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

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Codes and Standards Tech Team meeting
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U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration
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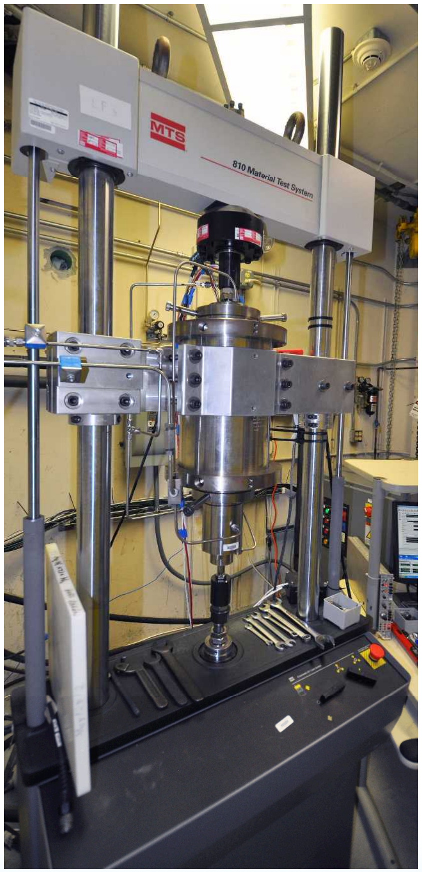
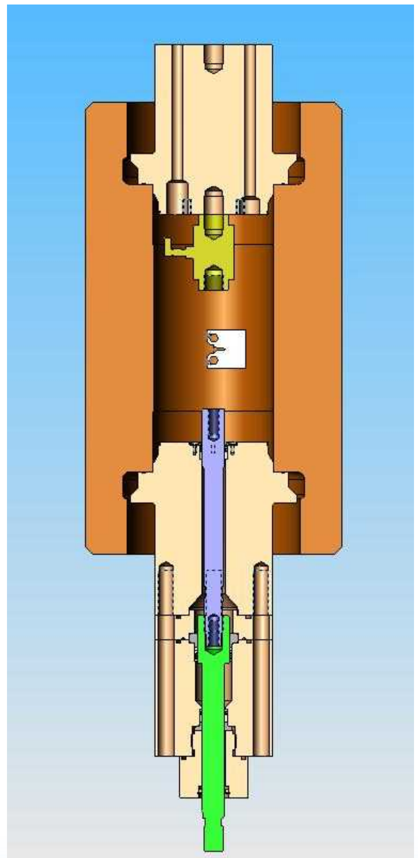
SNL features specialized systems for testing materials in high-pressure hydrogen gas

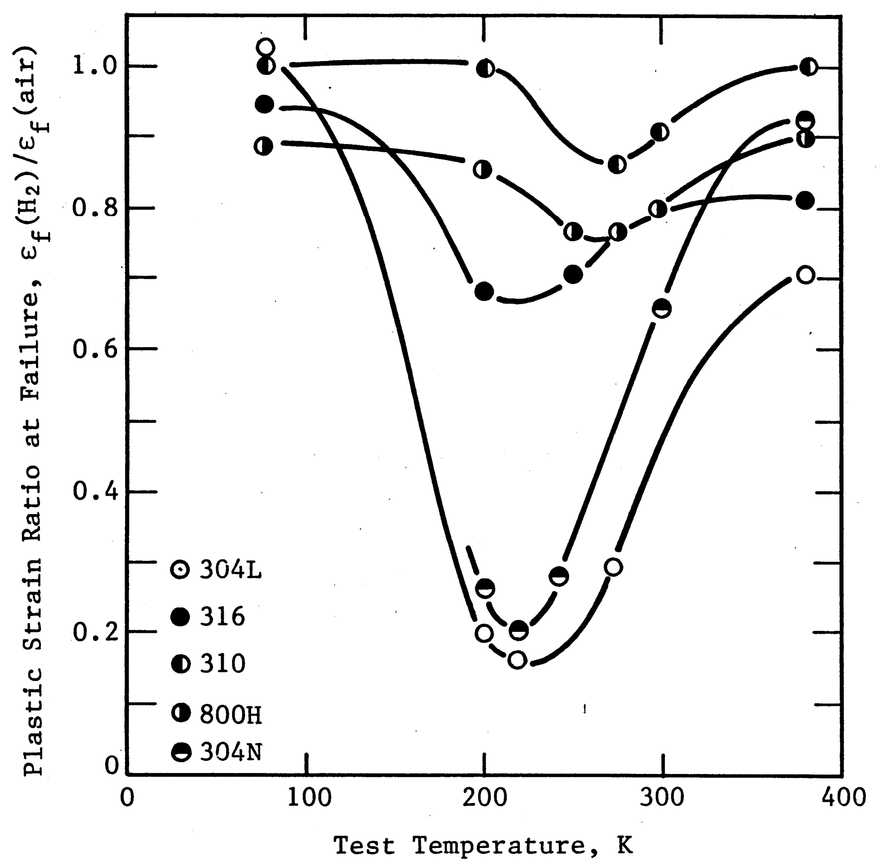




	Fatigue test specifications
Pressure	3-138 MPa
Temperature	21 ºC
Force	22 kN
Displacement	5 mm
Test control	0.001-10 Hz

