Design and Development of Fire Resistant Steels

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Enhanced structural steels

- Steels need to maintain strength in building fires.
- Delay building collapse.
- Extend time of structural safety to allow for evacuation.

Photo Credit: Eric Hensley, Wikimedia Commons

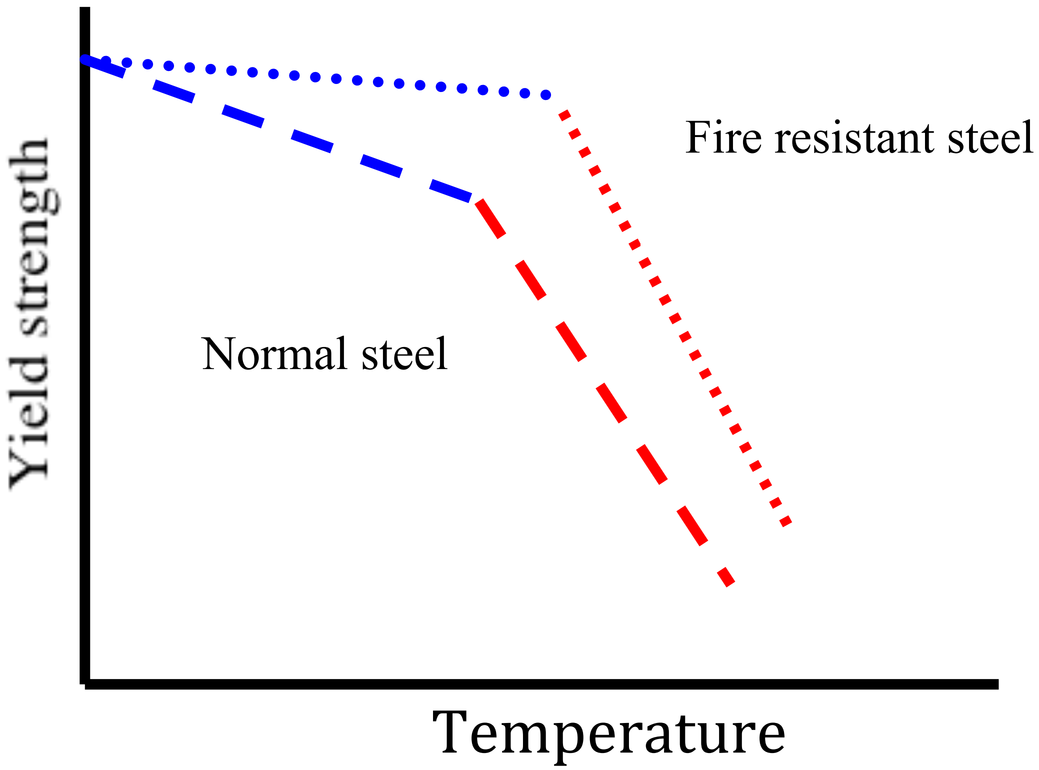
Construction standards

- Current building codes: 50% of room temperature yield strength at 550°C.
- Over the past 10 years, ASTM and NIST are discussing standards requiring 66% of yield strength maintained after 20 minutes at 600°C.

Photo credit: Purdue Engineers Test Effects of Fire on Steel Structures. Homel. Secur. News Wire (2010). at <http://www.homelandsecuritynewswire.com/purdue-engineers-test-effects-fire-steel-structures>

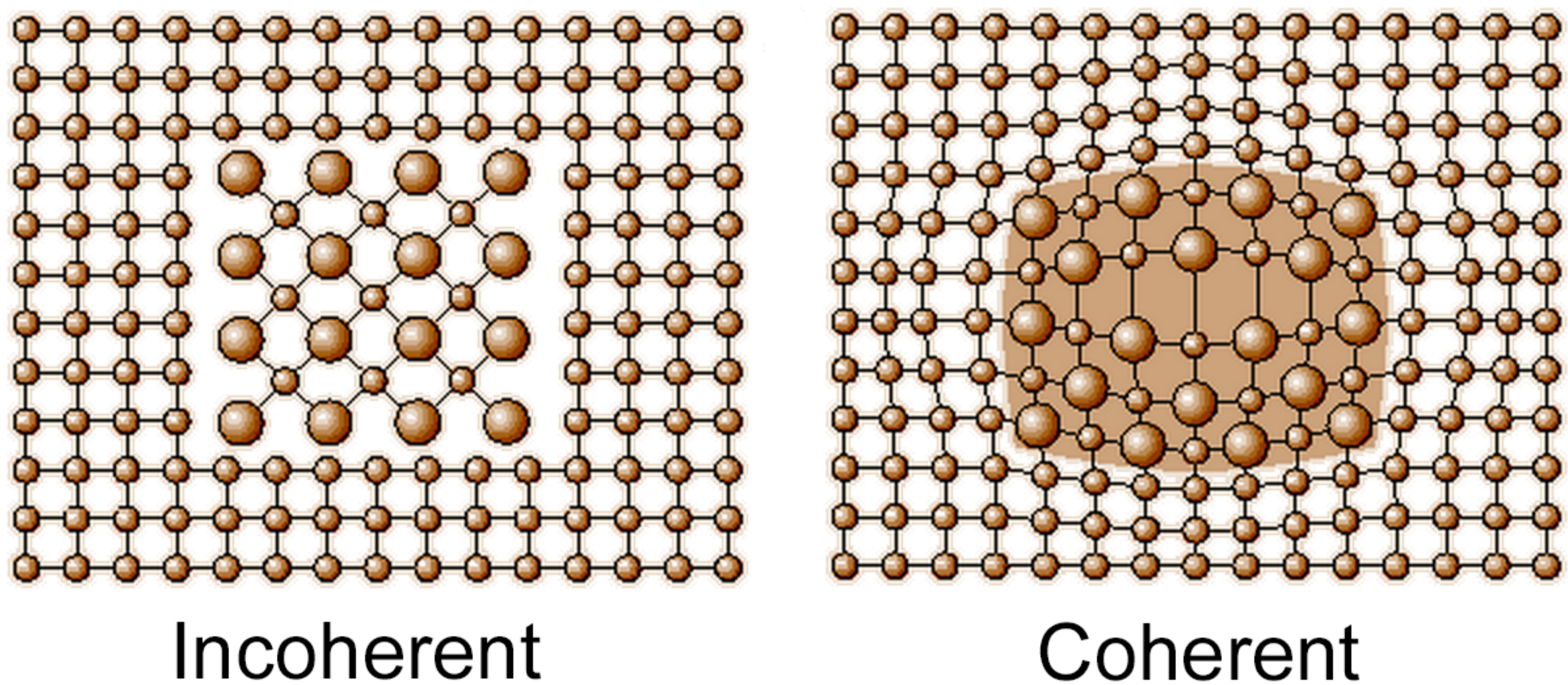
Fire resistant versus "normal" steel

- Delay onset of thermally activated failure processes.
- Enhanced safety for building occupants.
- Reduces need for volatile and labor intensive insulation.



Courtesy of Prof. Yip-Wah Chung

Incoherent versus coherent precipitates



- (Nb,V) carbonitrides form with a Baker-Nutting relationship.
- Pure NbC carbides have less than a 10% mismatch between lattice planes.
- (Nb,V) carbonitrides have less than a 6% mismatch.
- Misfit dislocations arise in semicoherent interfaces.

Image credit: Grote, K-H and Erik Antonsson. *Springer Handbook of Mechanical Engineering*. Springer-Verlag 2009.

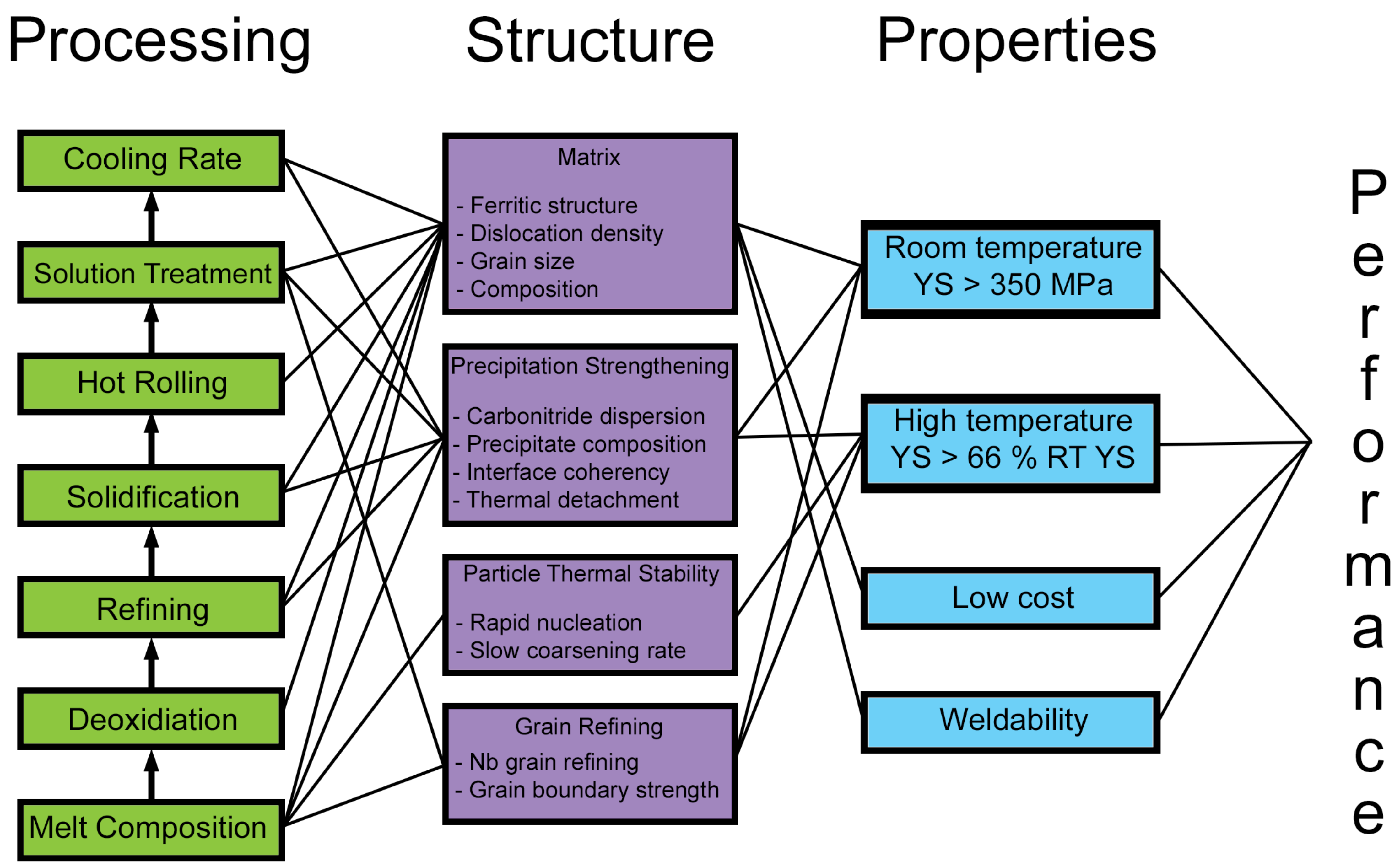
Design objectives

- **Primary:**
  - Meet or exceed proposed standards by designing a steel that maintains over 66% of the room temperature yield strength after 20 minutes of exposure at 600°C.
  - Room temperature yield strength of at least 350 MPa.
- **Secondary:**
  - Alloy content of V + Nb + Mo < 0.55 wt. %.
  - Carbon content < 0.1 wt. %.
  - No water or oil quench or thermo-mechanical processing.

Design strategies

- Form small, Nb and V based monocarbide (MC) precipitates.
- Reduce or eliminate higher order carbides and cementite to allow maximum MC formation.
- Use thermodynamic modeling to guide design process.

