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Fatigue-based materials selection and qualification

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Study Group on Materials Testing and Qualification for Hydrogen Service
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General standards for qualifying materials for hydrogen service

- ***CSA CHMC1 revision*** (CSA Group)
  - Methodology using *fatigue properties measured in gaseous hydrogen*
  - *Not specific* to application or component
  - Design approach is not specified (provides flexibility)
  - One testing option provides hydrogen safety factor
    - Multiplicative factor incorporated in design safety factors
  - Other testing options require properties measured in hydrogen be used in design
  - Rules for qualification of materials specifications
    - Requires comprehensive definition of material
    - Bounds qualification activity

CSA CHMC1

Test method for evaluating material compatibility in compressed hydrogen applications – Metals

First edition *– published 2012*: definition of procedures for mechanical property evaluation in gaseous hydrogen

Revised document *– published 2014*: methods for materials qualification

- Screening tests to determine compatibility without special design requirements for hydrogen service
  - Acceptable for aluminum alloys and austenitic stainless steels
- Safety Factor Multiplier Method
  - Fatigue testing determine additional safety factor for hydrogen for wide range of cycle life
- Design qualification method
  - Allows other documented fatigue design methods (eg ASME BPVC) with appropriate testing in gaseous hydrogen

CSA CHMC1 - 2012

First edition *– published 2012*: definition of procedures for mechanical property evaluation in gaseous hydrogen

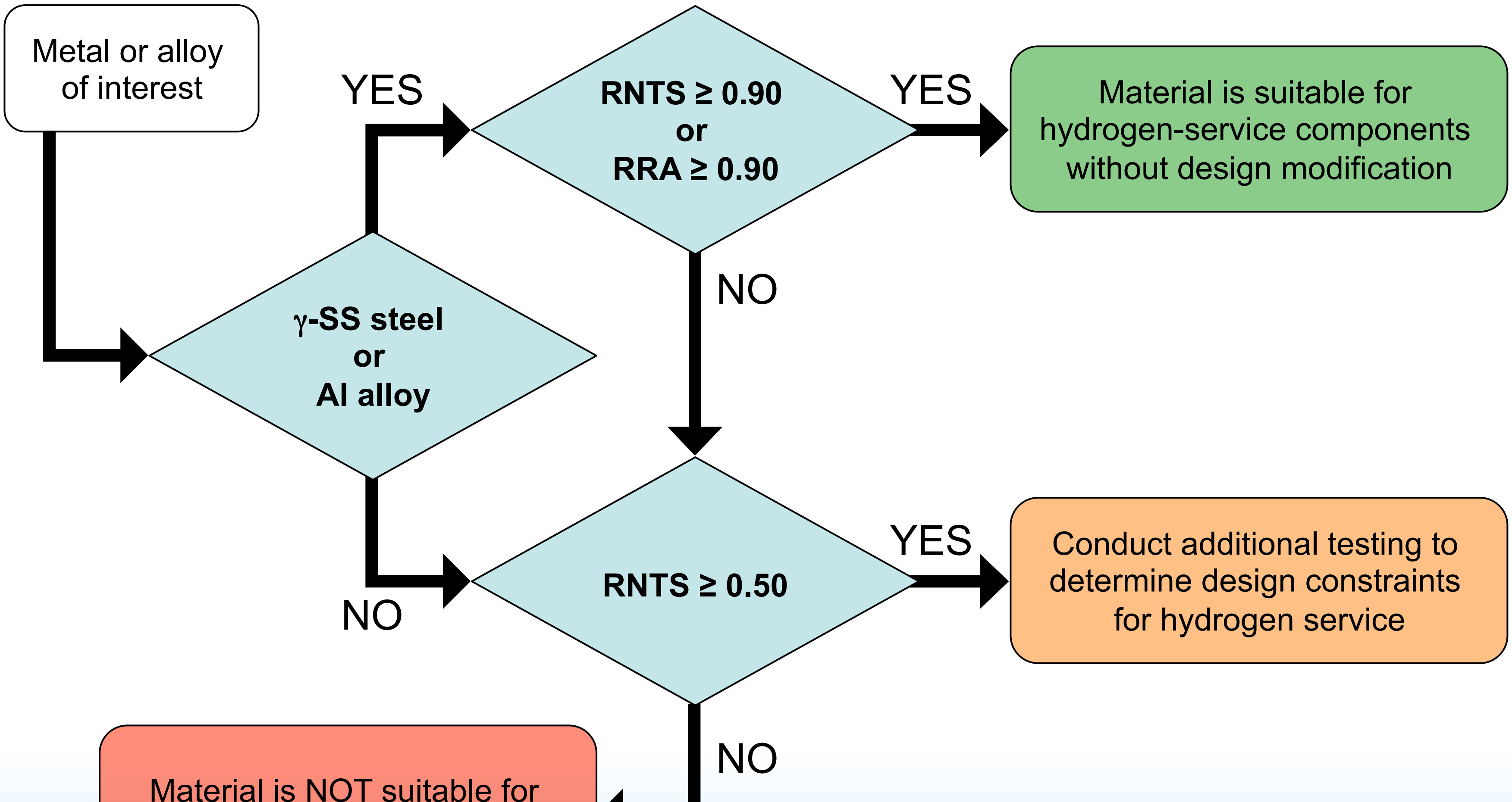
- **Part 1: Environment and equipment**
  - Hydrogen gas purity (includes requirements for measuring purity after test)
  - Instrumentation
  - Temperature
  - Pressure

