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

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Relevance and Objectives

Problem:

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

Objectives:

- ***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

Program Approach

The Hydrogen program at Sandia coordinates critical stakeholders and research to remove technology deployment barriers

- Strong partnerships with industry
- Participation in codes and standards community

Broad International Engagement

International R&D Programs (Hydrogenius, I2CNER, EU Joint Undertaking)

International Standards (ISO)

International Agreements (IEA, IPHE)

Project Approach

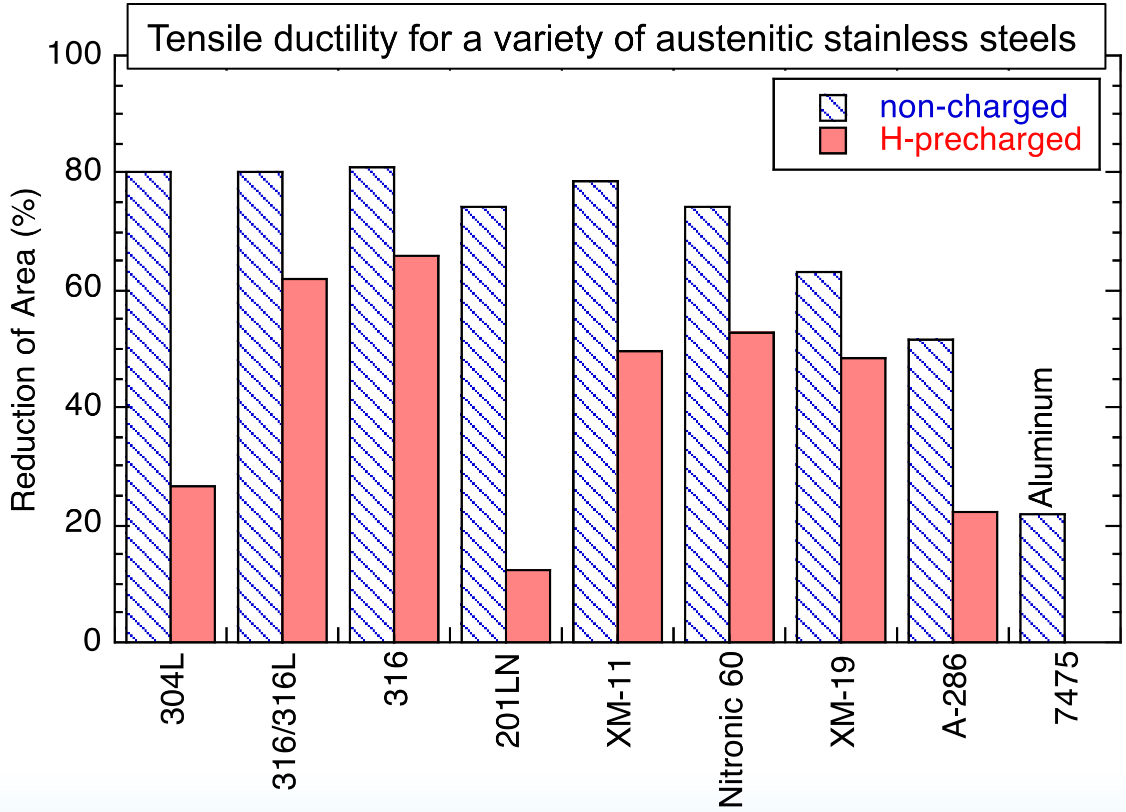
- Measure design metrics of low-cost austenitic stainless steels in hydrogen environments
  - Stress-based fatigue life
    - Fatigue life data can be used in design and therefore can be used quantitatively
  - Low nickel compositions
    - Nickel content drives cost
  - High-strength alloys
    - Higher stresses can be accommodated by higher strength materials
    - Higher stresses require less material
    - Less material = less cost
- Use type 316/316L as a benchmark for performance
- Use simplified test methods (when appropriate) to demonstrate performance of candidate materials

Partnerships

- Sandia National Laboratories
  - Core DOE capability for high-pressure hydrogen testing
  - Leverage between NNSA and EERE customers
  - Deep expertise in mechanical metallurgy of austenitic stainless steels
- Hy-Performance Materials Testing (Kevin Nibur)
  - Commercial testing expertise in pressure environments
  - Unique capabilities in the US
- Swagelok Company (Shelly Tang)
  - Component manufacturer
  - Materials selection and engineering analysis
  - Deep understanding of manufacturing with austenitic stainless steels
- Carpenter Technology (Sam Kernion)
  - Steel manufacturer
  - Metallurgical expertise and cost analysis

