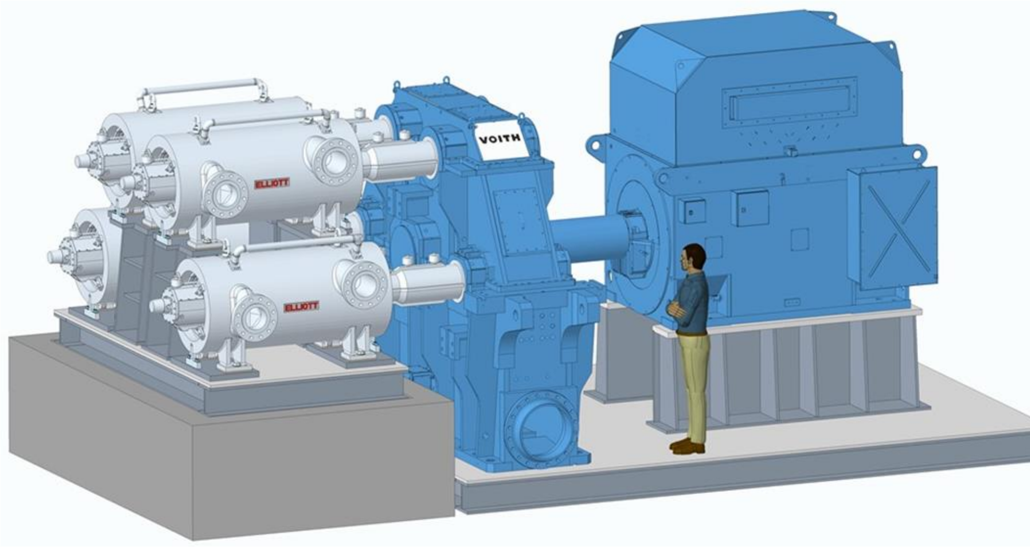
Qualification and Testing of High Strength Material for Hydrogen Compression

2022 Thermo-Mechanical-Chemical Energy Storage Conference

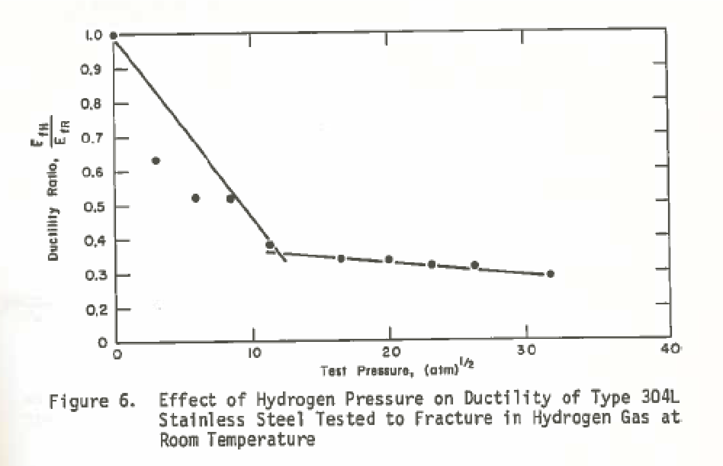
Hydrogen Compression

- Hydrogen is generated at atmospheric pressure
  - Goal is to reach 1,200 psi (8.3 MPa)
- Current Limitations
  - API 617
    - Maximum yield strength of 120,000 psi (827 MPa)
  - ASME Boiler and Pressure Vessel Code
    - Permits carbon steel to 13,000 psi (90 MPa)
  - API Recommended Practice 941
    - Provides temperature limitations for materials
    - Cites experience of carbon steel at 10,000 psi (69 MPa) at 430°F (221°C) if stress relieved
- No official standard for acceptance of higher strength materials



Influence of Hydrogen

- Hydrogen can have an embrittlement effect upon metallic materials
  - While the strength of the material remains unchanged, the ductility of the material can be significantly reduced
    - From a fracture mechanics or fit-for-service perspective, defects that are acceptable without Hydrogen may become unstable in the presence of Hydrogen



Effect of Hydrogen Pressure on Ductility of 304L Stainless Steel Tested to Fracture in Hydrogen Gas at Room Temperature
Source: Hydrogen in Metals, ASM, 1974