- **Part 2: Test methods**

  (Includes definition of testing parameters such as rate/frequency, specimen geometry, etc)
  - Slow strain rate tensile testing
  - Hydrogen-assisted cracking threshold stress intensity (K_{IH} and J_{IH})
  - Fatigue crack growth rate
  - Fatigue life tests (S-N fatigue methods)

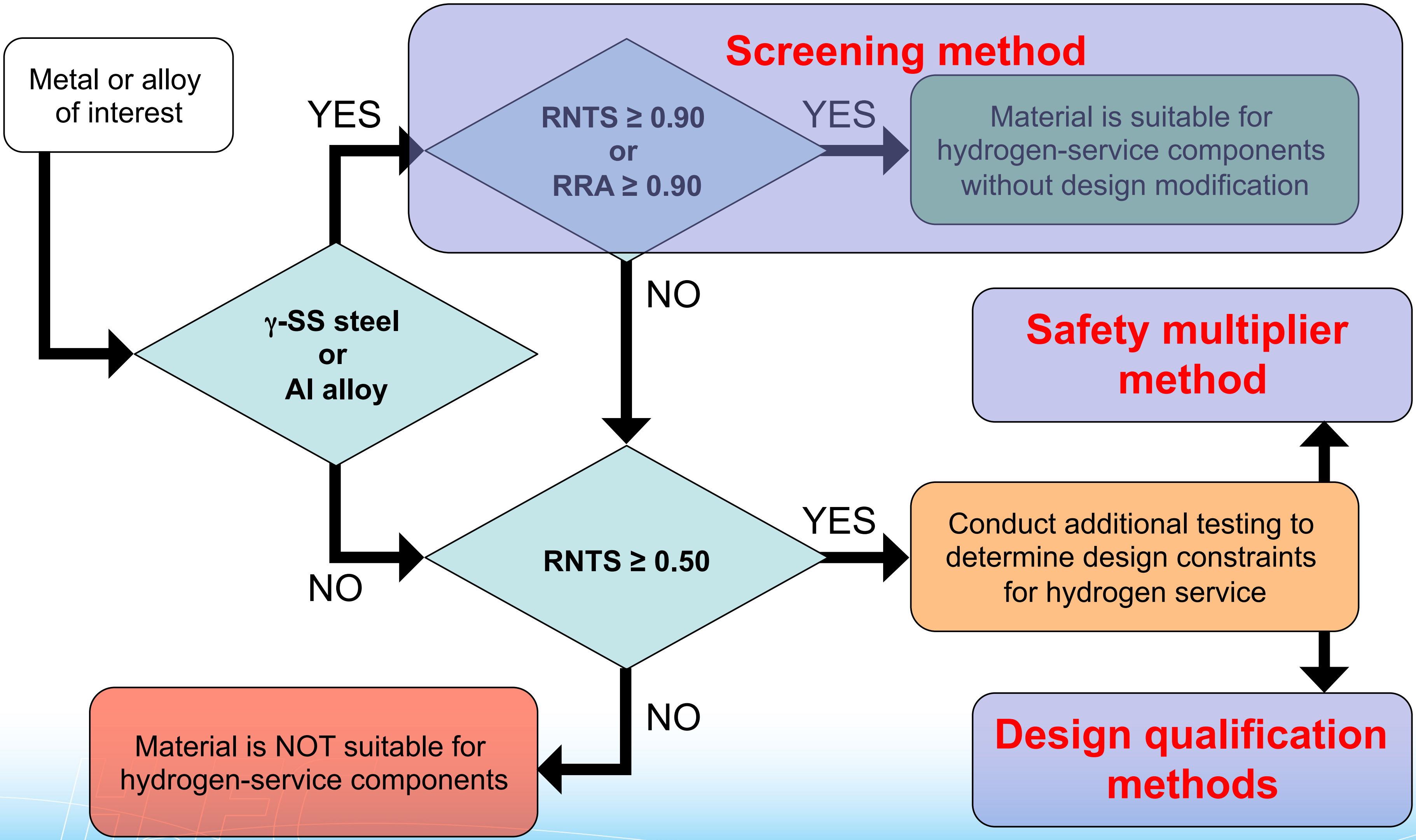
CSA CHMC1 - 2014

Revised document *– addition:* **Part 3: Material qualification**



RNTS = Notch Tensile Strength Ratio
RRA = Reduction of Area Ratio (smooth tensile)

CSA CHMC1 – 2014
Three options for material qualification



CSA CHMC1: Screening Method

- Screening method intended to facilitate certification of commonly-accepted materials with *minimum* testing in gaseous hydrogen environments
  - 316/316L alloys
  - 6061 aluminum alloys
  - Other austenitic stainless steels and aluminum alloys with equivalent behavior in dry gaseous hydrogen (e.g., type 310 and 317 stainless, 2000- and 7000-series aluminum alloys)
- Screening method is *not intended* to establish compatibility with applied loads or external environments (e.g., warm humid air)

CSA CHMC1: Safety Factor Multiplier Method

Notch Tensile Fatigue Tests

- Measure Wohler curves and determine stress amplitude (S) for number of cycles to failure (N) of 10^3, 10^4 and 10^5 in hydrogen and reference environments
  - $SF_3 = S3_R / S3_H$
  - $SF_4 = S4_R / S4_H$
  - $SF_5 = S5_R / S5_H$
  - $SF_0 = NTS_R / NTS_H$ (tensile test)
- Hydrogen safety factor: $SF_H = \max(SF_0, SF_3, SF_4, SF_5)$

