Fatigue-based materials selection and qualification for hydrogen fuel-cell electric vehicles

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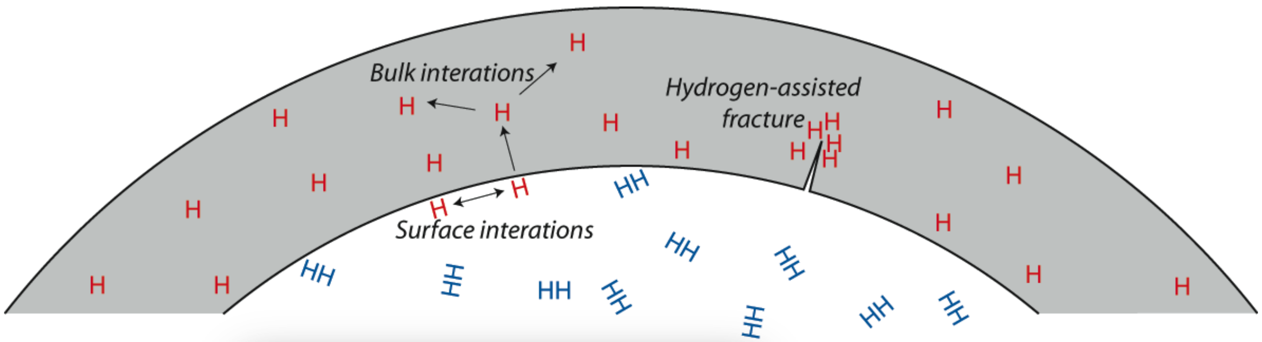
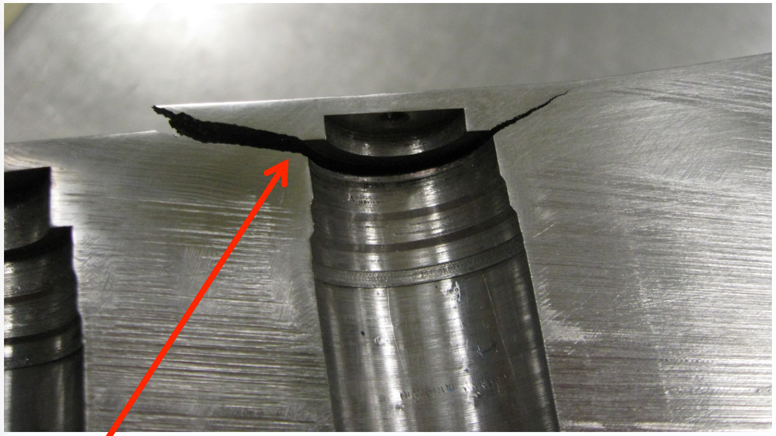
Why is materials selection an issue for hydrogen service?

