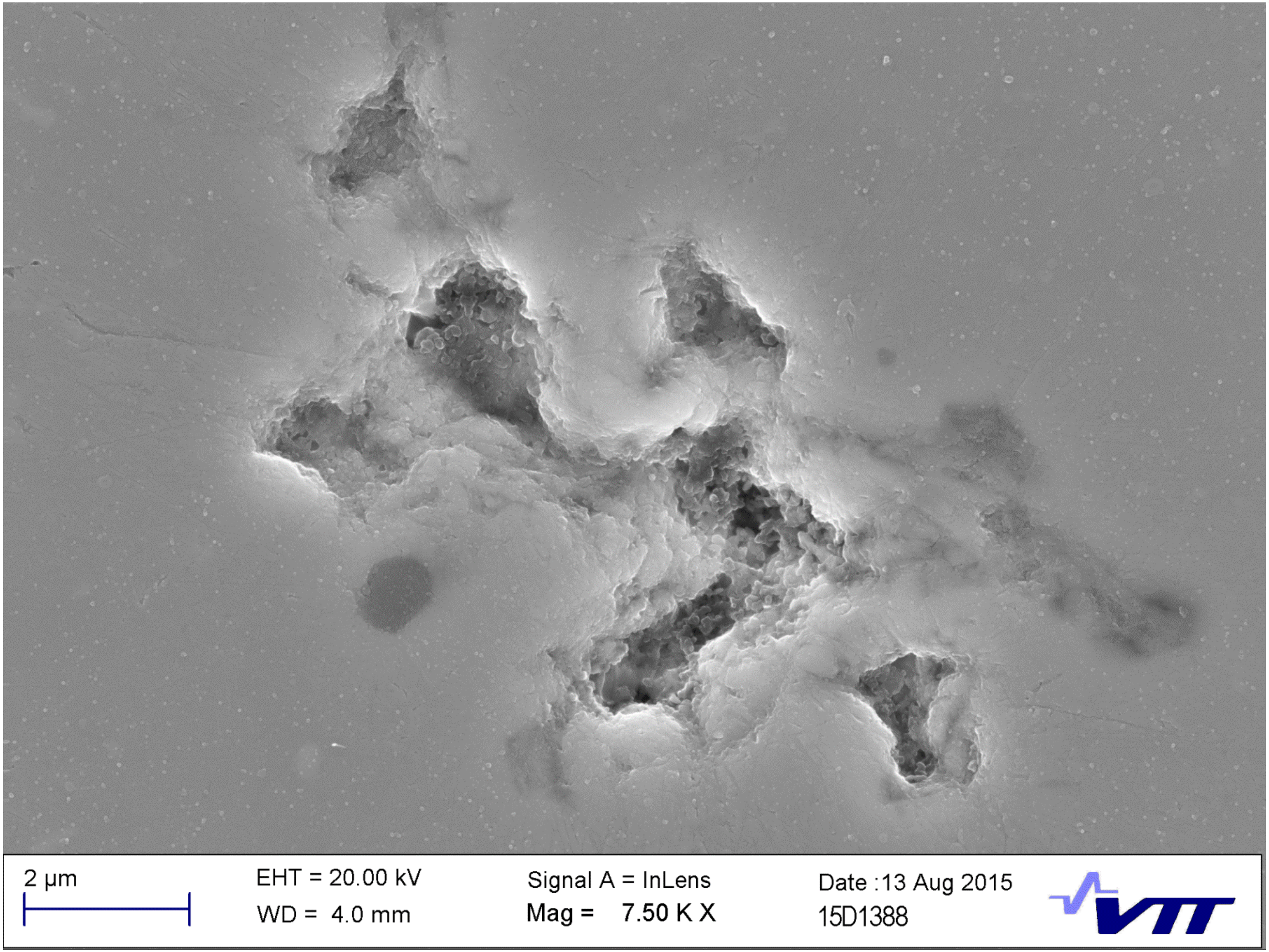
- In widespread use since 1970's, also for superheaters/reheaters, not in ASME code < short-term toughness (welded)
- Generally good indicated long term performance in Europe, > 200 kh in plant
- No systematic indications of low ductility, suggested relatively late emergence of creep cavitation damage in inspections
- Established steel ☺ - to be replaced ☹