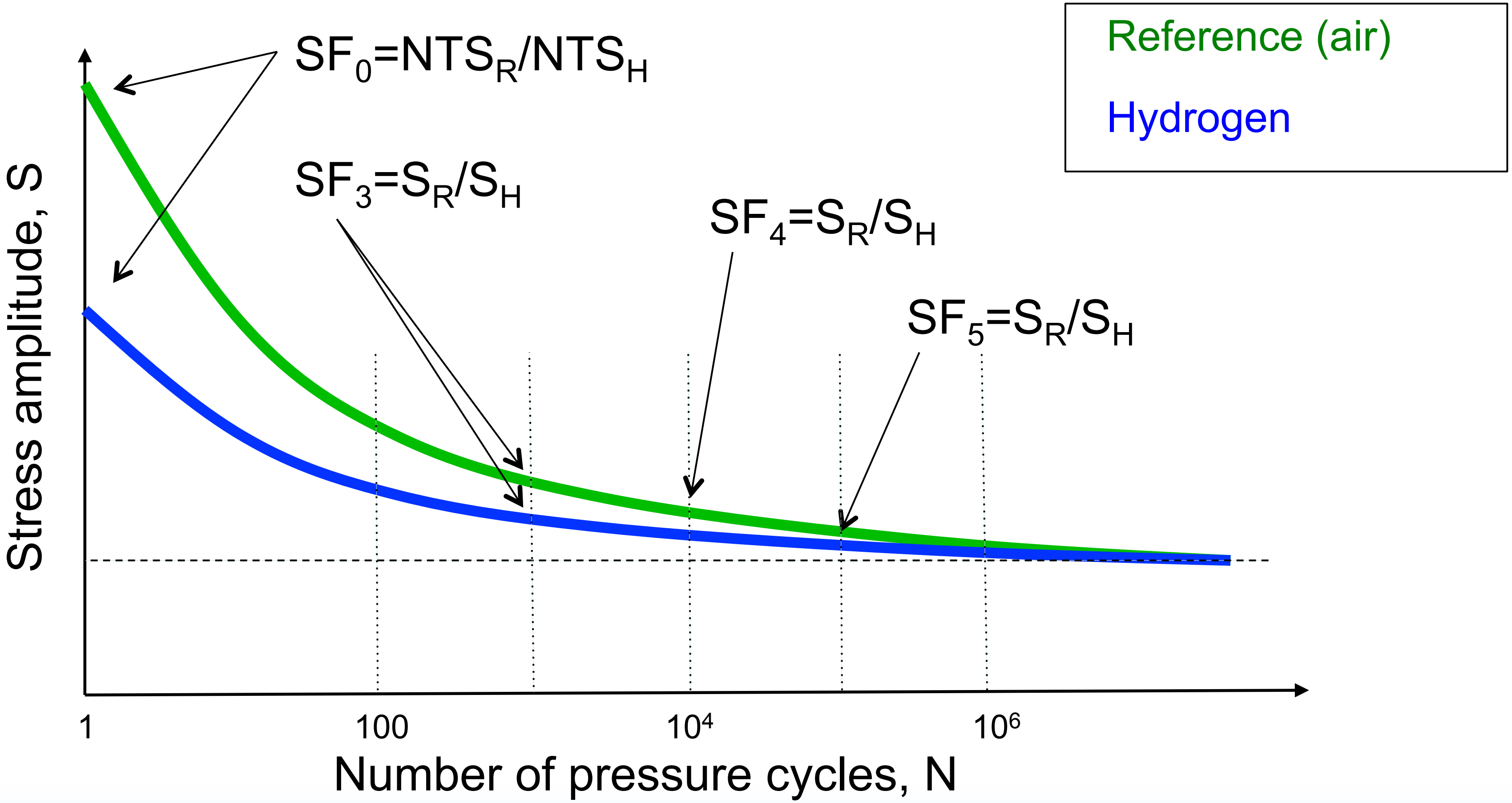
S3 = stress amplitude for failure at $N = 10^3$
S4 = stress amplitude for failure at $N = 10^4$
S5 = stress amplitude for failure at $N = 10^5$

