

R&D for Safety, Codes and Standards: Materials and Components Compatibility

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Livermore CA
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H₂FC

Outline

- **Materials selection**
 - How do we select materials for hydrogen service?
 - What are appropriate metrics for materials selection?
 - Tensile behavior
 - Fracture resistance
 - Fatigue performance
 - **Database is needed**
 - Moving beyond the technical reference
- **Testing methodologies and materials testing**
 - **Low-temperature assessments of materials properties**
 - **Pressure vessel steels**
 - Cr-Mo steels
 - Ni-Cr-Mo steels

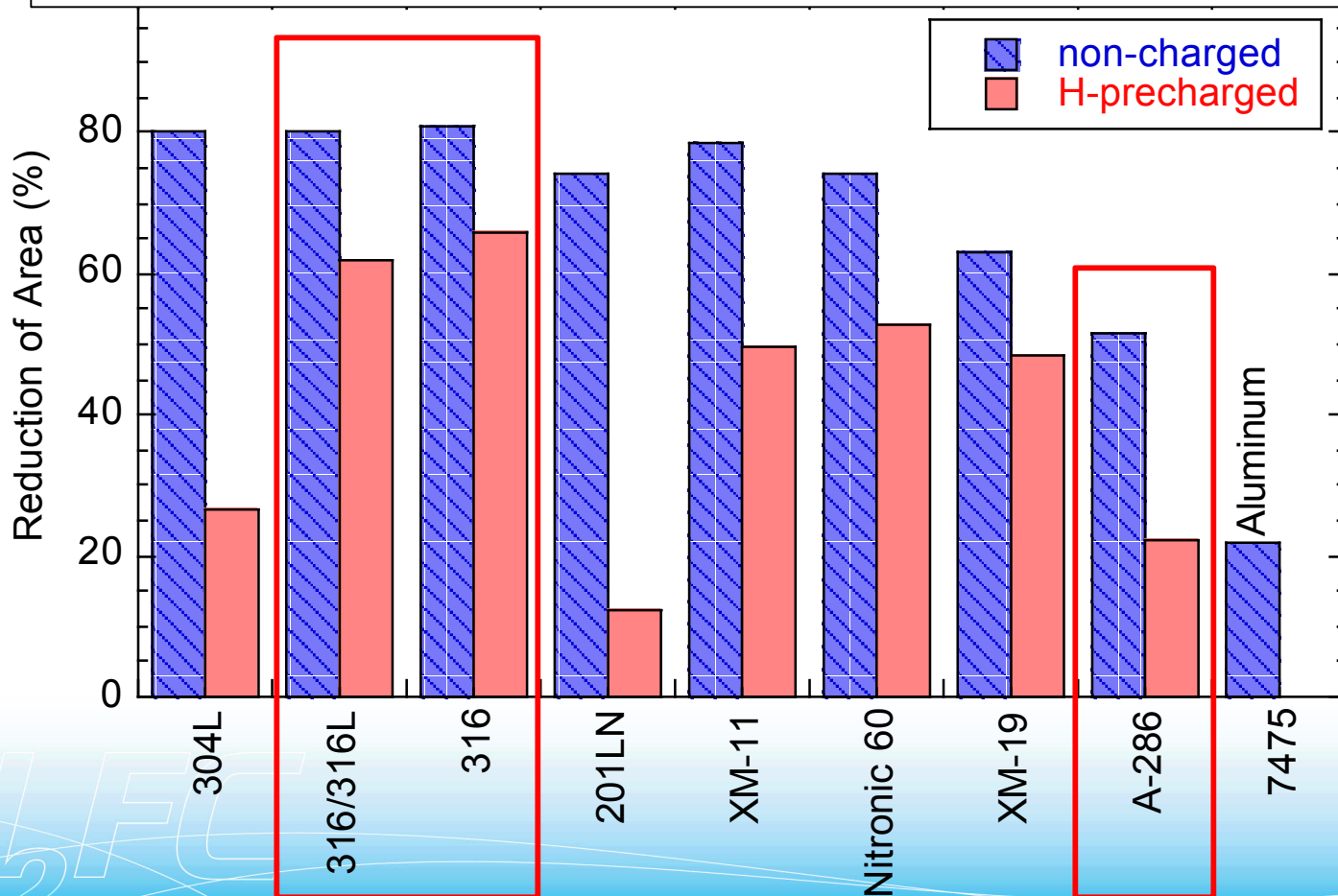
How do we select materials?

- Tensile properties
 - Used to certify microstructure and strength requirements
 - Ductility is used to assess gross microstructural defects
 - *Not used as design metric*
 - Hydrogen does not affect strength
- Fracture resistance
 - Criteria for assessing brittle failure/transitions
 - Used in design: *LBB, criticality of cracks*
- Fatigue performance
 - Several fatigue test methods
 - Used in design: *design life predictions and critical stresses/strains for infinite life*

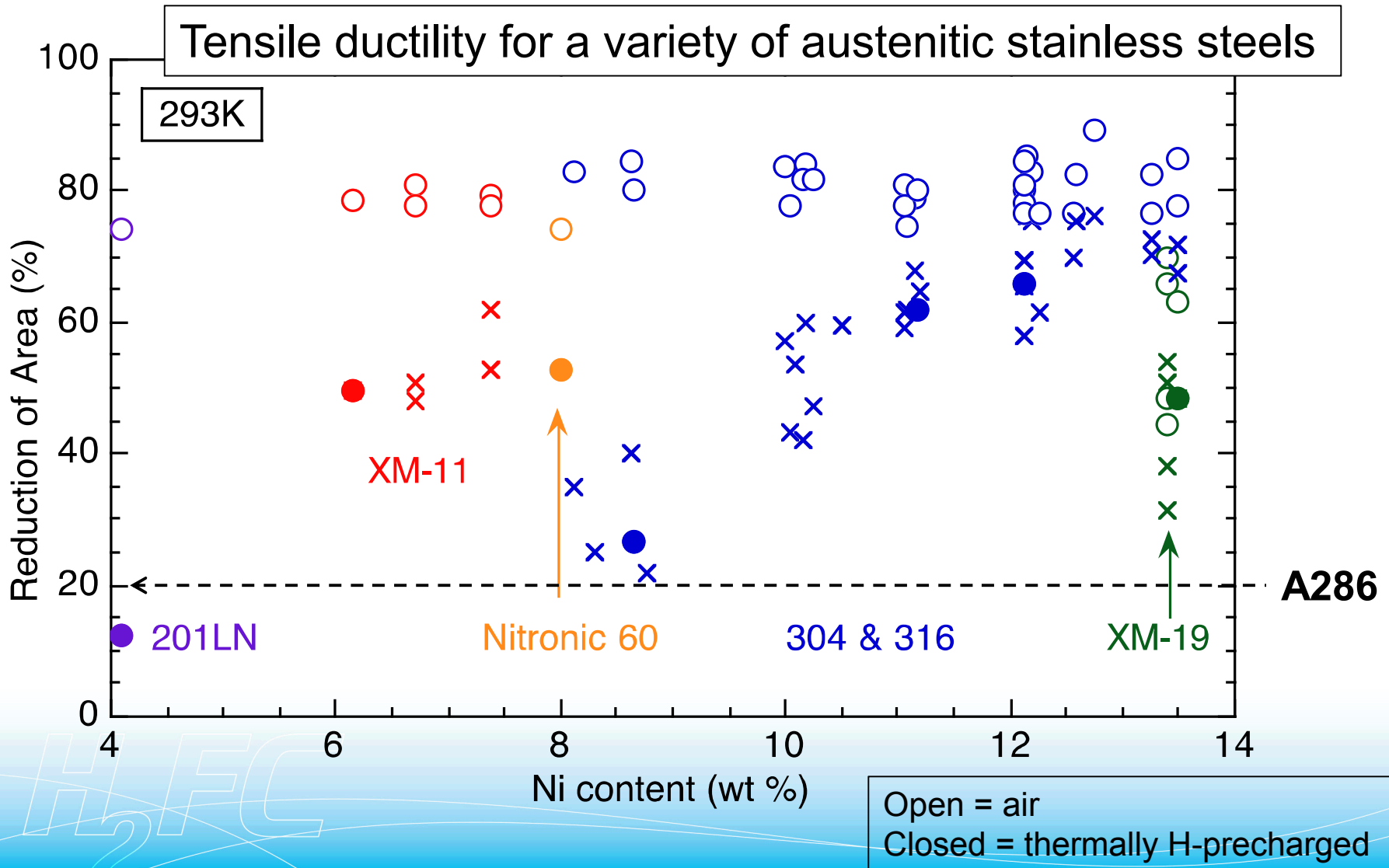
Many evaluations consider relative changes in properties as a metric for materials selection