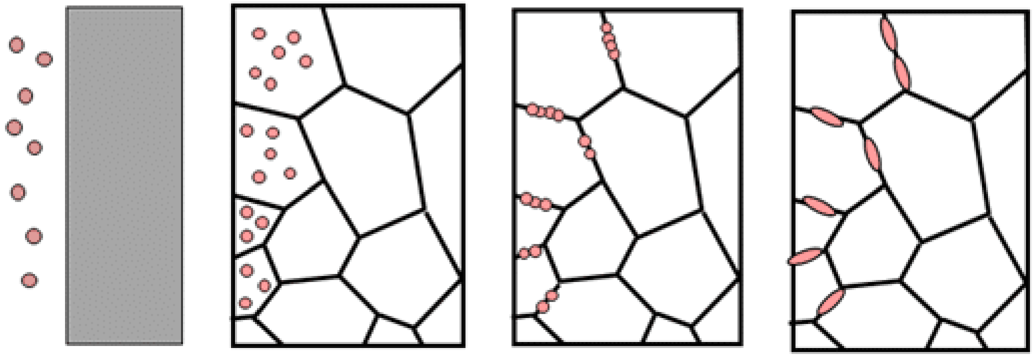
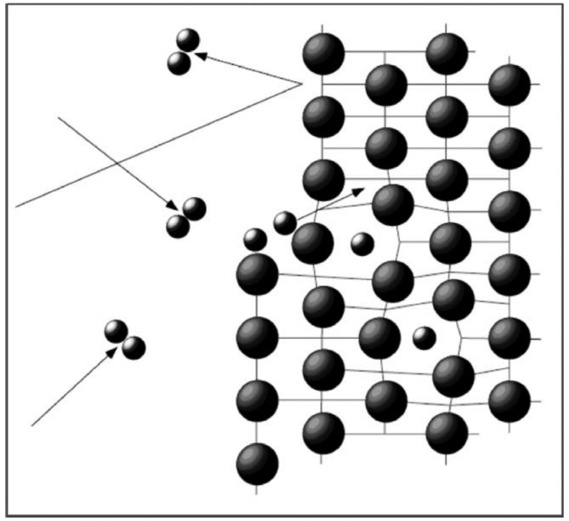


Illustration showing diffusion of atomic Hydrogen to grain boundaries within steel
Source: www.imetllc.com

Why Does Hydrogen Make Metals Brittle?

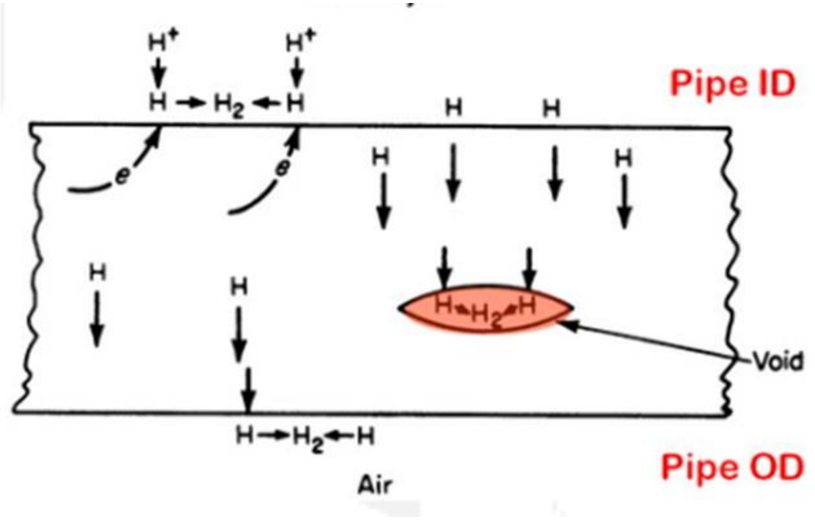
- Diatomic hydrogen (H_2) does not readily diffuse into steels
- Atomic Hydrogen penetrates the steel resulting in the loss of ductility
  - Leading theory is that the atomic Hydrogen recombines within the metal to form H2, react with carbon, accumulate at impurities
  - Requires a corrosion reaction occurring within the process
  - Hydrogen atoms can insert themselves at interstitial sites and does not allow dislocations to move