$_R$ = reference environment
$_H$ = hydrogen environment

Safety factor for design ➔

$$SF_{design} = SF_{component} \times SF_H$$

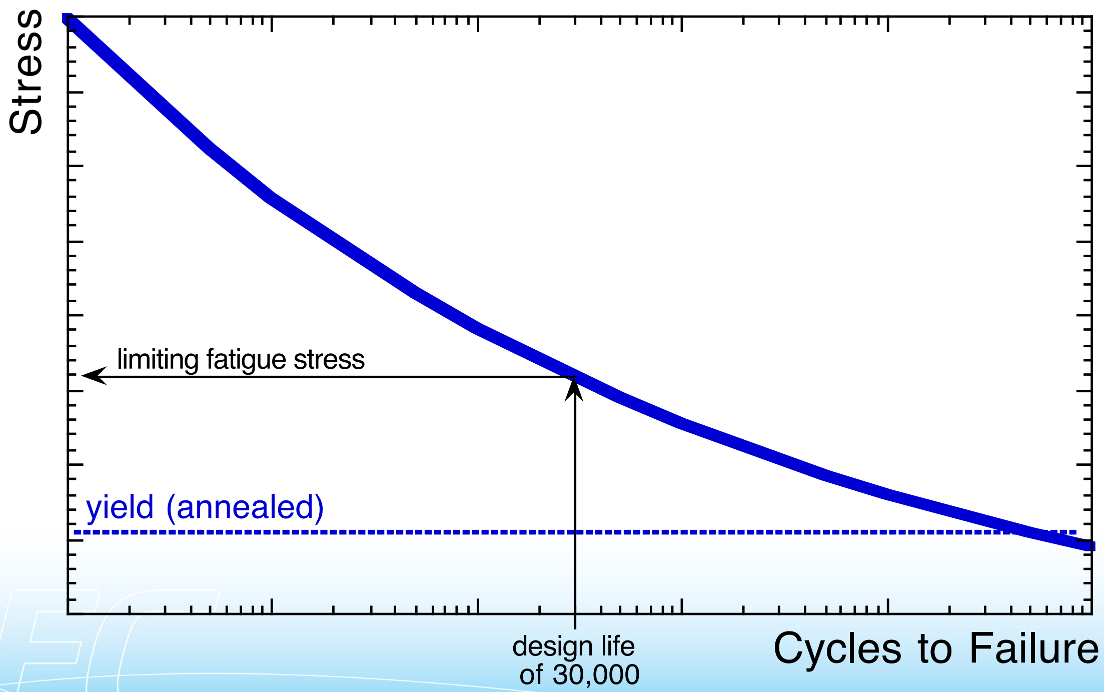
Schematic representation of Safety Factor Multiplier Method



In this example: $SF_H = SF_0 > SF_3 > SF_4 > SF_5$

Technical basis for additional modification to stress-based fatigue qualification

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



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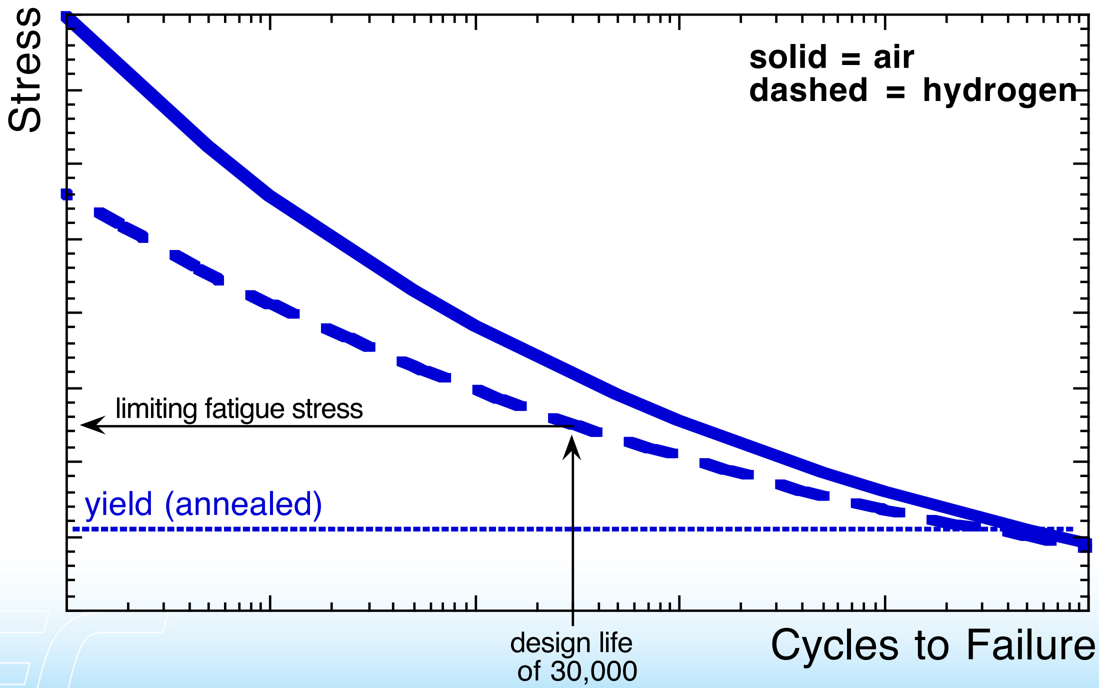
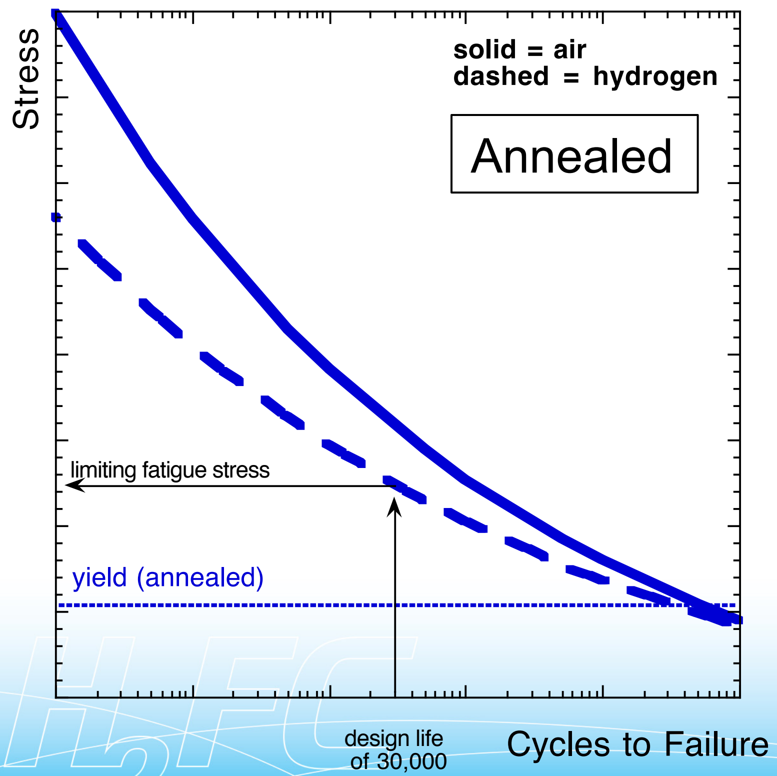
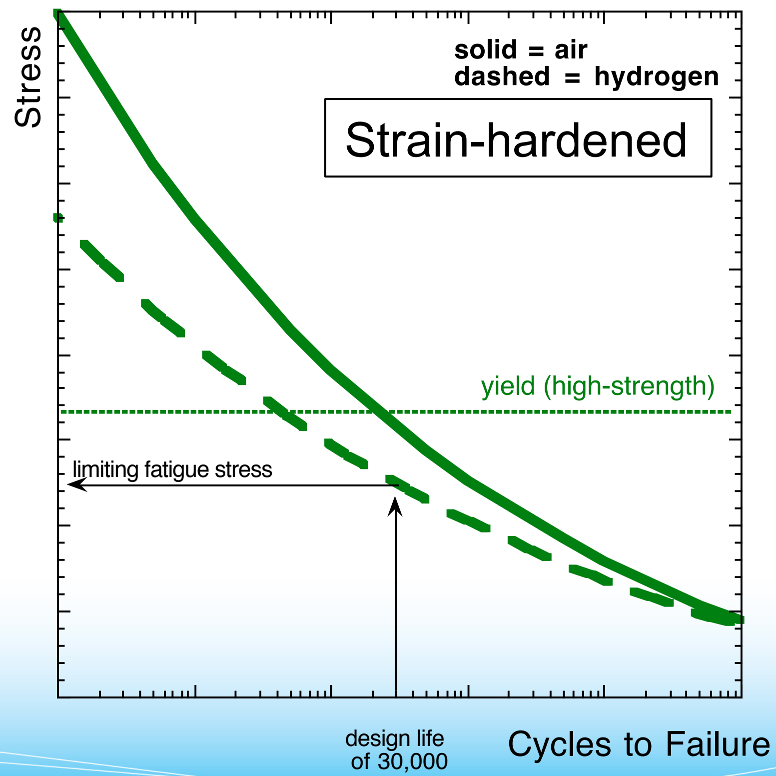