- Hydrogen degrades fracture and fatigue resistance of materials



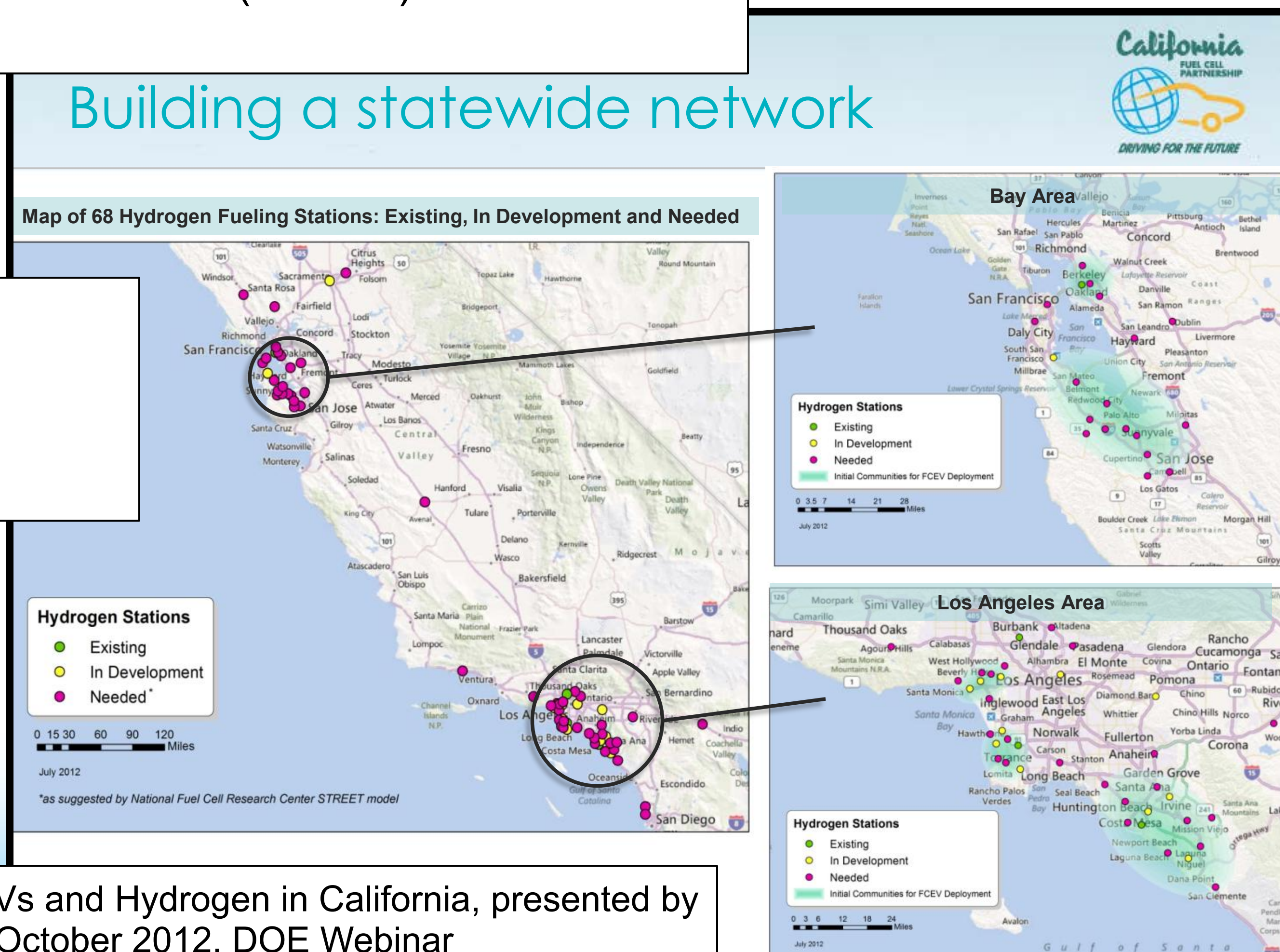
Hydrogen-induced failure of transport cylinder from the 1970s



Hydrogen-assisted fatigue crack initiated at site of stress concentration in diaphragm compressor

Why should we care about hydrogen FCEVs?

Goal for California:
- 68 fueling stations by the end of 2015
- serving 5,000-15,000 vehicles (FCEVs)



End of 2012 in CA
- 13 fueling stations
- 312 FCEVs

Source: California Fuel Cell Partnership (cafcp.org/roadmap)

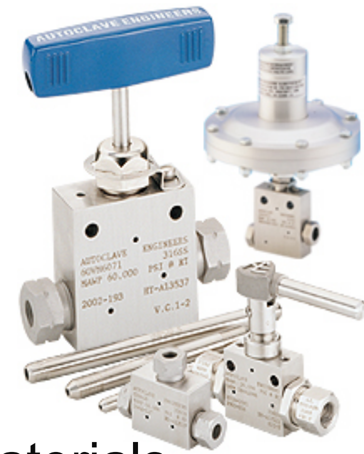
Slide taken from: FCEVs and Hydrogen in California, presented by Catherine Dunwoody, October 2012, DOE Webinar

Hydrogen Vehicles and Fueling Stations

Photo courtesy of GM

- Growing markets (worldwide estimates)
  - 200-400 light duty vehicles (automobiles on the road)
  - 100-150 heavy duty vehicles (buses, dump-trucks, yard-haulers, etc.)
  - 3,000 industrial trucks (forklifts)
  - >200 fueling stations for buses and automobiles
  - >50 forklift indoor/outdoor fueling sites
- Onboard storage: high-pressure gas at pressure up to 700 bar (10,000 psi)

Cost is an potential barrier to widespread deployment of hydrogen FCEVs



Problem:

- Balance of plant (BOP) onboard vehicles accounts for:
  - 30-57% of total fuel system cost
  - 15-20% of total fuel system mass
- Structural materials for BOP typically include expensive materials
  - Annealed type 316L austenitic stainless steel (Ni content >12 wt%)
  - A286 precipitation-strengthened austenitic stainless steel (Ni ~30 wt%)

Opportunities:

- ***Identify alternatives to high-cost metals for high-pressure BOP components***
  - Reduce cost by 35%
  - Reduce weight by 50%
- Refine methodologies for performance-based qualification of materials for BOP and for hydrogen service more broadly