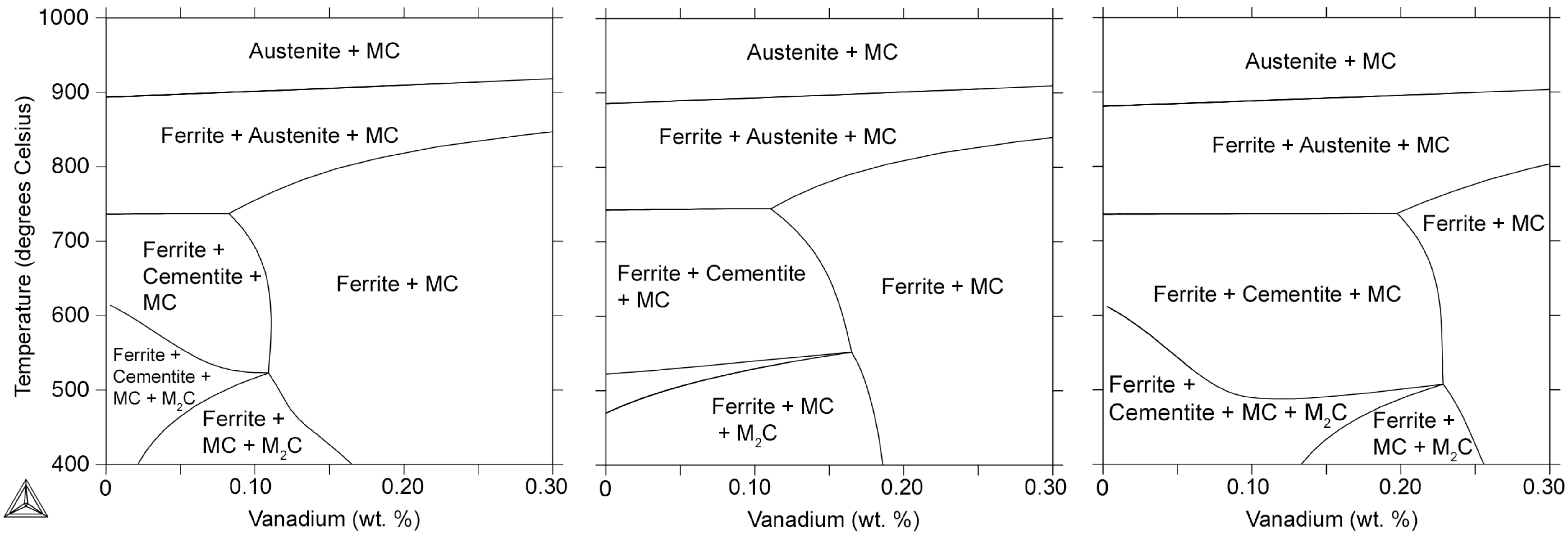
Systems design chart



Thermodynamic modeling

All compositions in wt. %

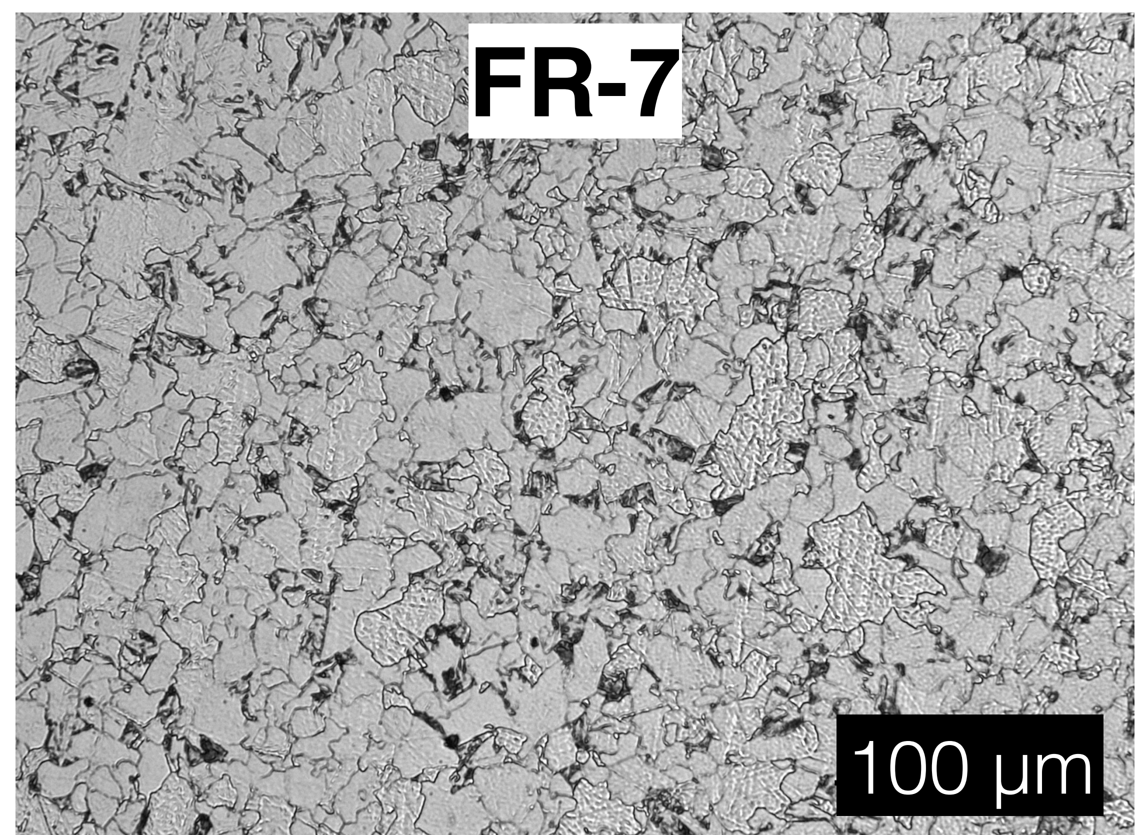
Base Alloy | Increased Cr | Increased C



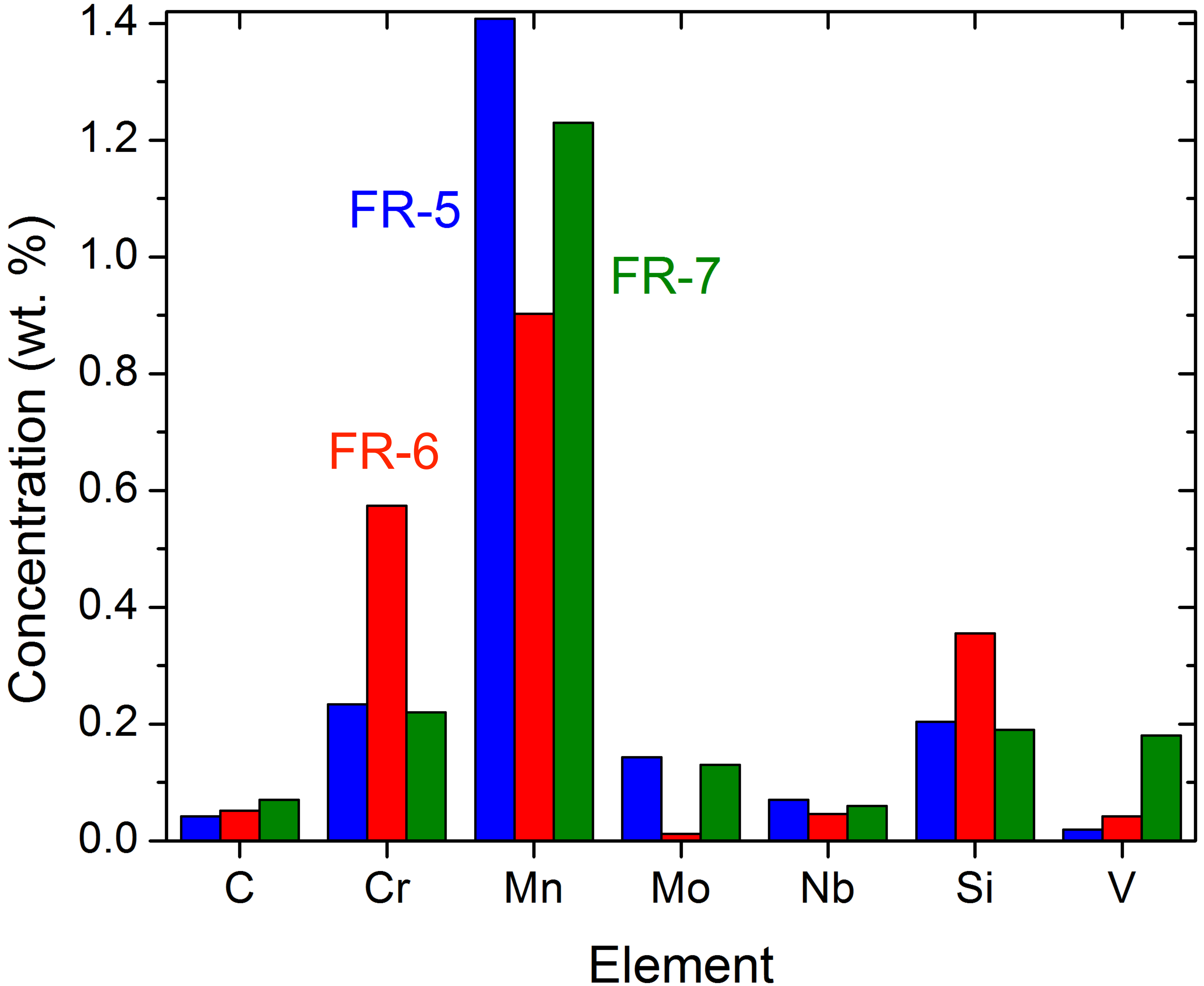
Base Alloy: 0.05-C 0.25-Cr 0.15-Mo 0.07-Nb

Experimental alloys

- Two commercial alloys, FR-5 and FR-6, supplied by Nucor.
- FR-7 created by arc melting FR-5 with C and V additions. Supplied by Sophisticated Alloys.



Experimental alloy compositions



Local electron atom probe (LEAP) experiments

- LEAP was used to investigate the presence of carbide precipitates.
- Size, distribution, and composition can be determined from the LEAP reconstruction.