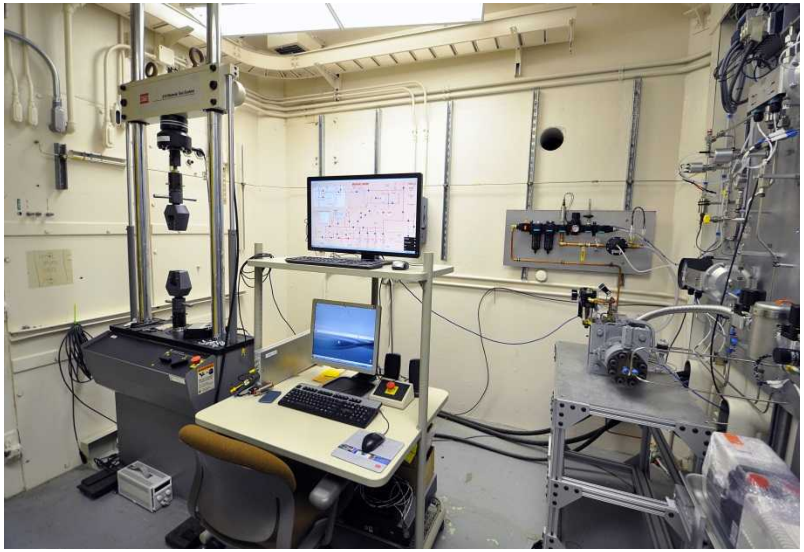
Current system for fatigue testing in hydrogen gas only operates at room temperature

Hydrogen compatibility of technology-critical stainless steels depends on temperature



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

Development of variable-temperature testing in high-pressure hydrogen: 2 of 3 subsystems installed



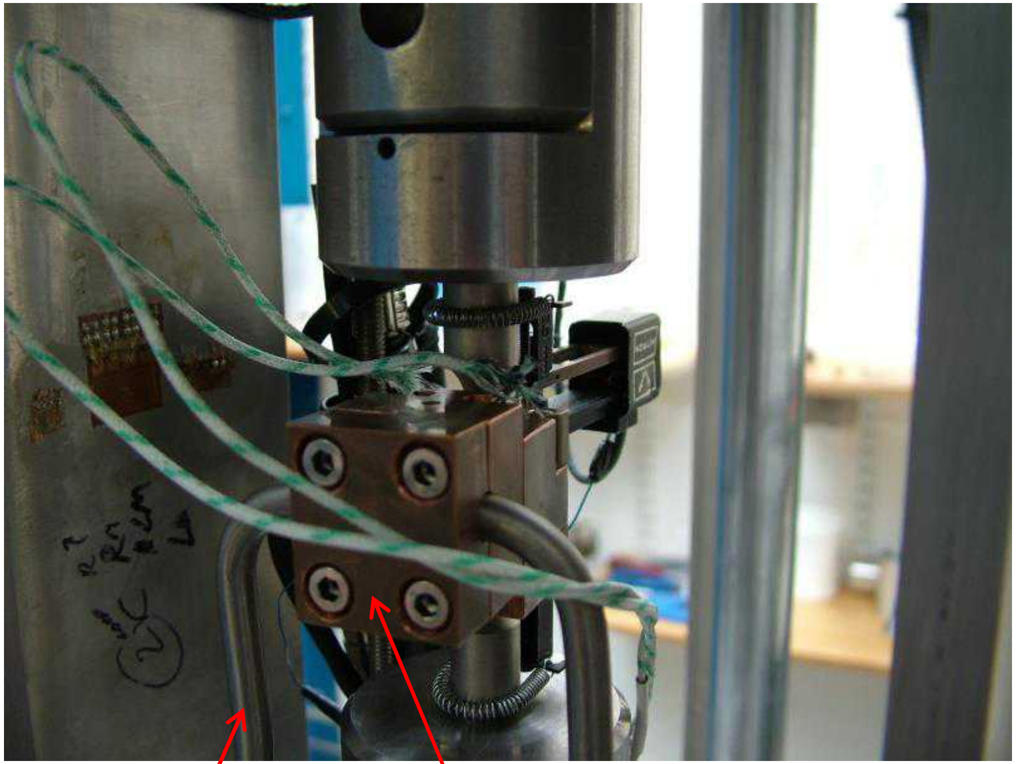
- Procured test frame, test controller, hydraulic pump, testing software

- Gas handling manifold designed and installed
- Software for manifold automation developed

- ***Remaining subsystem: pressure vessel with variable-temperature function***
  - ***External vs. internal cooling mechanism?***

Advancing Materials Testing in H_2 Gas meeting (April 2013) provided idea for internal cooling mechanism

