Considerations of Hydrogen Compatibility of Materials for Blending Hydrogen into the Natural Gas Network

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DOE Electricity Advisory Committee
April 13, 2020

SAND2020-XXXX PE

Motivation and Outline

- What is hydrogen embrittlement and when is it important?
- How does gaseous hydrogen affect fatigue and fracture of pipeline steels?
- Is there a threshold below which hydrogen effects can be ignored?
- Can the effects of hydrogen be masked by other physics?
- Where are the gaps in understanding structural integrity of hydrogen pipelines and piping?
- What is the implication of hydrogen on life of pipelines and piping?

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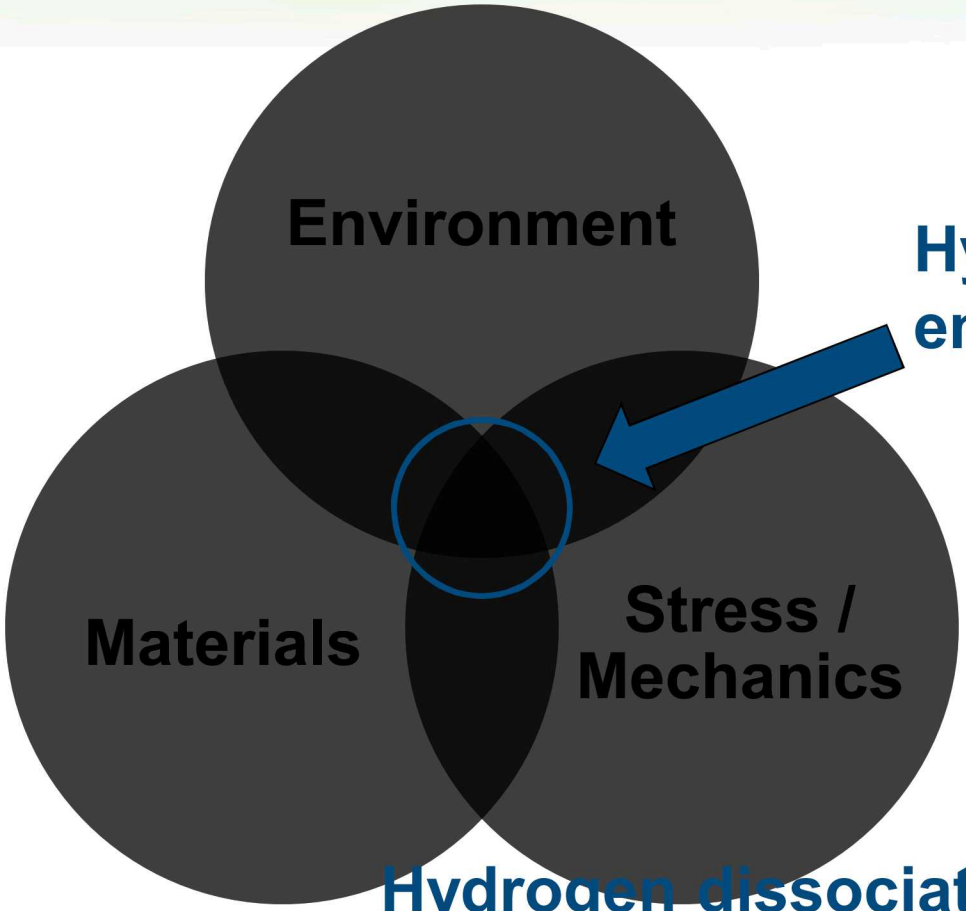
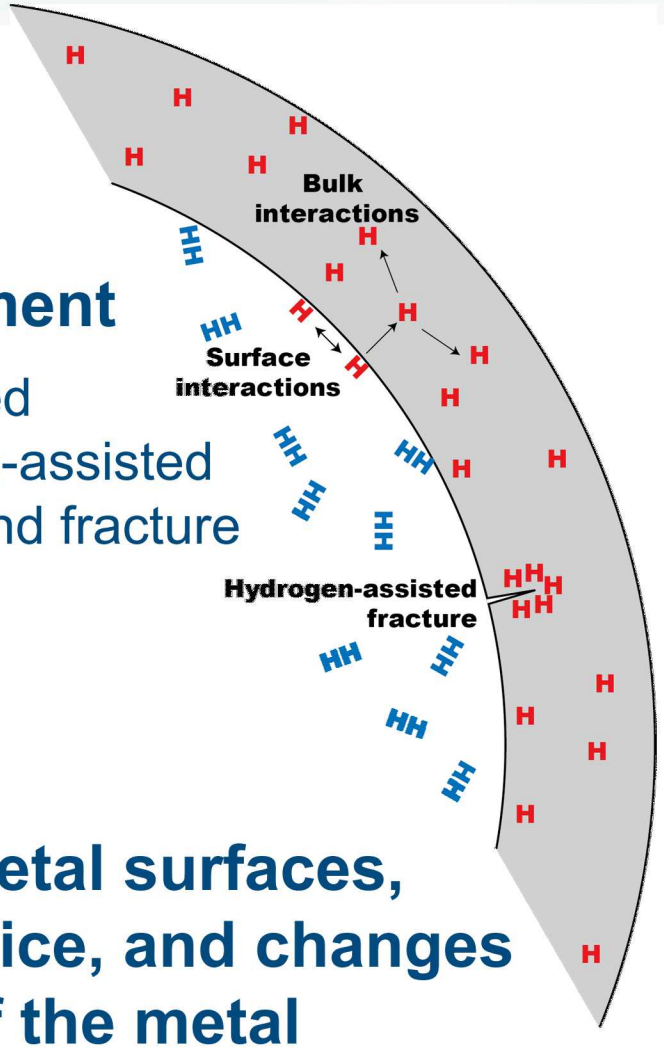
Hydrogen embrittlement occurs in materials under the influence of stress in hydrogen environments