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

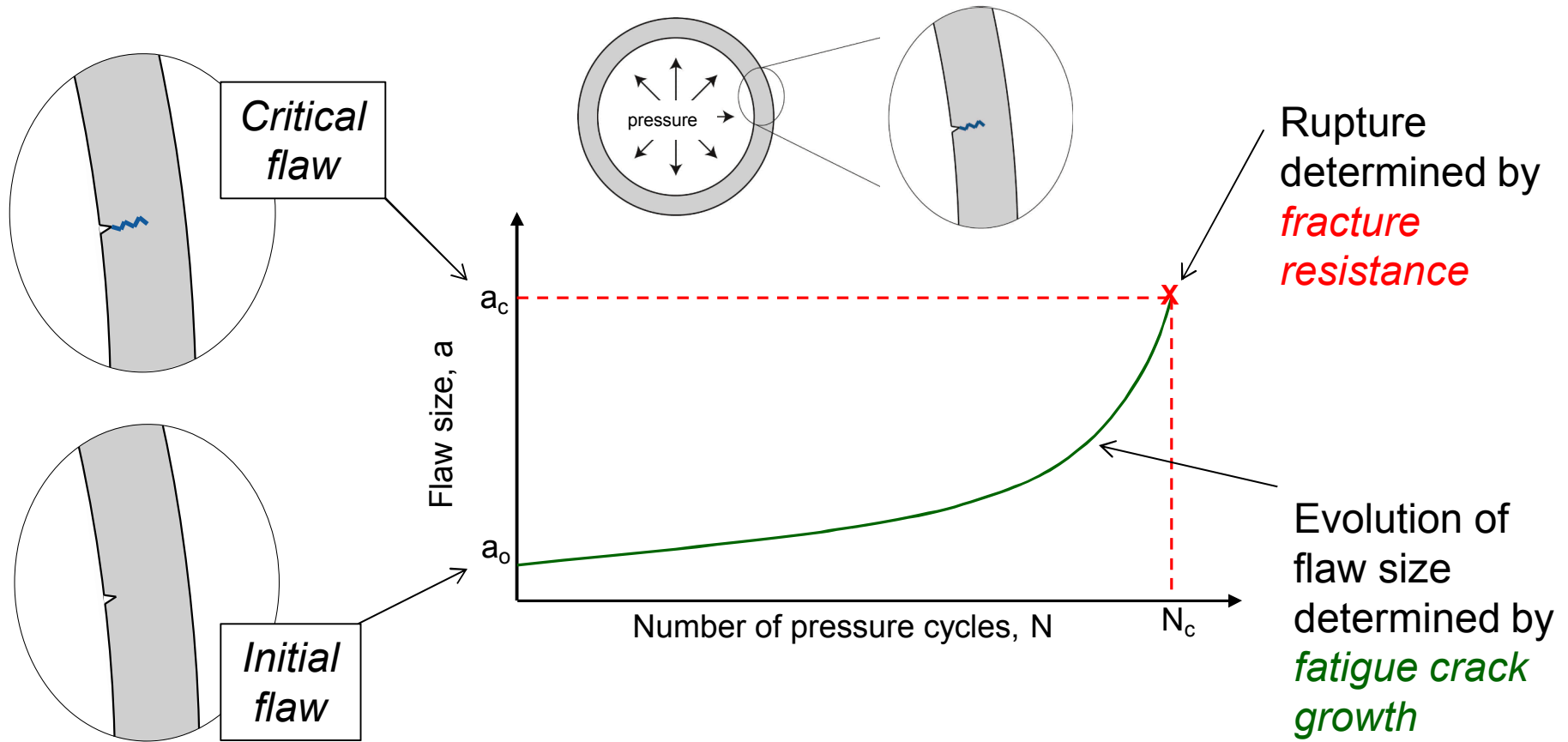
Tensile ductility for a variety of austenitic stainless steels



Why is A-286 considered appropriate for hydrogen service?