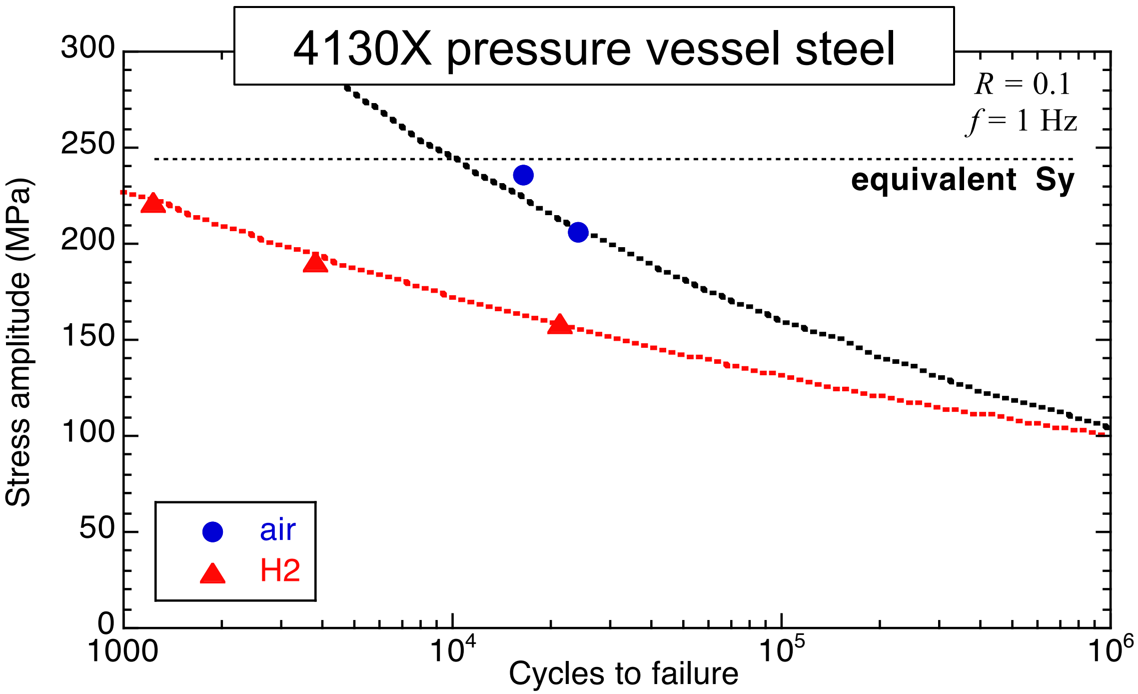
How do we take advantage intrinsic performance?