Specific features:

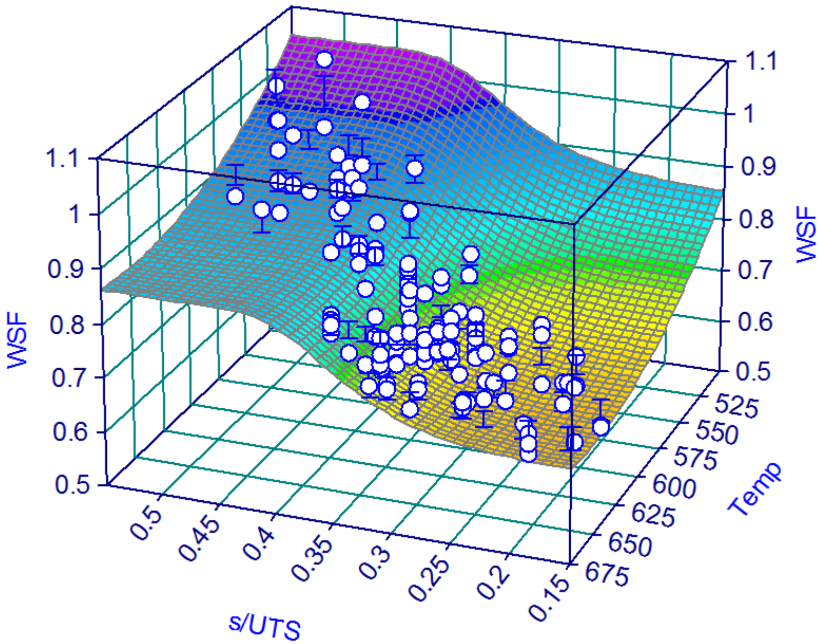
- 0.2%C, to be noted for welding
- Rupture strength ~96 MPa/560ºC/200 kh


10 µm
EHT = 20.00 kV
WD = 7.6 mm
Signal A = AsB
Mag = 500 X
Date :12 Aug 2015
15D1350


200 nm
EHT = 20.00 kV
WD = 4.0 mm
Signal A = InLens
Mag = 30.00 K X
Date :13 Aug 2015
15D1384


2 µm
EHT = 20.00 kV
WD = 4.0 mm
Signal A = InLens
Mag = 7.50 K X
Date :13 Aug 2015
15D1388