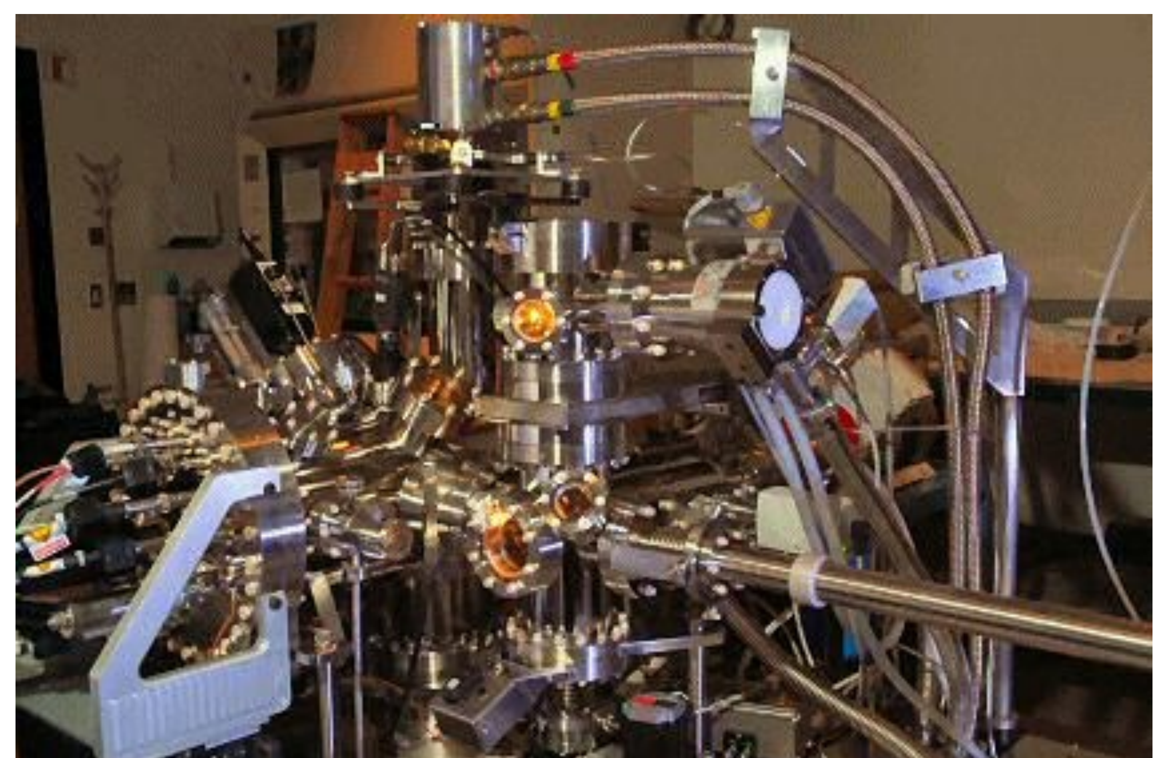
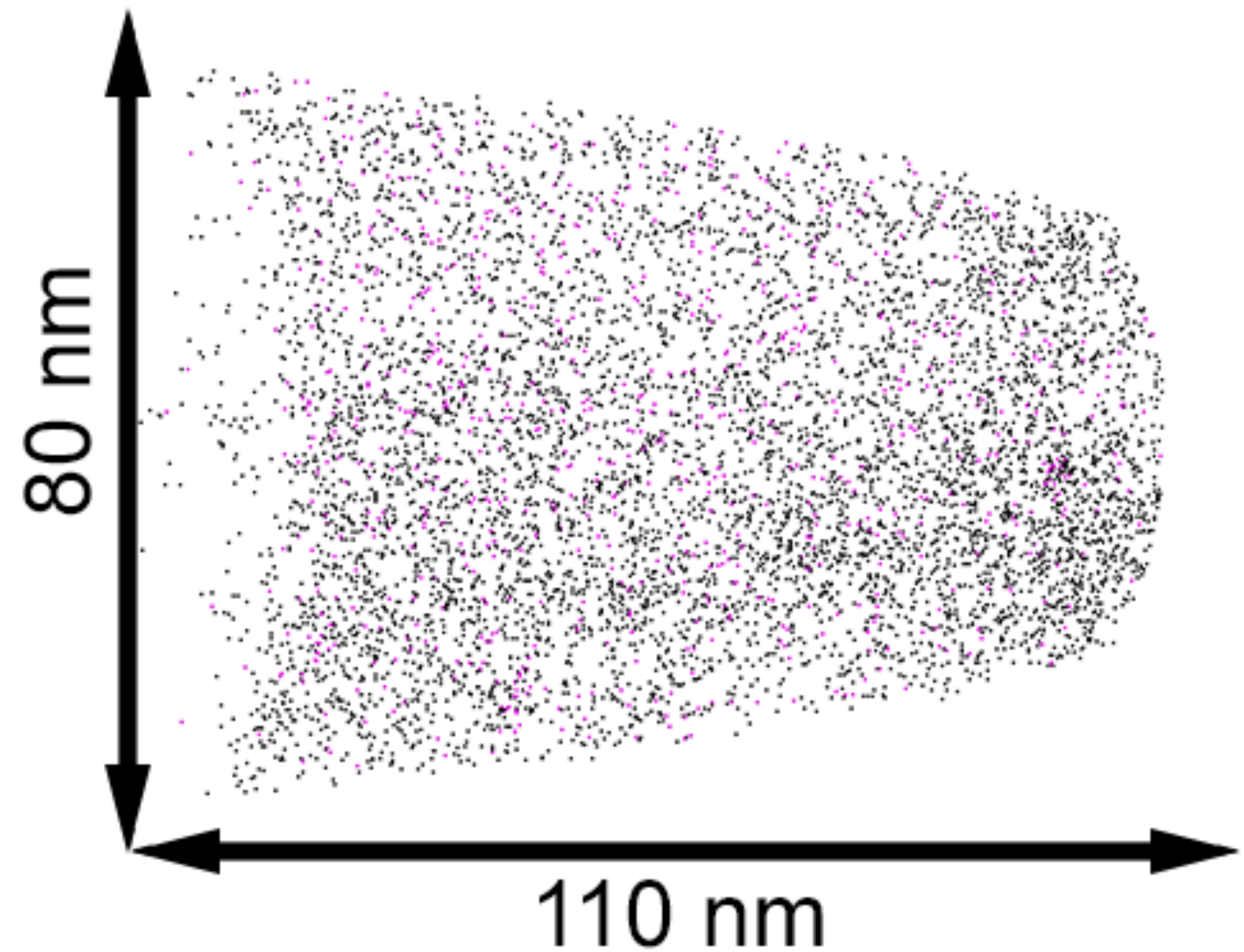


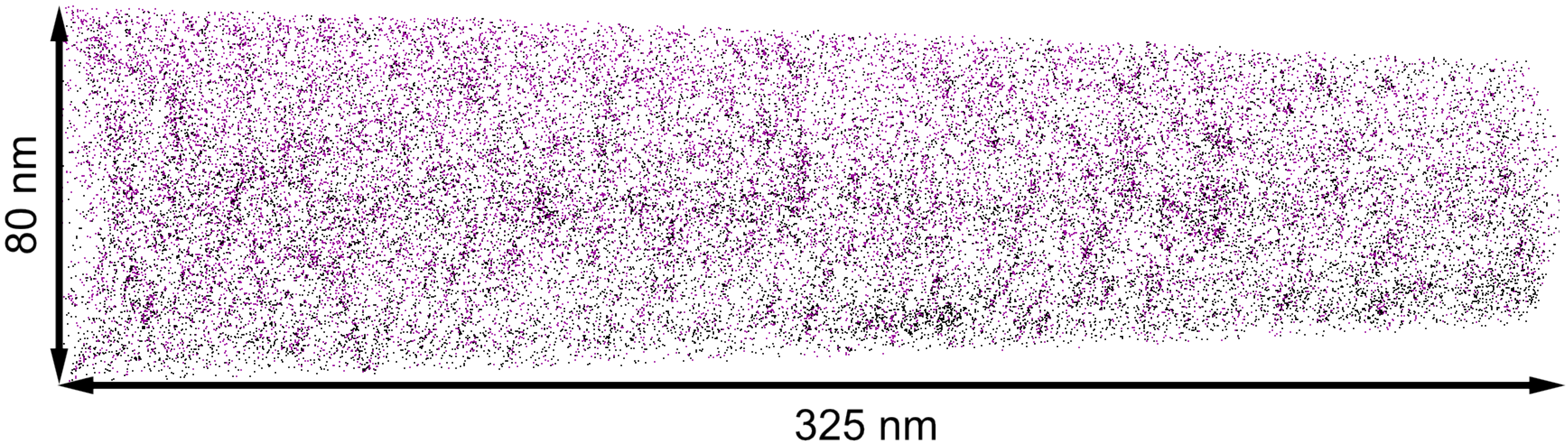
Photo Credit: NUCAPT

FR-5: Atom probe result from air-cooled sample



Only **Nb** & **C** atoms are shown

FR-5: Atom probe result from aging for 2 hours at 600°C

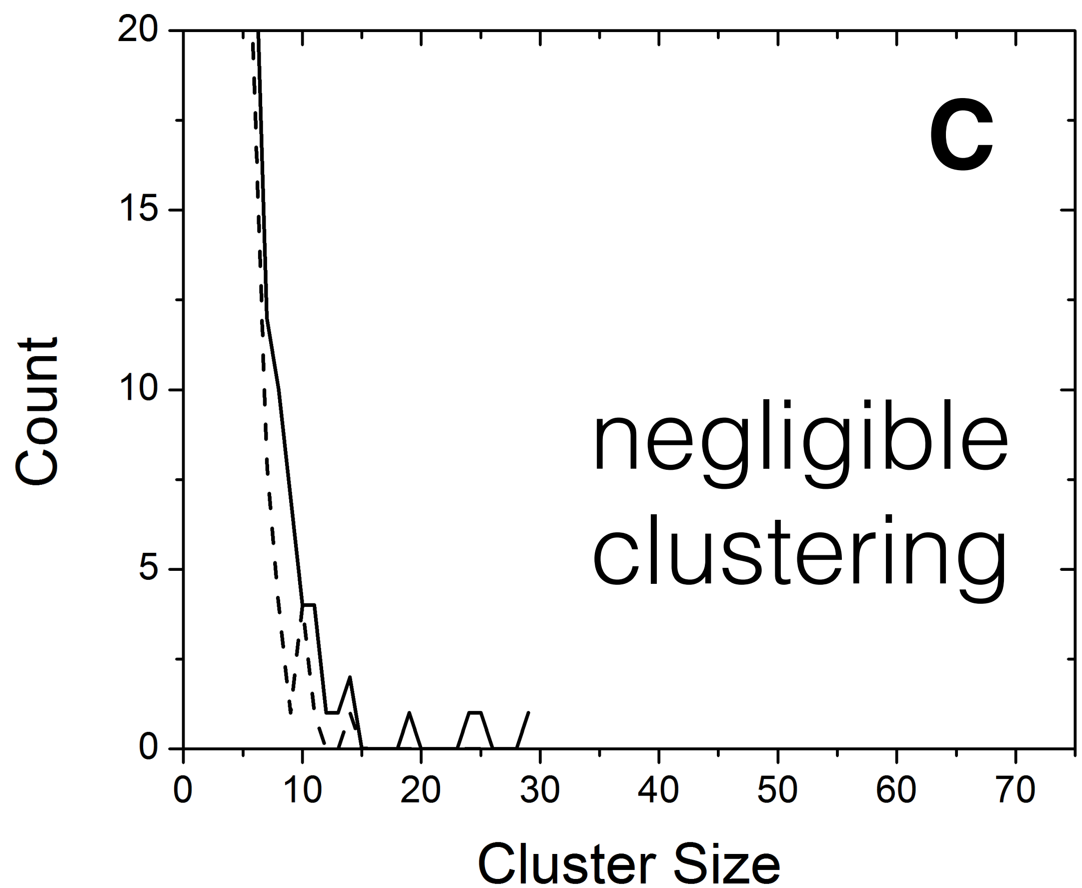


Only **Nb** & **C** atoms are shown

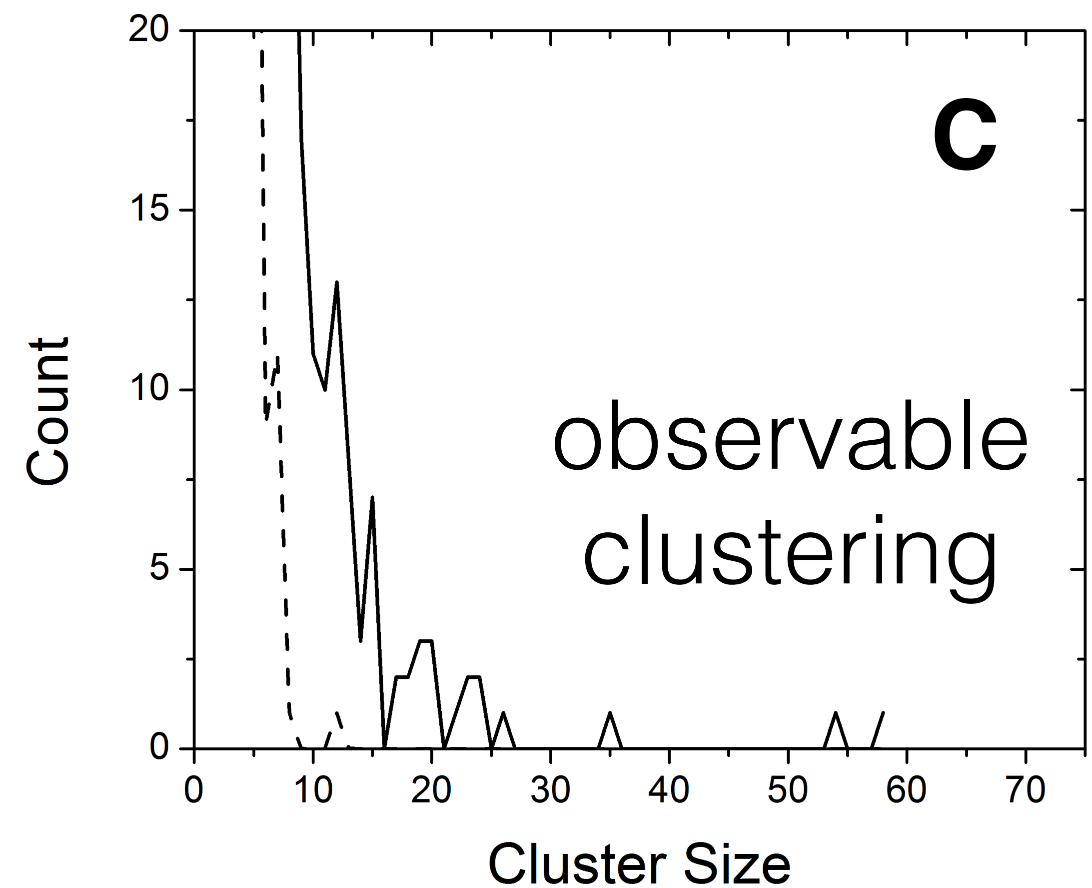
Evidence of clusters 1 nm in radius or less
(about 100 atoms)