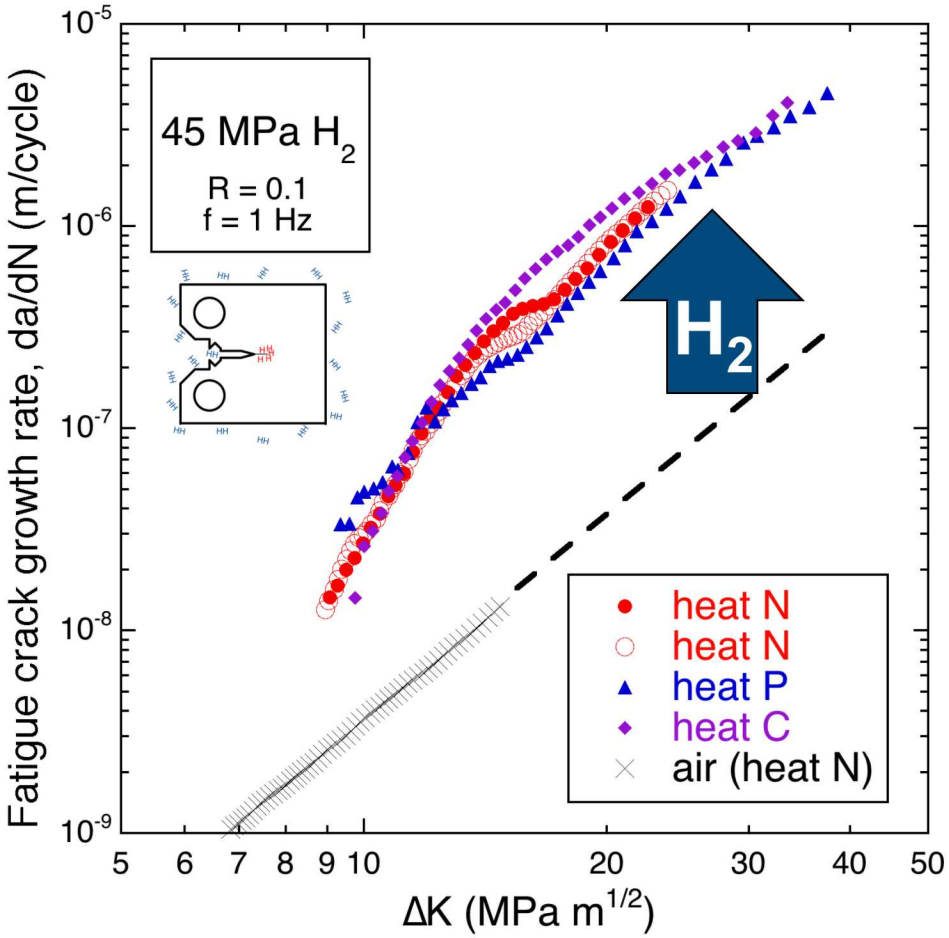
Hydrogen embrittlement

also called hydrogen-assisted fatigue and fracture



Hydrogen dissociates on metal surfaces, dissolves into the metal lattice, and changes the mechanical response of the metal

Is this material safe for use in gaseous hydrogen?