Experience on materials in service



s/UTS = stress/ tensile strength

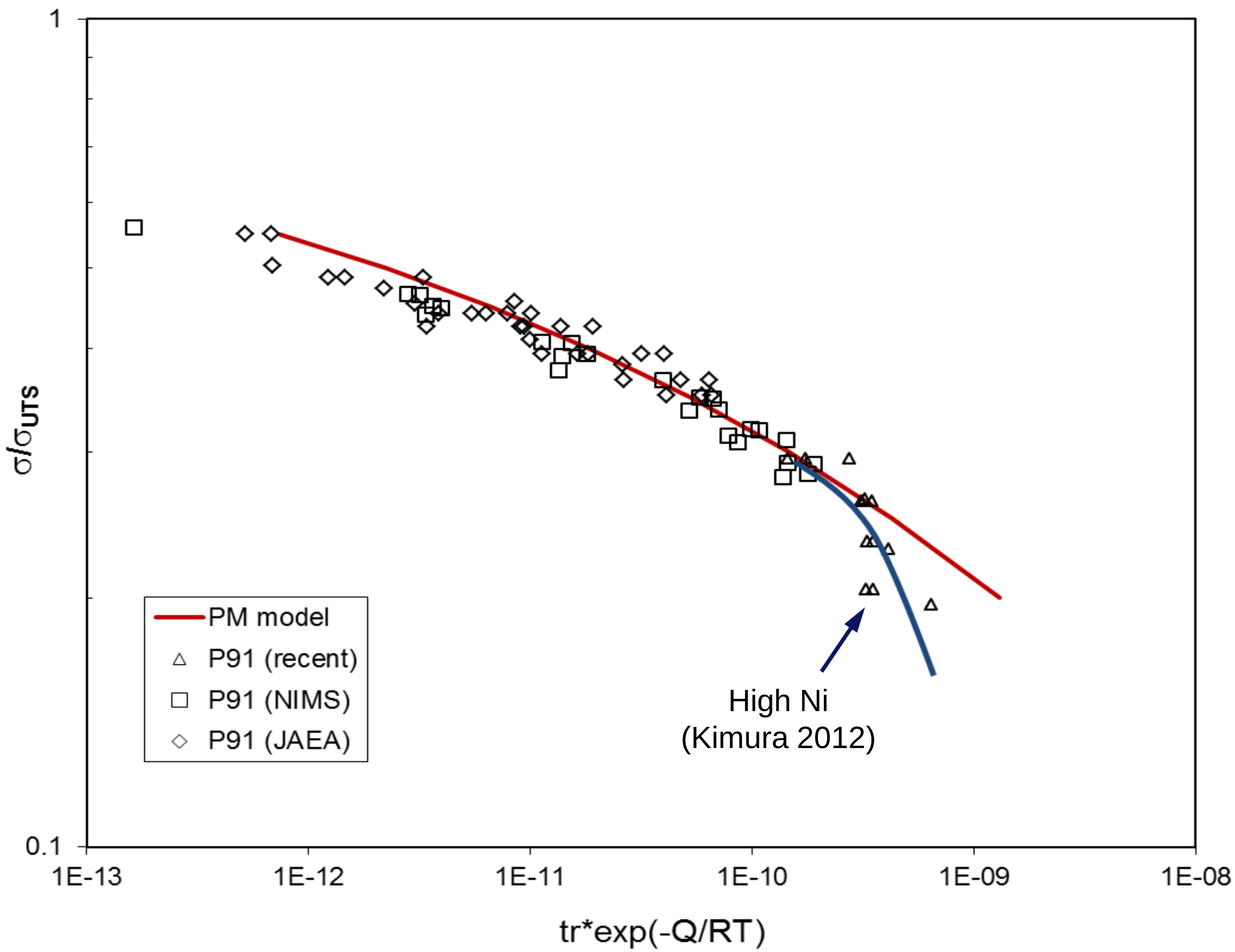
WSF < 0.8 at high temperatures

P91 (X10CrMoVNb9-1 EN 10216-2):

- In widespread use since 1990's, less for boiler internals than X20 (T91, lower Cr)
- Reported cases of early creep damage with high Al (Al:N), high operating temperatures
- No systematic indications of trouble when avoiding upper operating range ≥ 580ºC
- Established steel, less long term experience

Specific features:

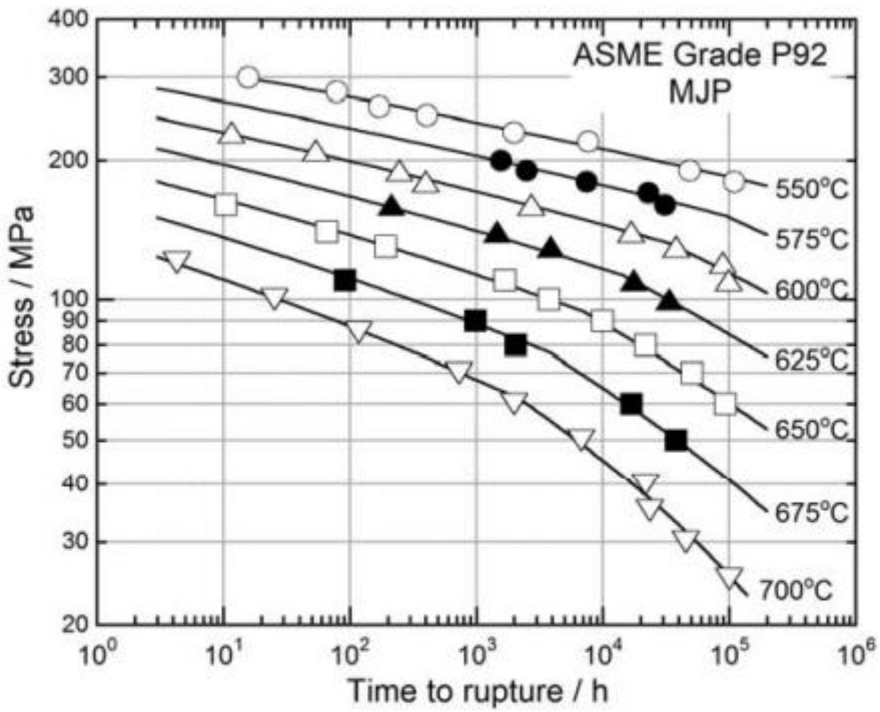
- 0.1%C, easier to weld than X20
- Rupture strength ~97 MPa/590ºC/200 kh



