Hydrogen:
Infrastructure Challenges and Case Studies

Bumpy Road or Expressway to a Clean Fuel Future?

11 March 2021

Agenda

1. Introduction
2. Presentation: Effects of Hydrogen on Elastomers (by Stress Engineering)
3. Presentation: Hydrogen Infrastructure Challenges (by Rebel Group)
4. Panel Discussion

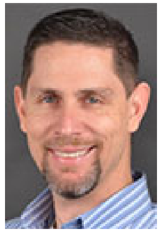
Speakers and Panelists

Marijn Bodelier
(Moderator)
Shareholder
Greenberg Traurig, LLP
Amsterdam

Heike Bernhardt
Technical Director
DEEP.KBB

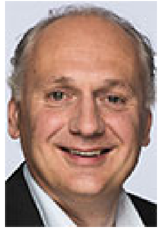
Dr. Martin Borning
Local Partner
Greenberg Traurig Germany, LLP

Dr. Suresh Divi, Ph.D., P.E.
Senior Associate
Stress Engineering

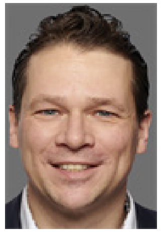


Eric Gage, P.E.
Principal
Stress Engineering

William Garner
Co-Chair, Energy & Natural Resources Practice
Greenberg Traurig, LLP



Marc van der Steen
Director-Shareholder
Rebel Group



Frederik de Vries
Senior Manager
Rebel Group

Effects of Hydrogen on Elastomers

In Natural Gas Transmission and Storage Systems

Date: 11 March 2021

Prepared for: General Audience

Prepared by: Eric Gage, PE

Taking on your toughest technical challenges.

SES Document No.: 2021-03-11 Effects of Hydrogen on Elastomers Rev 0

STRESS ENGINEERING SERVICES INC.®

an employee-owned company

Stress Engineering Services, Inc.

Founded in 1972

Stress Engineering Services is an independent, *employee-owned* consulting engineering firm that provides professional engineering services to a variety of industries worldwide.

Employees: **343** Engineers: **185** (avg tenure 11 yrs.)
Average Experience: 24+ years
Advanced Degrees: 69% Masters / PhD's

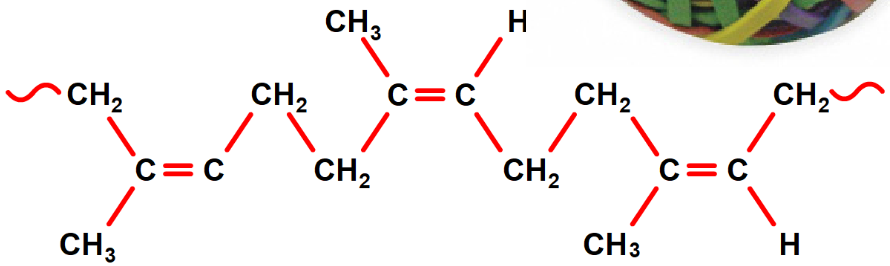
Engineering Disciplines

- **Materials**
- **Polymer Science**
- Mechanical
- Electrical
- Aerospace
- Marine
- Fluid & Thermal
- Civil
- Structural
- Electronics

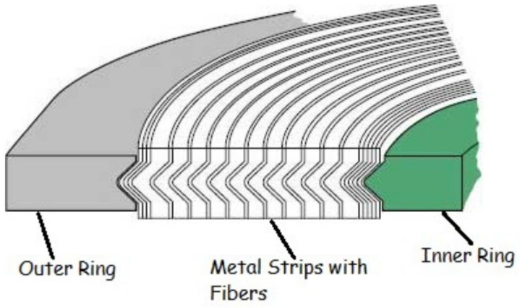
STRESS ENGINEERING SERVICES INC.® an employee-owned company

Elastomers Overview

- **Elastomer** - a polymer, such as natural or synthetic rubber, that is able to resume its original shape when a deforming force is removed
  - Pliable – Returns to its original shape
  - Made of long intertwined molecule chains



- Used frequently as SEALS against pressure
  - Static seals can be metal
  - Moving parts need forgiving seals - polymers