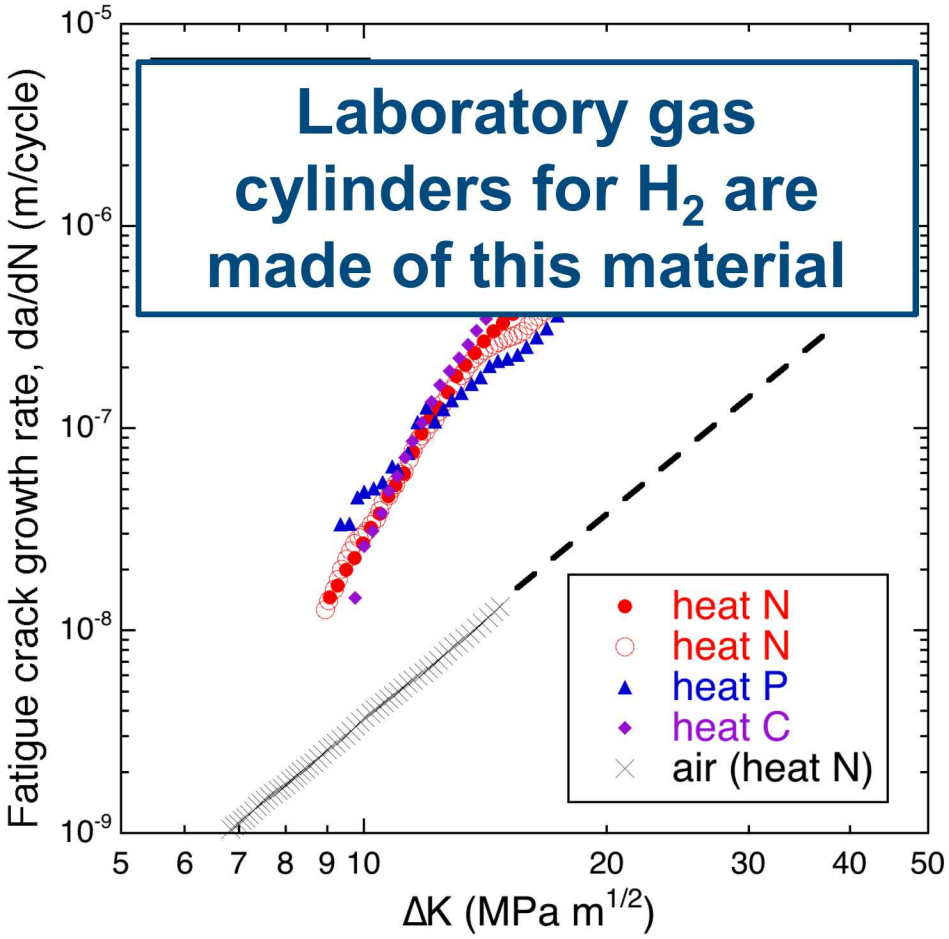


Fatigue

- Fatigue crack growth rate is accelerated by >10X in H_2 compared to air
- This material is safe for use in gaseous hydrogen.

True -- or -- False

Is this material safe for use in gaseous hydrogen?



It depends:

Materials requirements depend on the application and the design

- Gas cylinders are made from relatively low strength steels
- Wall stresses are relatively low
- Number of pressure cycles are modest
- Manufacturing defects are well characterized