P91 (X10CrMoVNb9-1):

- potential challenges from errors in welding, heat treatment, composition
- at least 30 years for ~ full service experience
- easier for industrial and biomass plants with modest operating temperatures

Experience on materials in testing & service



Kimura & Sawada 2015

P92 (X10CrWMoVNb9-2 EN 10216-2):

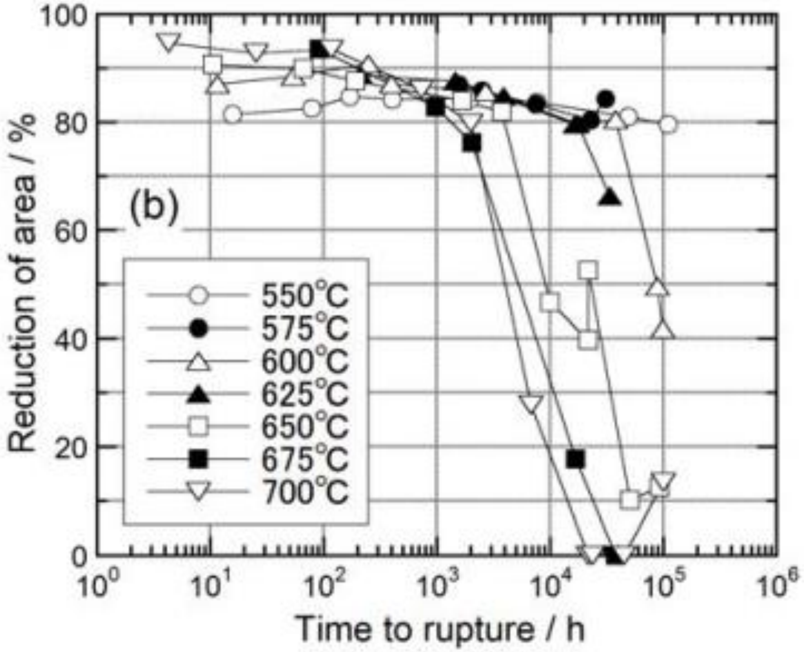
- Used since 1990's, mostly for heavy sections of large plants
- Suggested cases of low creep ductility (composition, fabrication) for upper range of operating temperatures (>600ºC)
- Mostly short to medium term operating experience, not yet a fully established steel

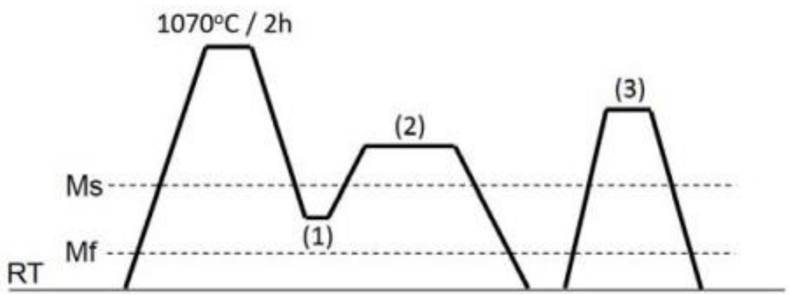
Specific features:

- 0.1%C, much more Laves phase than in P91 or X20
- Rupture strength ~101 MPa/600ºC/200 kh