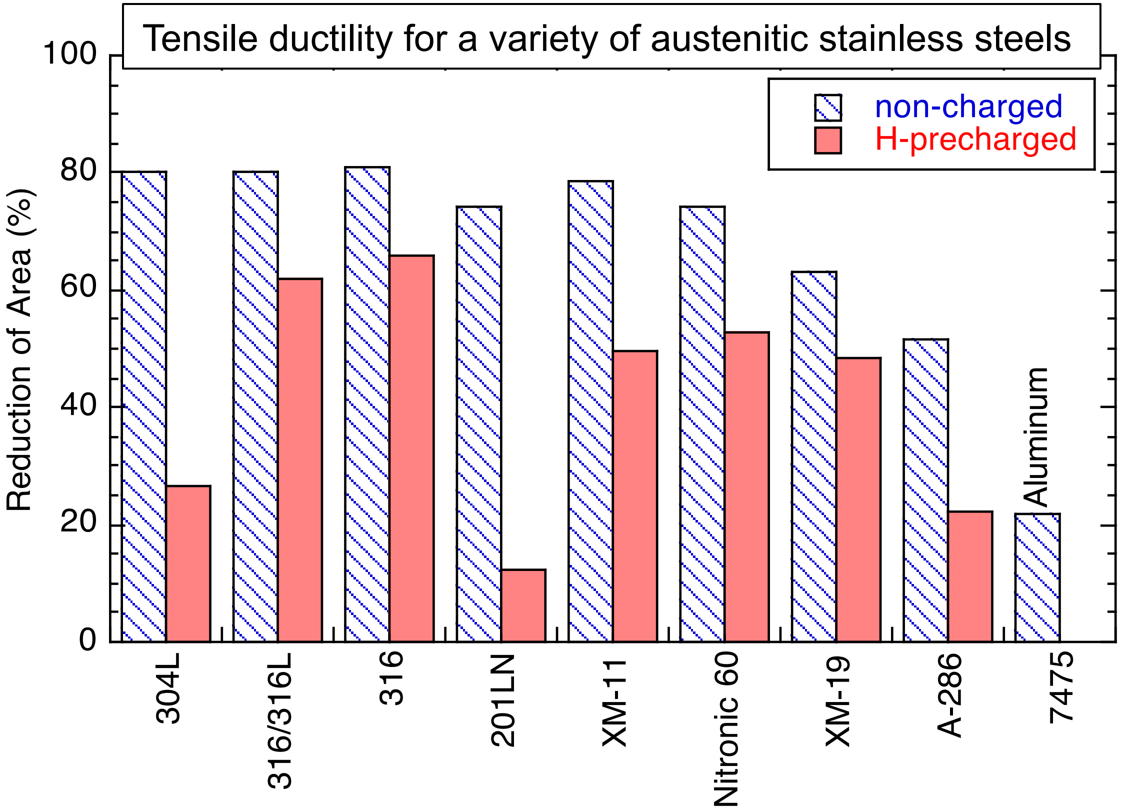
Technical basis for cost and weight reductions

- Relative component cost is estimated from the relative weight of material and material cost
  - Relative weight is determined from required thickness of material
  - Relative material cost is conservatively informed from price of bar material

$$t = \frac{PD}{2(SE + PY)}$$ ASME design equation

material	Relative material cost	Yield strength (MPa)	Relative weight	Relative component cost
316L	1.0	140	1.0	1.0
304L	0.84	140	1.0	0.84
CW 304L	1.7	345	0.46	0.78
XM-11	0.79	345	0.46	0.36
CW XM-11	1.6	620	0.17	0.27
CW XM-19	2.5	725	0.15	0.38

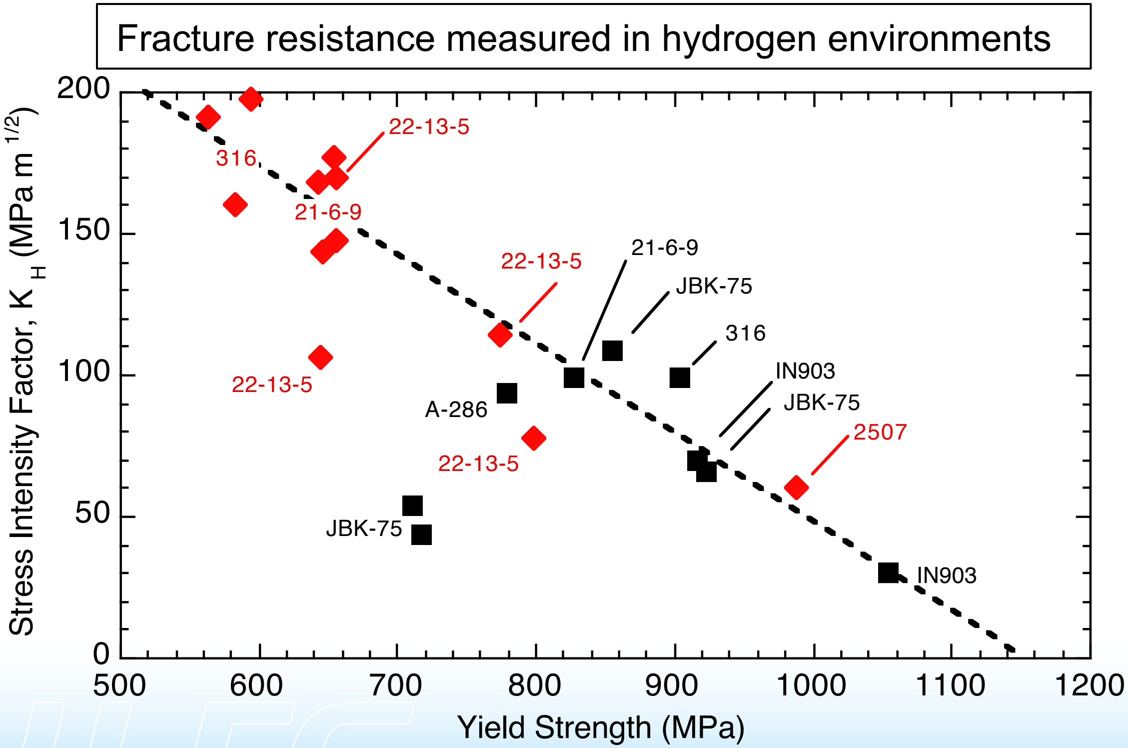
Why are materials such as 304L and XM-11 not considered for hydrogen service?