Lattice strain in a metallic material cause by an interstitial hydrogen atom

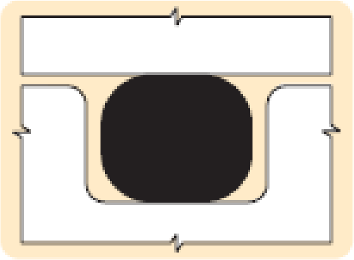
Considerations in Mechanical Testing

- Exposure to dry hydrogen gas prior to testing
  - Need to allow sufficient time for hydrogen interaction
  - Absorption rate of hydrogen varies by material
- Corrosion reactions creating atomic hydrogen do not create the same environment
  - Atomic hydrogen is absorbed into material
  - More detrimental effect
    - Can cause failures with no applied stress



Considerations for Rotating Equipment

- Pressure-Containing Components
  - Casing body
    - Avoid hydrogen embrittlement
    - Suitable for rated temperature and pressure
  - O-ring materials
    - Resist Rapid Gas Decompression (RGD)
- Rotating Equipment
  - Tensile strength
  - Yield strength
  - Fracture toughness in hydrogen environment
  - Fatigue endurance limit in hydrogen environment



ASTM E8

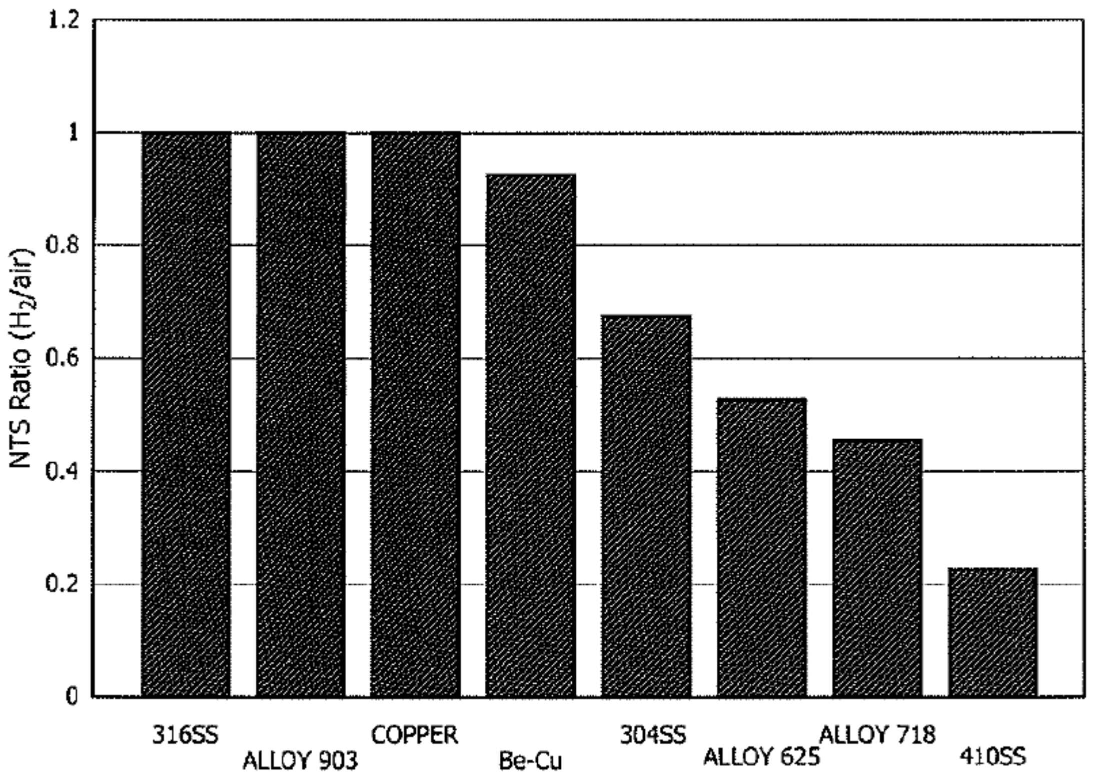
- Standard Test Method for Tension Testing of Metallic Materials
  - Develops standard data
    - Tensile Strength
    - Yield Strength
    - Elongation
    - Reduction of Area
  - Can be performed in hydrogen gas environment

ASTM G142

- Standard test for Determination of Susceptibility of Metals to Embrittlement in hydrogen Containing Environments at High Pressure, High Temperature or Both
  - Slow strain rate tensile test
  - Smooth or notched tensile sample
- Tensile sample is pulled to failure in Hydrogen environment
  - Susceptibility to hydrogen embrittlement is evaluated through comparison of mechanical properties in hydrogen environment to mechanical properties in a controlled environment.
    - Exposure time to test conditions is critical