Experience on materials in testing & service

Kimura & Sawada 2015

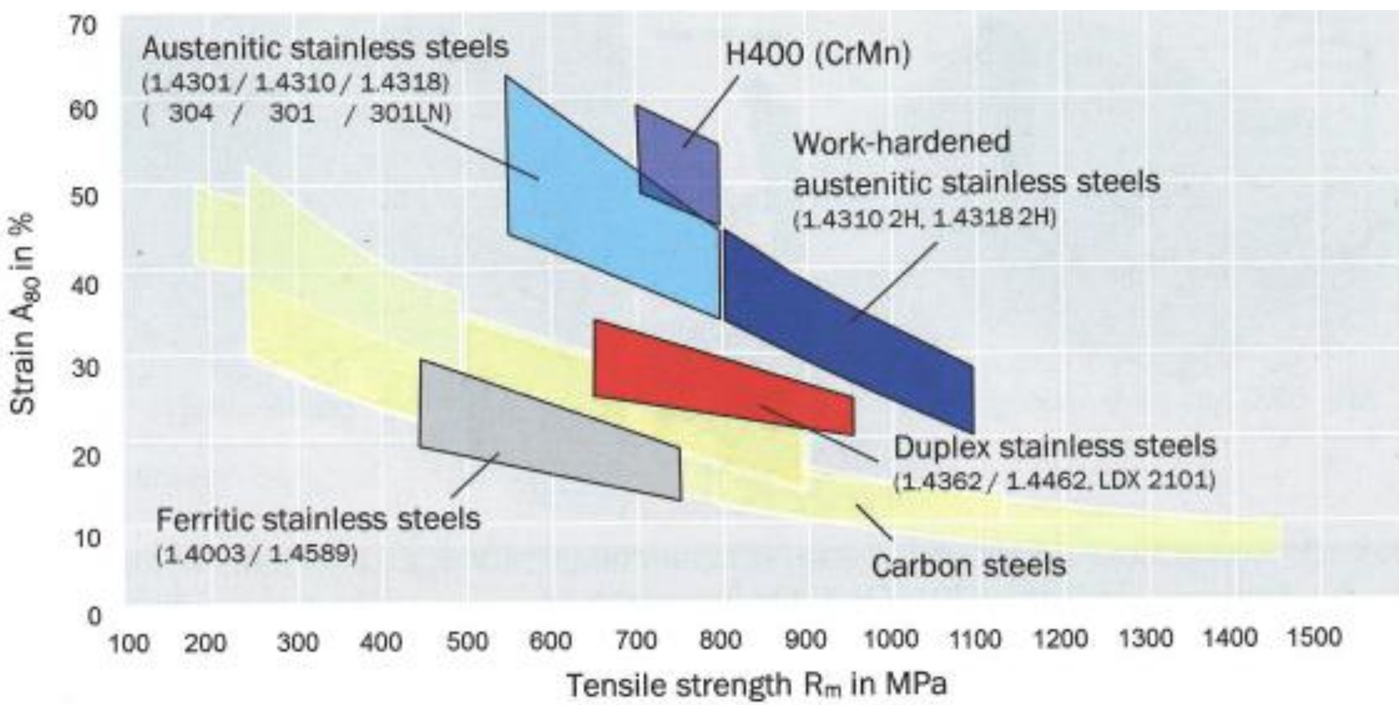




P92 (X10CrWMoVNb9-2 EN 10216-2):

- Creep ductility and toughness can be low (below half the yield stress)
- Suggested reasons: local concentrated strain near prior austenite gb's, cavitation from particle surfaces (MnS, Laves, BN, Al_2O_3)
- Suggested remedies:
  - reduction of impurities
  - adjusting composition
  - additional heat treatment
  (Kimura & Sawada 2015)