FR-5: Carbon clustering between 0 and 2 hours

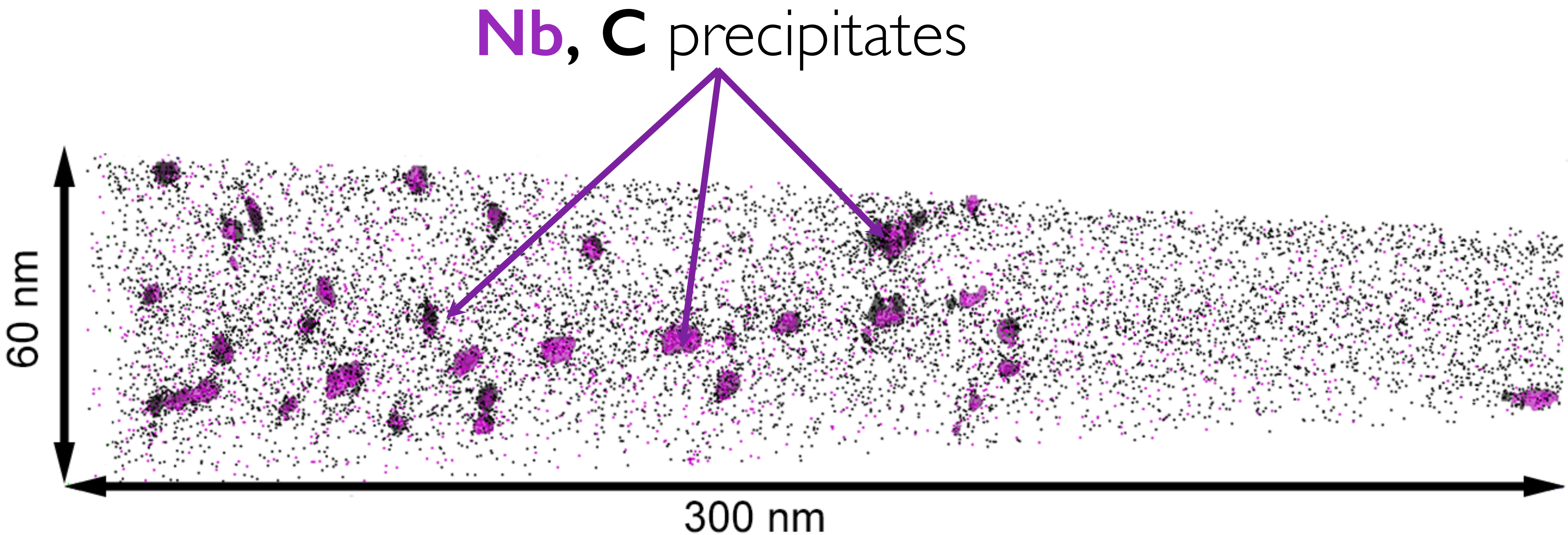
Air cooled



After 2 hrs at 600°C



FR-5: Atom probe result from aging for 6 hours at 600°C

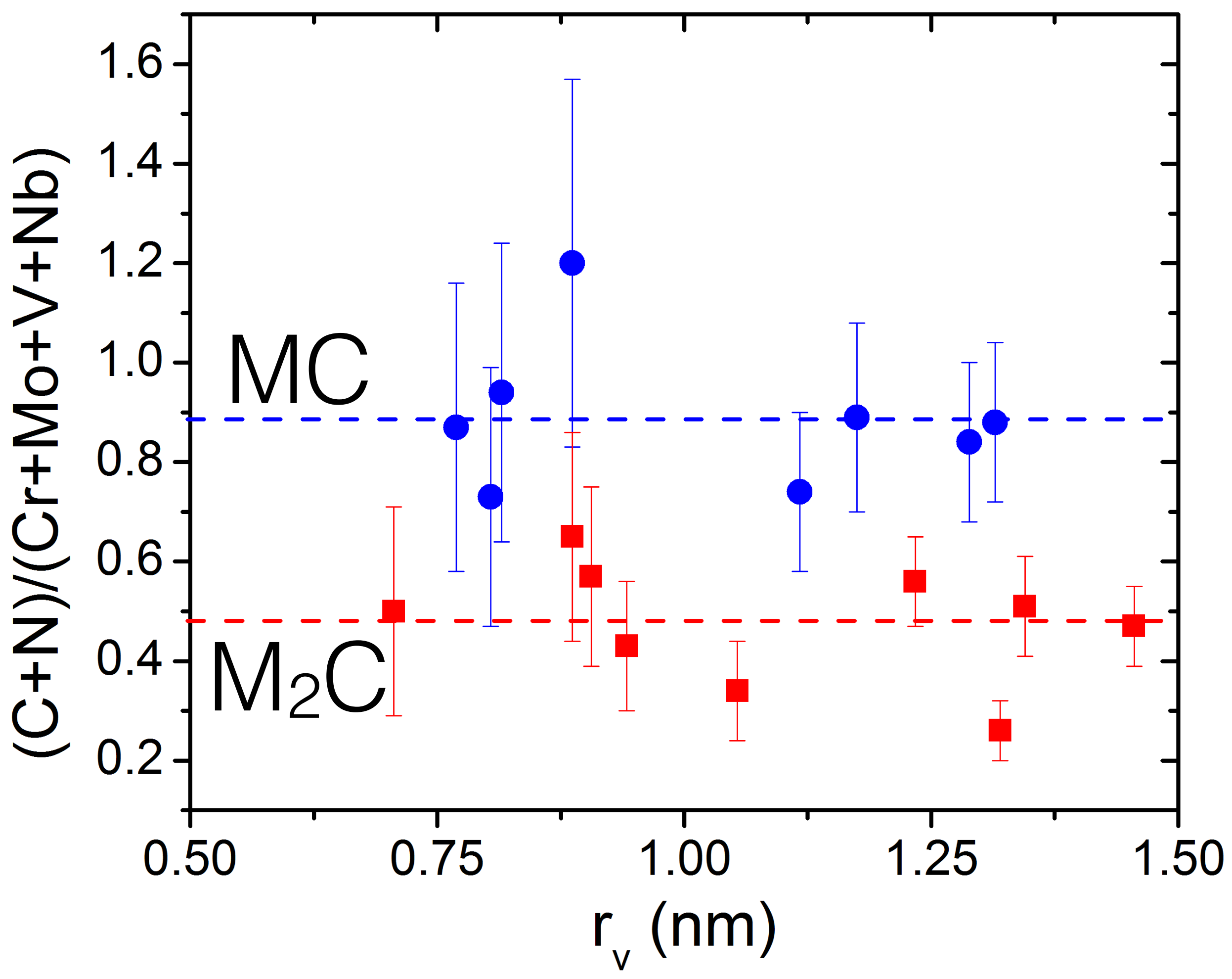


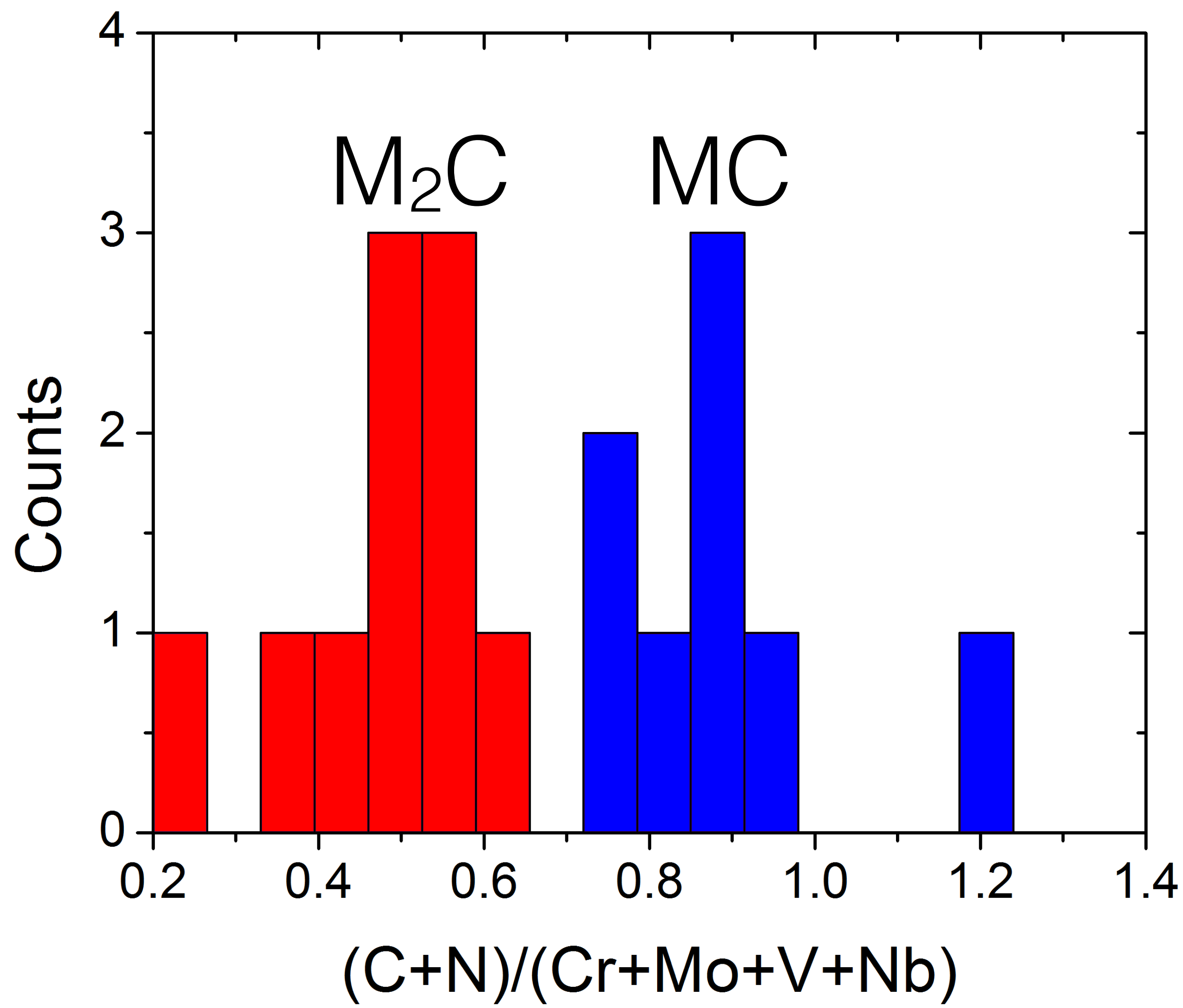
Only 50% of **Nb** & **C** atoms are shown

1% **Nb** isosurfacing and 1% **C** isosurfacing shown to emphasize precipitates

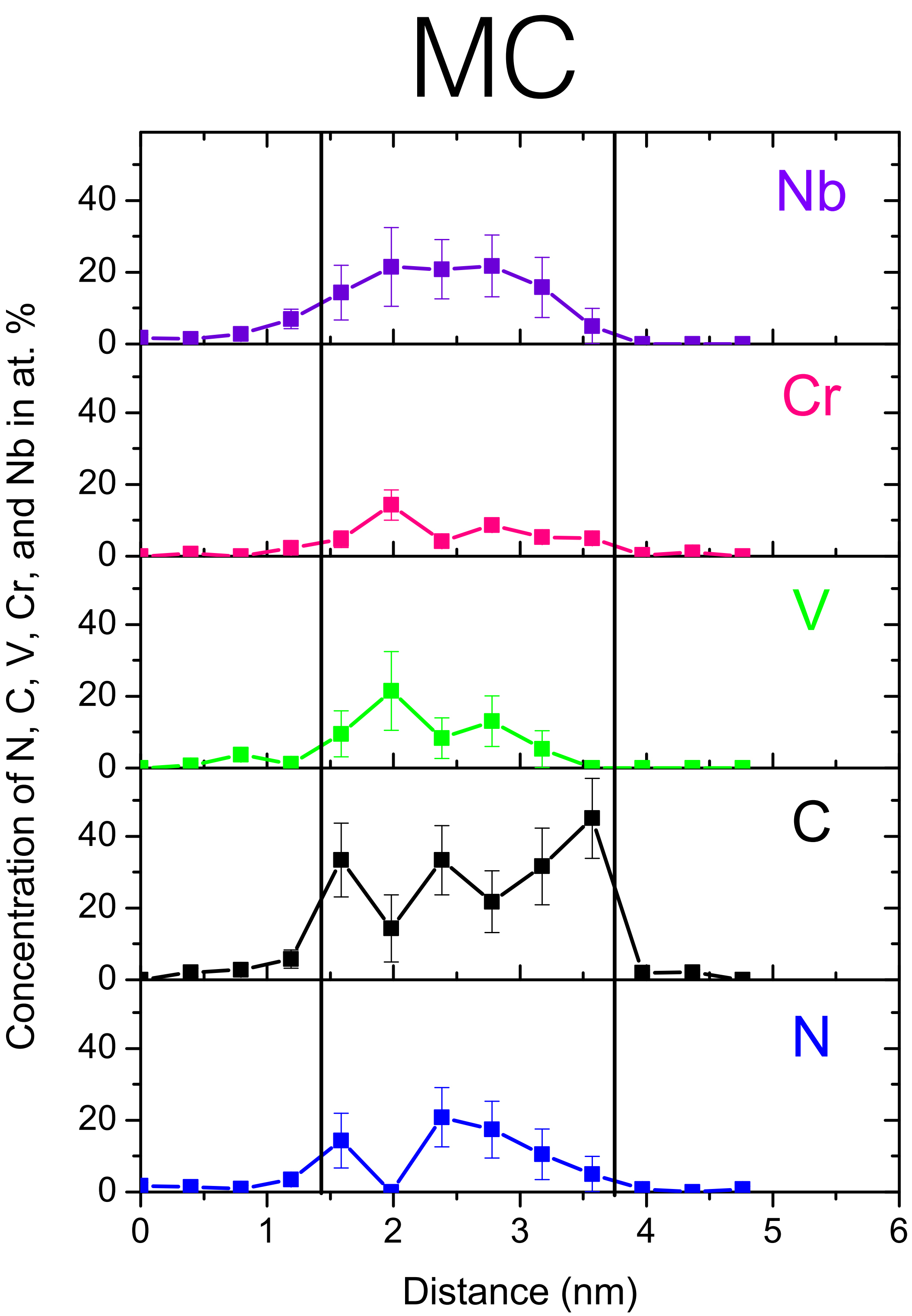
Existence of two types of precipitates based on (C+N)/M ratio