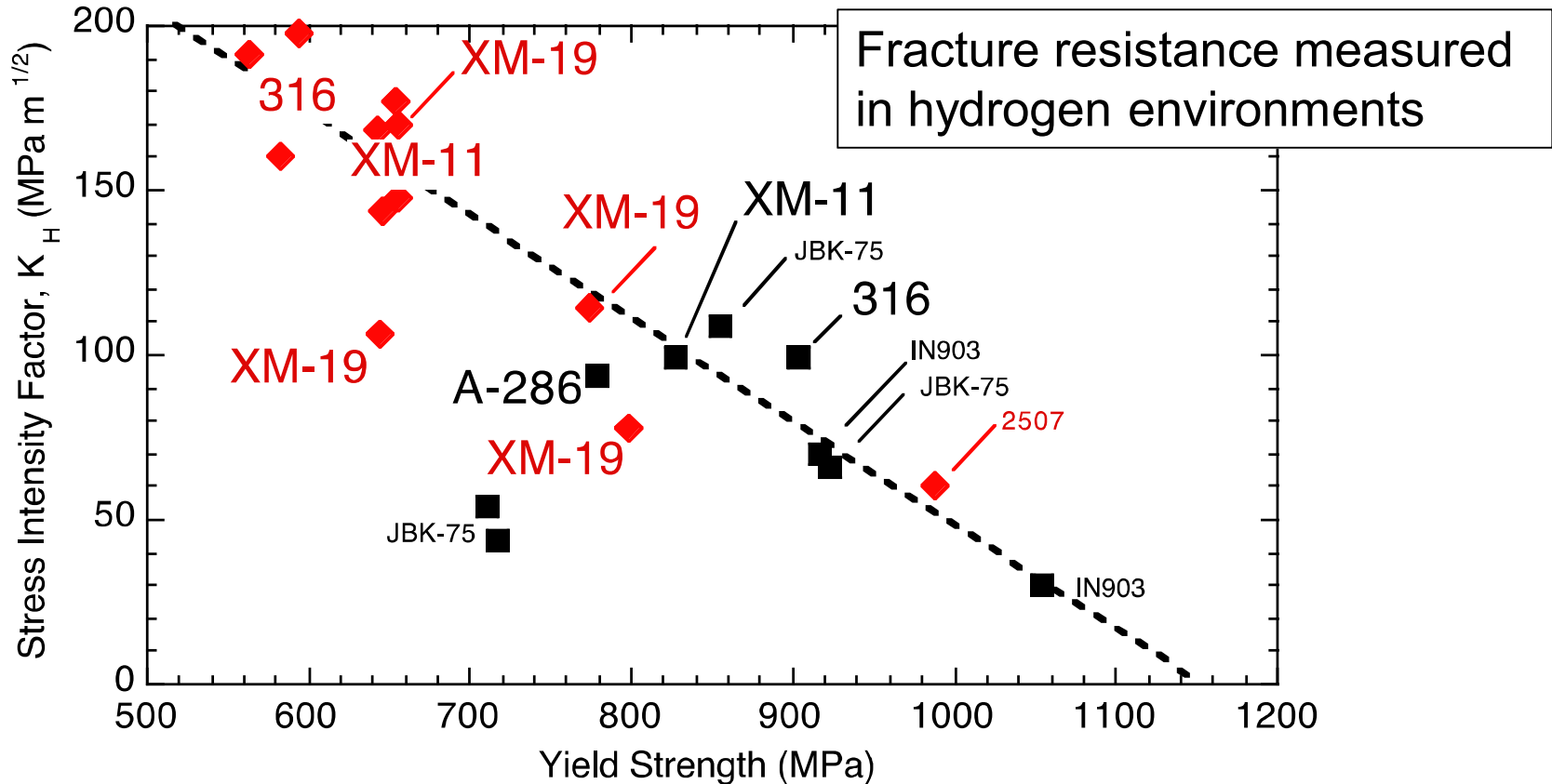


Fracture mechanics-based design is standardized



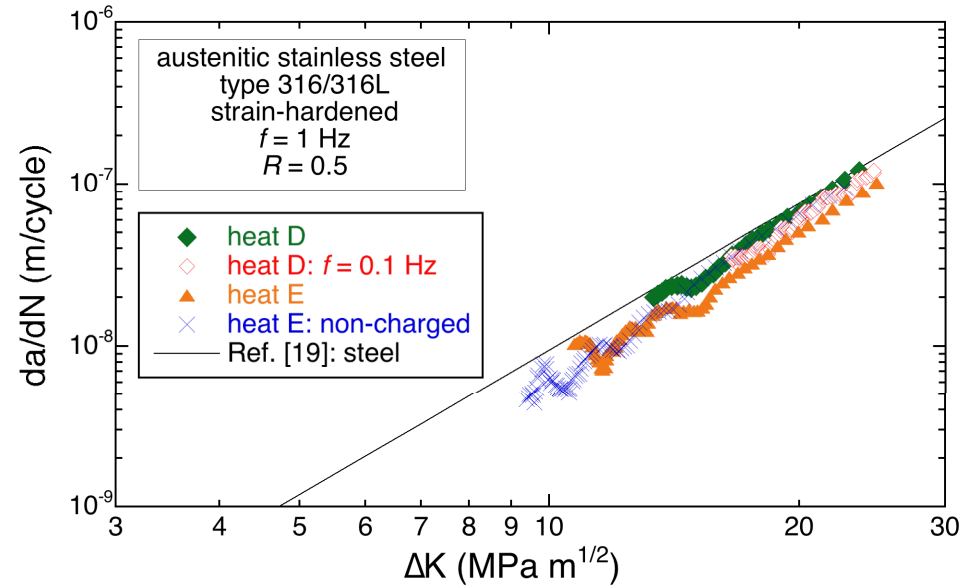
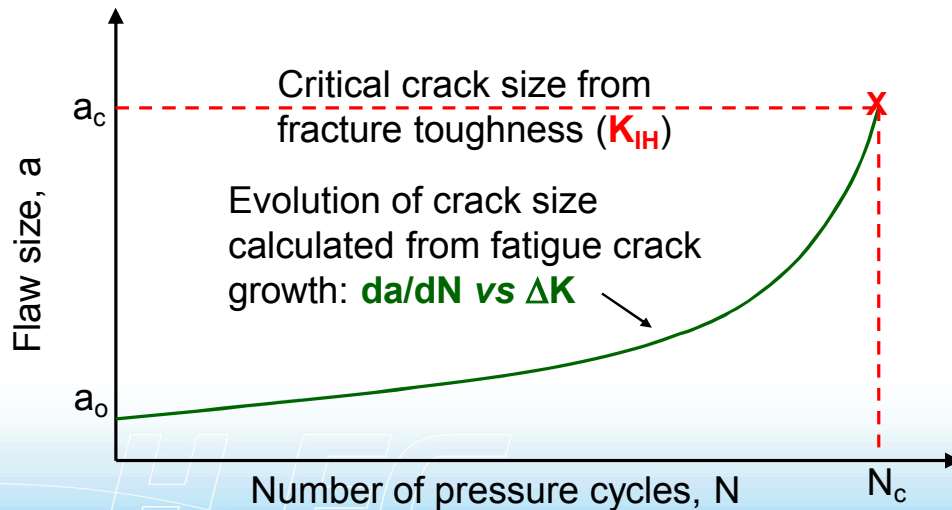
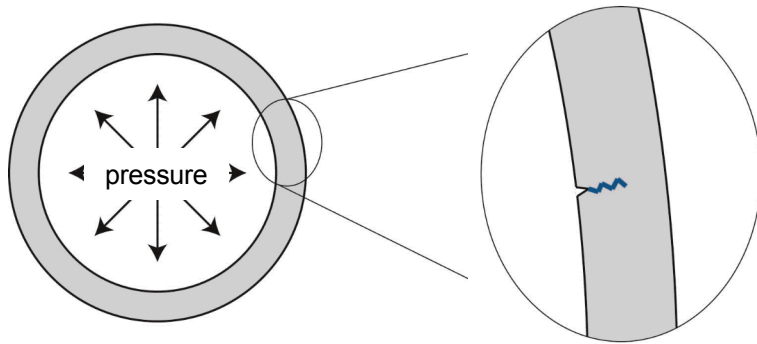
Materials performance (fracture and fatigue) in hydrogen can be used for materials selection

Fracture resistance is dependent on strength and microstructure (not necessarily composition)



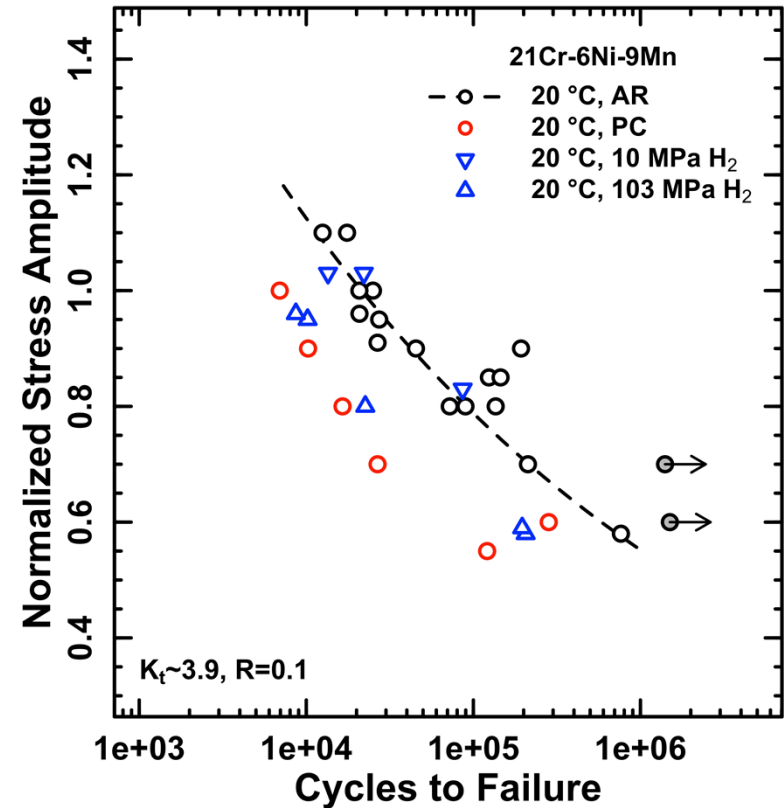
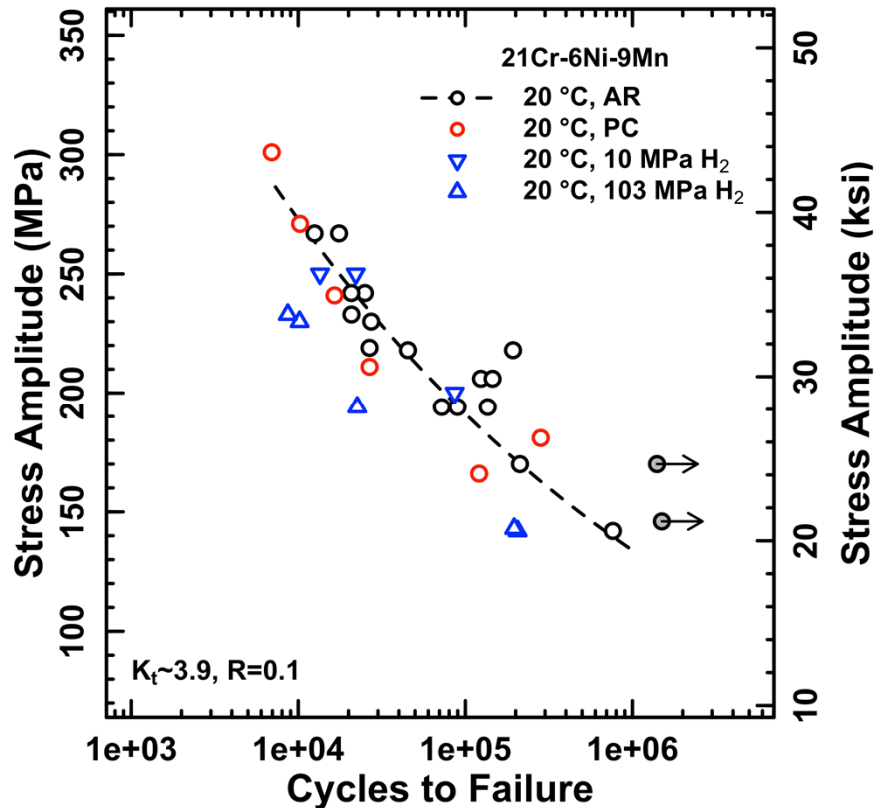
Strength and fracture properties can be used directly in the design of pressure components and systems

Fatigue crack growth can be used for *life prediction* or *inspection intervals* (ASME BPVC VIII.3 KD-4)



Fatigue crack growth design methodologies can be difficult to apply to complicated geometries