Strength vs. ductility / toughness

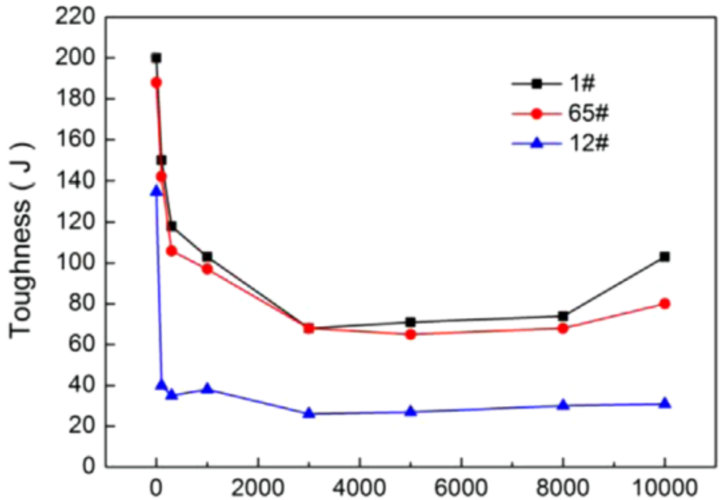


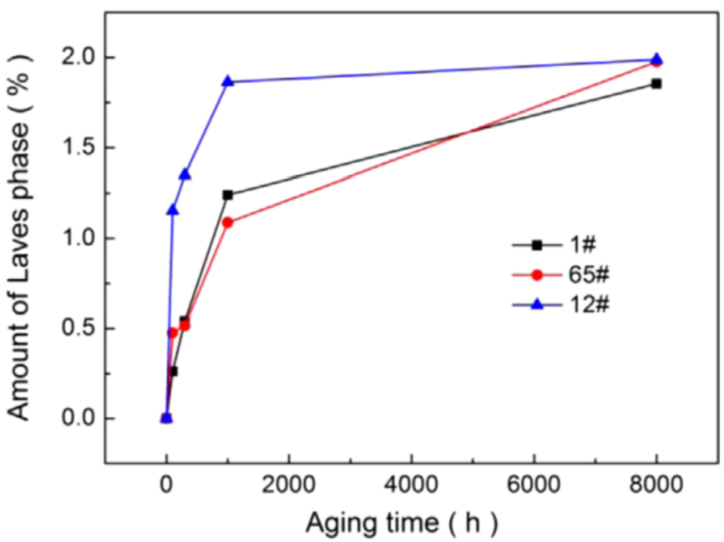
Heikkinen et al. 2015

Trends:

- increasing strength tends to be accompanied with lower ductility and toughness
- characteristic behaviour for given material class
- not entirely inevitable: exceptions by materials design, also general improvement through e.g. cleaner steels
- often poor correlation in short term (creep) testing

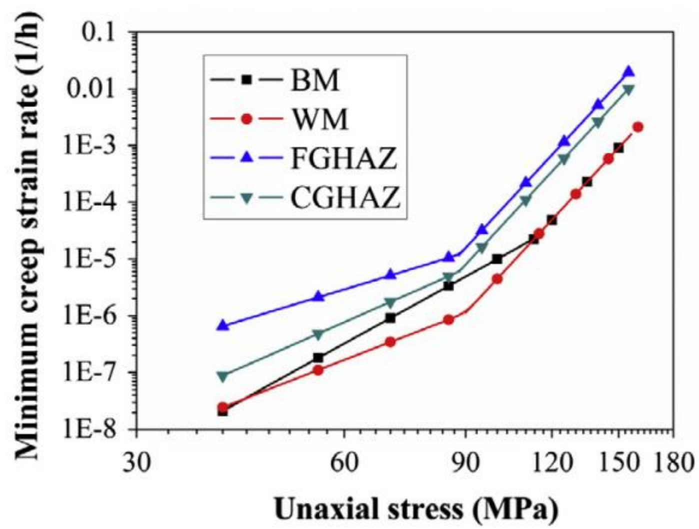
Experience on materials in testing & service