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

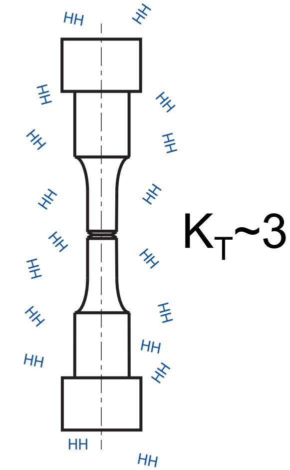




Preliminary results: pressure vessel steel

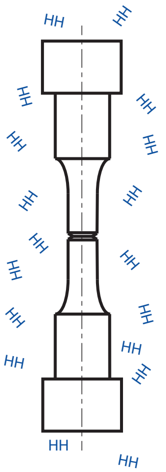


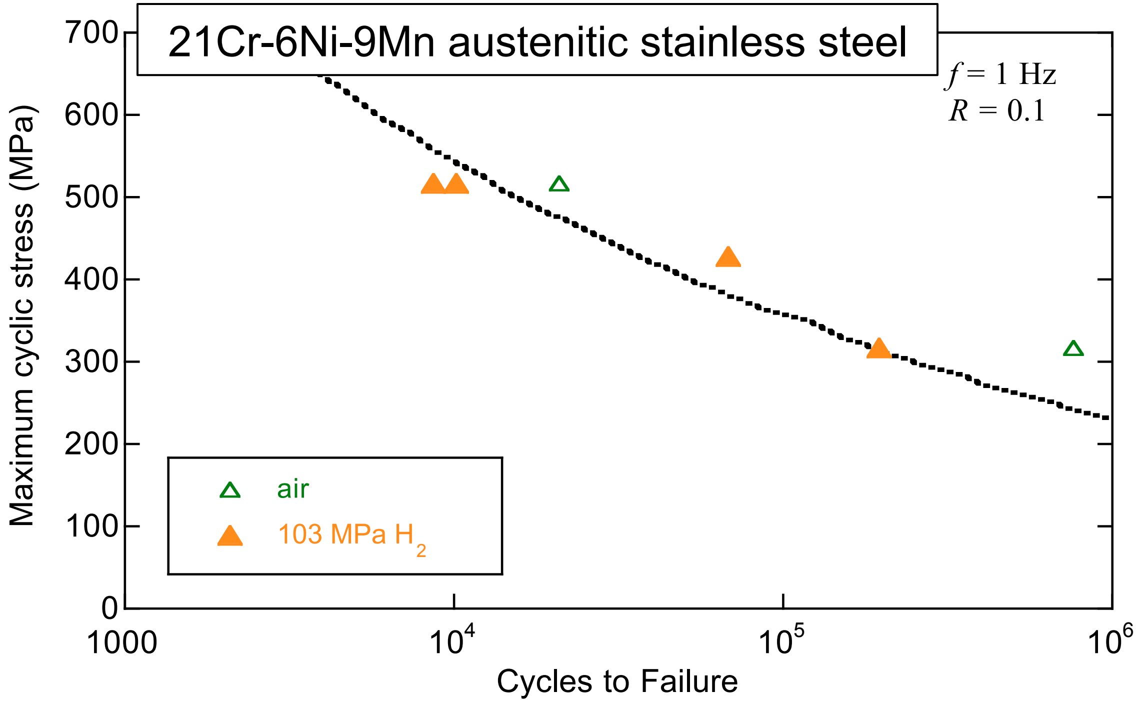
Tension-tension fatigue of standard notched tensile specimen (after ASTM G142)



- 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
- Test results serve as a means to evaluate one of the testing options in the new CSA CHMC1 standard

Preliminary results: high-strength austenitic stainless steel

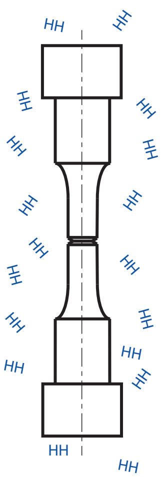


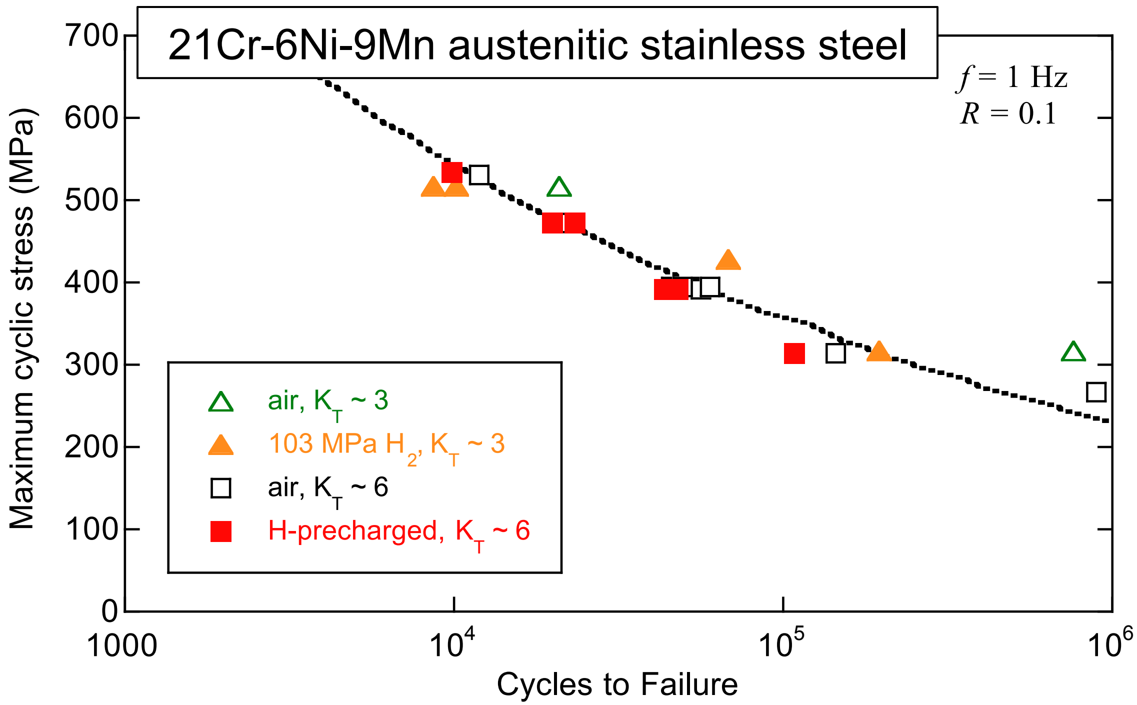


- Strength of annealed 21Cr-6Ni-9Mn is >2x strength of annealed type 316L
- Cost of 21Cr-6Ni-9Mn bar material is ~80% of type 316L bar