Fatigue life measurements can also be used to assess component life (ASME BPVC VIII.3 KD-3)



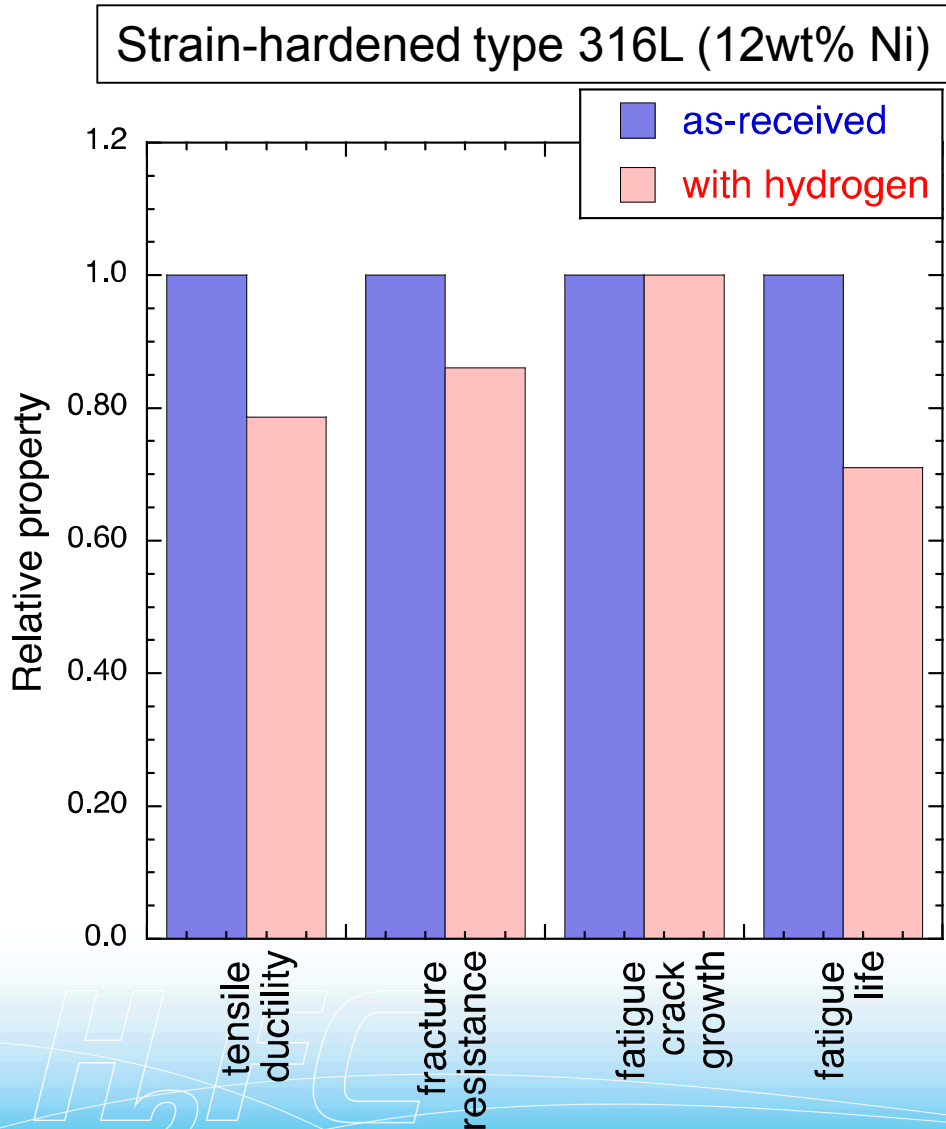
Fatigue life design enables performance consistent with the service environment

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Databases and Handbooks of engineering properties are necessary for design of components

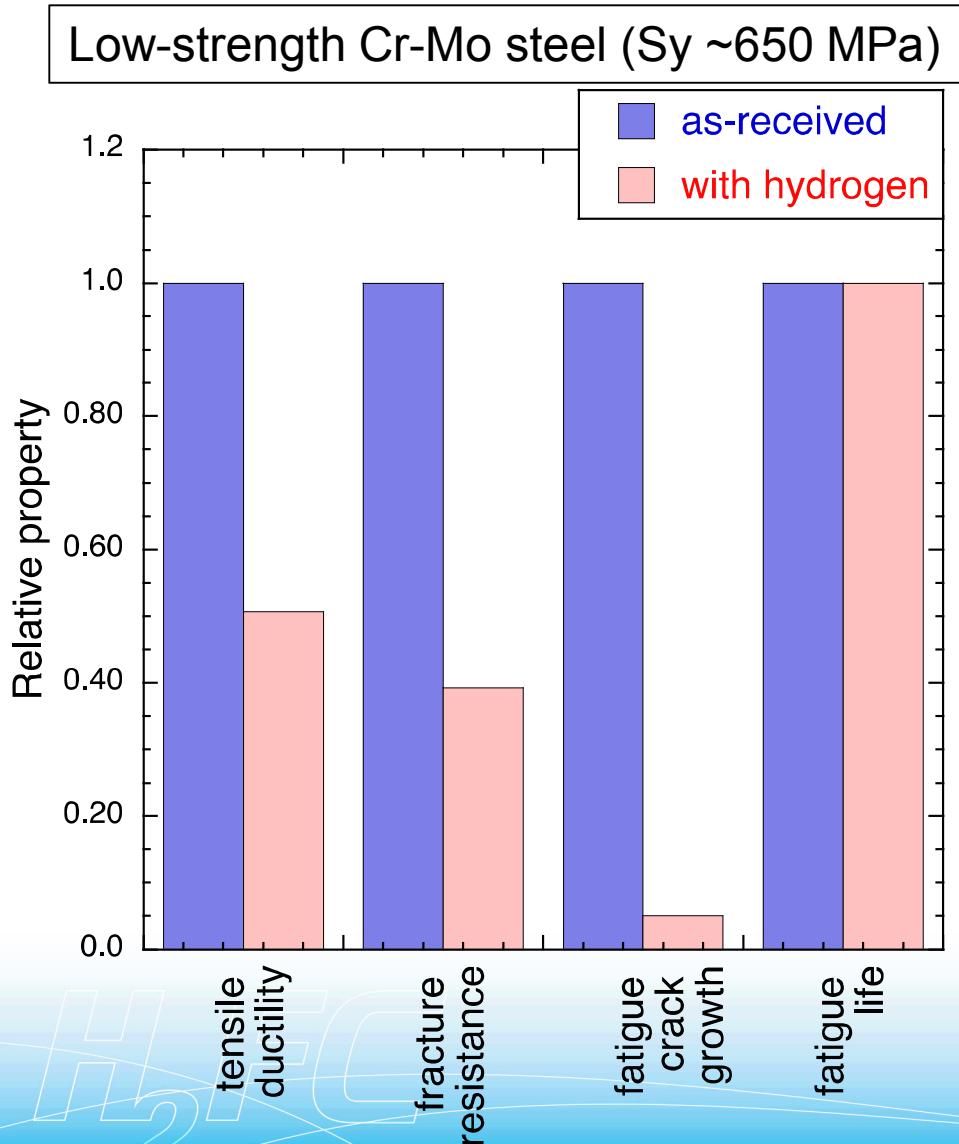
Relative metrics only tell part story



- Each property tells a slightly different story
- Is a relative change of 20% significant? 30%? 50%?
 - Depends on the absolute value
 - Depends on the design requirements