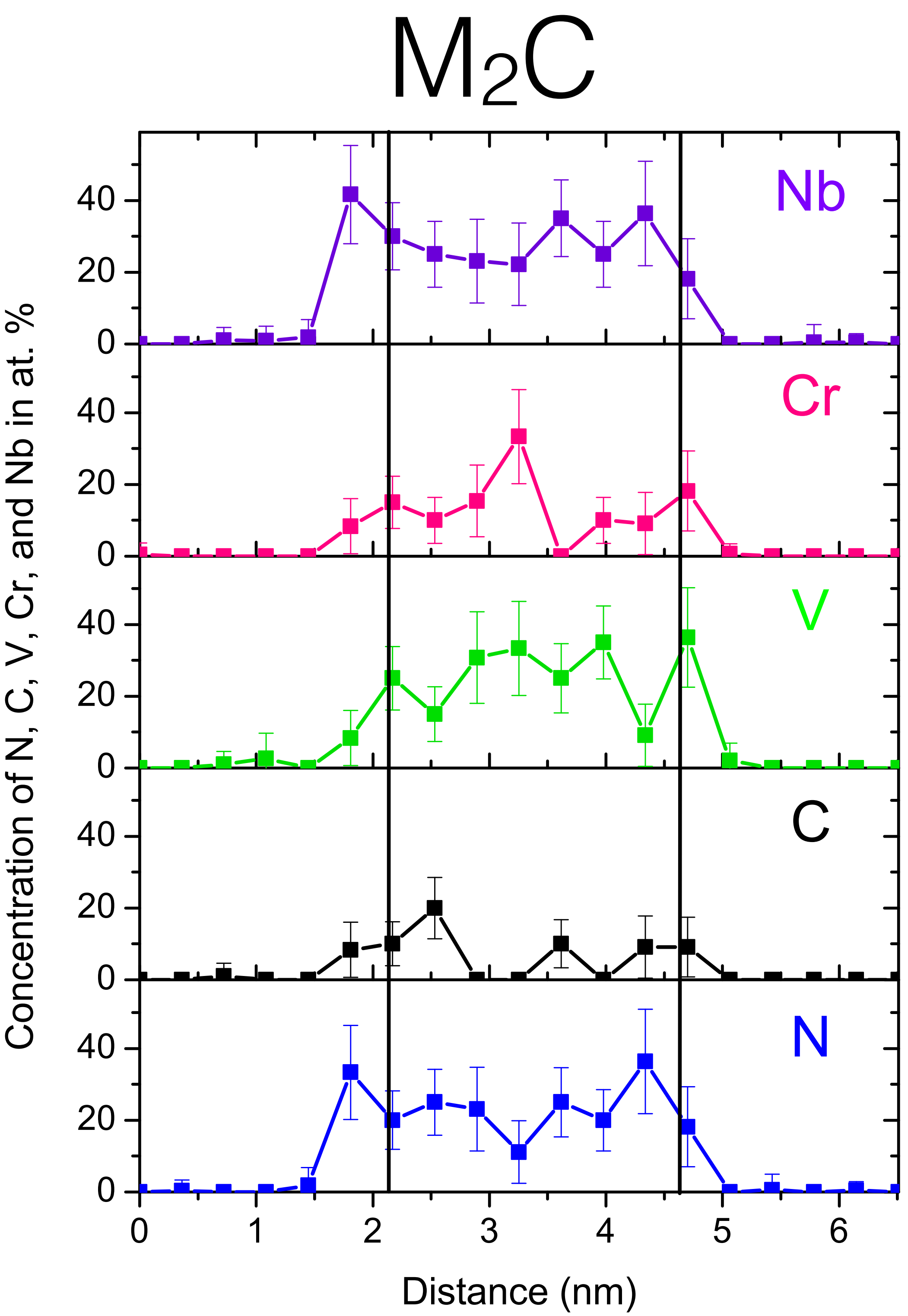
M = Cr + Mo + V + Nb



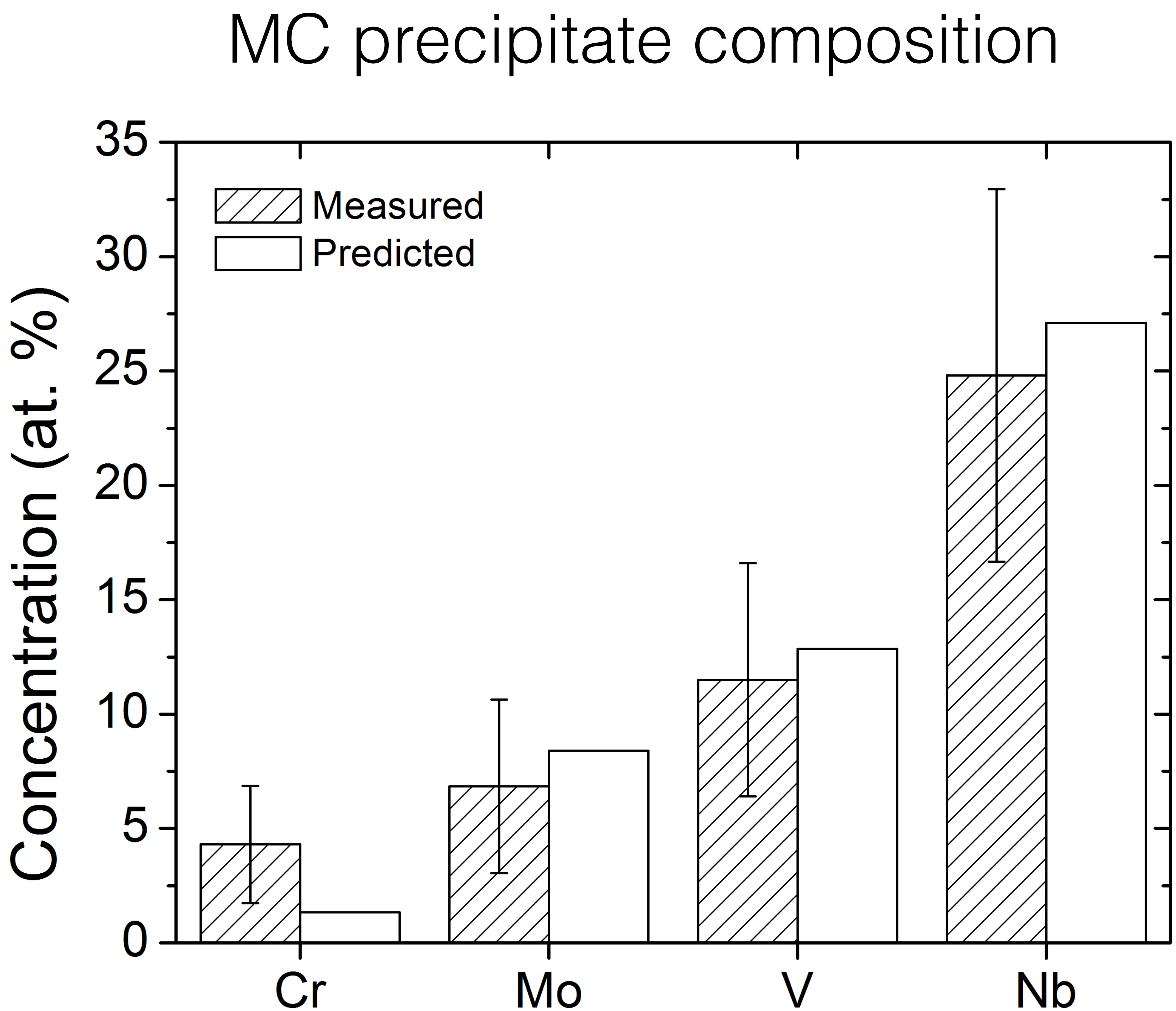


Composition profiles of typical precipitates





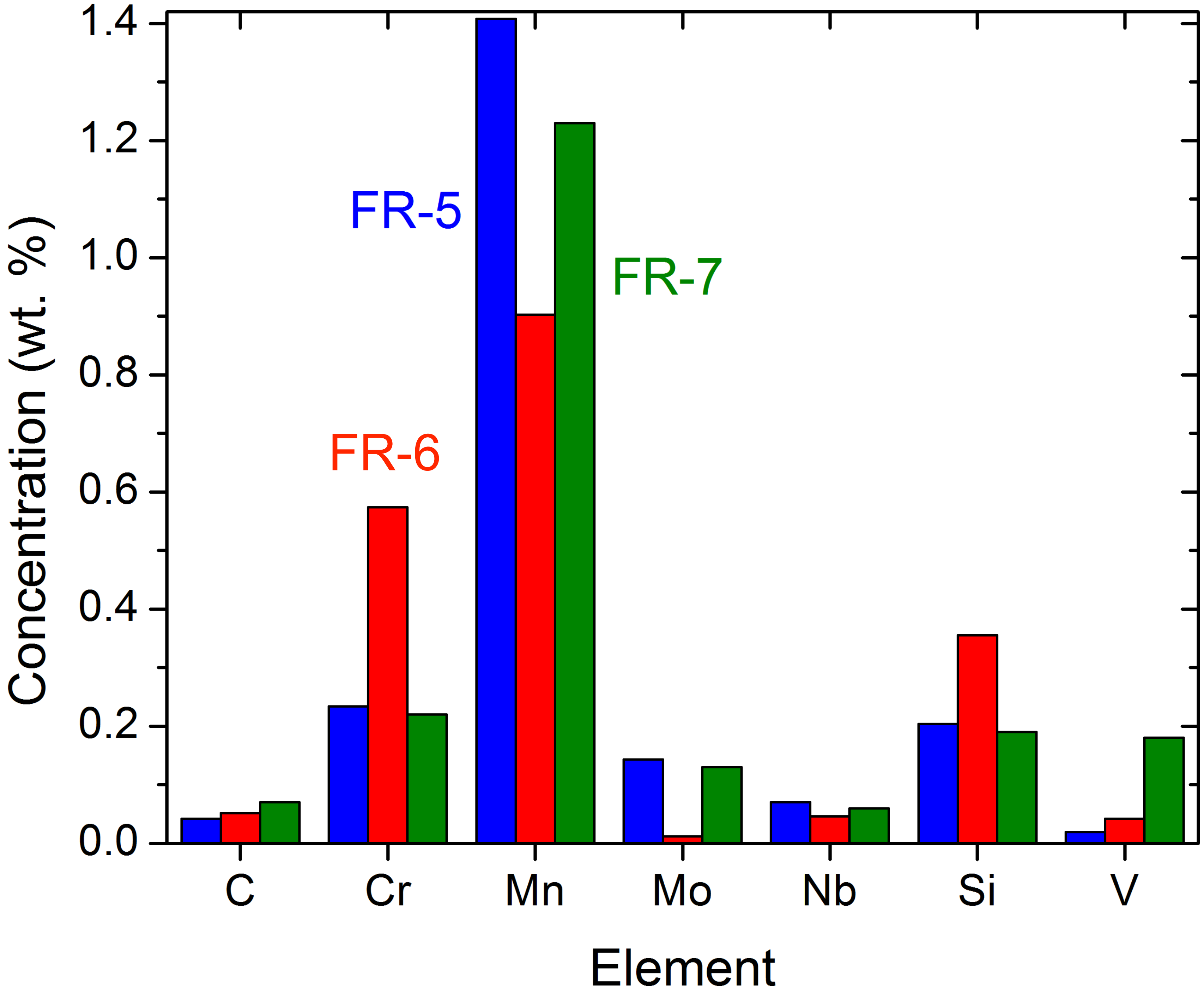
Composition comparison with Thermo-Calc



Mechanical Testing Parameters

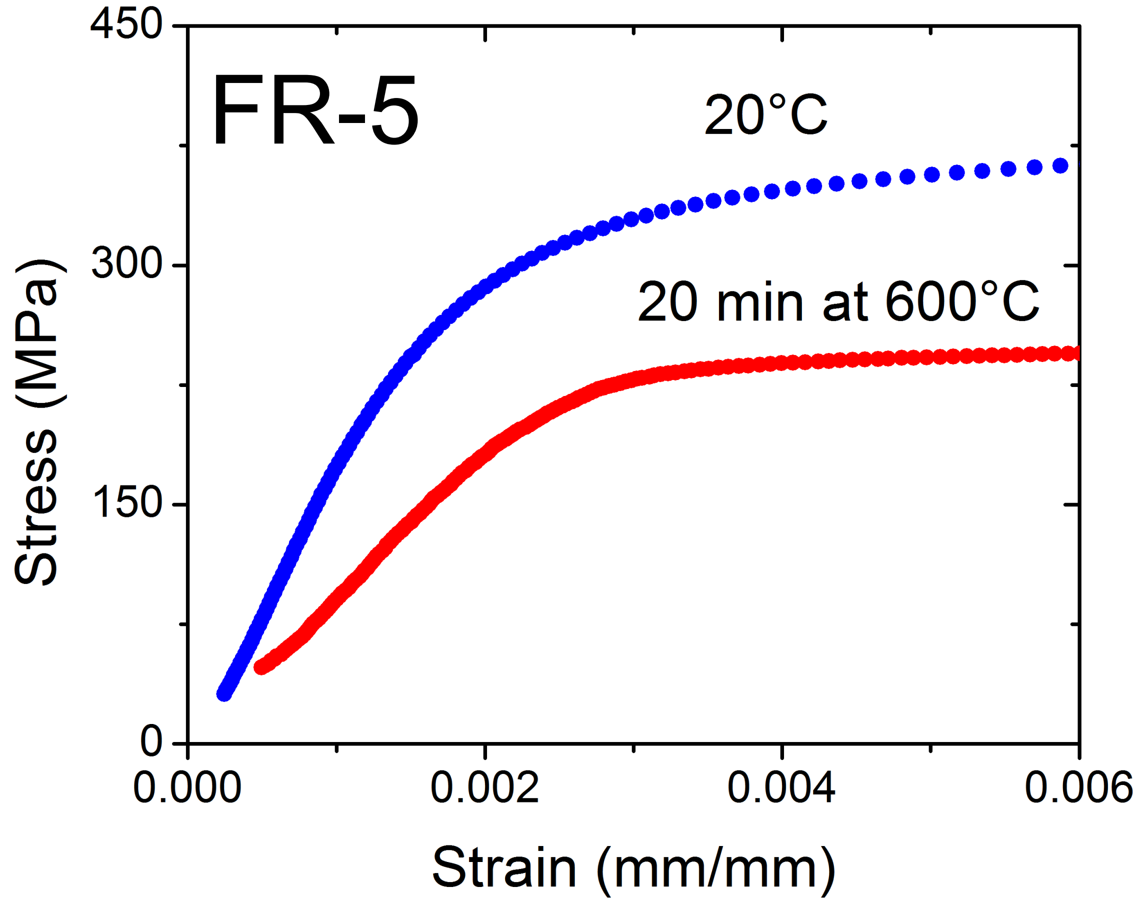
- Conducted in accordance with ASTM standards.
- Strain rate 0.005 ± 0.002 1/min.
- High temperature tensile tests conducted in atmosphere.
- High temperature compression tests conducted under controlled environment.

Experimental alloy compositions

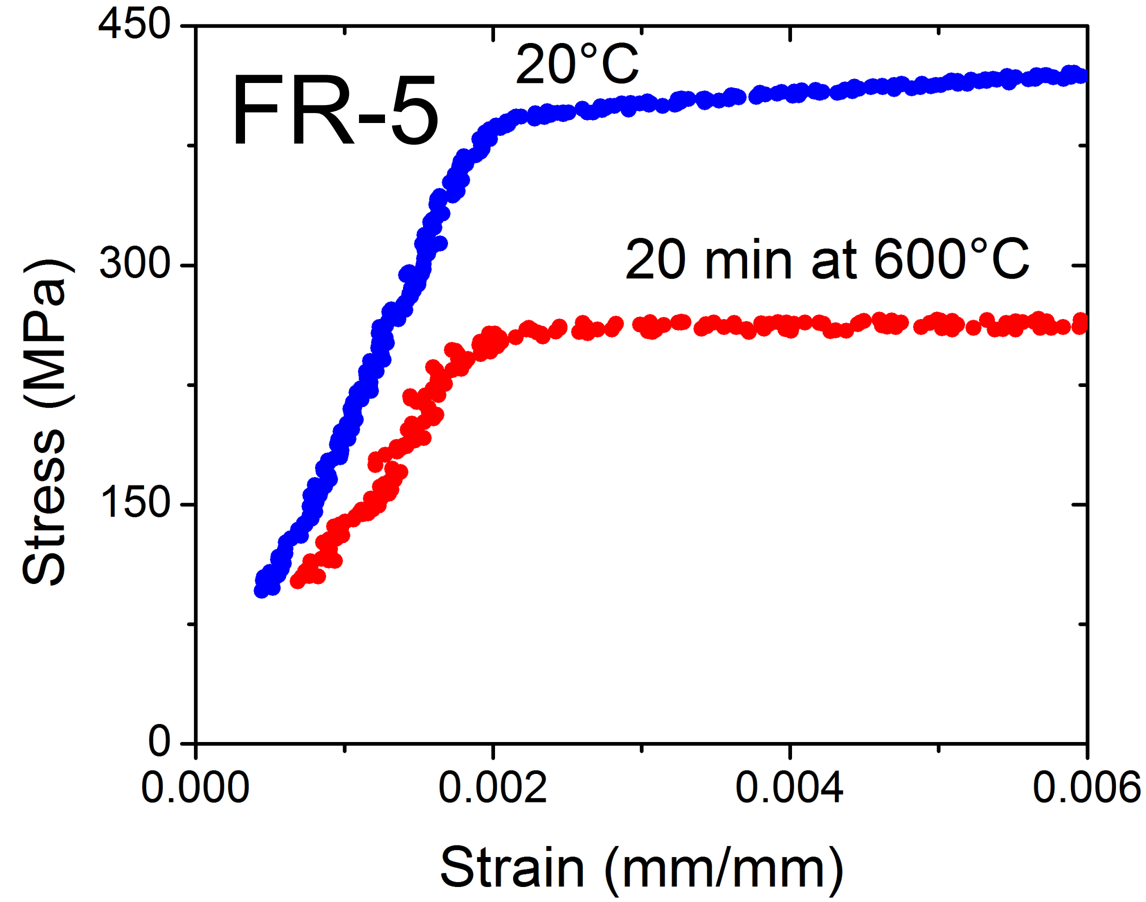


FR-5: Stress-strain curves at 20°C and 600°C (held for 20 min)