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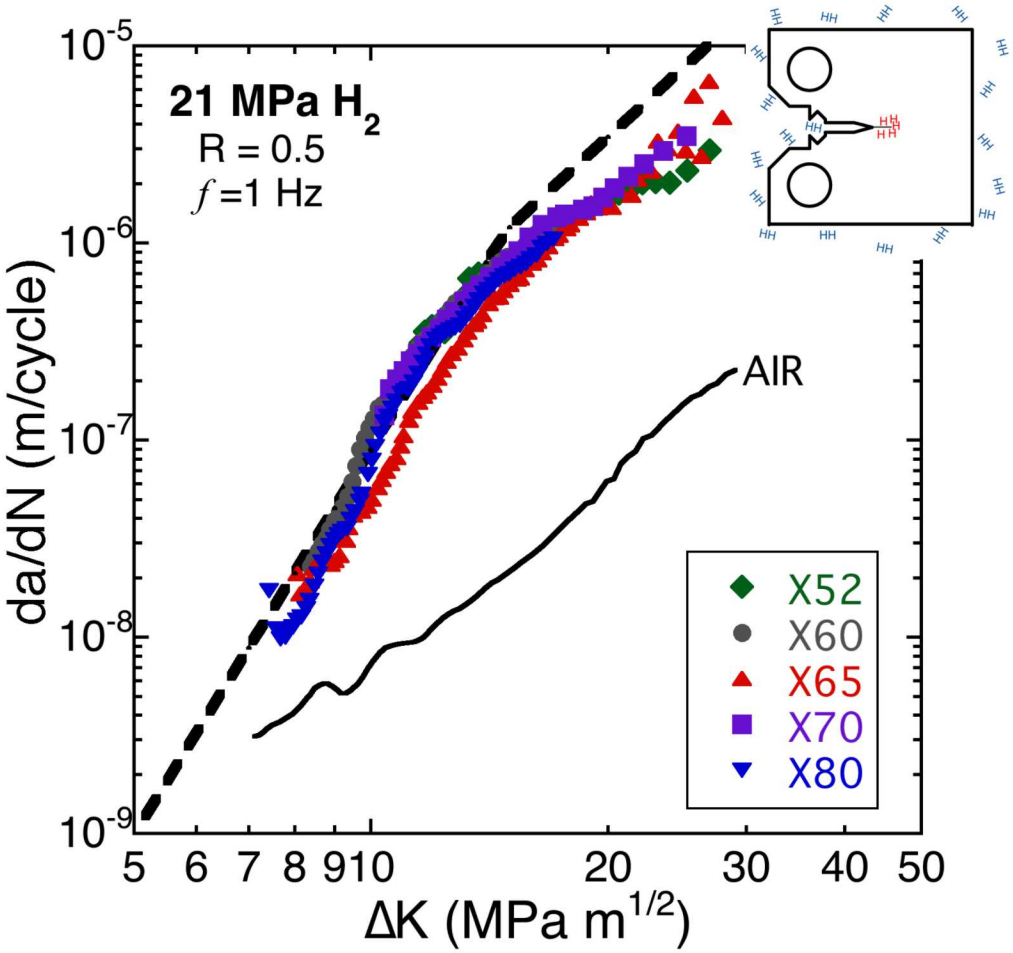
Pipeline steels tend to show very similar fatigue crack growth rates in gaseous hydrogen



- A wide variety of pipeline steels display similar fatigue response in high-pressure gaseous hydrogen
- Fatigue crack growth rates in hydrogen scale approximately with square root of pressure (not shown)
  - Upper 'plateau' is independent of pressure

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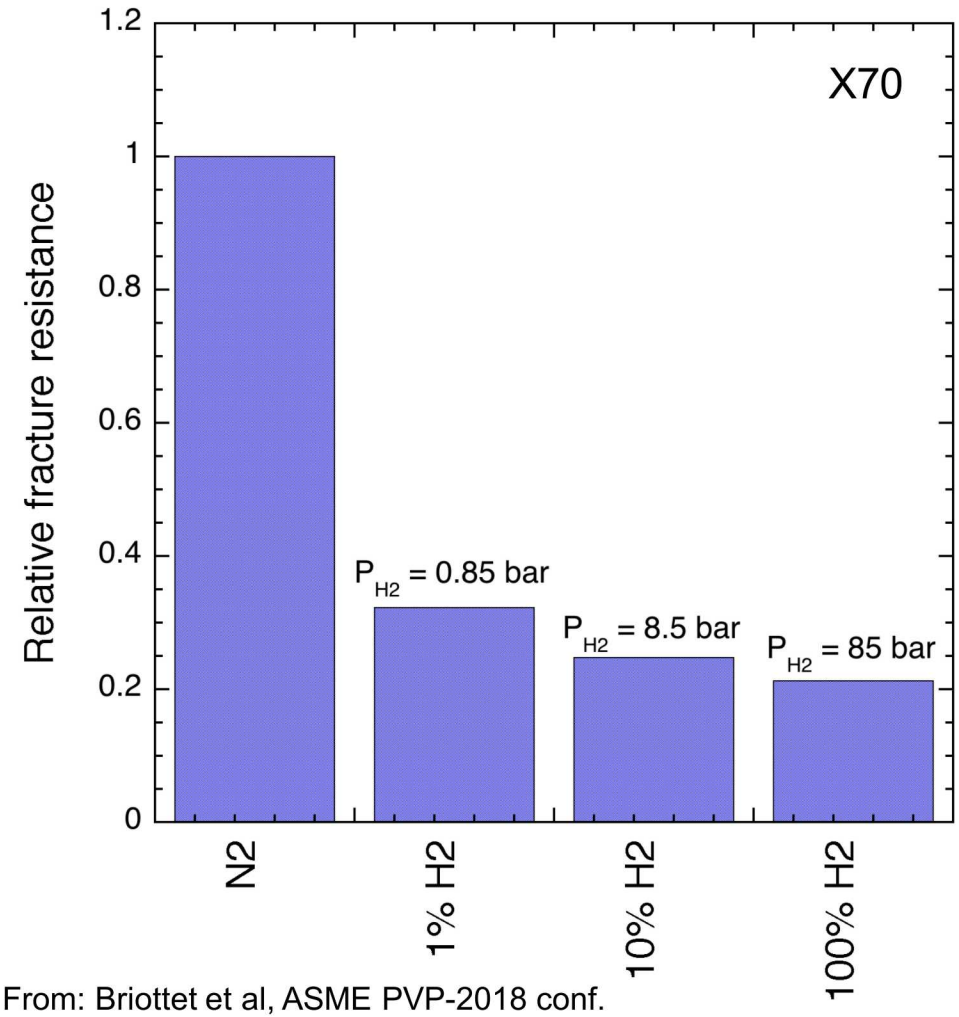
Low pressure hydrogen has substantial effect on fracture resistance of pipeline steels