Databases of properties in hydrogen environments are needed

Relative metrics only tell part story



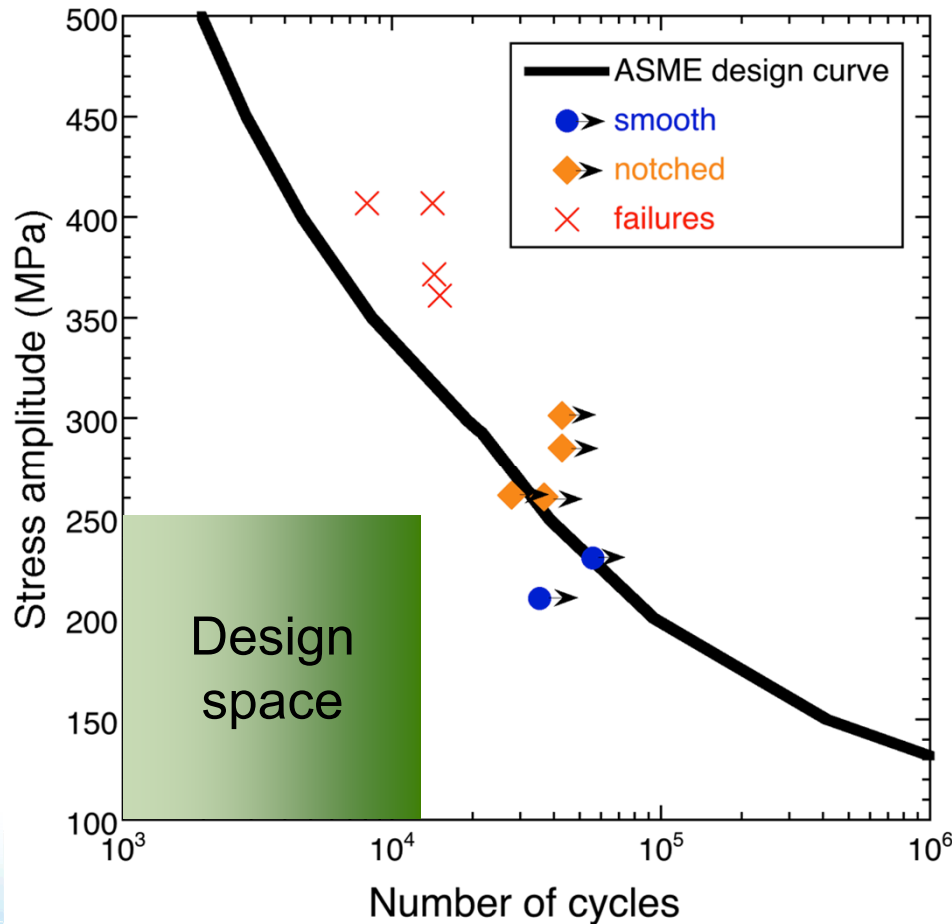
- Which metric is appropriate?

Answer: depends on design criteria

- This steel is used every day to store high-pressure gaseous H₂

Suitability for a given application depends on design criteria **AND** properties in relevant environment

Low-strength Cr-Mo steels are appropriate for very specific conditions



Design criteria

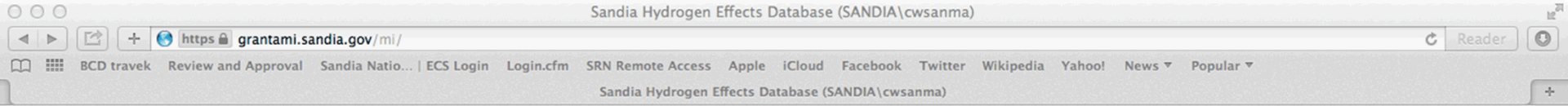
- $S_u < 890$ MPa
- hoop stress $\leq 0.4 S_u$
- Must satisfy LBB

Collectively, these criteria imply:

- Low stresses (ie, fatigue stress amplitude is relatively low)
- Driving forces for cracking are lower than subcritical cracking thresholds

ASME design curve: carbon and low alloy steels with UTS = 620 MPa

Sandia Hydrogen Effects Database




Tools

Contents

Sandia Hydrogen Effects Database

- Materials
 - Materials Pedigree
 - Subset:Materials Pedigree (Default)
 - Metals and Alloys
 - Ferrous
 - Non-ferrous
 - Aluminum
 - Wrought
 - 7000 series (Zn-alloyed)
 - 7475
 - T7351
- Test Data: Tensile
- Test Data: Fatigue Crack Growth
 - Subset:Test Data: FCG (Default)
 - Metals and Alloys
 - Ferrous
 - Alloy Steels
 - Carbon Steels
 - Non-ferrous
 - Aluminum
 - Wrought
 - 7000 series (Zn-alloyed)
- Test Data: Fracture Toughness
 - Subset:Test Data: Fracture Toughness (Default)
 - Metals and Alloys
 - Ferrous
 - Alloy Steels
 - Carbon Steels
 - Non-ferrous
 - Data Citation

Sandia Hydrogen Effects Database



Home Map Tutorials

The Sandia Hydrogen Effects Database is a pilot replacement of **The Technical Database for Hydrogen Compatibility of Materials** that will be available through July 2016. It complements the **Technical Reference for Hydrogen Compatibility of Materials**. It is a repository of technical data measured in hydrogen that is meant to be an engineering tool to aid the selection of materials for use in hydrogen.

This database is read-only, but contributions are welcome by emailing **Richard Karnesky**.

To get started, browse the tree in the left-hand pane or search for a material, project or within the whole database using the relevant search box.


To watch the tutorials on basic functionalities of the software, click on the 'Tutorials' tab.

Search for a Material

Search for a Data Citation

Search the entire database

[Link to Database Map](#)



[View Map](#)

Sandia Hydrogen Effects Database

Sandia Hydrogen Effects Database (SANDIA\cwsanma)

https://grantami.sandia.gov/mi/

BCD travel Review and Approval Sandia Natio... | ECS Login Login.cfm SRN Remote Access Apple iCloud Facebook Twitter Wikipedia Yahoo! News Popular

Sandia Hydrogen Effects Database (SANDIA\cwsanma)

GRANTAMi Home Optimize Substitute Substances Reports Quick Search Advanced Search Help Settings

Tools View Tools Units

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 - Carbon Steels
 - Low Carbon Steels
 - Wrought
 - API-5LX
 - X42
 - X60 HIC
 - X80
 - SAN2010
 - LT
 - Air
 - H2-5.5 MPa
 - H2-21 MPa
 - SAN2011
 - SAN2011-30% polygonal f
 - Non-ferrous
 - Test Data: Fracture Toughness
 - Data Citation

Low Carbon Steel, API-5LX, X80, H2-21 MPa, Longitudinal-Transverse (LT)

▼ Specimen Information

| | |
|-----------------------------|------------------------------|
| Form | skelp |
| Specimen orientation | Longitudinal-Transverse (LT) |

▼ Test Conditions

| | |
|----------------------------------|-----------|
| Test Environment Gas | H2-21 MPa |
| Test Environment Pressure | 21 MPa |
| Test Temperature | 23 °C |

▼ da/dn - deltaK Results

da/dn vs. ΔK Hide Graph

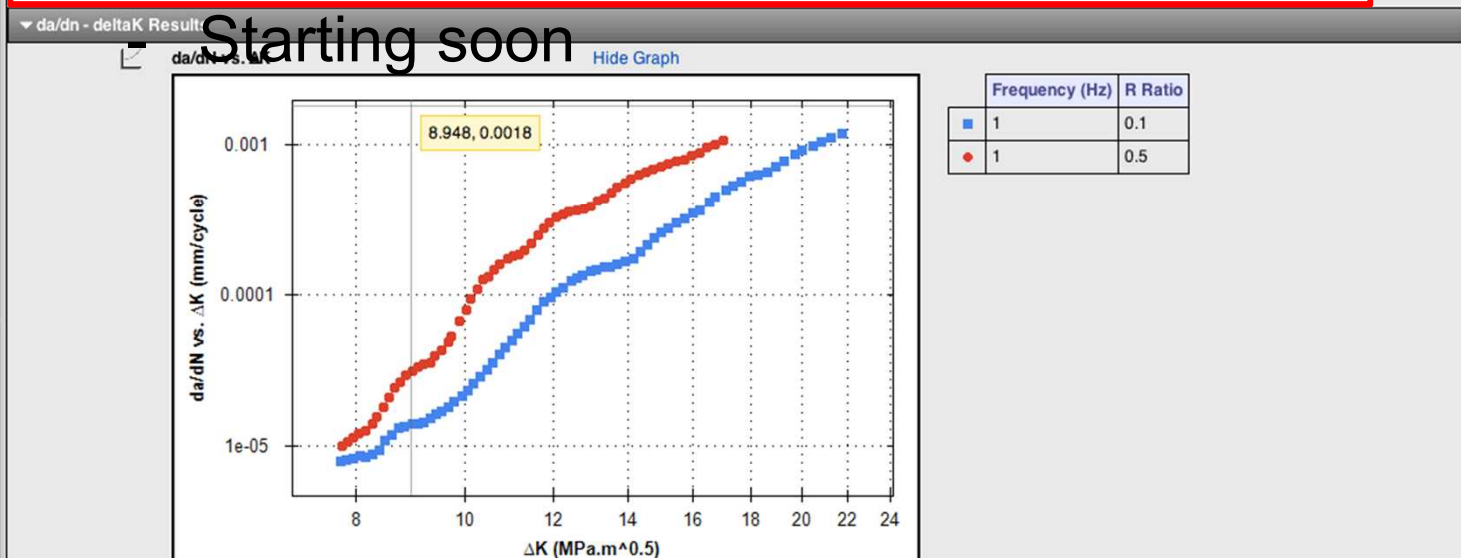
| Frequency (Hz) | R Ratio |
|----------------|---------|
| 1 | 0.1 |
| 1 | 0.5 |

Sandia Hydrogen Effects Database

- Granta is leader in data management tools
- Hydrogen effects database will be made available to Granta-users
- *Trial program*: available as read-only interface through URL to all interested users

The screenshot shows the GrantaMi software interface. The browser address bar displays 'https://grantami.sandia.gov'. The main window title is 'GRANTAMi'. The left sidebar shows a tree view of the database structure under 'Contents'.