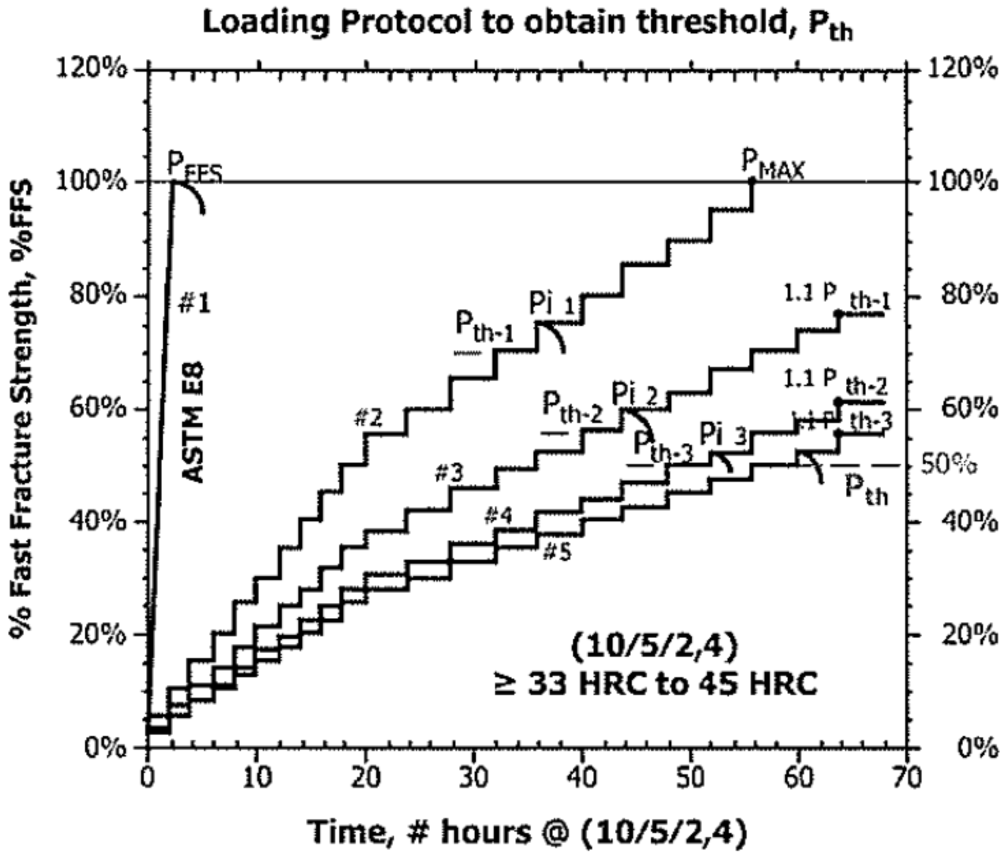
ASTM G142

- Notched tensile sample ratio for various alloys in 35 to 69 MPa (5,076 to 10,000 psi) gaseous hydrogen versus air tested at room temperature