TWI Ltd, UK



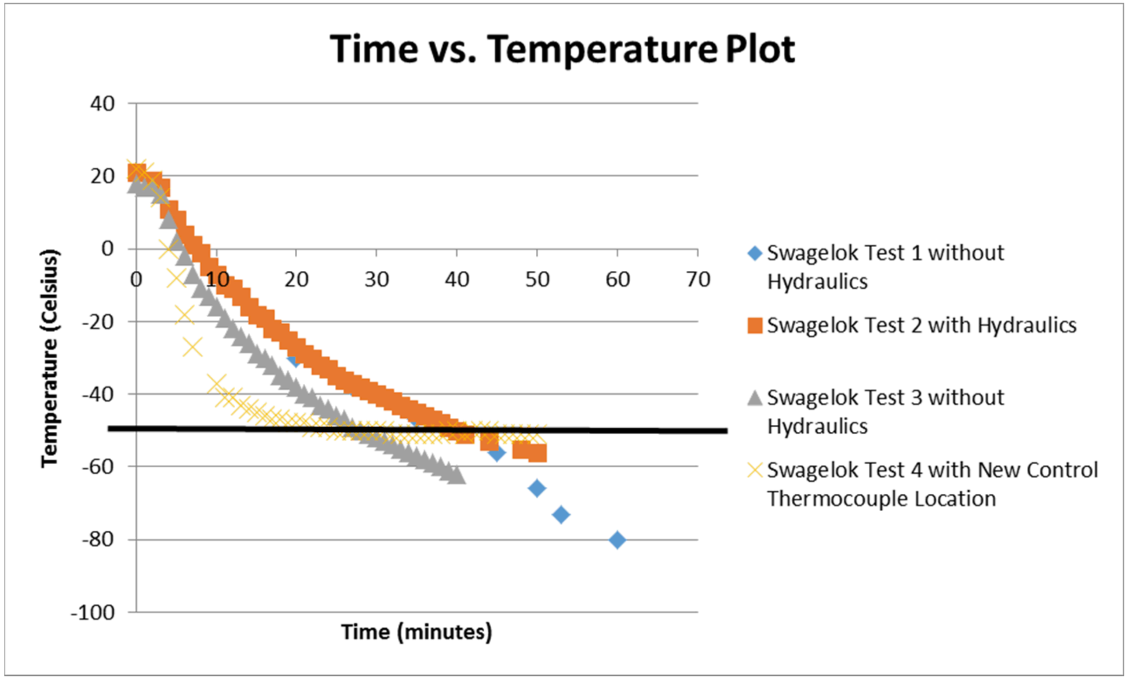
cooling block

cooling coil

Final steps in designing and procuring pressure vessel with internal cooling mechanism

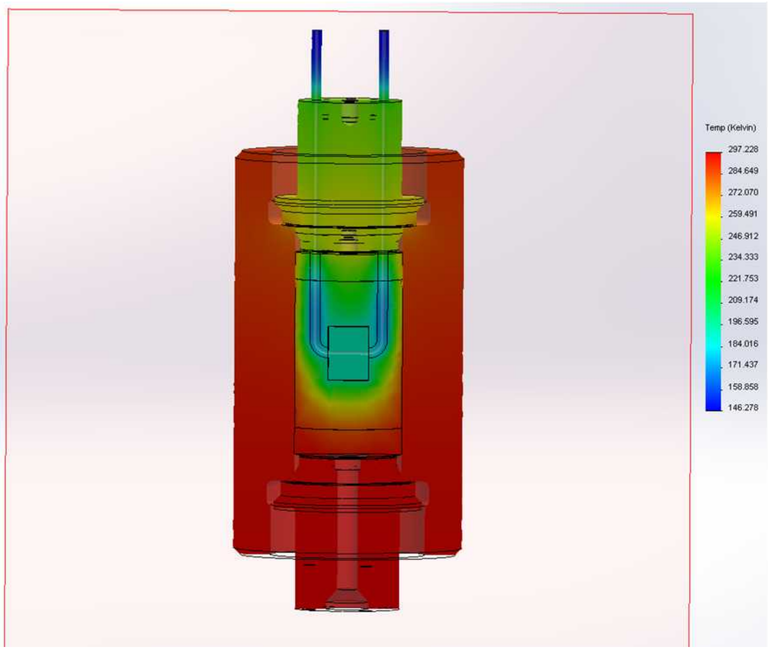
- Refine design details of internal cooling hardware
  - Determine internal diameter of cooling tube through protoyping
- Conduct thermal analysis of concept pressure vessel with internal cooling mechanism (Z. Harris, Boise State University)
  - Develop modeling tool for determining temperature distribution in pressure vessel
- Develop and issue detailed pressure vessel design specifications (including internal cooling mechanism) for RFQs

Internal cooling mechanism prototyping yielded specifications for system



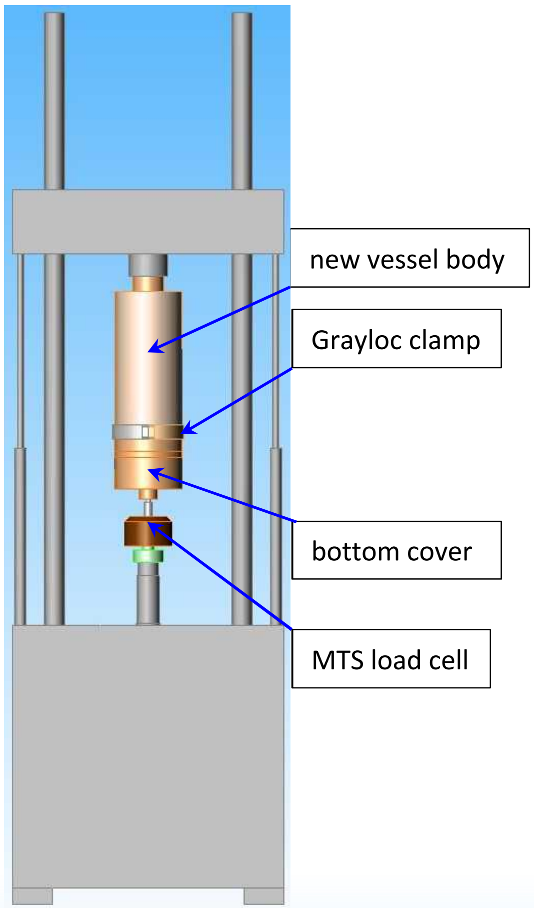
- Target specimen temperature: -50 ^{o}C
- Coolant fluid: liquid nitrogen
- Minimum tube inner diameter: 0.125 in