- 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

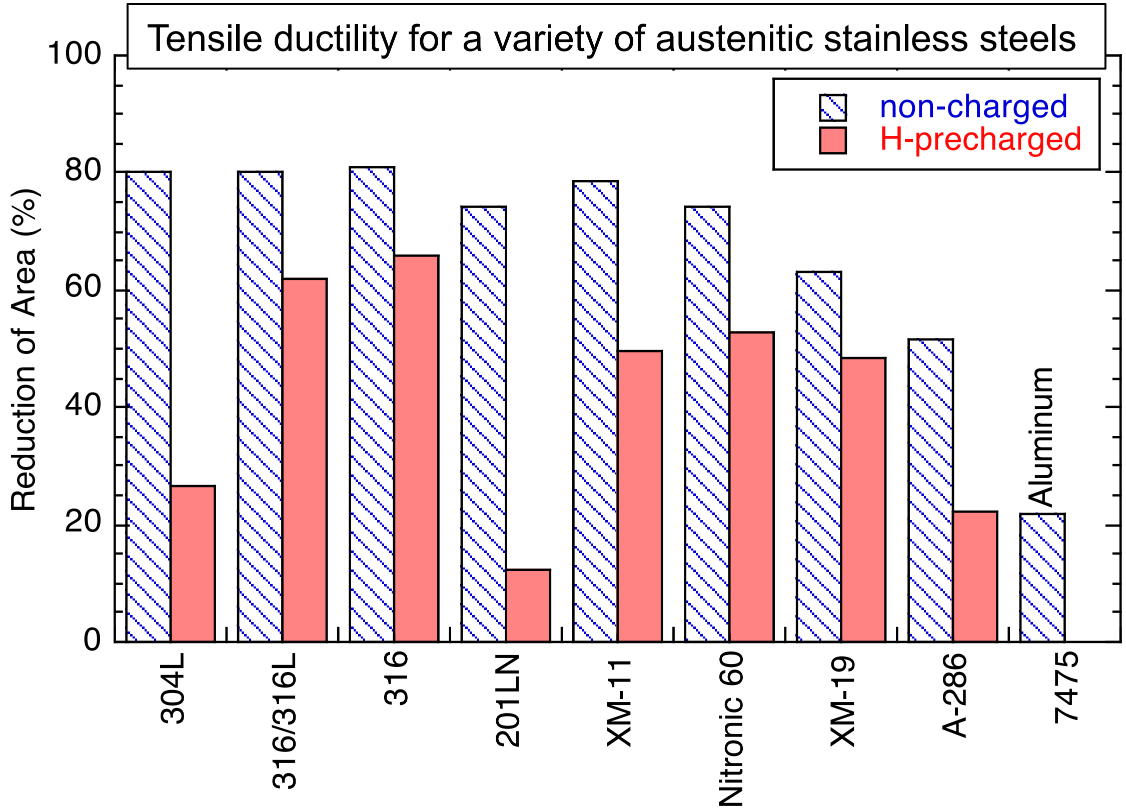




- Strength of annealed 21Cr-6Ni-9Mn is >2x strength of annealed type 316L
- Cost of 21Cr-6Ni-9Mn bar material is ~80% of type 316L bar