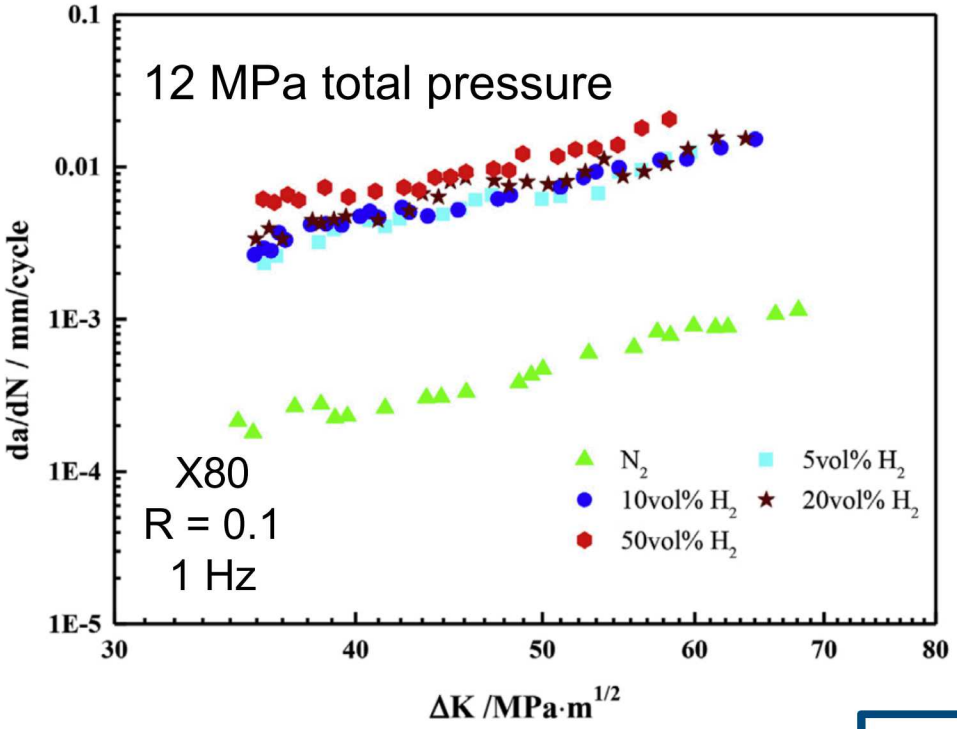


From: Briottet et al, ASME PVP-2018 conf.

- Measurements of fracture resistance in gaseous mixtures of H_2 and N_2 show substantial effects of H_2
- 1% H_2 is only modestly different than 100% H_2

<1 bar of H_2 reduces fracture resistance

Low pressure hydrogen has substantial effect on fatigue crack growth of pipeline steels



From: Meng et al, *IJ Hydrogen Energy* **42** (2017) 7404.

