Evolution of Ferritic/Martensitic Steels for Elevated-Temperature Service

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Higher Operating Temperatures Sought For Steels for Fusion

- Upper operating temperature for reduced-activation ferritic/martensitic steels is 550-600°C
- ODS steels are a possible long-range solution for higher temperatures
- Steels have been developed for power-generation industry for higher temperature operation than present reduced-activation steels

New Steels Developed for Power-Generation Industry

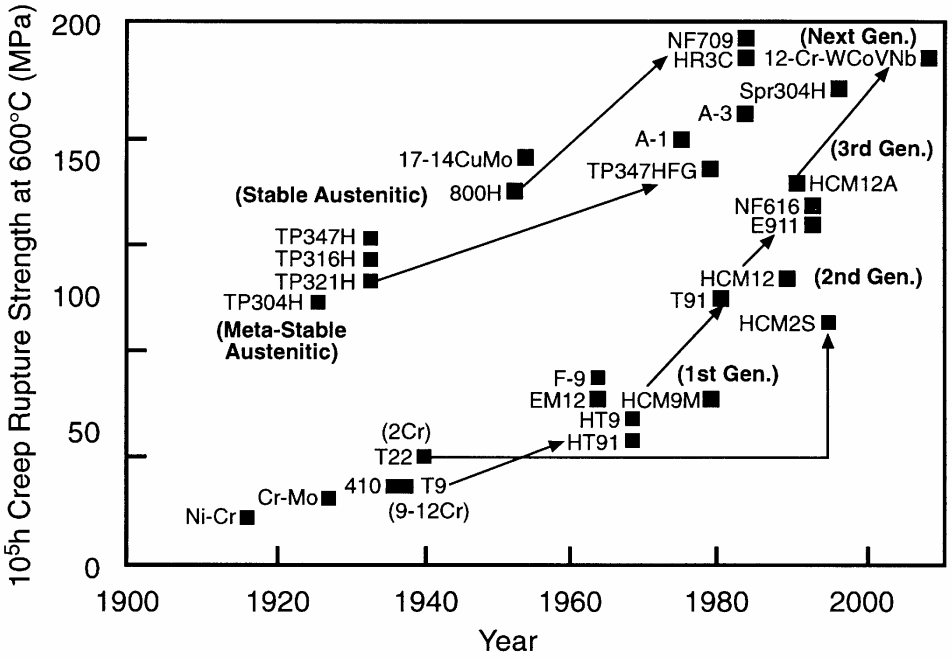
- Industry has emphasized improved efficiency (higher temperatures) for over 60 years
- From 1920 on, the need for higher temperatures has led to an evolution in the development of the Cr-Mo steels for power-generation systems
- Strength and operating temperatures have steadily increased with these developments