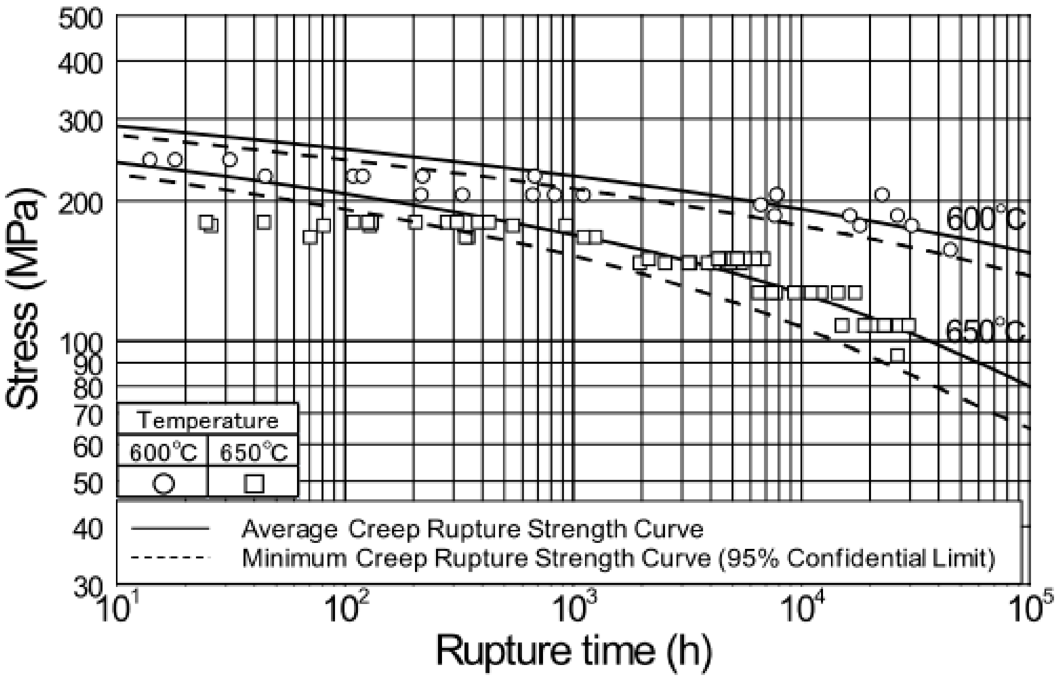
P92

- Charpy V energy decreases with ageing but in PM less than in WM(?), and in any case less than in X20 $\rightarrow$ of concern?
- Much of ageing and creep testing short-term, typically < 10^4 h $\rightarrow$ could be inconclusive
- Retards accumulation of valuable evidence, except for that from plant, and possibly welds



Shi 2011, Yan & Liu 2016

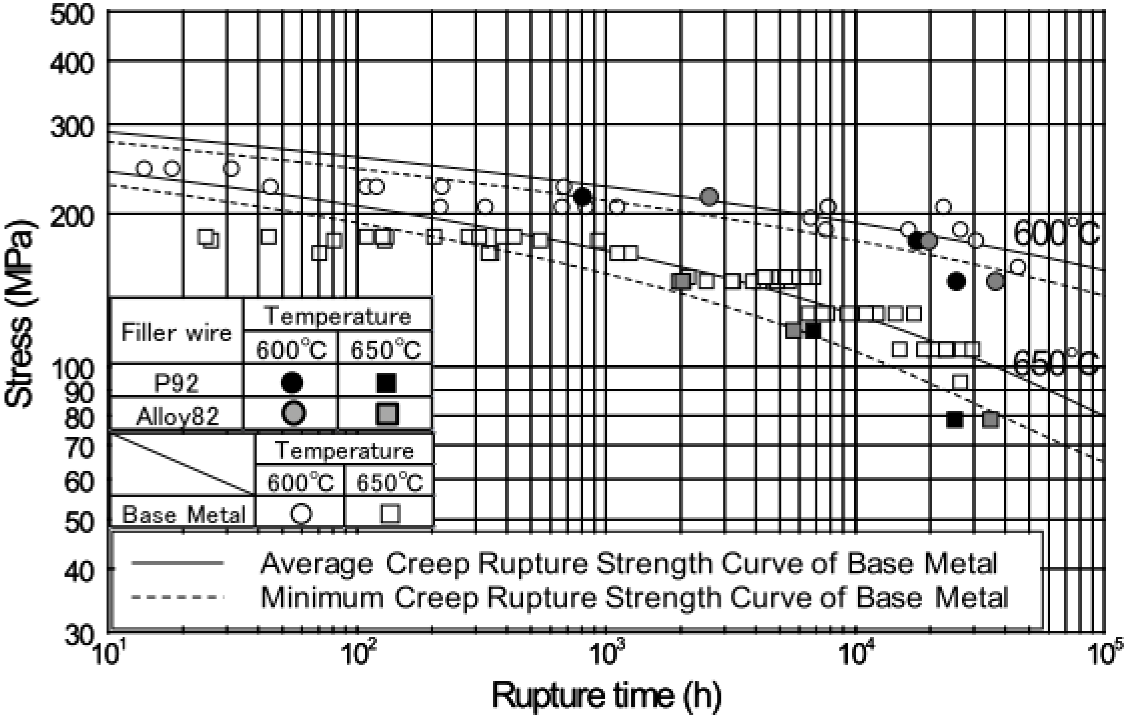
9Cr-3W-3Co-0.02Nd (P93?)