- **Measurements in gaseous mixtures of H_2 and N_2 show acceleration of fatigue crack growth rate with 5% H_2**
  - **But little additional acceleration with higher H_2 content**

Small amounts of hydrogen can have substantial effect on fatigue and fracture

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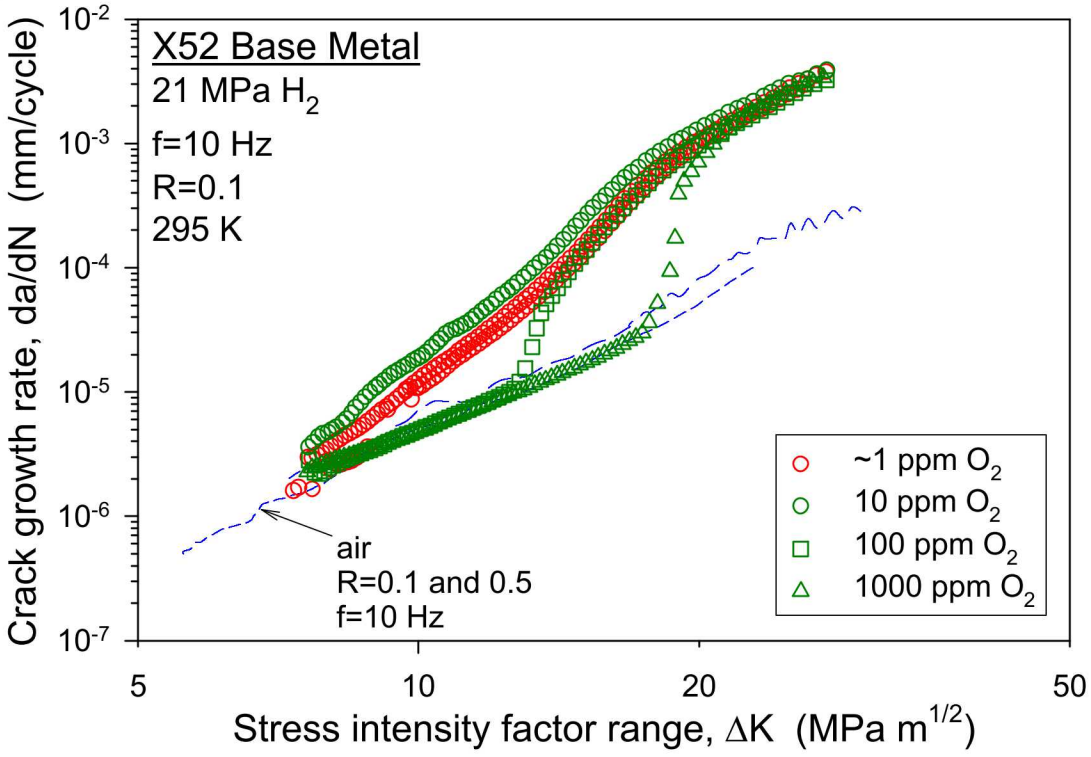
Impurities can influence measurements, but can also provide pathways to mitigate the effects of hydrogen



- **Passivating chemical species can mitigate H_2-accelerated fatigue crack growth rates at low ΔK**
- **Attributed to diffusion to new crack surfaces**

From: Somerday et al, *Acta Mater* **61** (2013) 6153.

Impurity content in H_2 can have substantial effect on both measurements and in-service performance

Note: These oxygen contents are well below the flammability limit and do not pose a hazard. 1000 ppm = 0.1% O_2 which is commonly quoted maximum in NG streams

The role of mixed hydrogen gas environments and impurities should be considered carefully

- Small partial pressure of gaseous H_2 can have substantial effect on fracture and fatigue of steels
- Oxygen can mitigate effects of H_2 in ferritic steels
  - Sensitive to mechanical and environmental variables
  - Other passivating species can have similar effects
- Structural integrity of pipelines carrying mixed gases will depend sensitively on the details
  - NG has many impurities, which can mitigate H_2 effects
  - Pure methane is inert and even small additions of H_2 can be significant

Materials compatibility for hydrogen containment structures depends on the application and the design

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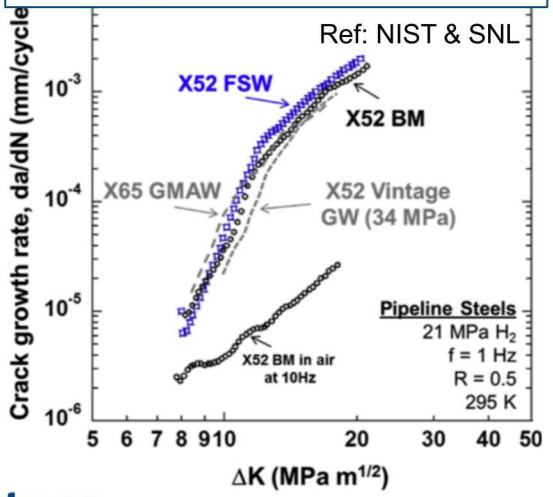
- What is the implication of hydrogen on life of pipelines and piping?