Evolution of Steels for Power-Generation Industry

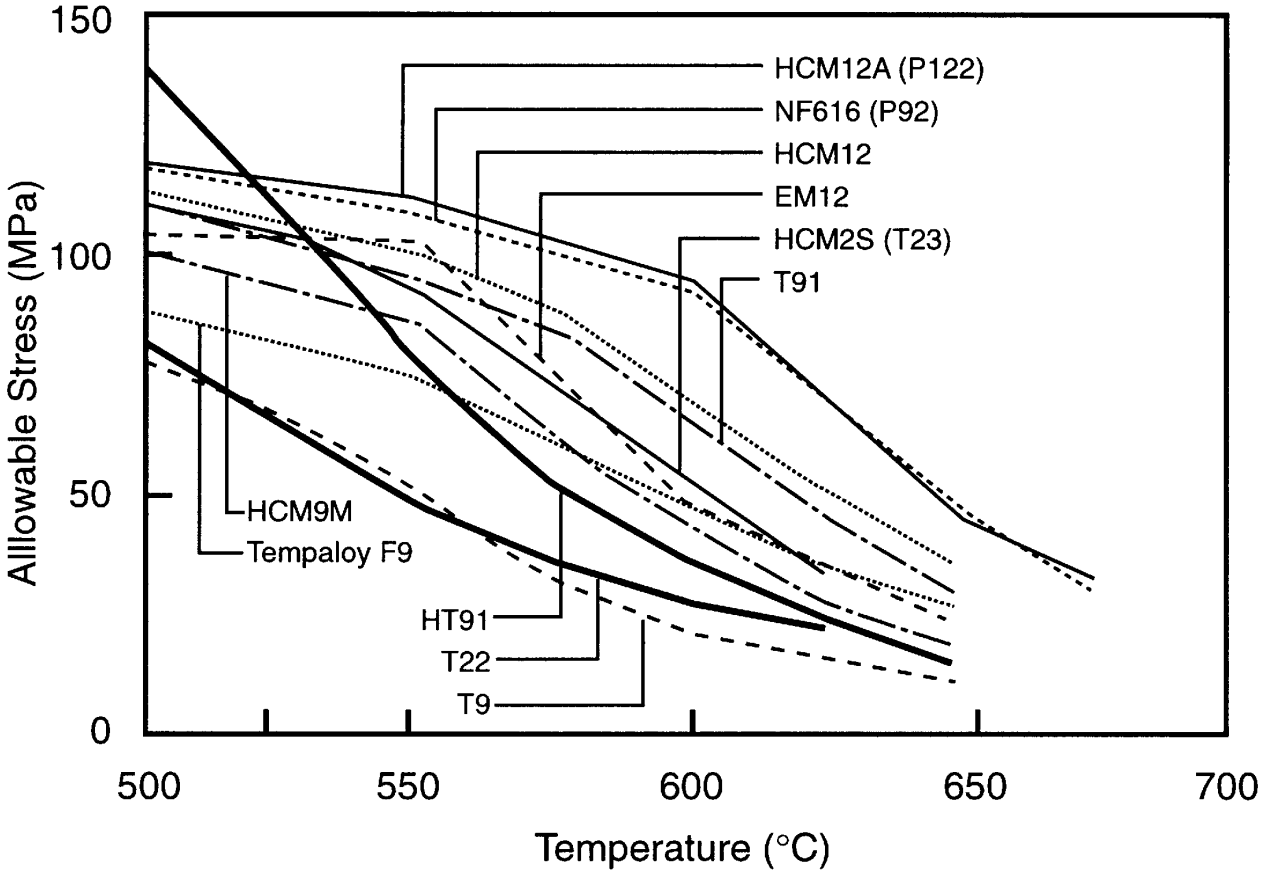
Generation	Years	Steel Modification	10^5 Creep-Rupture Strength	Steels	Max Use Temperature (°C)
0	1940-60		40	T22, T9	520-538
1	1960-70	Addition of Mo, Nb, V to Simple Cr-Mo steels	60	EM12, HCM9M, HT9, HT91	565
2	1970-85	Optimization of C, Nb,V	100	HCM12, T91, HCM2S	593
3	1985-95	Partial Substitution of W for Mo	140	NF616, E911, HCM12A	620
4	Future	Increase W and Add Co and Cu	180	NF12, SAVE12	650