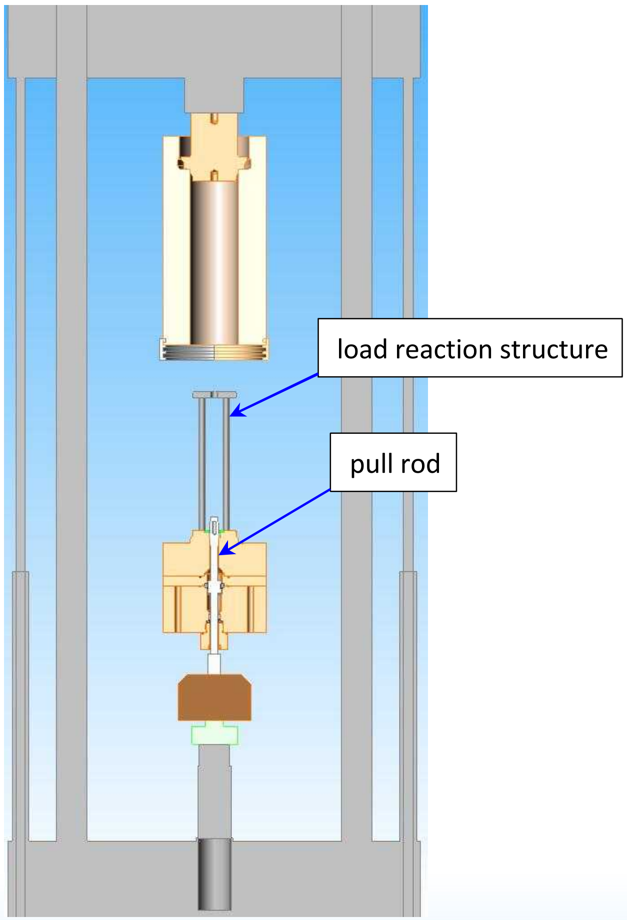
SolidWorks modeling framework developed to simulate temperature distribution in pressure vessel

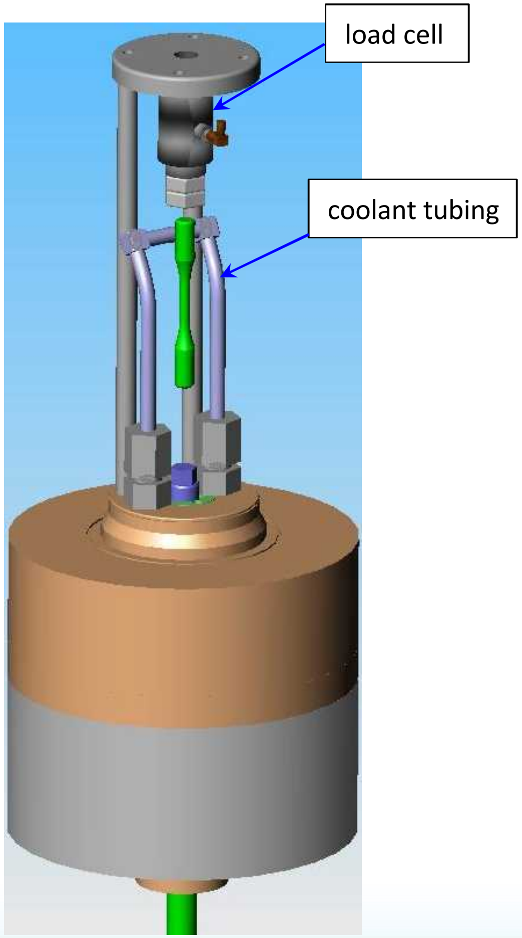


- Copper chill block and stainless steel tubing at target temperature of -50 °C
- Pressure vessel shell and bottom cap at room temperature
- Top cap temperature below 0 °C
  - In this pressure vessel design, temperature may impact seal and feedthrough specifications

Accommodating internal cooling mechanism required modification of pressure vessel design



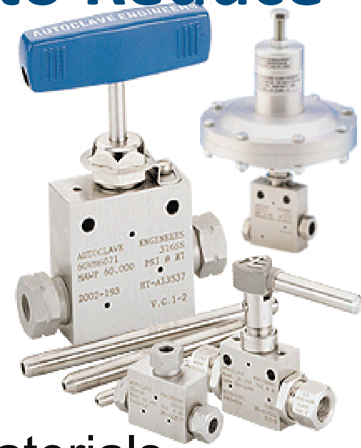




Pressure vessel specifications finalized: RFQs issued to potential vendors

New DOE H2 storage project:

Innovative Materials Selection and Testing to Reduce Cost and Weight of BOP



Problem:

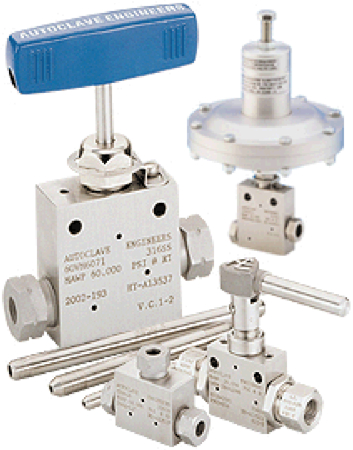
- Balance of plant (BOP) onboard vehicles accounts for:
  - 30-57% of total fuel system cost
  - 15-20% of total fuel system mass
- Structural materials for BOP typically include expensive materials
  - Annealed type 316L austenitic stainless steel (Ni content >12 wt%)
  - A286 precipitation-strengthened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