Tension



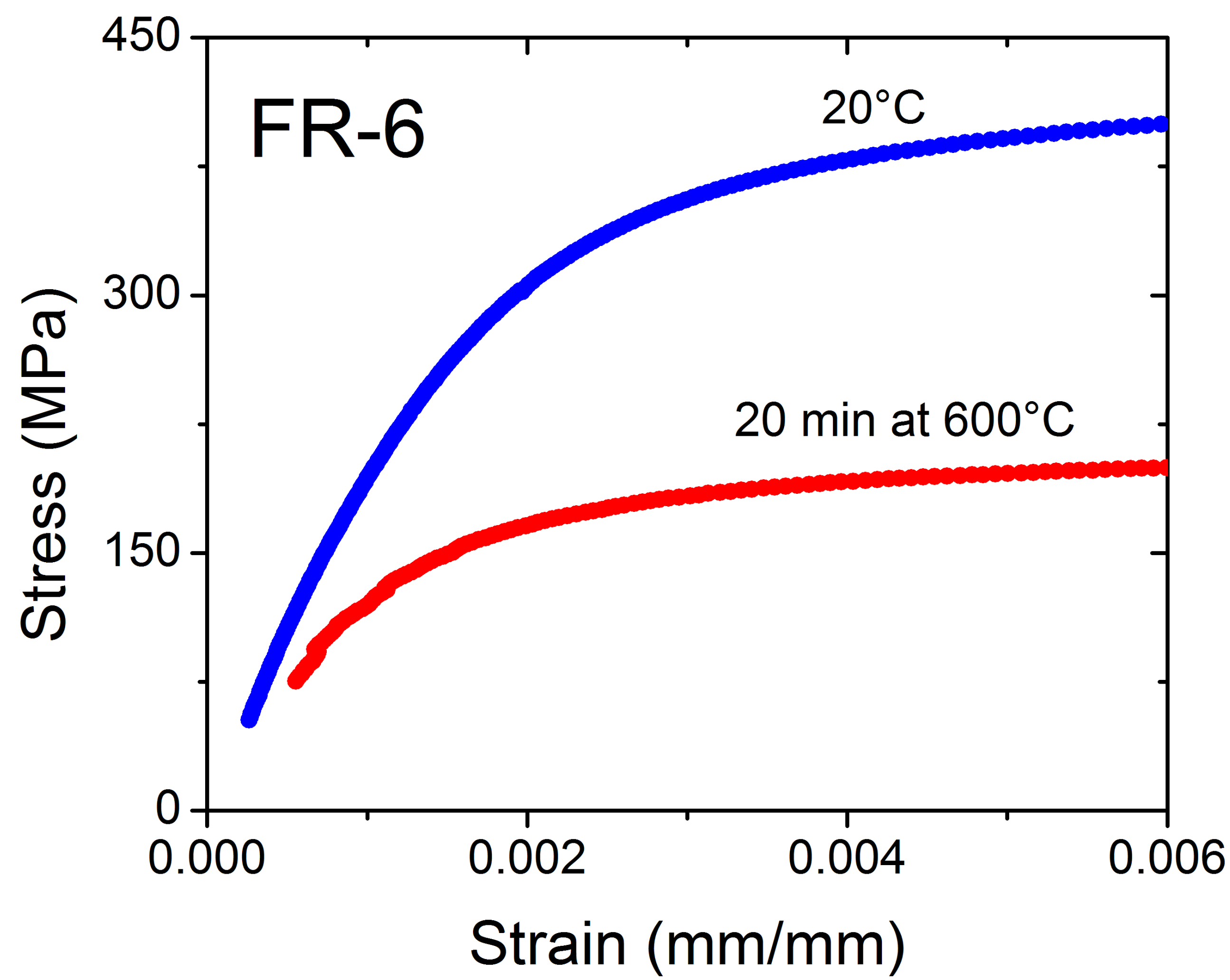
Compression



Yield strength (YS) ratio 0.67 ± 0.06

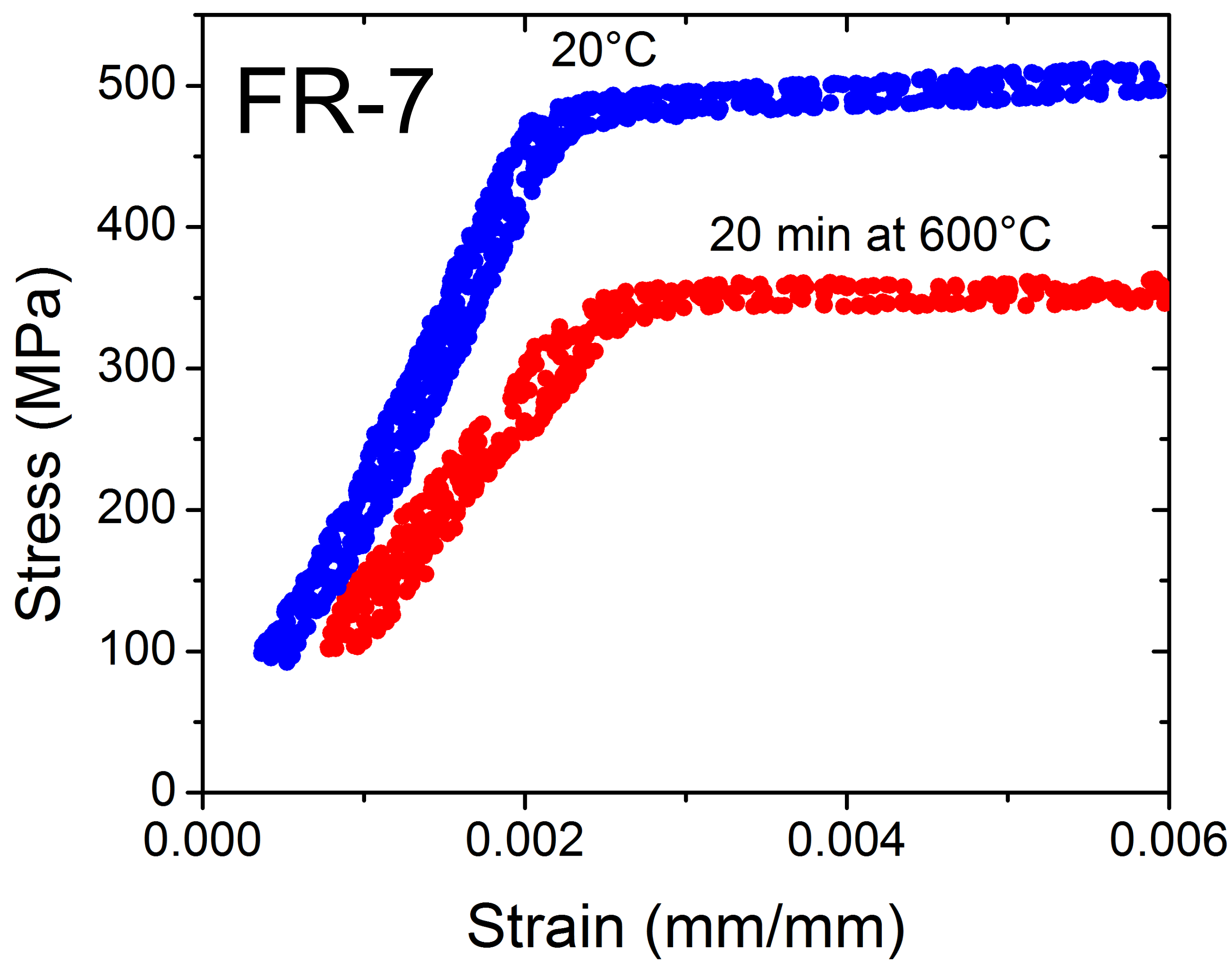
YS ratio 0.64 ± 0.03

FR-6: Tensile curves at 20°C and 600°C (held for 20 min)



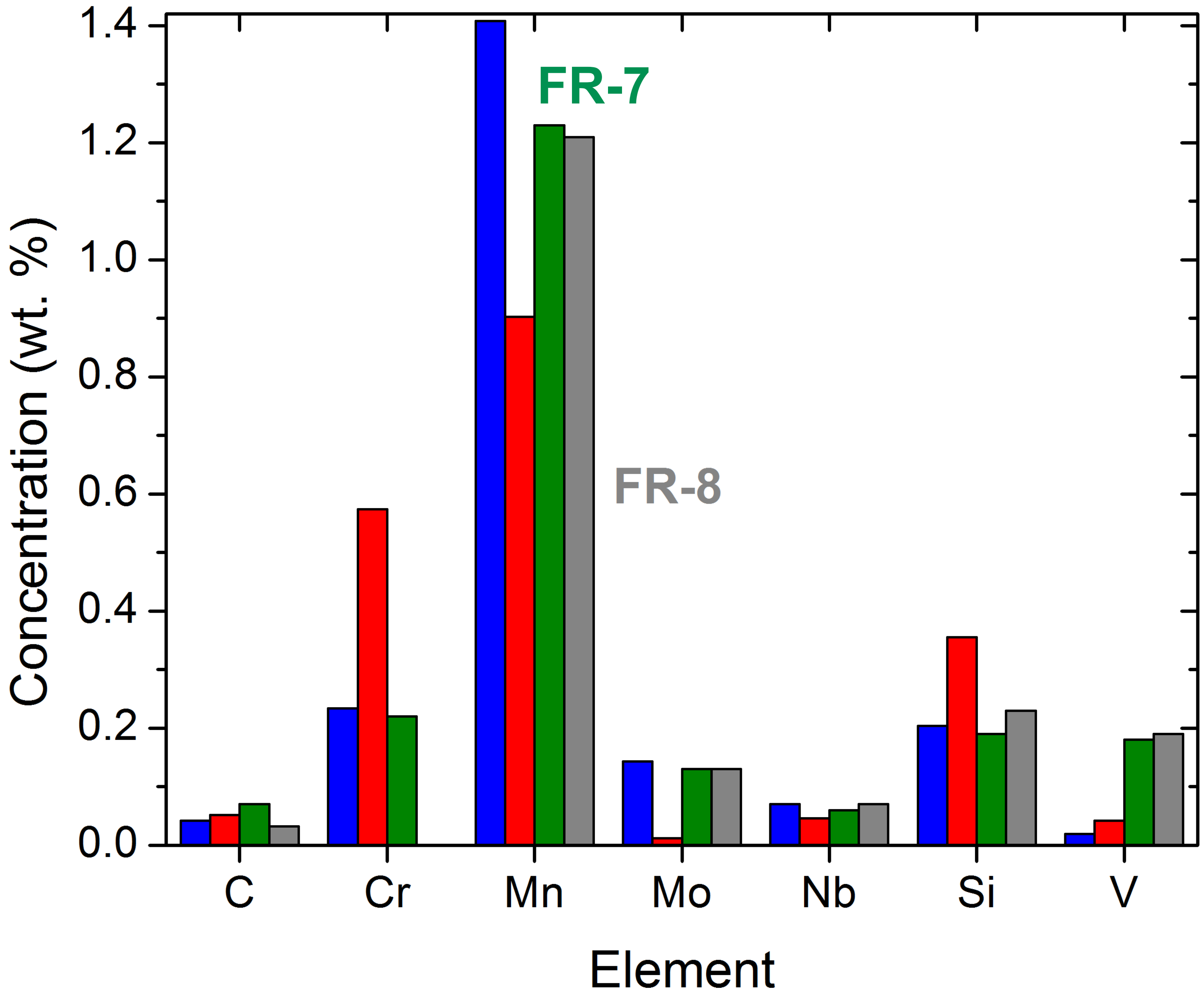
YS ratio 0.50 ± 0.02

FR-7: Compression curves at 20°C and 600°C (held for 20 min)