Technical Basis

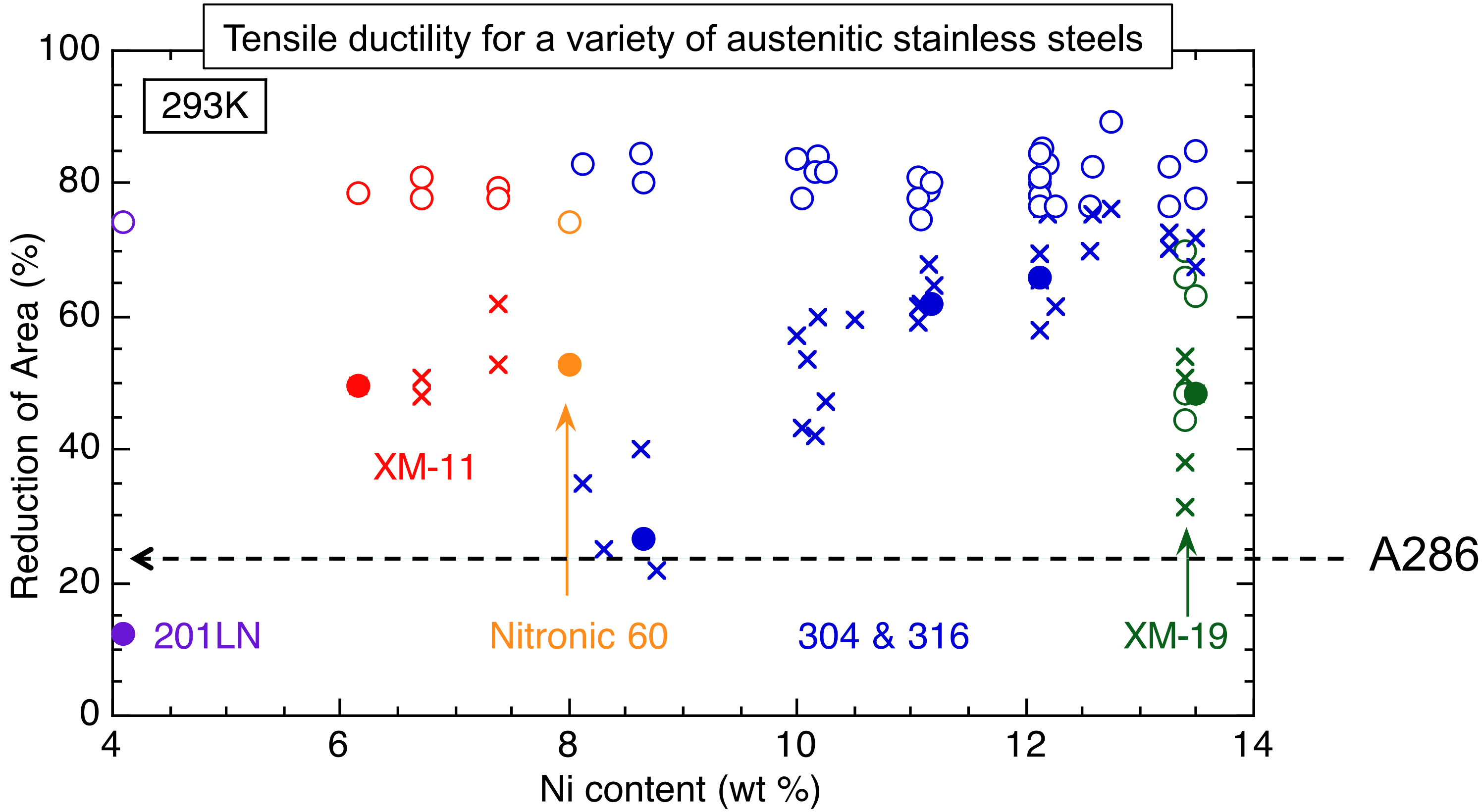
- Composition/alloy affects tensile ductility of austenitic stainless steels in hydrogen environments



- Both 316/316L and A286 are used in hydrogen systems
- Why not other materials such as 304L and XM-11?