Motivation

- Annealed type 316 & 316L alloys remain the primary “material of choice” for tubing, fittings and valves in hydrogen fuel applications
  - Low strength and high cost
  - *Are there opportunities to lower cost and maintain H_2 compatibility?*

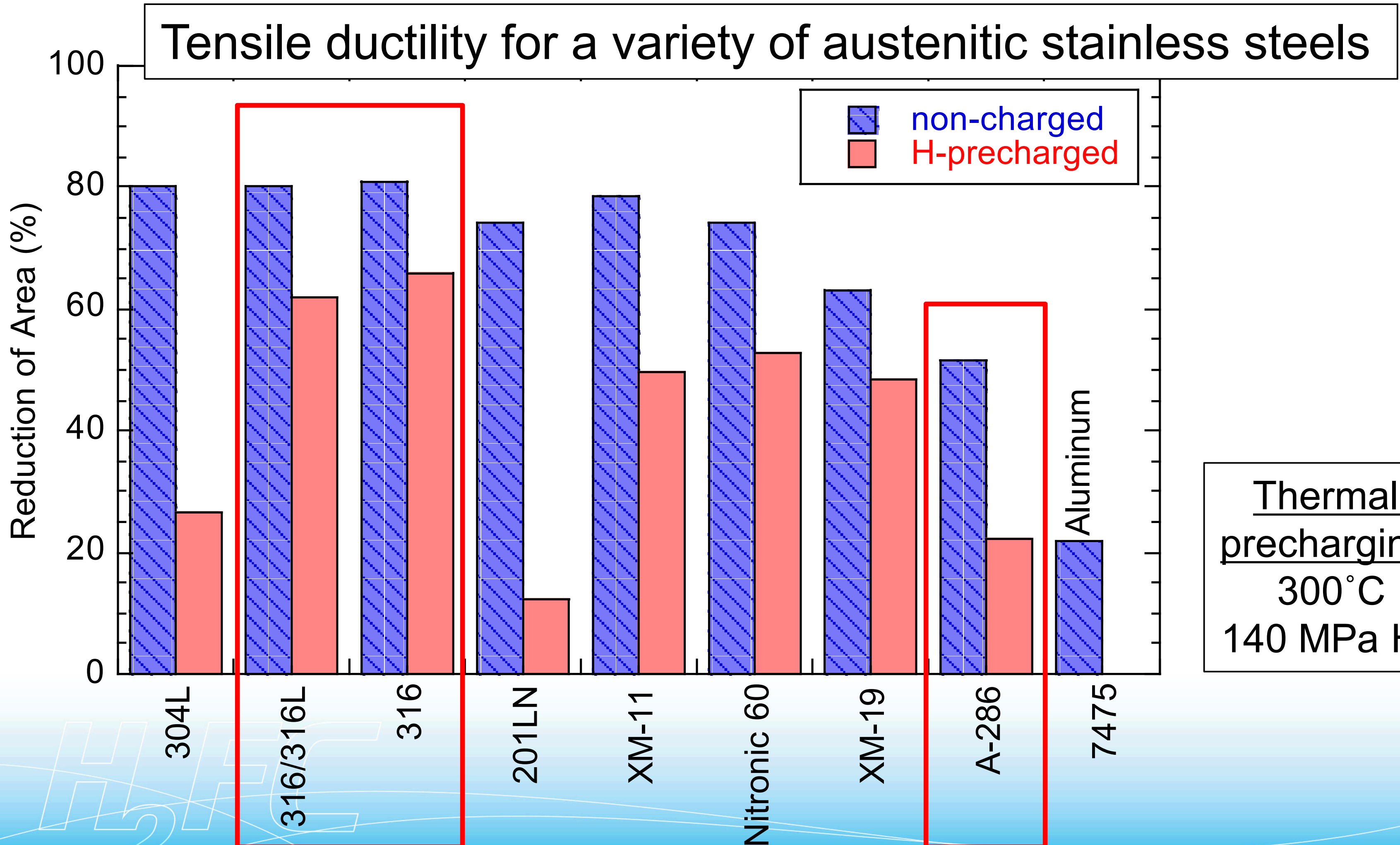


- There exists an extensive database of properties for austenitic stainless steels in hydrogen environments
  - *Is this data sufficient for identifying lower-cost, H_2-compatible alternatives to 316 alloys?*