- Composition/alloy affects tensile ductility of austenitic stainless steels in hydrogen environments
- Both 316/316L and A286 are used in hydrogen systems

Fracture data suggests other stainless alloys perform similar to 316 alloys

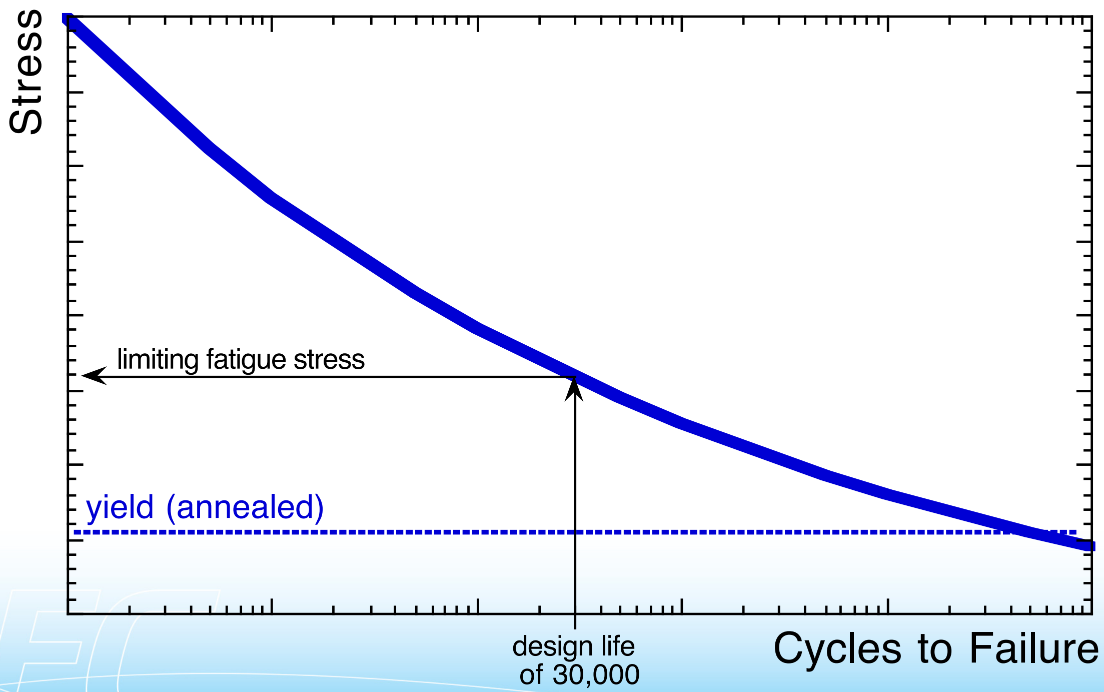
- Fracture mechanics (and fracture properties) can be used directly in the design of pressure components



- Fracture resistance in hydrogen environments depends on strength and microstructure
  - not necessarily composition
- Fracture mechanics can be difficult to implement in design

Fatigue life assessment suggests that life is not limited by fatigue for BOP applications

- For moderate design life, the limiting fatigue stress is greater than the yield strength
- Design stresses are typically < yield strength
- Result: very conservative designs



Effects of hydrogen on annealed austenitic stainless steels may not limit fatigue life for BOP applications