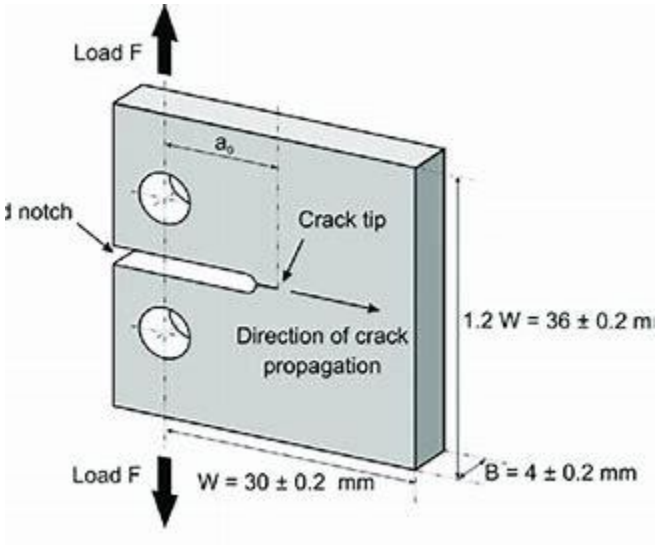
ASTM F1624

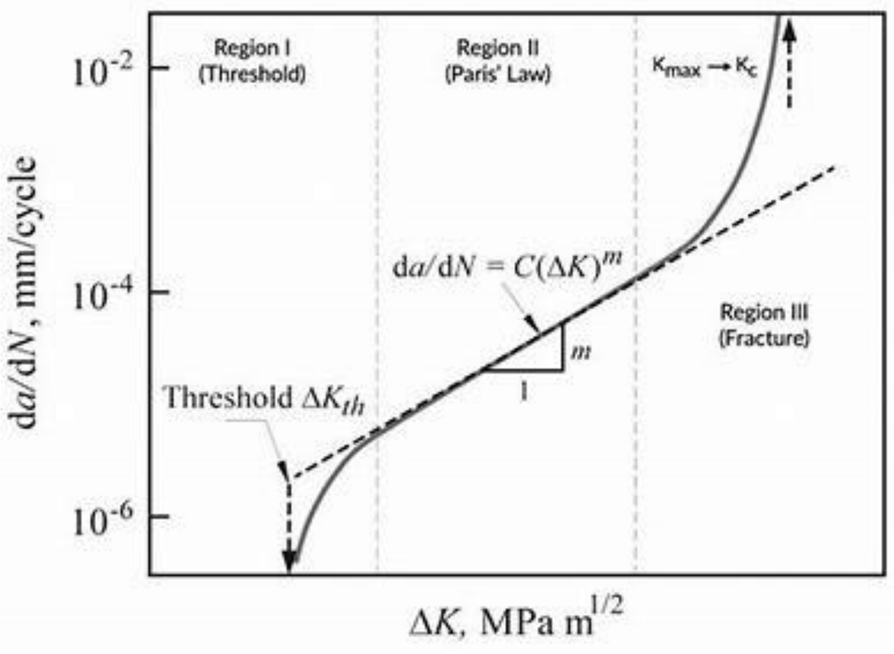
- Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Method
    - Rising step load test
    - Utilized to measure the threshold stress level
    - Threshold stress intensity (K_{TH}) can be determined in a hydrogen environment
    - Critical for defect tolerant design



ASTM E647

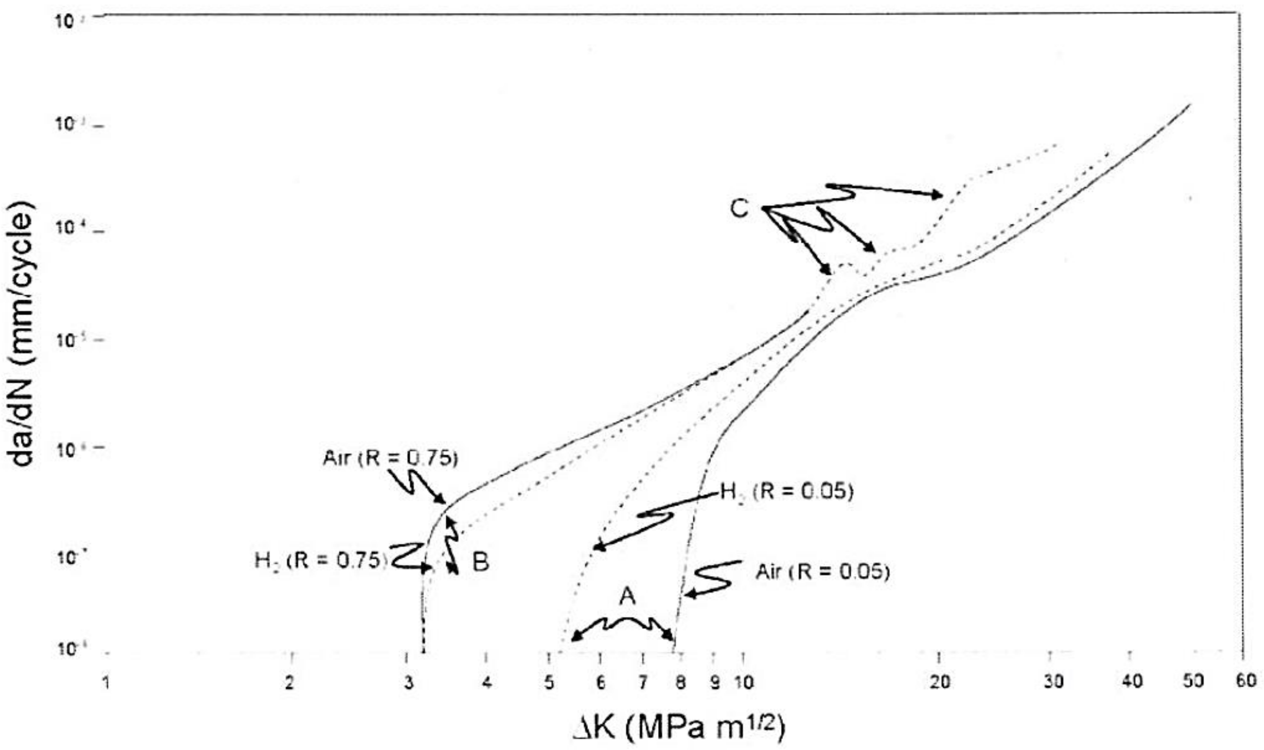
- Standard Test Method for Measurement of Fatigue Crack Growth Rates
  - Used to determine fatigue crack growth rates
  - Alternating stress is applied
  - Crack growth per cycle is measured