Rupture strength is in MPa

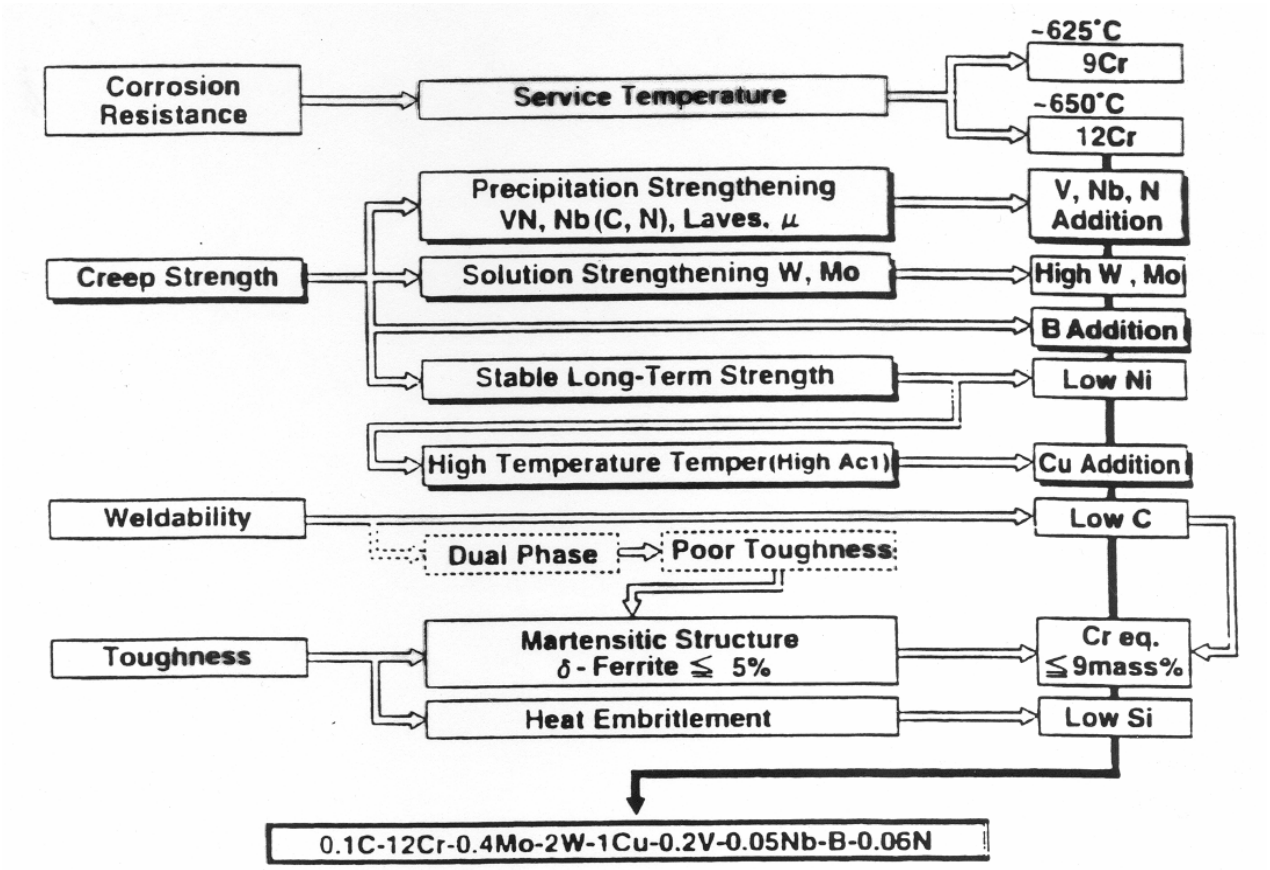
Development of Steels Produced Steady Increase in Creep Strength



Comparison of Allowable Stresses of Ferritic Steels for Boilers



Alloy Design for HCM12A



Steels Capable of 620-650°C Have Been Developed

- Three new ferritic/martensitic steels, NF616, HCM12A, and E911 (generation 3) have been developed and shown to be capable of operation up to 620°C (code approved to 620°C)
- Two steels, NF12 and SAVE12, capable of operating up to 650°C are in developmental stage
- Concern with oxidation at 650°C indicates steels for this temperature must contain 12% Cr

Development of Reduced-Activation Steels Needed to Reach Beyond F82H

- New reduced-activation steels need to be developed if fusion steels are to go beyond second generation of power-generation steels
- If reduced-activation versions cannot be developed, relative benefits of reduced-activation and higher operating temperatures may need to be evaluated