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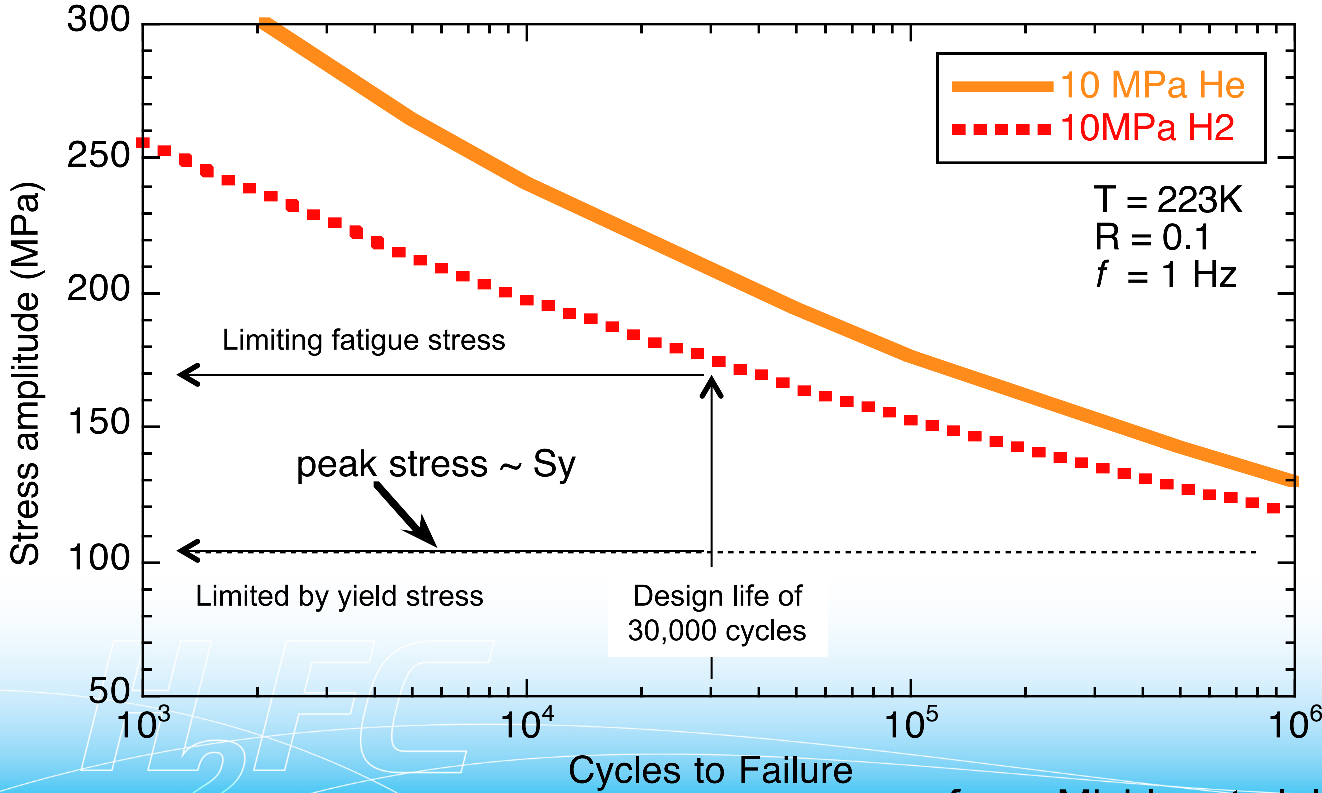
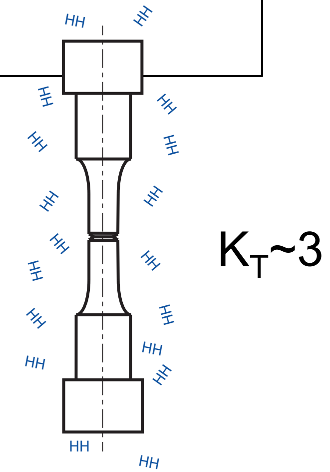