Technical Basis

- Tensile ductility is not used directly in design

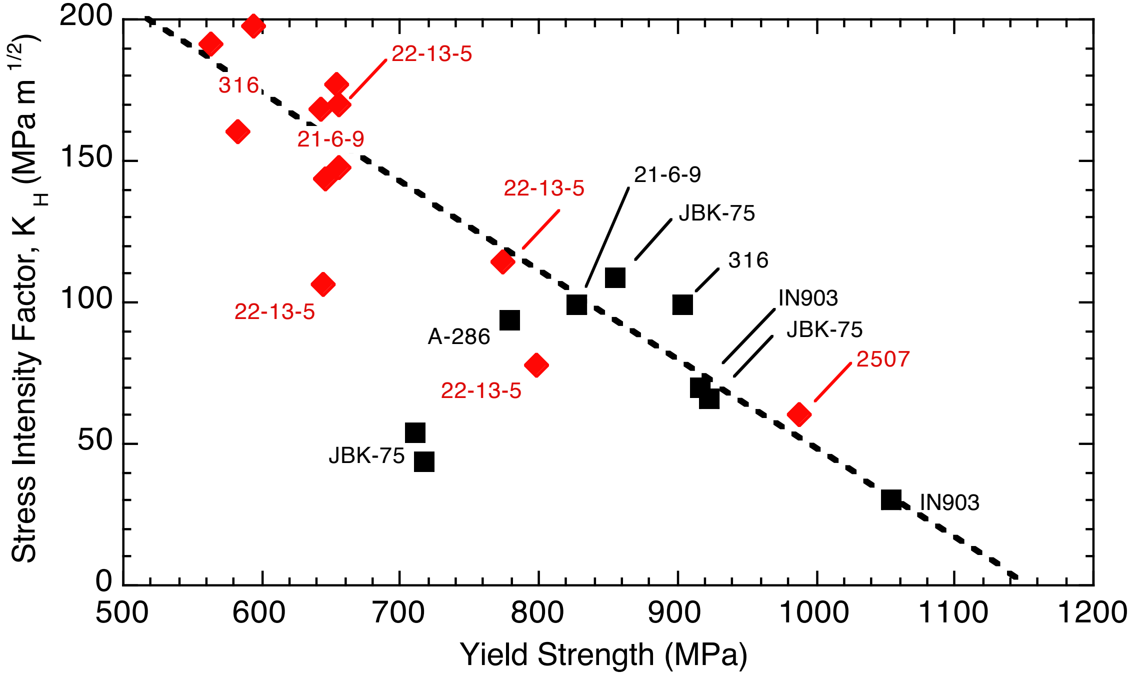


If there is no design criteria associated with tensile ductility, what tensile ductility is necessary for pressure applications?

Technical Basis

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

Fracture resistance measured in hydrogen environments



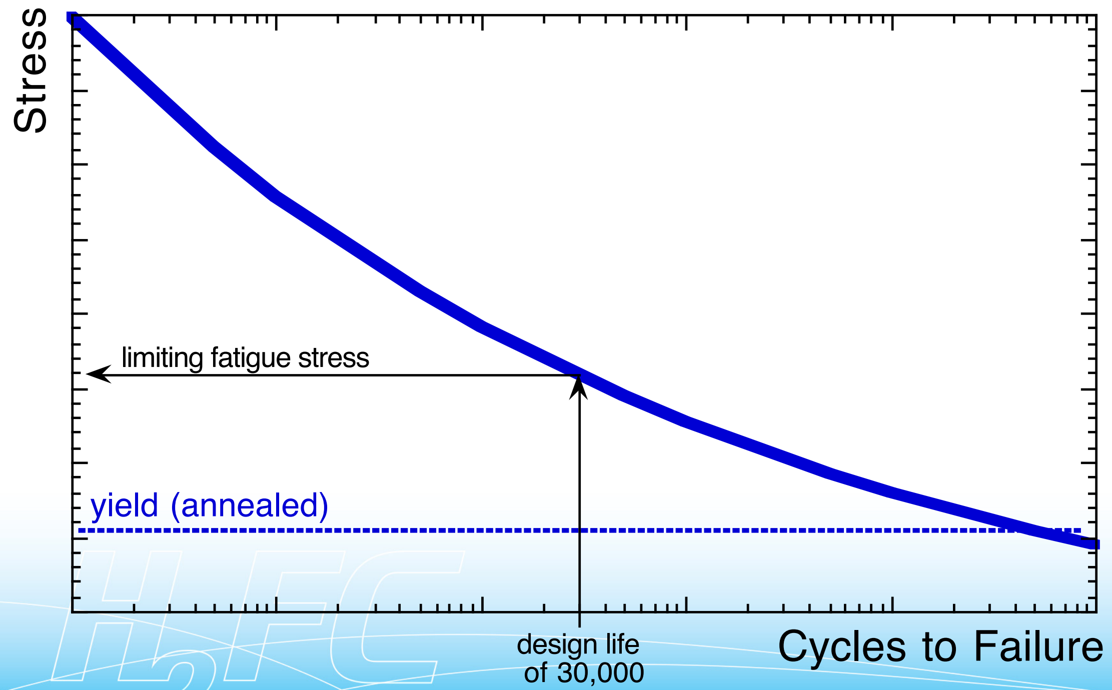
- Fracture resistance in hydrogen environments depends on strength and microstructure
  - not necessarily composition
- Fracture mechanics can be difficult to implement in design