Materials data suggest no 'showstoppers' to integration of hydrogen in existing infrastructure

- **Transmission pipelines**
  - ***API steel grades*** **(including welds): wealth of data exists for fatigue & fracture properties measured in gaseous H_2**
- **Distribution piping and components**
  - **Includes a diverse range of materials, many of which have not been evaluated**
  - ***PE pipe*****: Hydrogen effects on fatigue and fracture of polyethylene (PE) pipe have not been systematically studied**
    - **Pressure and resulting stresses are generally low, suggesting cautious optimism (PE also used in FCEV fuel tanks)**
- **Mixed gas environments**
  - **Role of gas impurities is not well understood, especially in dynamic environment (do not need to consider if designed for pure H_2)**

Example data for welds



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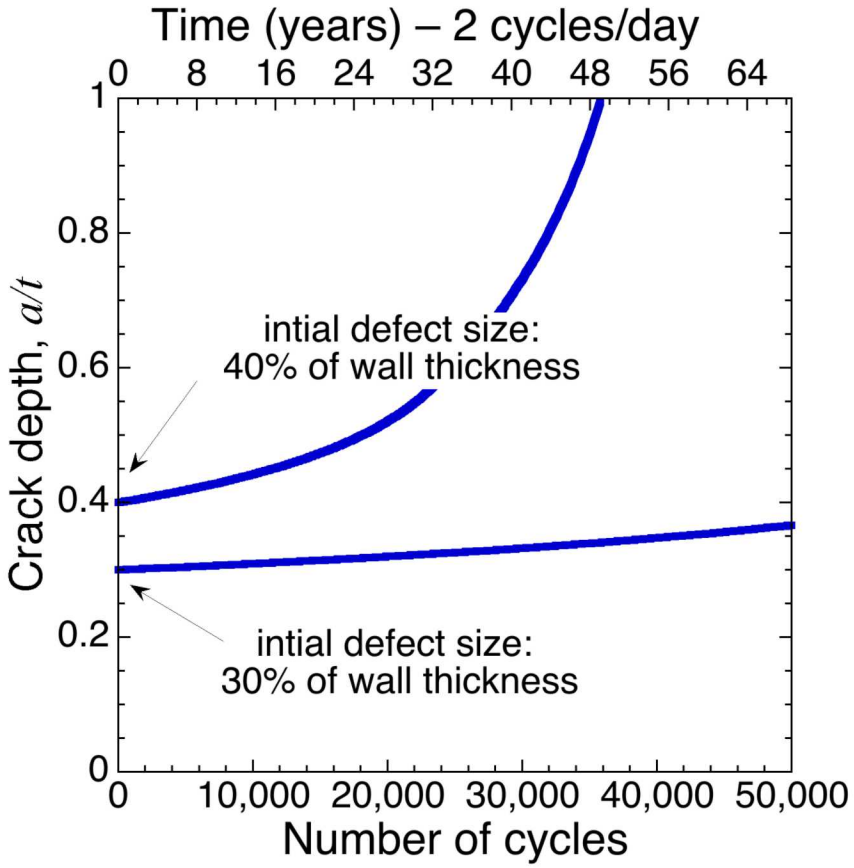
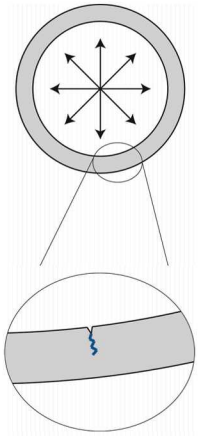
Predicted lifetime of hydrogen pipeline with growing fatigue crack



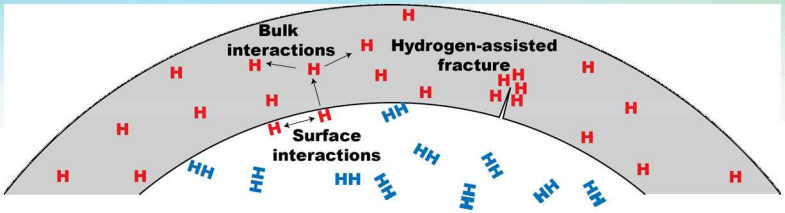
Assuming

- OD = 762 mm, t = 15.9 mm
- Pressure cycles between 4 and 7 MPa
- Constant crack shape ($a/2c$)
- Large initial defects
- Fatigue crack growth rates in pure H_2 (at higher pressure)