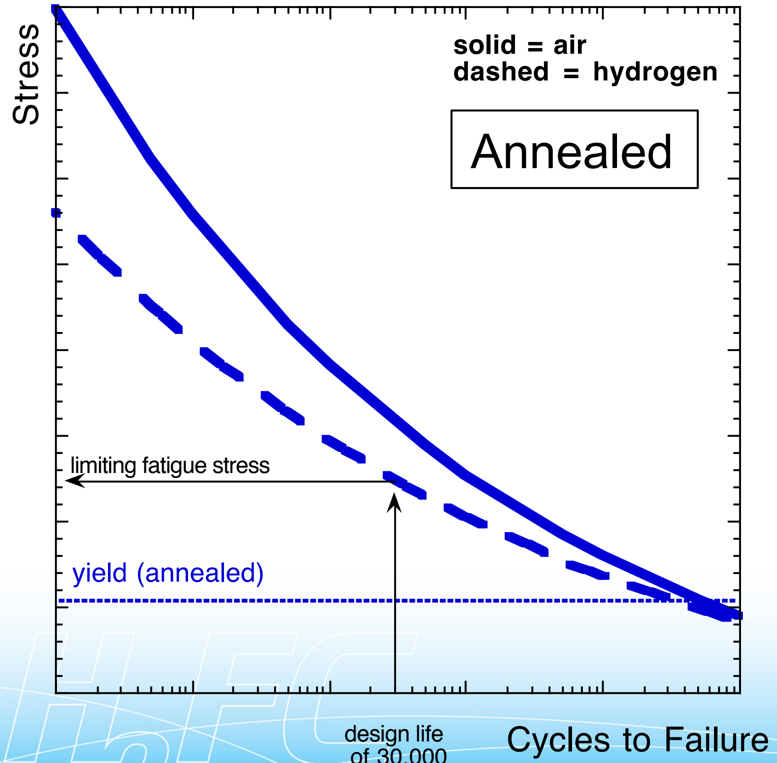


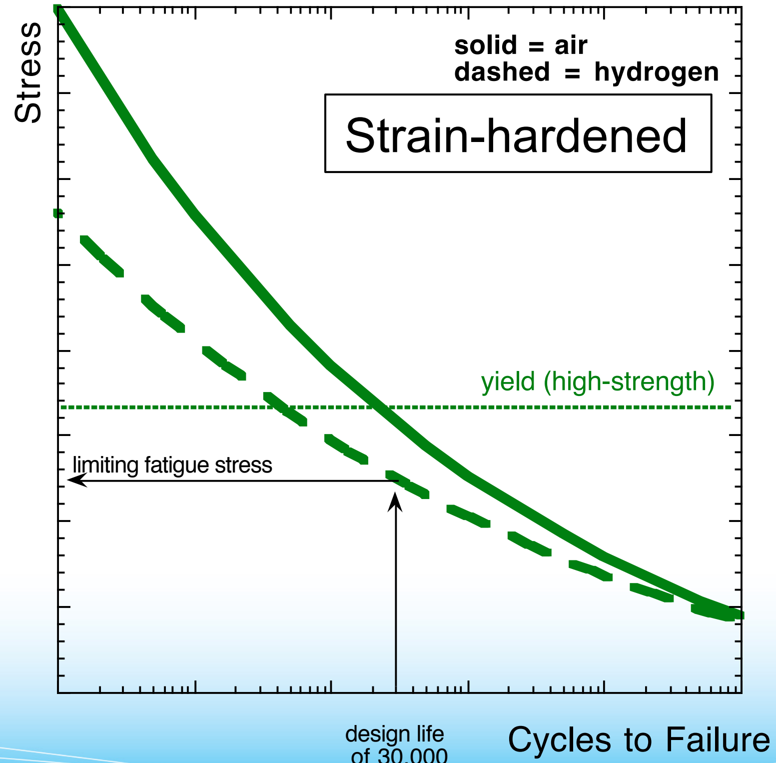
Tension-tension fatigue of standard notched tensile specimen (after ASTM G142)

from: Michler et al. IJ Fatigue 51 (2013) 1-7.

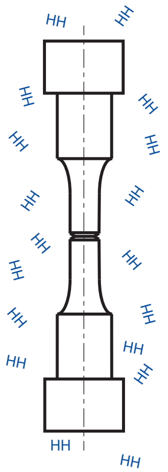
How do we take advantage intrinsic performance?

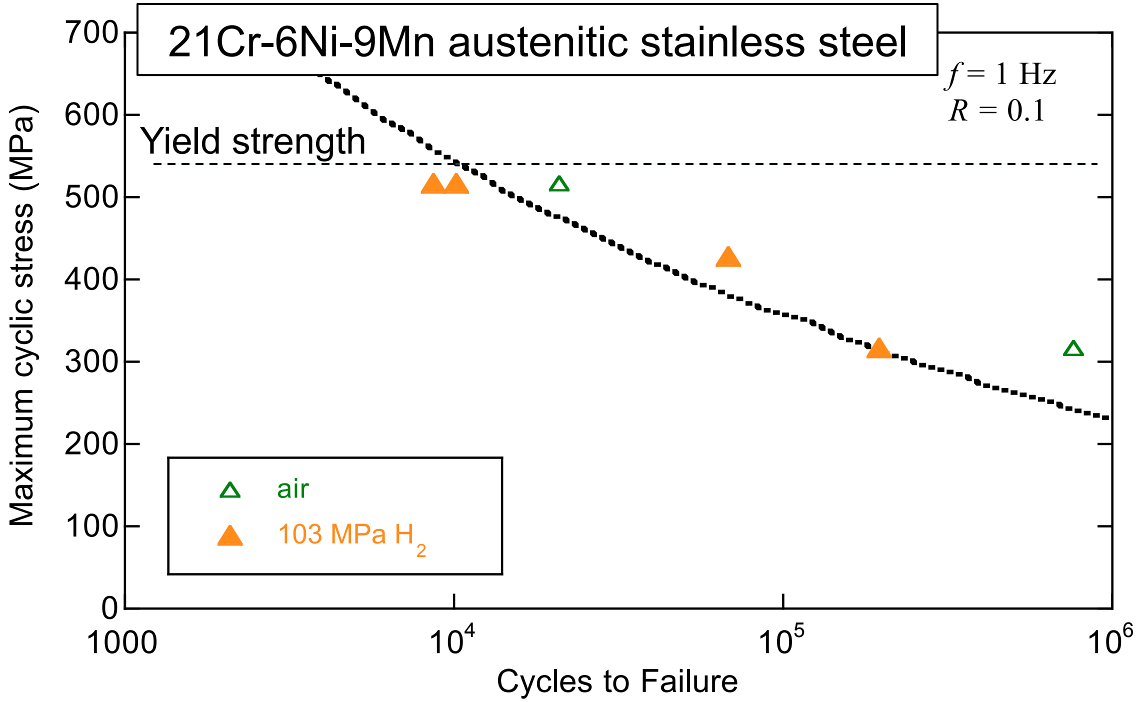
- By increasing the strength, higher fatigue stresses can be accommodated in design
  - Higher stress = less material
  - Less material = lower cost