- Fracture properties suggest that a variety of austenitic stainless steels could be compatible with hydrogen environments

Technical Basis

- What are the failure modes?
- What engineering data is widely employed in design of structural systems?

Answers:
- Fatigue is a common failure mode and
- Fatigue life design is commonly employed using relationship between stress and cycles to failure



- 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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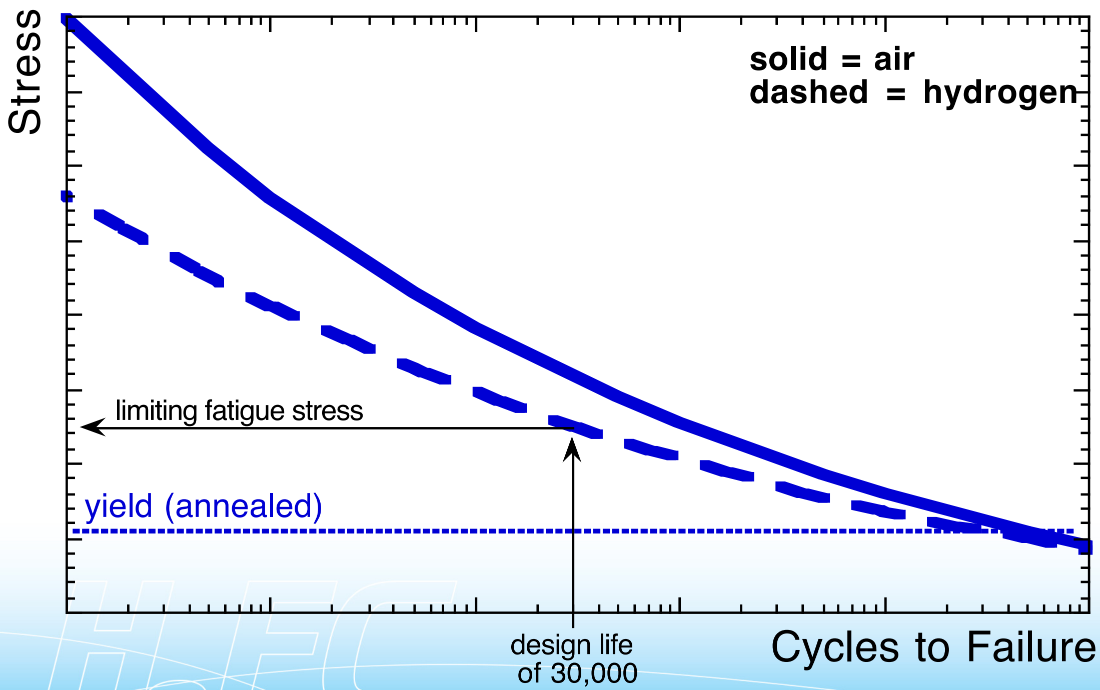