Advances in New Steels Involved the Use of N, B Cu, and Co

- N is used to form stable vanadium carbo-nitrides and nitrides
- B is associated with the $M_{23}C_6$ and refines the size and number density of precipitates
- Cu is used as an austenite stabilizer (Ni accelerates the coarsening of $M_{23}C_6$)
- Co is used as an austenite stabilizer (not available for nuclear applications)

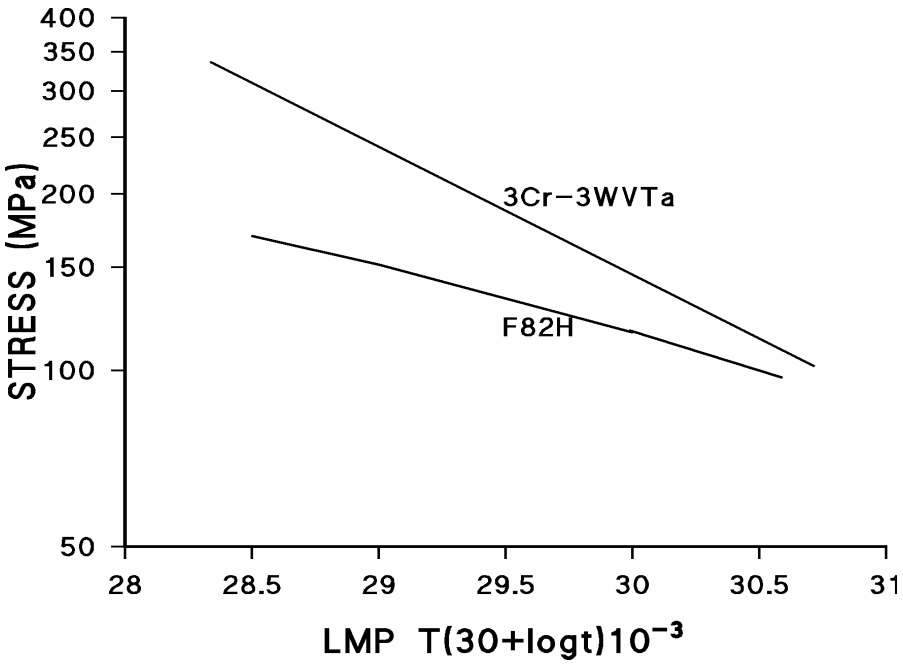
Other High-Temperature Steels Have Been Investigated

- 9Cr-3W-VNbBN steel with 3% Pd
  - Strengthened by stable $L1_0$ Fe-Pd intermetallic
  - Homogeneous precipitation (<100 nm particles)
- 15Cr-6W-3Co-1MoVNbNB Steel
  - Properties comparable to third-generation steels
  - Improved oxidation resistance
- A-21 steel

A-21 Is Dispersion-Strengthened by Conventional Processing

- A-21 steel: Fe-9.5Cr-3Co-1Ni-0.6Mo-0.3Ti-0.07C
  - Precipitation strengthened by TiC
  - Particles: 5-20 nm, 5×10^{21} m^{-3}
  - Large $M_{23}C_6$ particles not present in the steel
  - Matrix is low-carbon martensite
  - Steel may not have to be tempered
- A-21 without Co has been developed (Ni used as the austenite-stabilizing element)

Improved Reduced-Activation Steels Can be Developed



- 3Cr-3WVTa steel has excellent creep properties
- Steel developed in fusion program
- Steel being pursued for applications in petrochemical and power industries

Summary and Conclusions

- Ferritic/Martensitic steels are the only viable structural materials available for fusion now and in the near future
- Reduced-activation steels are limited to 550-600°C
- If higher operating temperatures are required, new reduced-activation steels will need to be developed
- Steels developed in the power-generation industry allow higher temperature operation
- If new reduced-activation steels are not developed, the power-generation steels could be considered for fusion