- Sandia Hydrogen Effects Database
 - Materials
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Growing demands for low-temperature testing in high-pressure hydrogen system

- BMW and Opel active in coordinating activity to provide data to industry
 - Coordination through SAE

| | |
|----------------------------|--|
| parameter | 3. option: comparison with the new high pressure test equipment and proof of comparability of test results |
| test method | 1 st SSRT & 2 nd Fatigue Life Test |
| Indicator for HEE | RRA |
| test numbers per medium | 3-5 (Depending on Scattering) |
| material (*) | 1.4435 (12,5-12,7% Ni) (***) TBC, PREFERENCE LOW NICKEL |
| heat treatment | solution annealed |
| material condition | uncharged |
| specimen manufacturer | MPA or SANDIA |
| specimen diameter | 4 mm |
| specimen surface condition | precision-turned |
| notch factor | smooth |
| temperature | -65°C (to be verified) |
| H2 pressure | 700 bar |
| H2 quality | 6N |
| strain rate | 5,5e-5 /s (0.1 mm/min) |

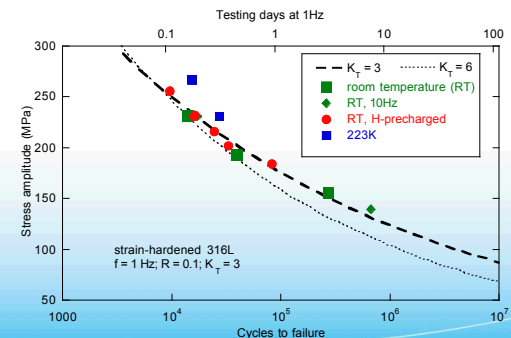
(*) using materials with significant HEE
 (***) AVIF Var. 2 (internal description of MPA)

(***) HEE expected with this testing conditions and first new results with 700 bar H2 generated

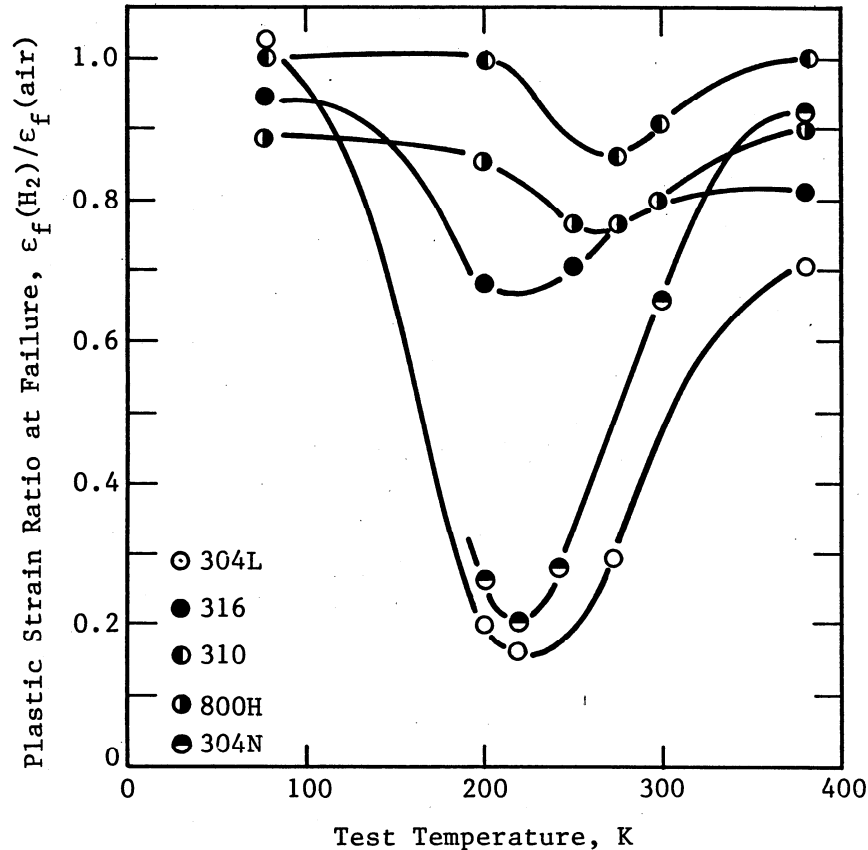
| Phase | Temperature (K) | Hydrogen Pressure (MPa) | Maximum fatigue stress (MPa) | Approximate maximum load (kN) | Number of specimens |
|-------|-----------------|-------------------------|------------------------------|-------------------------------|---------------------|
| 1 | 293 | 10 MPa H2 | Monotonic loading to failure | | 3 |
| | | | 500 | 6.3 | 4 |
| | | | 400 | 5.0 | 4 |
| 2 | 220 | 100 MPa H2 | Monotonic loading to failure | | 3 |
| | | | 500 | 6.3 | 4 |
| | | | 400 | 5.0 | 4 |

- IPHE round robin testing to establish fatigue testing methods
 - Draft test plan has been developed

- H2 Storage project on materials for BOP
 - Fatigue test matrix established with industry partners



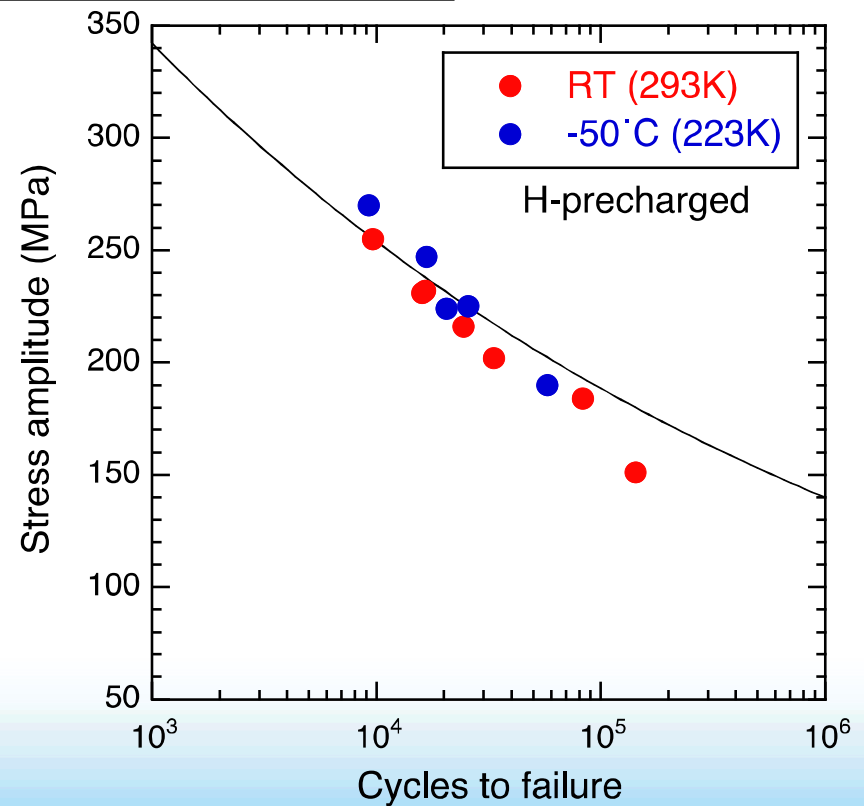
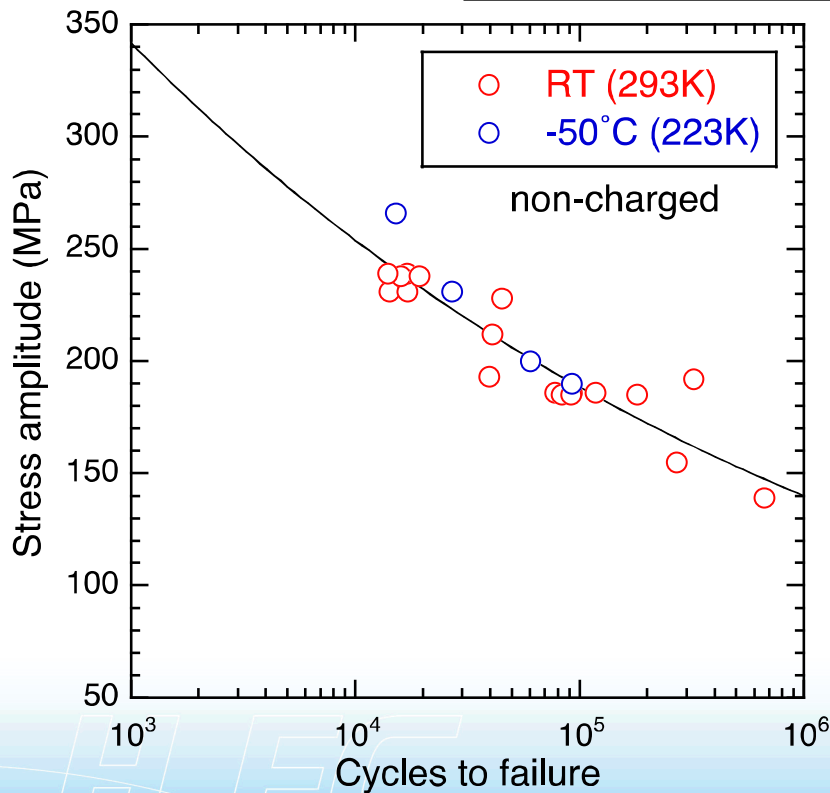
Hydrogen compatibility of technologically-relevant stainless steels depends on temperature