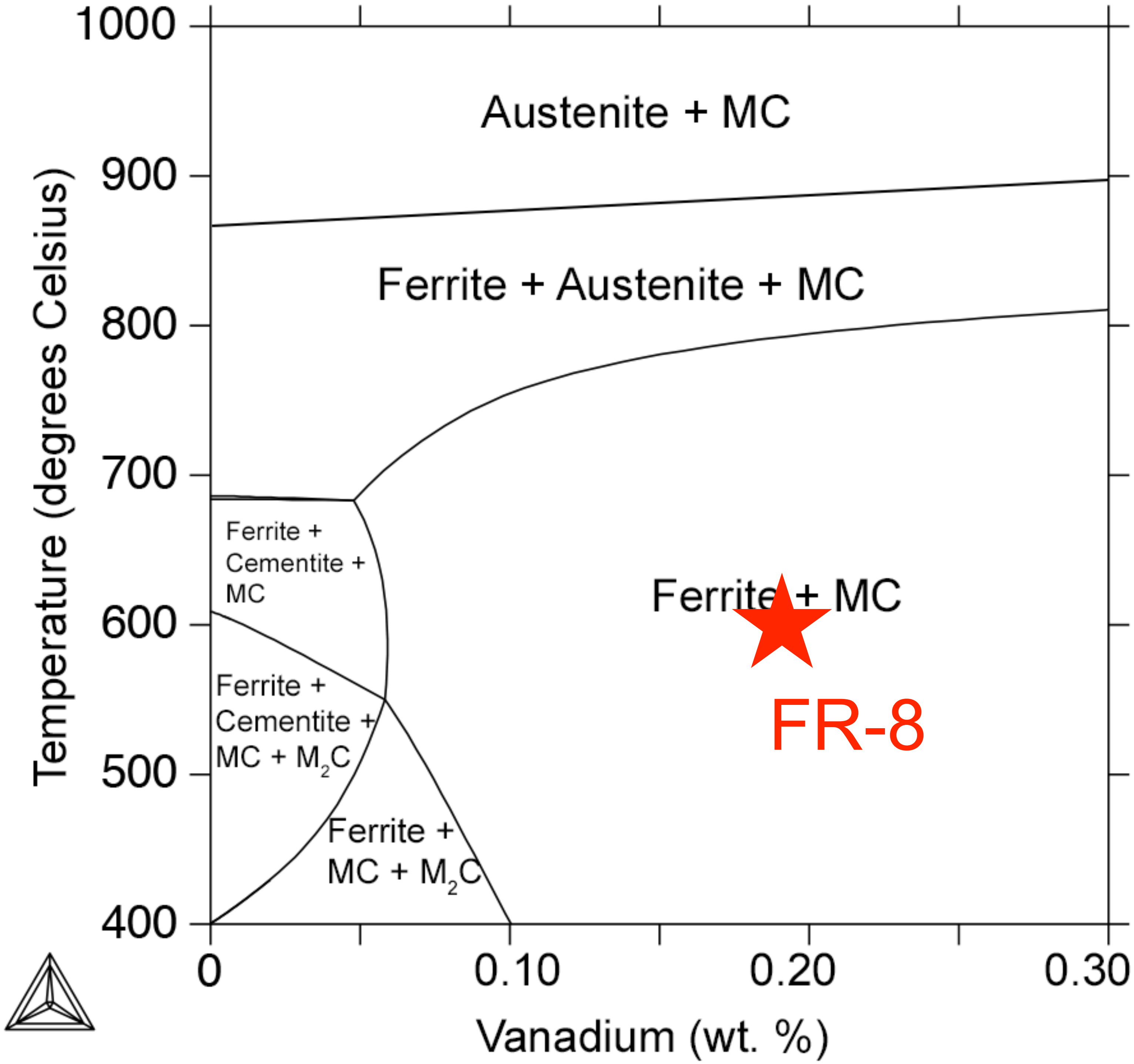
YS ratio 0.72 ± 0.03

Alloy Compositions



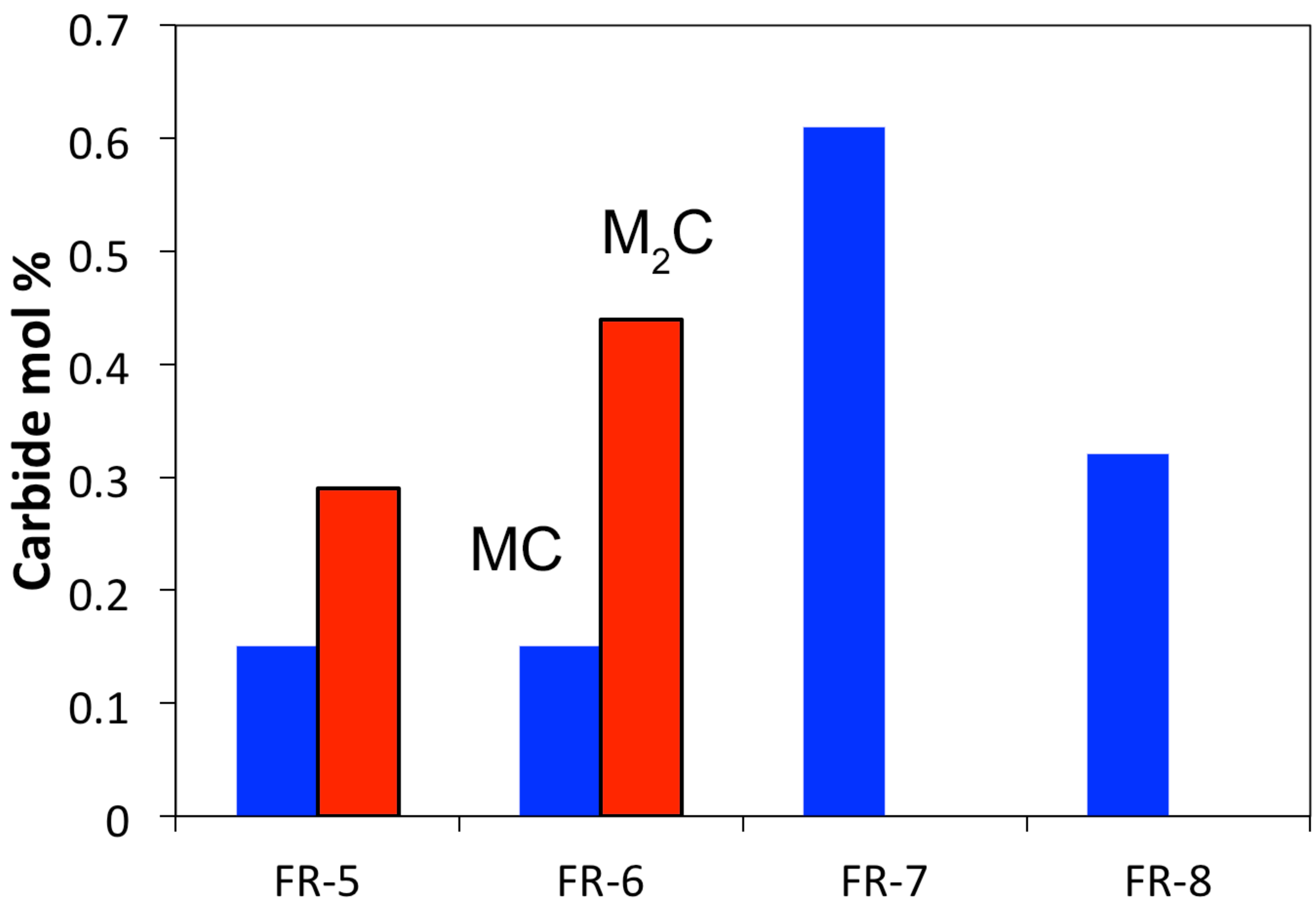
FR-8 supplied by Sophisticated Alloys

FR-8 Isopleth

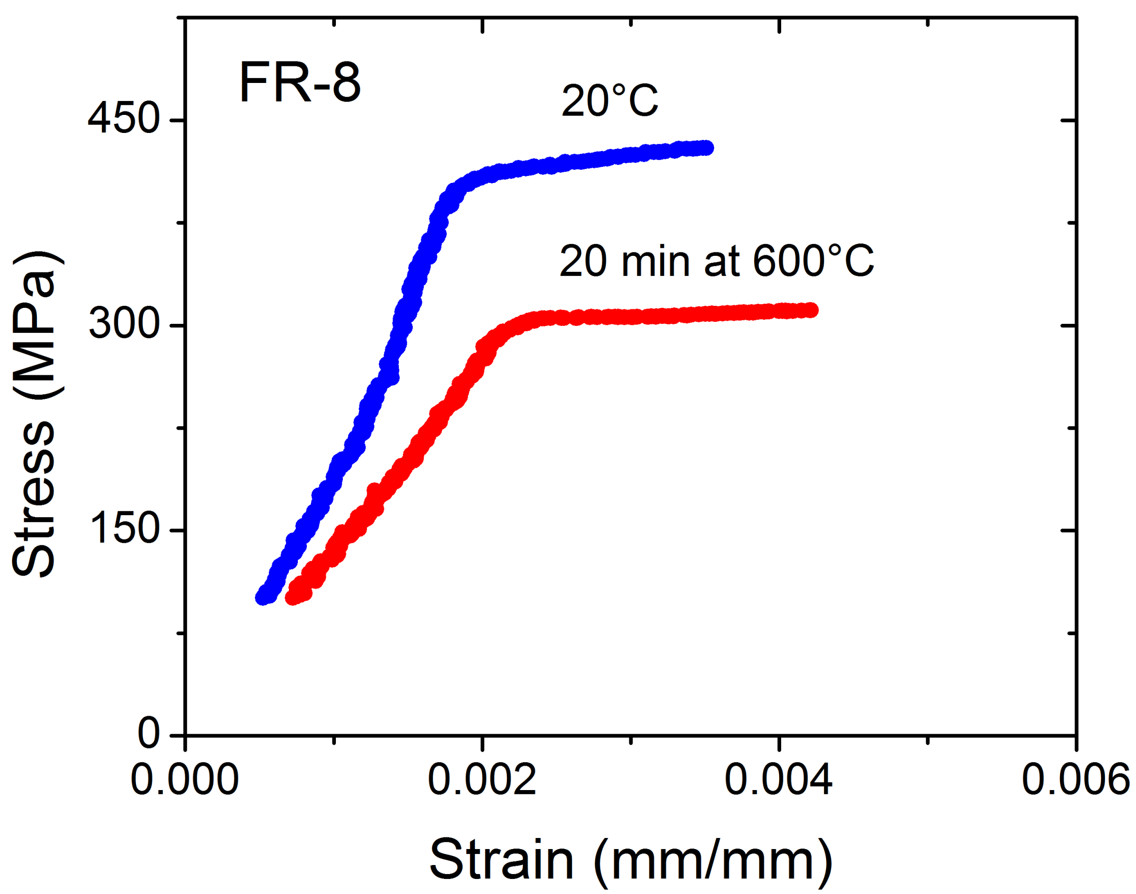


MC phase fraction contributes to high temperature strength

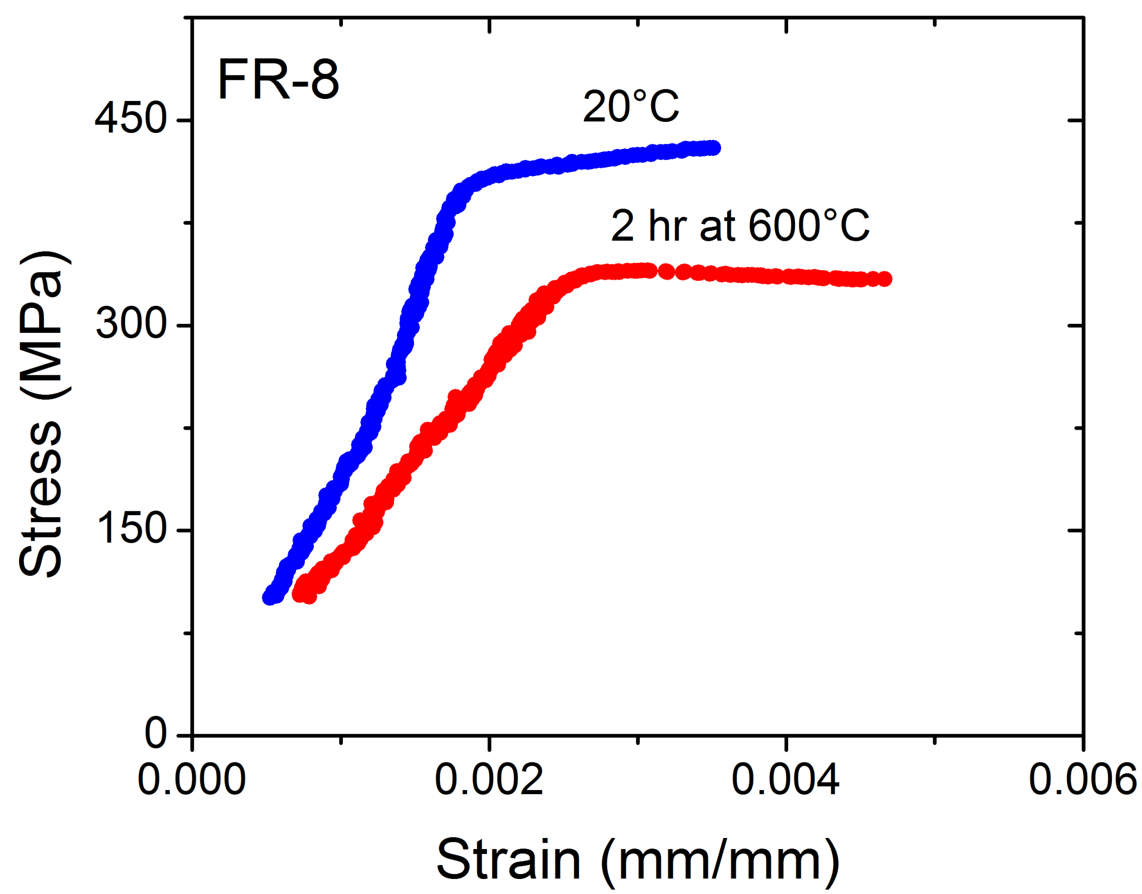
Calculated equilibrium carbide phase fraction



FR-8: Compression curves at 20°C and 600°C



YS ratio 0.71 ± 0.04



YS ratio 0.81 ± 0.06

Initial conclusions and future work

- Design process resulted in a steel that exceeded the goal: reaching over 70% YS retention after 20 minutes, and over 80% YS retention after 2 hours of exposure to 600°C.
- Thermo-Calc accurately predicted the composition of small carbonitride precipitates.
- Future work: predict interfacial energy and coherency to optimize precipitate composition.

Creep resistant steels for steam turbines

- Current Ni based superalloys are expensive.
- Steels currently creep too rapidly to be used for ultra supercritical (USC) steam generators.