Element	Target	Improvement
9Cr	· Long-term creep strength	Creep strength of base metal
3W	· Solution strengthening · Laves phase precipitation strengthening	
0.01B	· Suppression of coarsening of $M_{23}C_6$ on G.B.	
0.01N (low-N)	· Suppression of Z-phase and BN precipitation	
0.02Nd	Suppression of S segregation	Creep ductility
3Co	Stability of martensite	Toughness
0.01B	Suppression of fine HAZ	Creep strength of welded joint

Hamaguchi et al. 2015

9Cr-3W-3Co-0.02Nd (P93?) welded

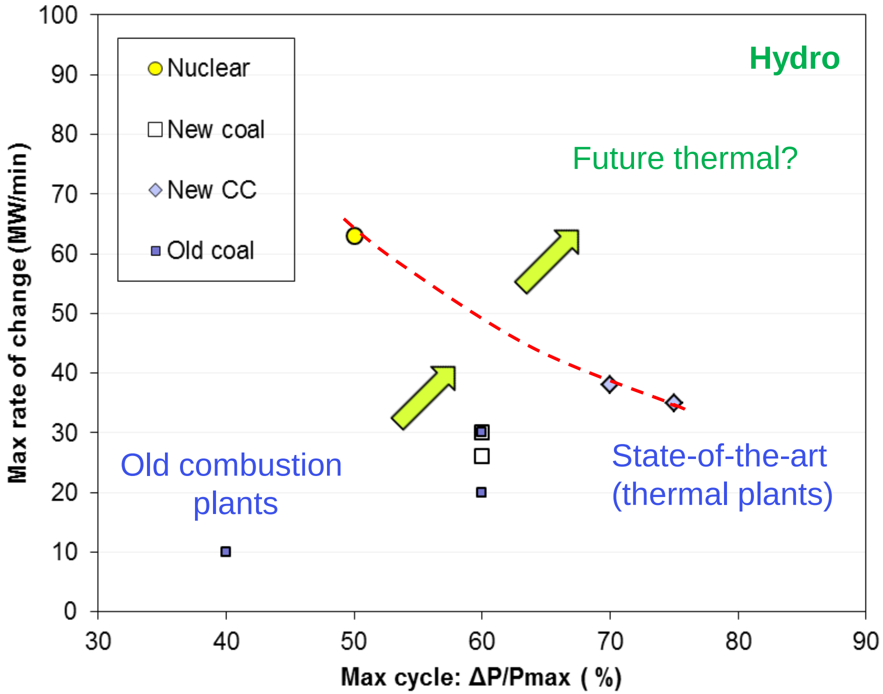


Hamaguchi et al. 2015

Observations:

- testing up to about 45 000 h, downward trend accommodated in the fitting model?
- P92 under- and Alloy82 over-matching?
- failure positions in longest tests: type IV avoided?
- often poor correlation in short term (creep) testing

Materials / solutions for cycling (CF) service



Challenges:

- Early CF methods developed for aerospace Ni alloys with design life ~10^4 h → HT but no long tests
- For land-based equipment with design life of more than $2{\cdot}10^5$ h, long holds make slow testing of both conventional & new materials

→ more emphasis on modelling and monitoring of equipment condition

- Improved resistance to more extensive cycling, reduced minimum loads (not only a materials issue)

Conclusions - summary

- **HT steel evolution for pressure equipment** is gradual and requires

  - long term qualification for first introduction

  - status of new material until initial adjustments and further evidence have accumulated to show trusted limits of application

  - dealing also with new challenges like those from cyclic/intermittent service, cost bias from subsidies, etc.

- **Each new generation** of successful steels provides

  - improved thermal and resource efficiency

  - process-independent advantages for any equipment with suitable service conditions (temperature, loads, chemical environment)

Thank you