Capabilities needed for materials testing (particularly fatigue) in high-pressure hydrogen gas over range of temperature

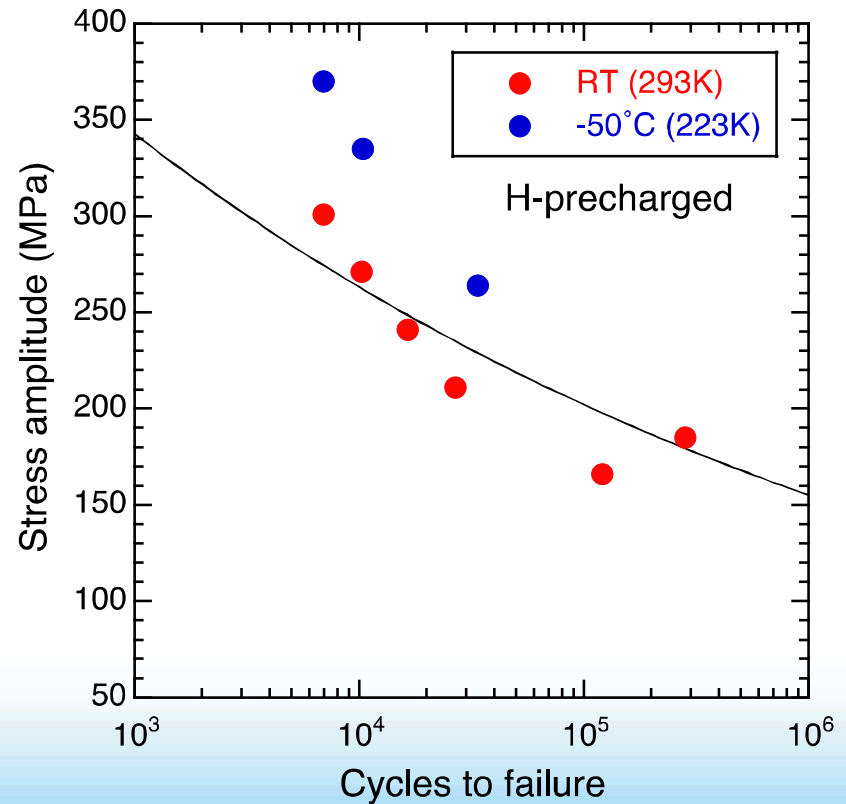
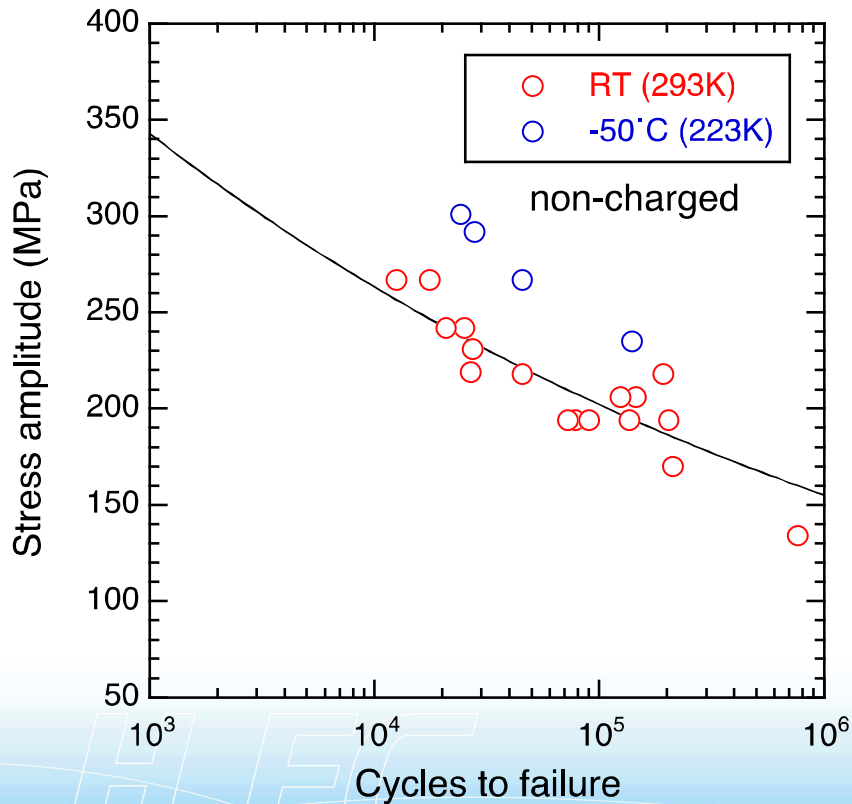
Fatigue life measurements at low temperature indicate tensile trends cannot be extrapolated to design relevant parameters

Strain-hardened type 316L (12wt% Ni)

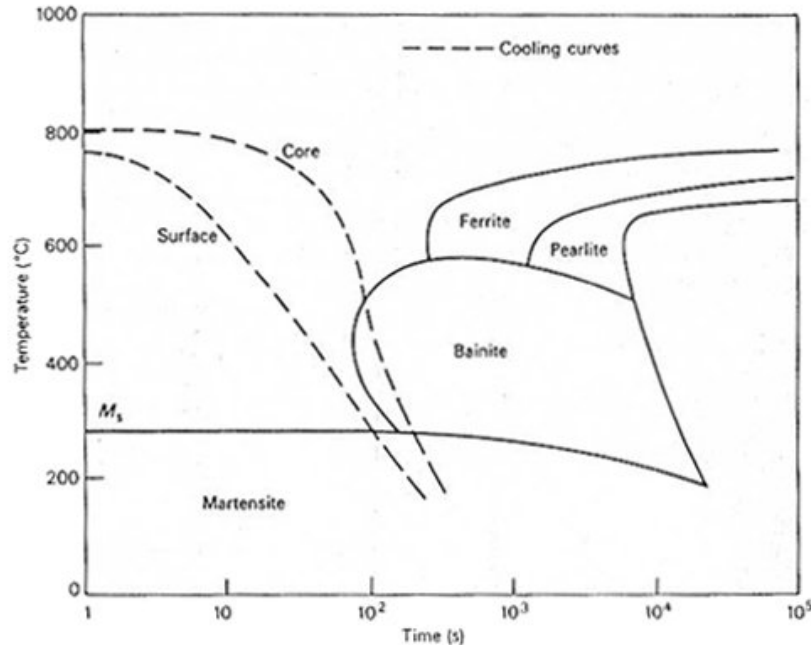


Fatigue life measurements at low temperature indicate tensile trends cannot be extrapolated to design relevant parameters

Annealed XM-11 austenitic stainless steel (21Cr-6Ni-9Mn)



Multiple industry stakeholders interested in qualifying high-hardenability steels for H₂ vessels