Materials: austenitic stainless steels

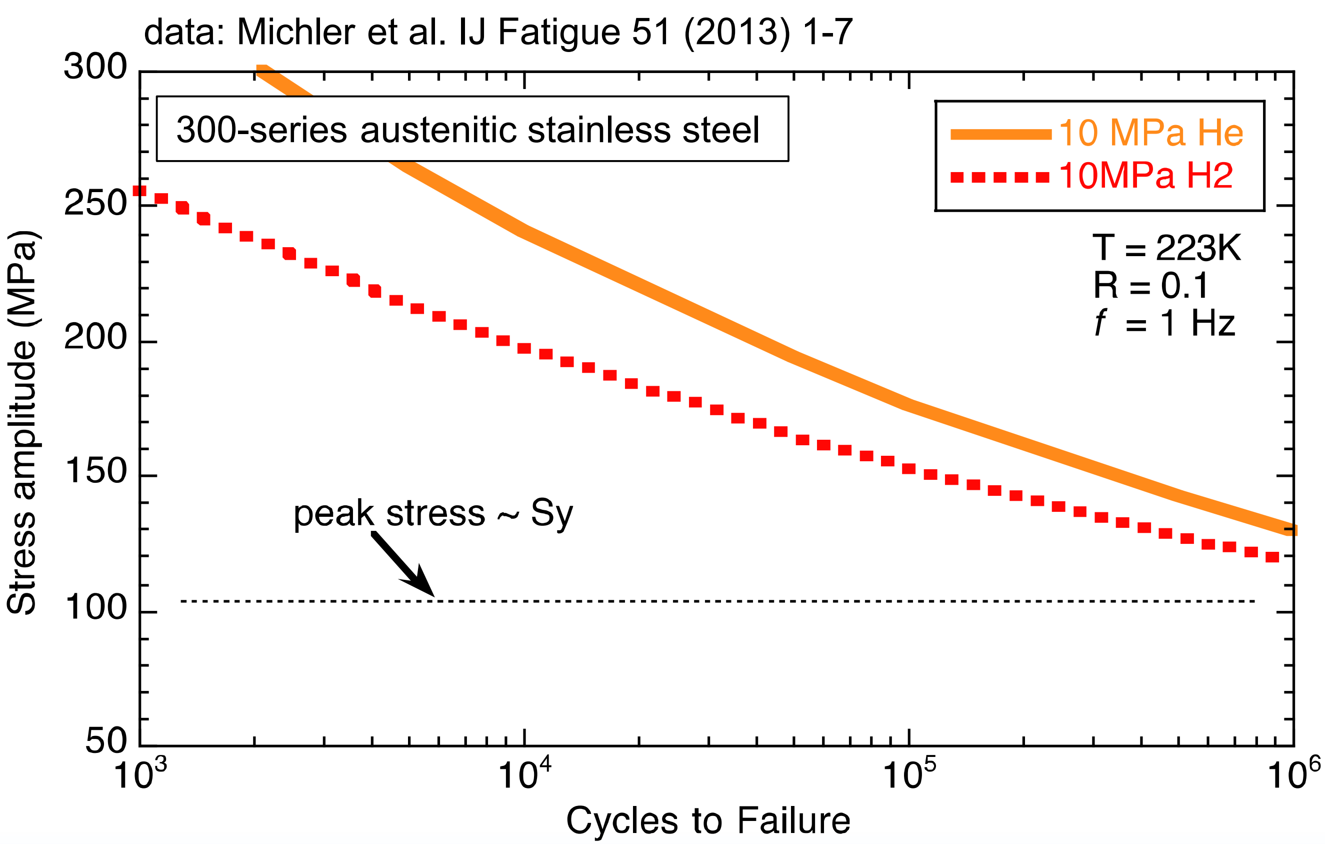
alloy	Cr	Ni	Mn	Mo	C	N
304L	18.3	8.7	1.4	0.34	0.016	0.08
316/316L	16.8	11.2	1.6	2.0	0.02	0.02
316	17.8	12.1	1.2	2.1	0.046	0.02
201LN	16.2	4.1	6.6	0.34	0.024	0.14
XM-11	20.4	6.2	9.5	NR	0.033	0.26
Nitronic 60	16.5	8.0	7.4	NR	0.071	0.14
XM-19	21.0	13.5	6.0	2.1	0.01	0.33
A-286	13.9	24.3	0.11	1.2	0.04	NR

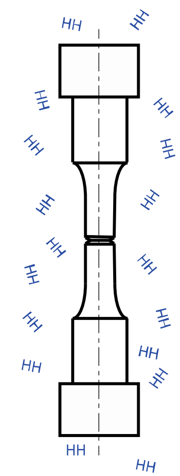
Most extensive data are tensile properties: are these sufficient for selecting alternate materials?