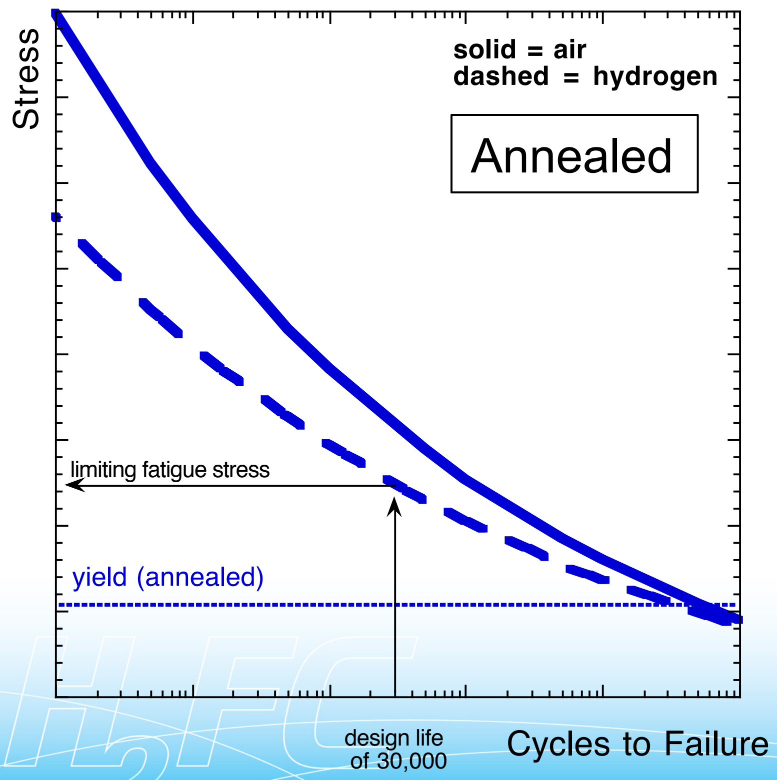
- For moderate design life, the limiting fatigue stress is greater than the yield strength
- Design stresses are typically < yield strength
- Result: very conservative designs

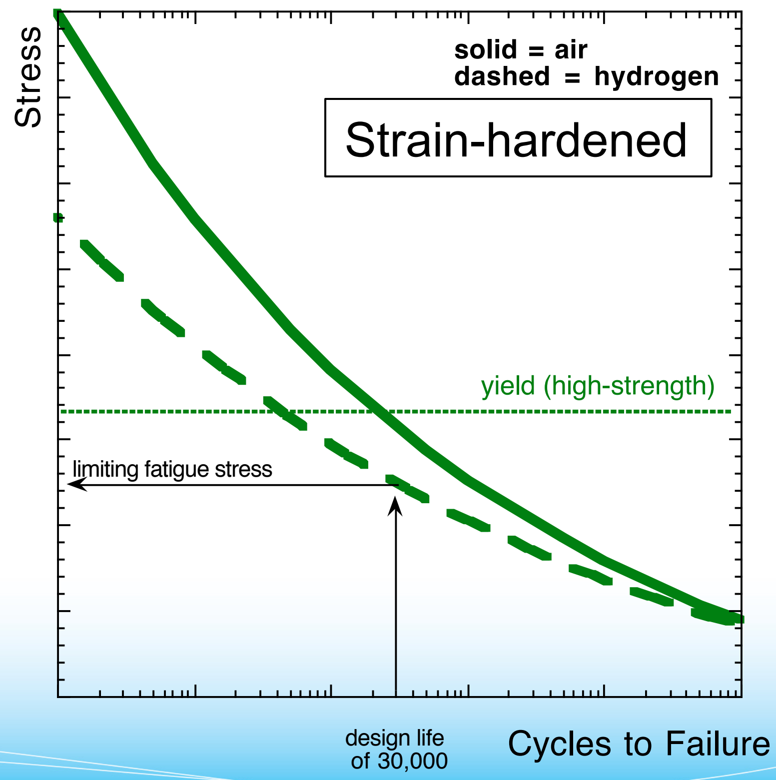
Technical Basis

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

$$t = \frac{PD}{2\left(SE + PY\right)}$$

ASME design equation





Technical Basis

- 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

Milestones

Task 1: Fatigue life of baseline material

- Generate benchmark fatigue life curves
- Measure fatigue life at low temperature
- Correlate results from internal and external hydrogen
- Quantify effects of pressure on fatigue life

Go/No Go: Demonstrate that fatigue life method can be applied in external hydrogen

Materials:

Baseline:	type 316/316L	>12 wt% Ni, YS ~ 250 MPa

Environments:

Internal H:	[H] ~ 140 wppm	
External H:	P = 10 MPa	low-pressure at HPMT
	P = 100 MPa	high-pressure at SNL
Temperature:	T = 293 K	high P, low P, internal H
	T = 220 K	low P, internal H

Milestones

Task 2: Quantify fatigue life of commercially available alternatives to type 316/316L (i.e., low-nickel austenitic stainless steel)

- Room temperature fatigue life of low-nickel alloys (Ni ≤ 6wt%)
- Low temperature fatigue life
- Validate correlation between internal and external hydrogen
- Quantify cost and weight reductions

Go/No Go: Select materials for Task 3 that can achieve targets based on extrapolation of measured fatigue life