Preliminary results: high-strength austenitic stainless steel

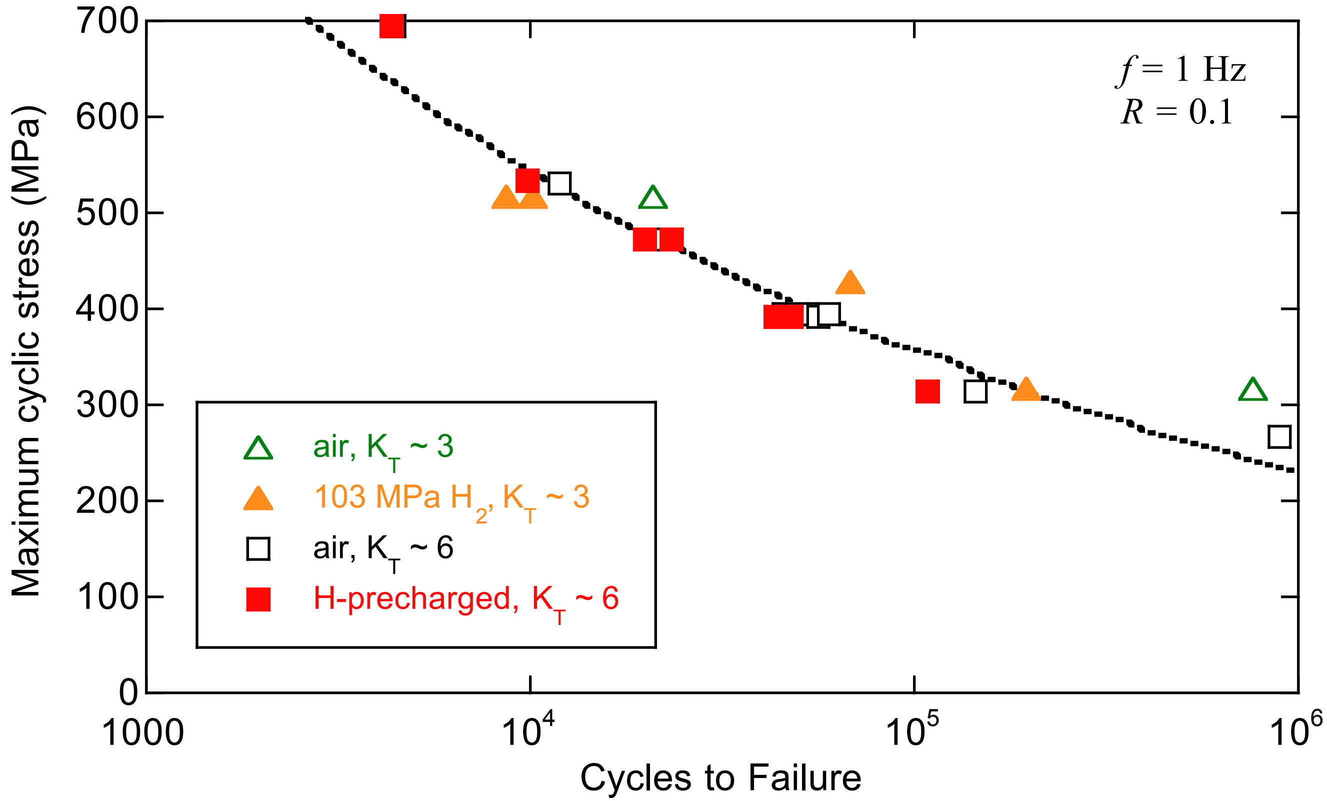




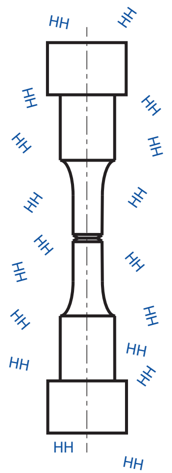
- Strength of annealed 21Cr-6Ni-9Mn is >2x strength of annealed type 316L
- Cost of 21Cr-6Ni-9Mn bar material is ~80% of type 316L bar