- Increasing the operating temperature in USC steam generators will reduce greenhouse gas emissions worldwide.

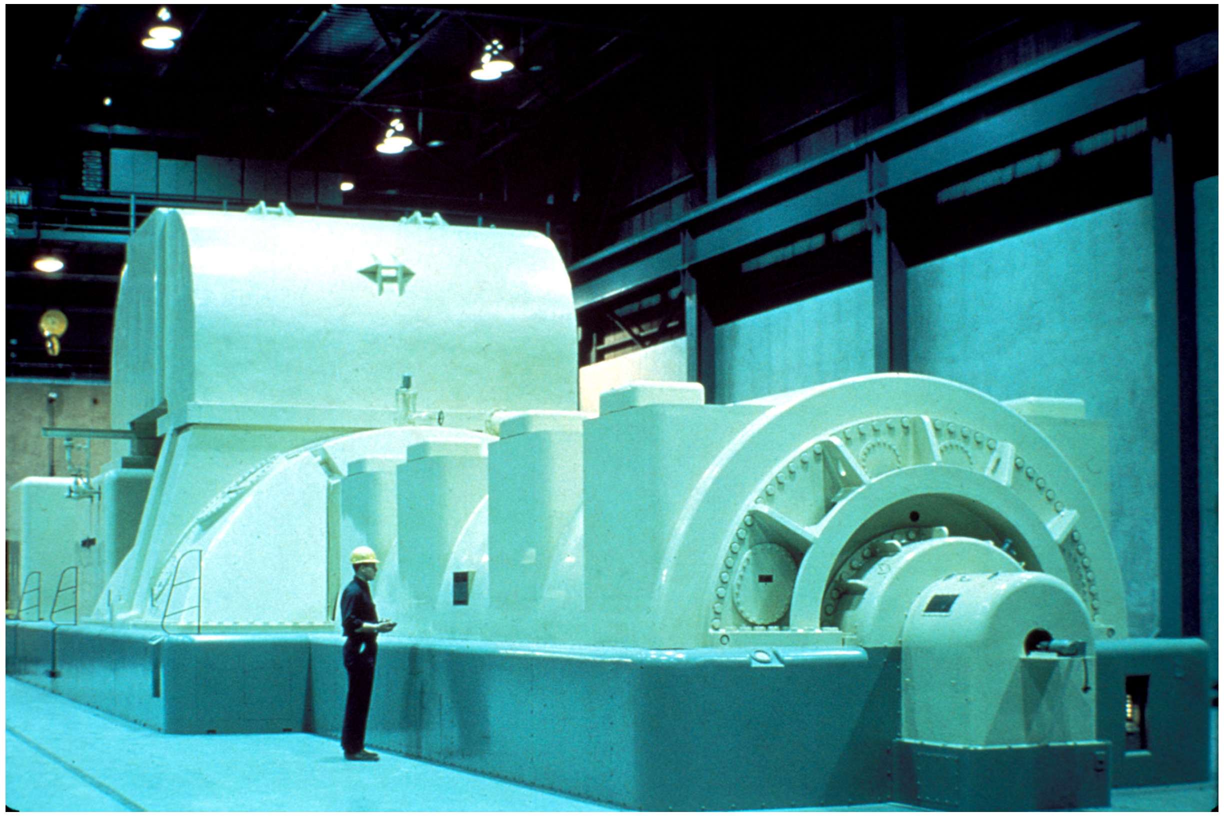


Photo credit: NRC

Creep resistant steel alloys for steam turbine applications

- Requires at least 9 wt. % Cr for corrosion resistance.
- Creep resistance at 35 MPa at temperatures over 620°C.
- Minimize alloy content to remain cost competitive with current options.

Photo credit: General Electric Company. http://www.ge-energy.com/products_and_services/services/steam_turbines_power_generation_services/

Concluding remarks

- We have built a foundation of theoretical models that predict experimental observations.
- I have confidence that we will be able to use this design process to achieve the proposed goals.
- The development of an effective steel for steam turbine use has the potential to change the world.

Acknowledgments

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- Dr. Shrikant Bhat for his help and insight
- Nucor and Sophisticated Alloys for providing the alloys.
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Thank you!

Questions?