Materials:			
		type 204Cu	~2 wt% Ni, YS ~ 250 MPa
		XM-11	~6 wt% Ni, YS ~ 500 MPa
Environments:			
	Internal H:	[H] ~ 140 wppm	
	External H:	P = 10 MPa	low-pressure at HPMT
		P = 100 MPa	high-pressure at SNL
	Temperature:	T = 293 K	high P, low P, internal H
		T = 220 K	low P, internal H

Milestones

Task 3: Demonstrate targets for cost and weight reduction

- Demonstrate 50% reduction of weight
- Demonstrate 35% reduction of cost
- Benchmark fatigue performance of functional alloys
  - Nitronic 60 (gall-resistance)
  - Sandvick HP-160 (very high-strength pressure tubing)

Engineering output: Table estimating maximum allowable fatigue stress to achieve a minimum of 30,000 cycles to failure

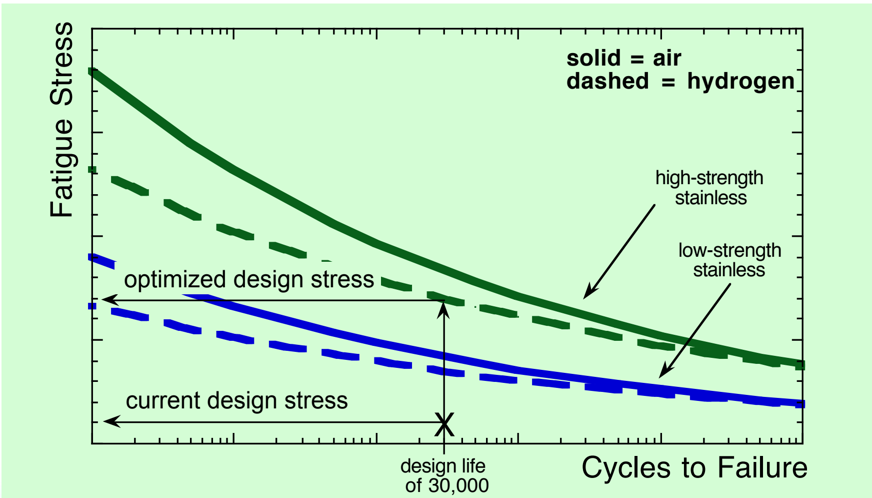
Materials:	
strain-hardened type 316/316L	YS ≥ 600 MPa, 10-14% Ni
strain-hardened XM-11	YS ≥ 800 MPa, ~6% Ni
Environments:	
Internal H:	[H] ~ 140 wppm
Temperature:	T = 293 K
	T = 220 K

Summary

Innovative materials selection and testing to reduce cost and weight of BOP

Technology

The primary goal of this effort is to quantitatively identify commercial alloys to replace type 316/316L at cost and weight reduction of 35% and 50% respectively. This will be achieved by determination of the maximum allowable stresses in low-cost, high-strength austenitic stainless steels to achieve design life of 30,000 fatigue cycles (higher operating stress equates to lower weight). This concept does not seek to identify materials that are immune to hydrogen embrittlement, rather a comprehensive test program evaluates the effects of hydrogen on fatigue performance such that hydrogen embrittlement can be effectively managed in design.



This figure shows schematically the anticipated effects of hydrogen on fatigue and the performance improvement that can be realized by using high-strength austenitic stainless steels

Key Partnerships

Sandia National Laboratories, Hy-Performance Materials Testing, Carpenter Technology, Swagelok Company

Program Summary

Period of performance: 36 months

Federal funds: $1.2M
Cost-share: $149K
Total budget: $1.35M

	Key Milestones & Deliverables
Year 1	• Fatigue life curves of type 316L austenitic stainless steel in gaseous hydrogen at low temp. • Performance-based evaluation of lower cost testing options
Year 2	• Projected cost and weight savings that can be achieved with austenitic stainless steels • Quantitative fatigue analysis of alternatives to type 316L in hydrogen environments
Year 3	• Quantitative stress-based fatigue life basis for 50% weight and 35% cost reduction of BOP components by informed materials selection

Technology Impact

Type 316L is state-of-the-art for high-pressure hydrogen components. Exclusive use of this material limits innovation and design efficiencies. Fatigue testing of commercial austenitic stainless steels demonstrates substantial opportunity for cost and weight savings for onboard storage of hydrogen

Low-cost, high-strength alloys can be used in gaseous H2 systems