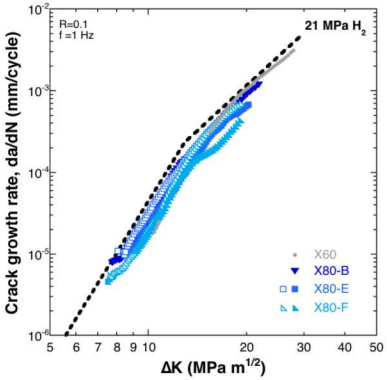


- **10,000s of cycles are needed to extend the crack**
- **At 2 cycles per day, decades are needed to advance the crack**

Summary

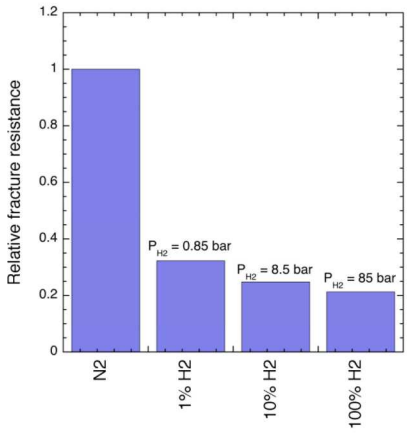


- **What is hydrogen embrittlement and when is it important?**
  - *Hydrogen degrades mechanical properties of most materials*



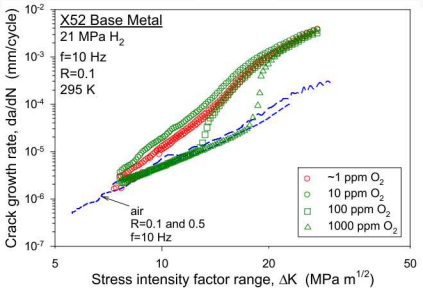
- **How does gaseous hydrogen affect fatigue and fracture of pipeline steels?**
  - *Fatigue is accelerated by >10x and fracture resistance is reduced by >50%*

- **Is there a threshold below which hydrogen effects can be ignored?**
  - ***NO**, even small amounts of hydrogen have large effects*



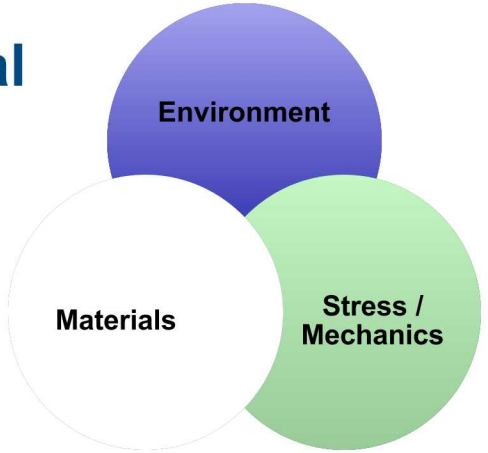
Summary

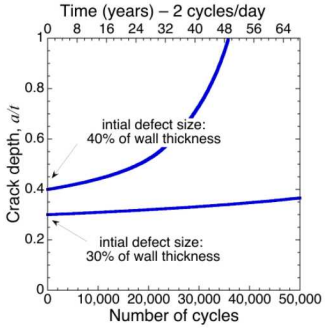
- **Can the effects of hydrogen be masked by other physics?**



  - *Oxygen and other passivating chemical species can mitigate the effects of hydrogen in some cases, which perhaps can be exploited*

- **Where are the gaps in understanding structural integrity of hydrogen pipelines and piping?**
  - *Materials on the distribution side have not been thoroughly evaluated – but operate at low pressure and low stress*





- **What is the implication of hydrogen on life of pipelines and piping?**
  - *In most cases, hydrogen does not threaten the structural integrity of pipelines and piping*

Thank you for your attention

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- Joe Ronevich jaronev@sandia.gov

Additional resources:

- https://energy.sandia.gov/transportation-energy/hydrogen/materials-components-compatibility/
- Technical Reference: https://www.sandia.gov/matlsTechRef/
- Hydrogen-materials database: https://granta-mi.sandia.gov
- Additional detail on hydrogen effects in pipeline steels and life calculations can be found in SAND2018-14013 PE