Thermal precharging: 300˚C 140 MPa H2

Fatigue performance more effective metric for materials selection



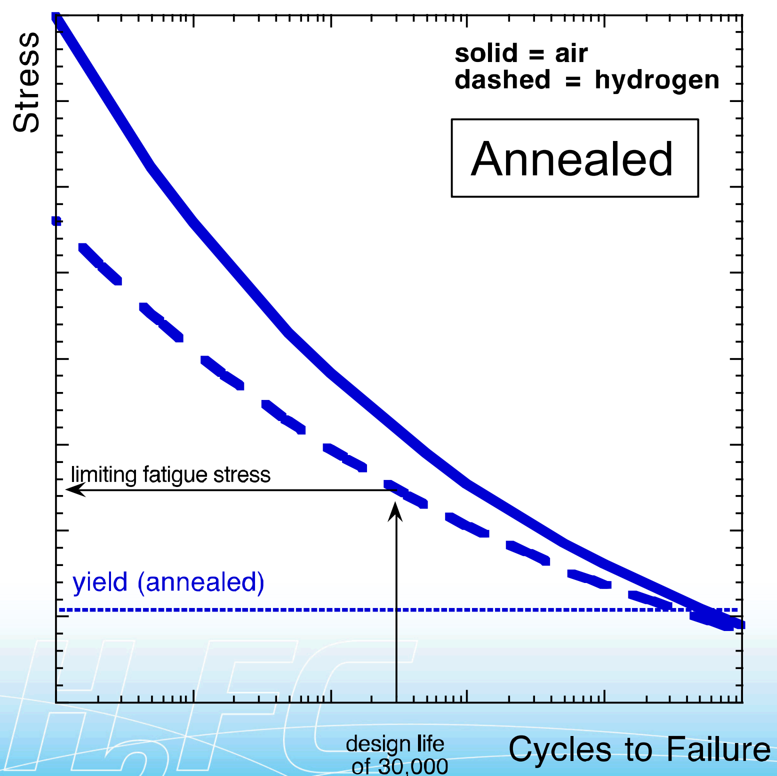


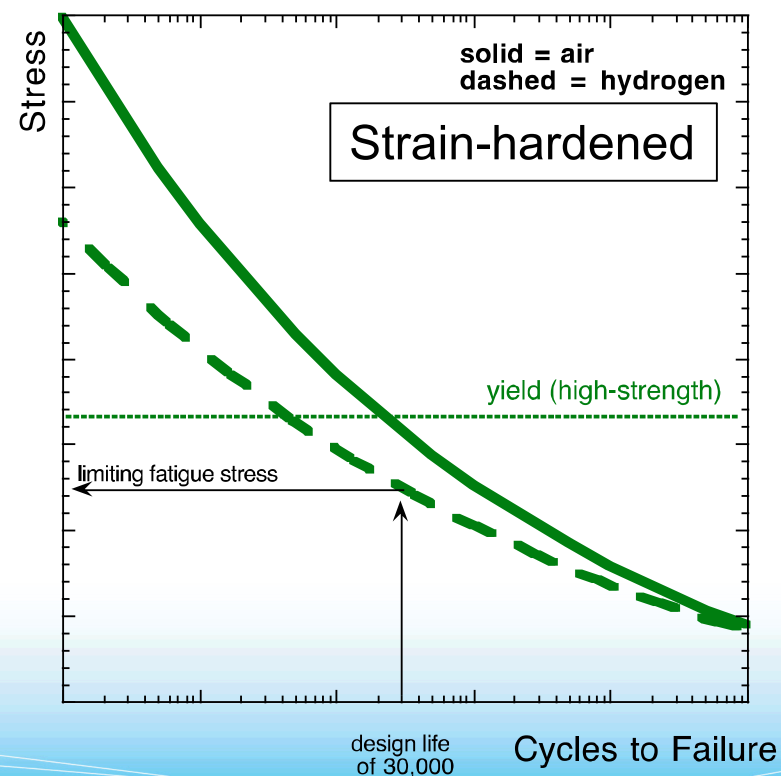
Tension-tension fatigue of standard notched tensile specimen (after ASTM G142)

Fatigue data demonstrate that H_2 compatibility depends on stress level

How do we take advantage of fatigue performance?

- Fatigue performance can serve as quantitative criterion for accommodating higher stresses in design
  - Higher stress = less material
  - Less material = lower cost





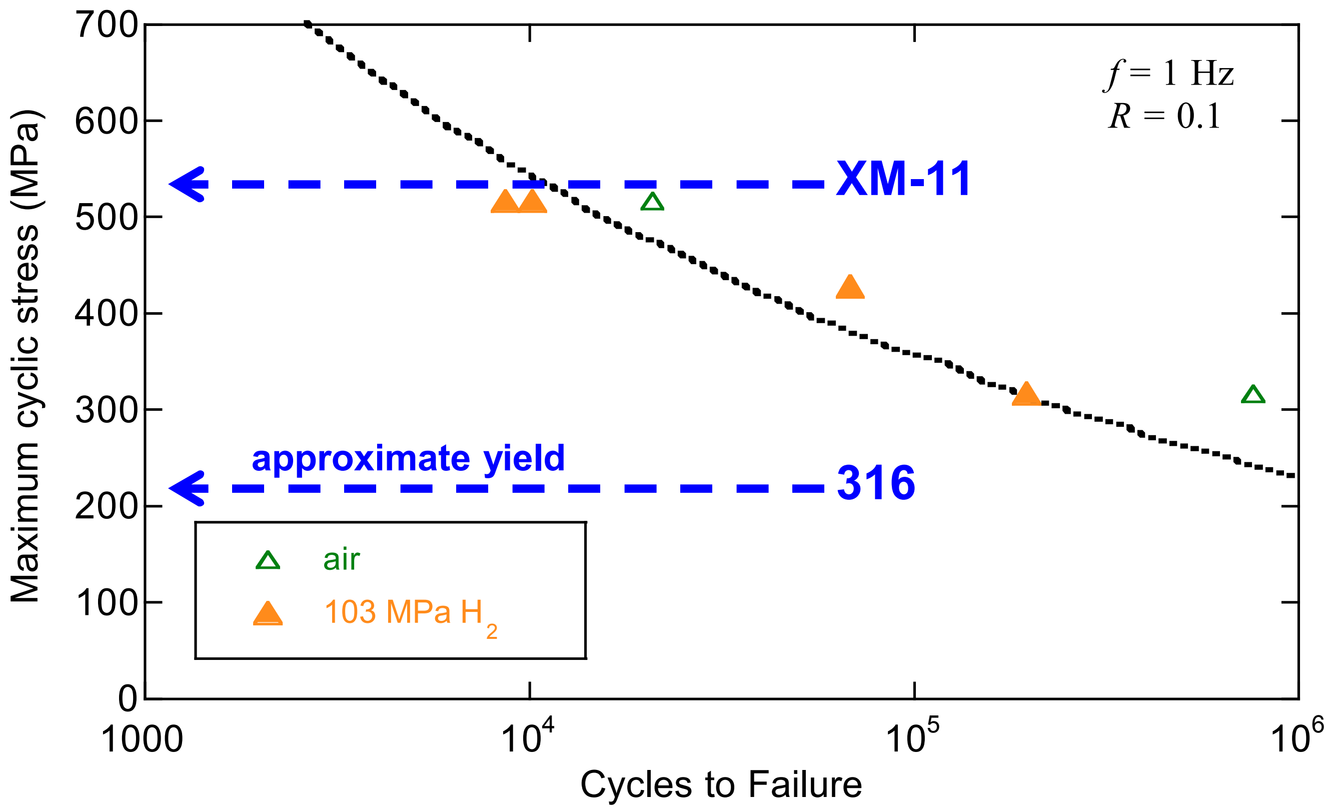
Based on potential weight and reductions, what are candidate materials for evaluation?