ASTM E647

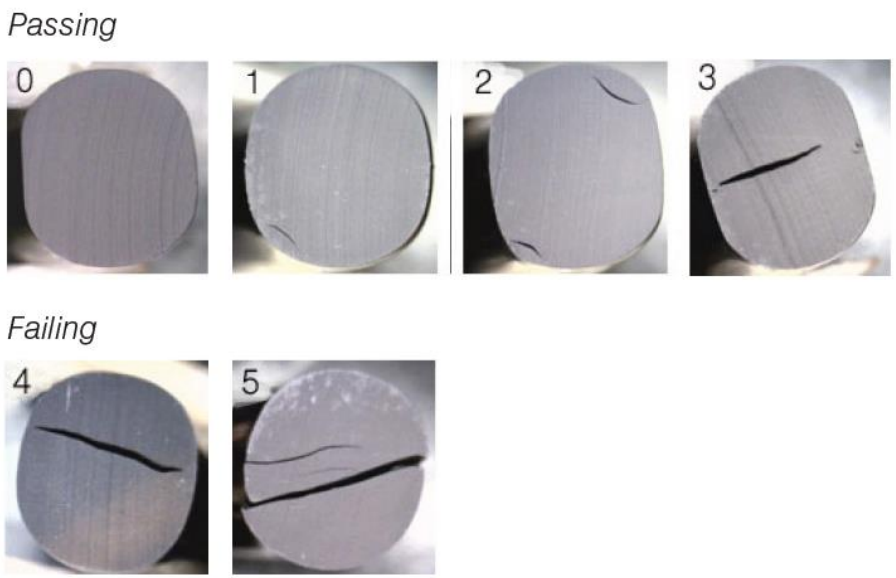
- Hydrogen environment can influence threshold stress level for fatigue cracking



ISO 23936-2

- Petroleum, petrochemical and natural gas industries – Non-metallic materials with media related to oil and gas production – Part 2: Elastomers
- Rapid Gas Decompression Testing
  - Performed in hydrogen environment

ISO Test Results					
	Test 1	Test 2	Test 3	Test 4	Test 5
Number of cycles	8				
Gas mixtures	90% CH_4/10% CO_2				
O-ring size	-312				
Pressure	2,175 psi (150 bar)				
Temperature	210°F (100°C)	355°F (180°C)	355°F (180°C)	450°F (230°C)	390°F (200°C)
Decompression rate	290 psi (20 bar)/min.	290 psi (20 bar)/min.	1,450 psi (100 bar)/min.	1,450 psi (100 bar)/min.	2,175 psi (150 bar)/min.
Rating	0.0.0.0	0.0.0.0	0.0.0.0	1.1.0.0	0.0.0.0



Summary

- Pressure-containing materials have referenced limits for hydrogen service
  - ASME Boiler and Pressure Vessel Code
  - API Recommended Practice 941
  - O-ring materials need to consider Rapid Gas Depressurization
- Rotating equipment currently limited by API 617
  - Applies 120,000 psi (827 MPa) maximum yield strength for all materials
  - Exceeding this limitation requires consideration of environmental properties
    - Threshold tensile stress for crack growth
      - Determines fracture toughness for defect tolerant design
    - Fatigue threshold in hydrogen environment
      - Rotating equipment, so exceeding threshold limit will lead to failures

The world turns to Elliott.