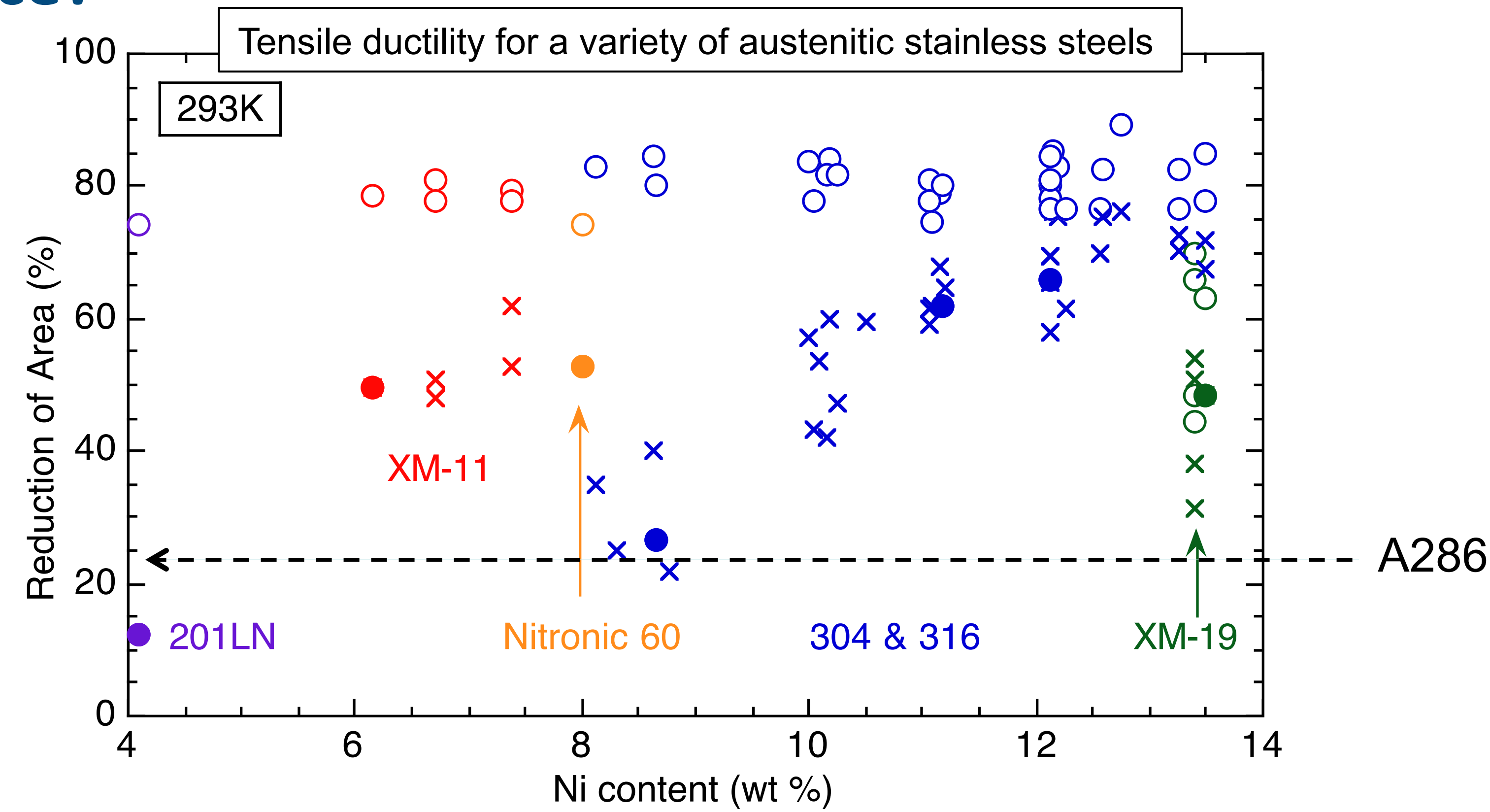
- Available data is incomplete (inconsistency of notch acuity and environments)
- Initial results suggest some correlation between internal and external H
- Data at low temperature is needed

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

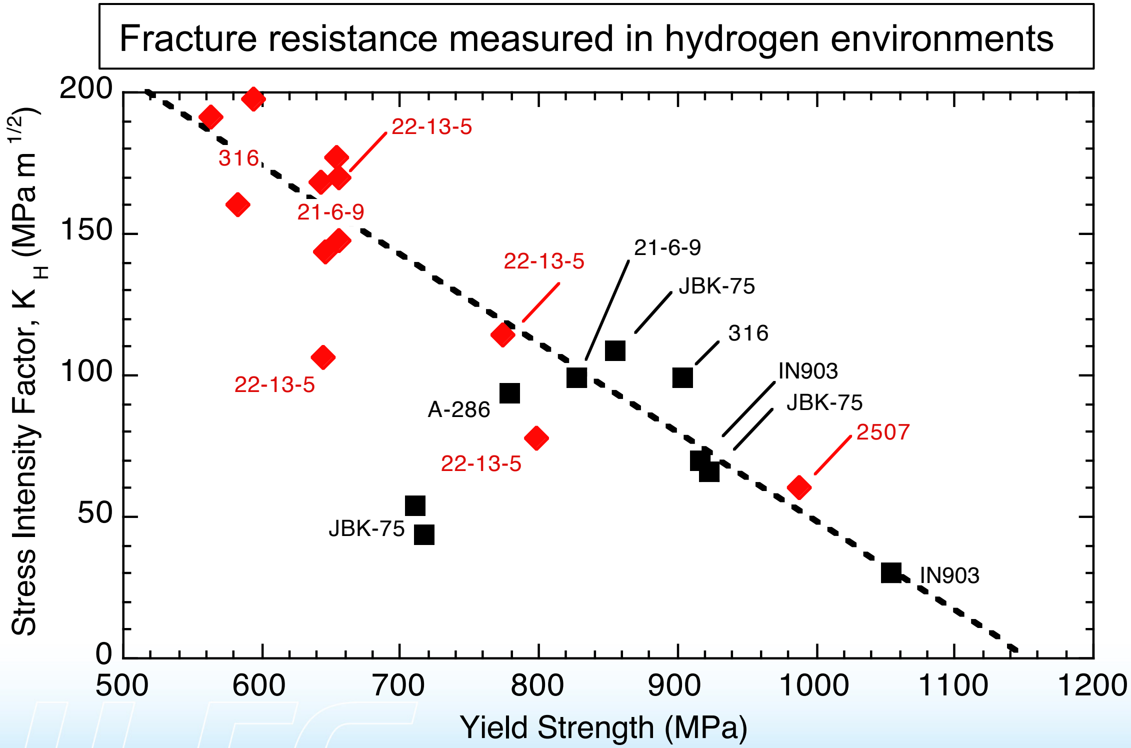
Why is A-286 considered appropriate for hydrogen service?



- Tensile ductility is not used directly in design
- If there is no design criteria associated with tensile ductility, what tensile ductility is necessary for pressure applications?

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