- 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

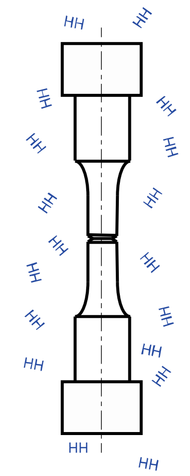
$$t = \frac{PD}{2(SE + PY)}$$ ASME design equation

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

Preliminary fatigue results for XM-11

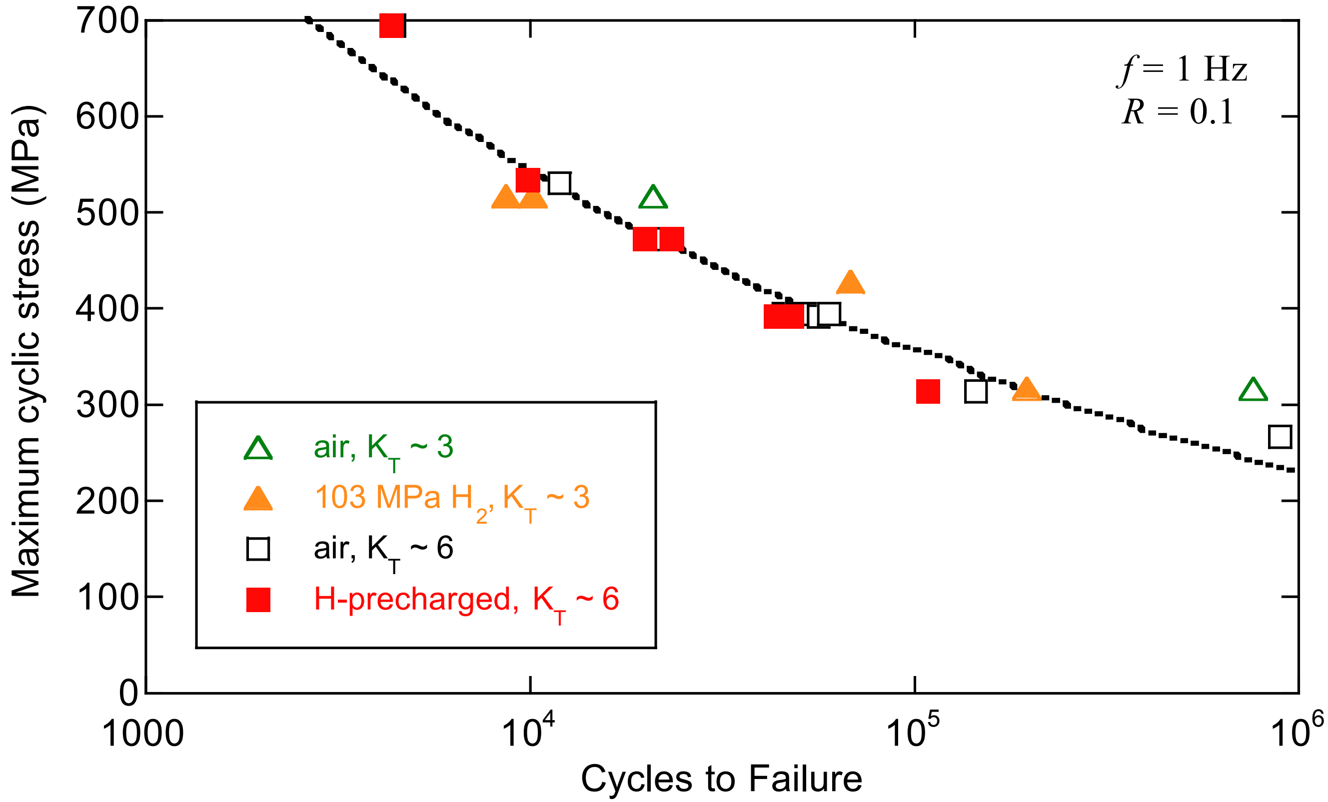


XM-11 austenitic stainless steel

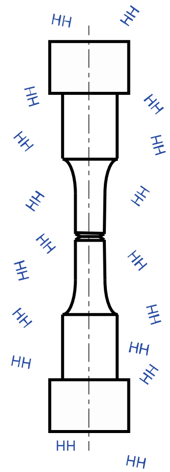


- High fatigue stress can be achieved with cycles to failure greater than 10,000 cycles
- Broader evaluation of methodology requires testing under combination of *low temperature* and high pressure

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

Summary

- Development of variable-temperature testing in high-pressure hydrogen: 2 of 3 subsystems installed
  - Mechanical testing components and automated gas manifold
- Specifications for pressure vessel with internal cooling mechanism complete
  - RFQs issued to potential vendors
- New project for identifying lower-cost, H_2-compatible stainless steels for FCEV BOP components
  - Material selection based on fatigue performance in high-pressure H_2 gas
  - Higher-strength materials may offer component cost savings through reduced material quantities