- Hydrogen reduces total fatigue life
- High fatigue stress can be achieved with cycles to failure greater than 10,000 cycles
- Broader evaluation of methodology requires testing under combination of low temperature and high pressure

Preliminary results: internal versus external H

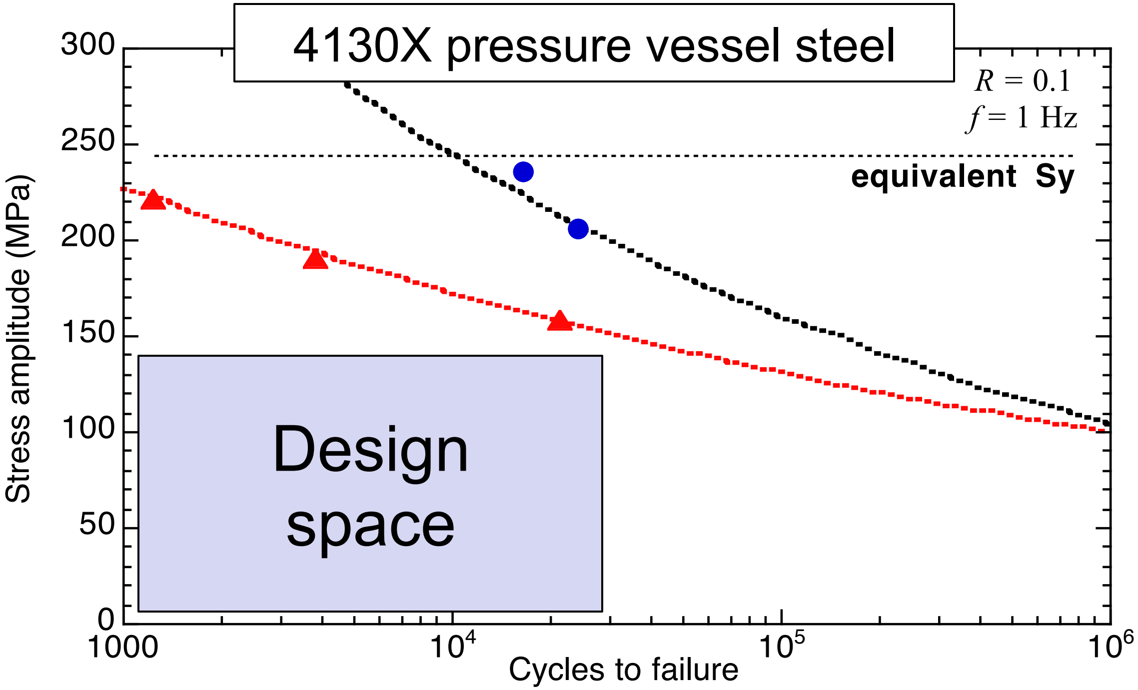


XM-11 austenitic stainless steel



- Available data is incomplete (inconsistency of notch acuity and environments)
- Initial results suggest some correlation between internal and external H
- Data at low temperature is needed

Fatigue life methods can also be applied to steels for other applications, such as pressure vessels



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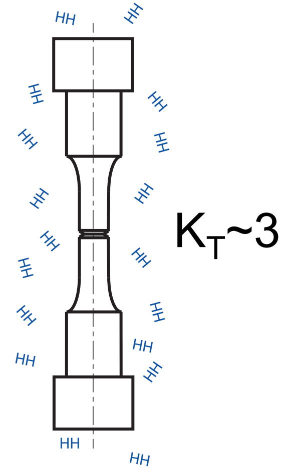

- Initial results for pressure vessel steel follow anticipated trends
- Additional data is needed to demonstrate reproducibility and consistency, as well as to coordinate with efforts in the international community
- Fatigue life methods to qualify materials for hydrogen service is receiving attention in Japan and in Europe

Summary

- Hydrogen FCEVs are coming to many neighborhoods in California in 2015-16 (also in Germany and Japan)
  - Hydrogen fuel will be stored on the vehicle at pressures up to 700 bar (10,000psi)
- Cost of gas handling equipment is becoming a critical bottleneck (also weight for mobile applications)
  - Hydrogen safety is of critical concern
  - Materials selection for hydrogen service is a challenge, currently limited to a few select (expensive) alloys
- Fatigue life assessment suggests that hydrogen fueling applications may not be fatigue limited
  - Higher-strength alloys/conditions may enable more efficient structural designs
  - *We should qualify materials based on relevant quantities*