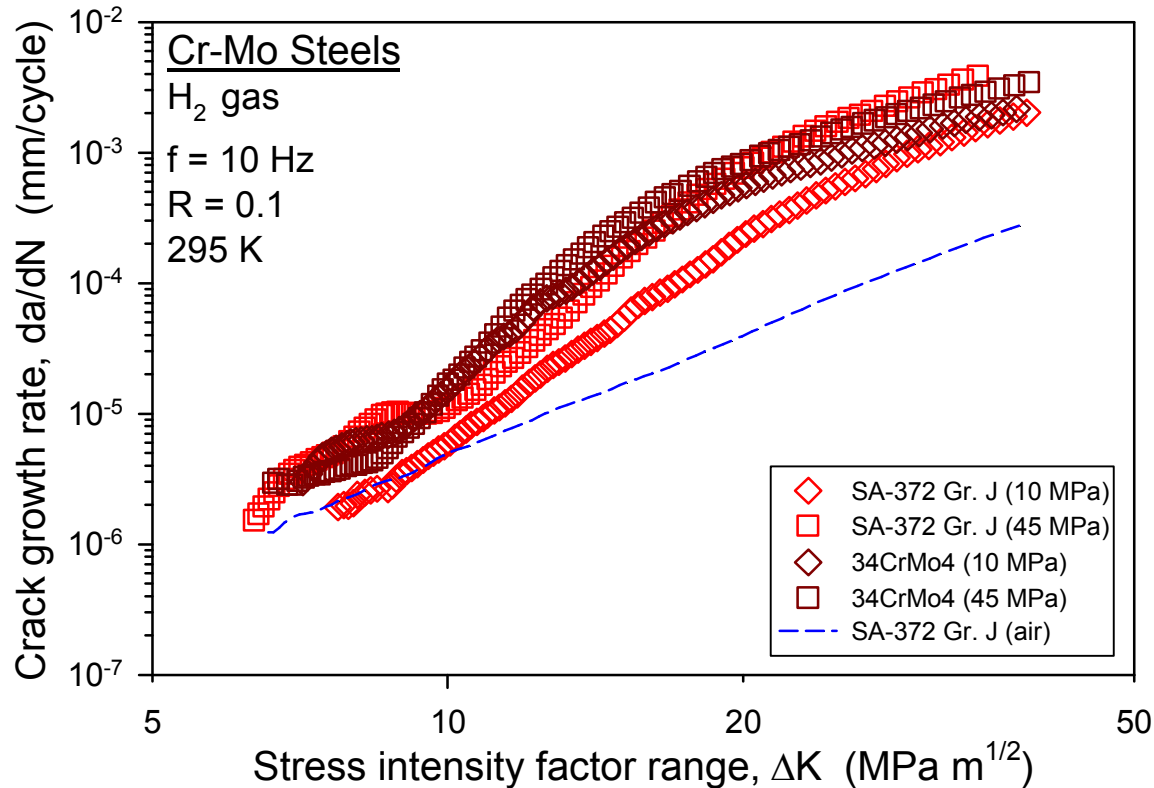


- Need to quench both surface and core of steel vessel wall to 100% martensite
- Phase transformation (e.g., bainite) start extended to longer times for “high hardenability” steels

- Hardenability of current Cr-Mo steels in H₂ pressure vessels (e.g., SA-372 Gr. J) limits wall thickness to ~38 mm (1.5 in)
- Higher-hardenability steels favorable for high-pressure H₂ vessels
 - Reduce heat treatment variability in thick-walled steel vessels
 - Reliably increased wall thickness allows design of steel vessels with increased inner diameter (greater volume)
- Assembling international consortium of industry stakeholders to characterize H₂ compatibility of high-hardenability steels
 - Fatigue crack growth and fracture threshold testing of high-hardenability steels in Hydrogen Effects on Materials Lab at SNL

Ni-Cr-Mo steels display higher hardenability than Cr-Mo steels

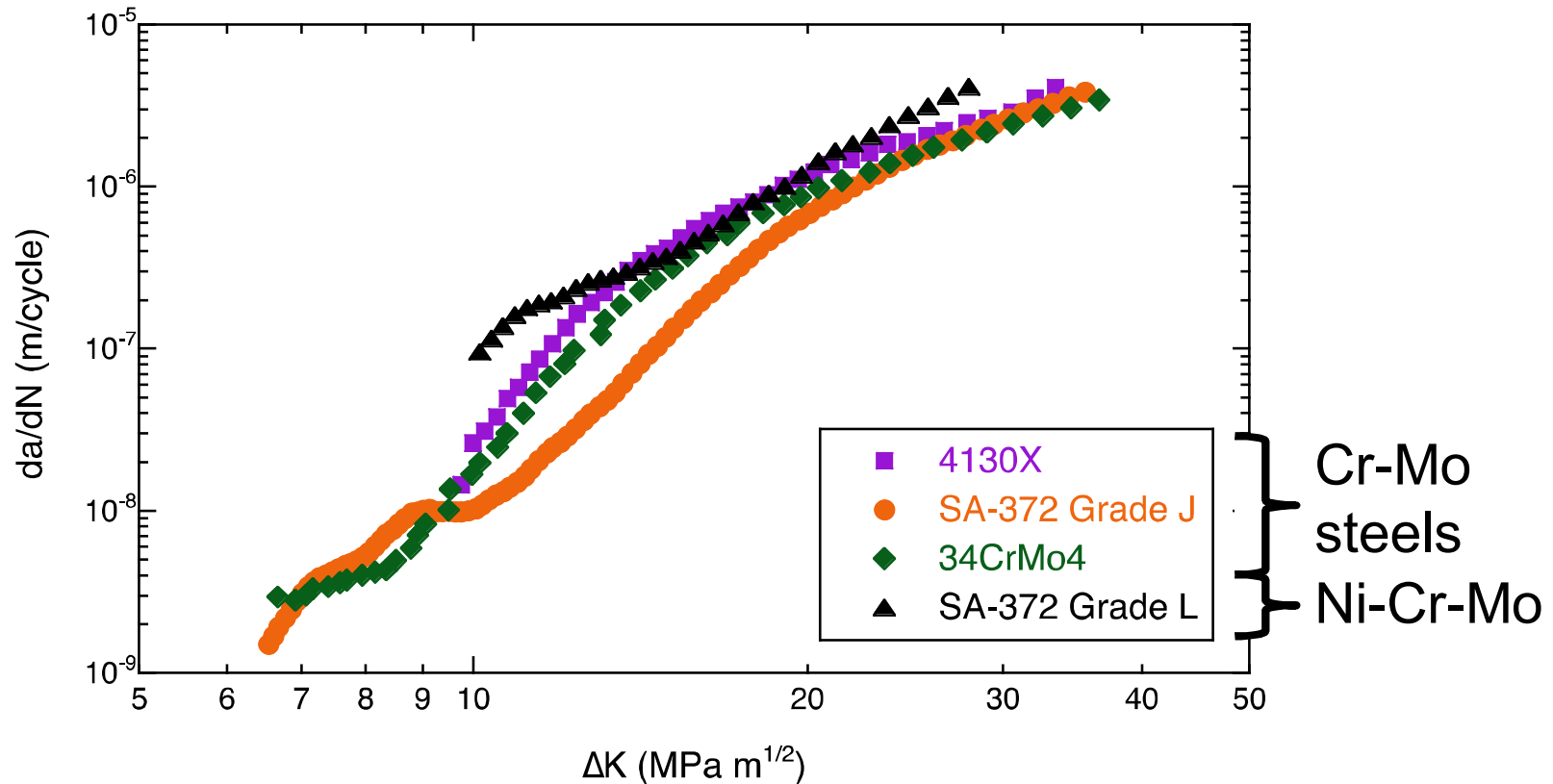
Fatigue crack growth rates for Cr-Mo steels



Fatigue crack growth rates in H₂

- approach rates in air at lower ΔK
- are an order of magnitude (or more) greater at high ΔK

Fatigue crack growth rates for Ni-Cr-Mo steels



Preliminary results, differences associated with pressure and frequency

- 4130X and Gr. L tested at 1Hz, others at 10 Hz
- Gr. L tested in hydrogen at 106 MPa, others at 45 MPa

Summary

- Materials selection requires assessment of hydrogen-affected properties relevant to the design method being utilized
 - Tensile behavior is not sufficient for design of components
 - Relative properties are generally not adequate
- Databases/handbooks of properties measured in hydrogen environments are needed for designers
- Materials performance at low-temperature must be considered for some applications
 - Unlike tensile properties, fatigue performance will not always be limited by low temperature condition
- International consortium of industrial stakeholders for testing of high-hardenability pressure vessel steels (Ni-Cr-Mo steels)
 - Preliminary data suggest similar performance as Cr-Mo steels