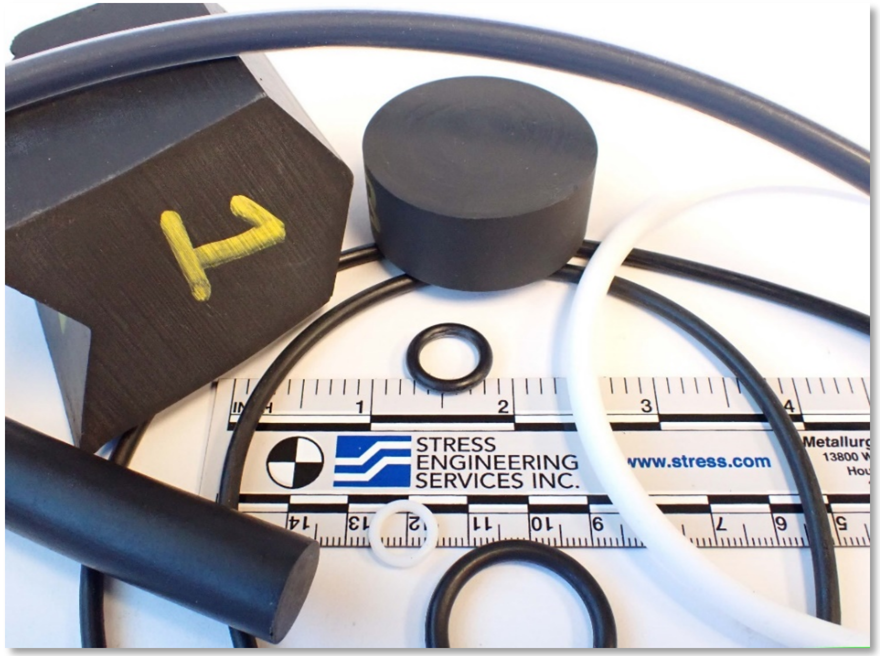


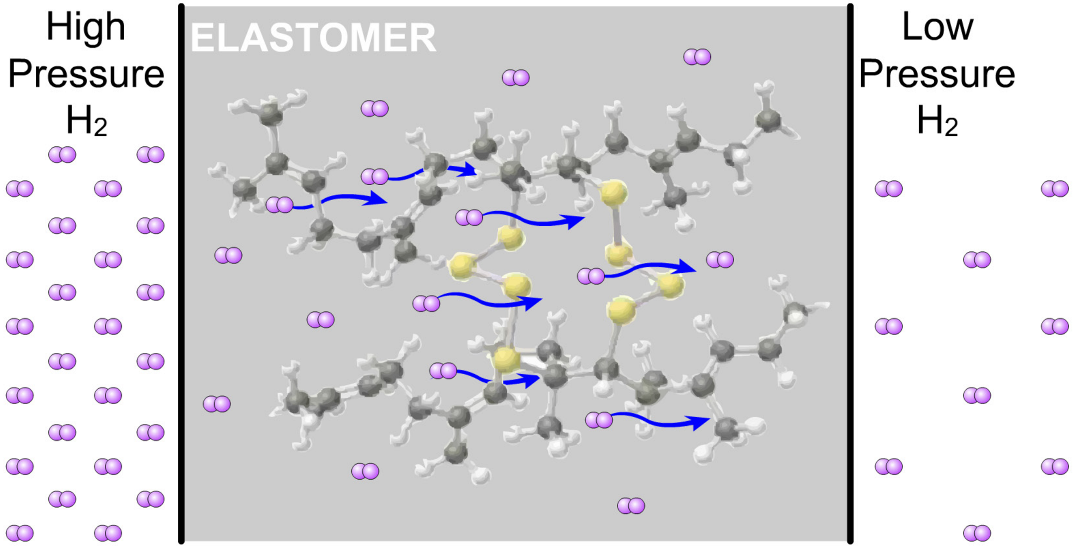
Gas vs. Rubbers

- Diffusion – Gas migrates through rubber
  - Rubbers have voids in their molecular structure
  - Small gas molecules migrate between the chains

- Solubility – Gas that parks inside

- Permeability – product of Diffusivity and Solubility
  - Highly dependent on temperature

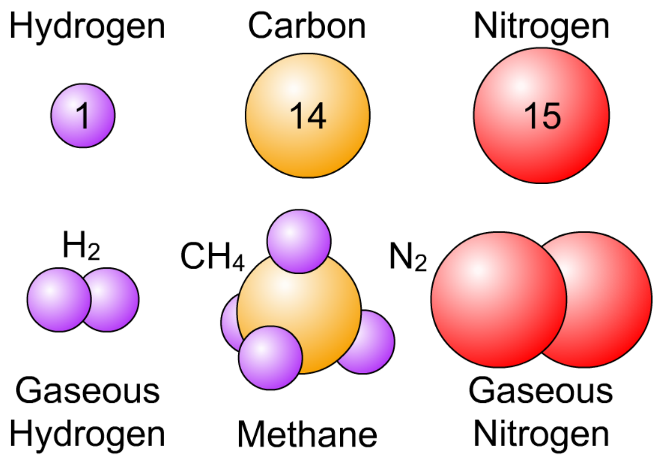




Hydrogen vs. Methane

- Lots of seal materials in Energy Industry
  - NBR (Buna Nitrile)
  - FKM (Viton)
  - PTFE (Teflon)
  - HDPE (High Density Polyethylene)
  - All in different hardnesses

- Diffusion affected by
  - Gas molecule size *(hydrogen 3x volumetric leakage as methane)*
  - Elastomer makeup
  - Temperature
  - Pressure

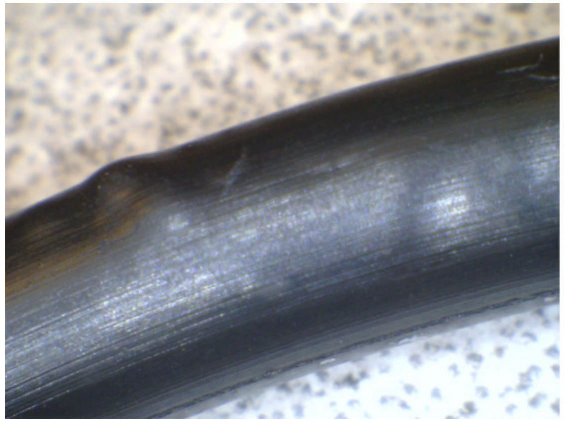


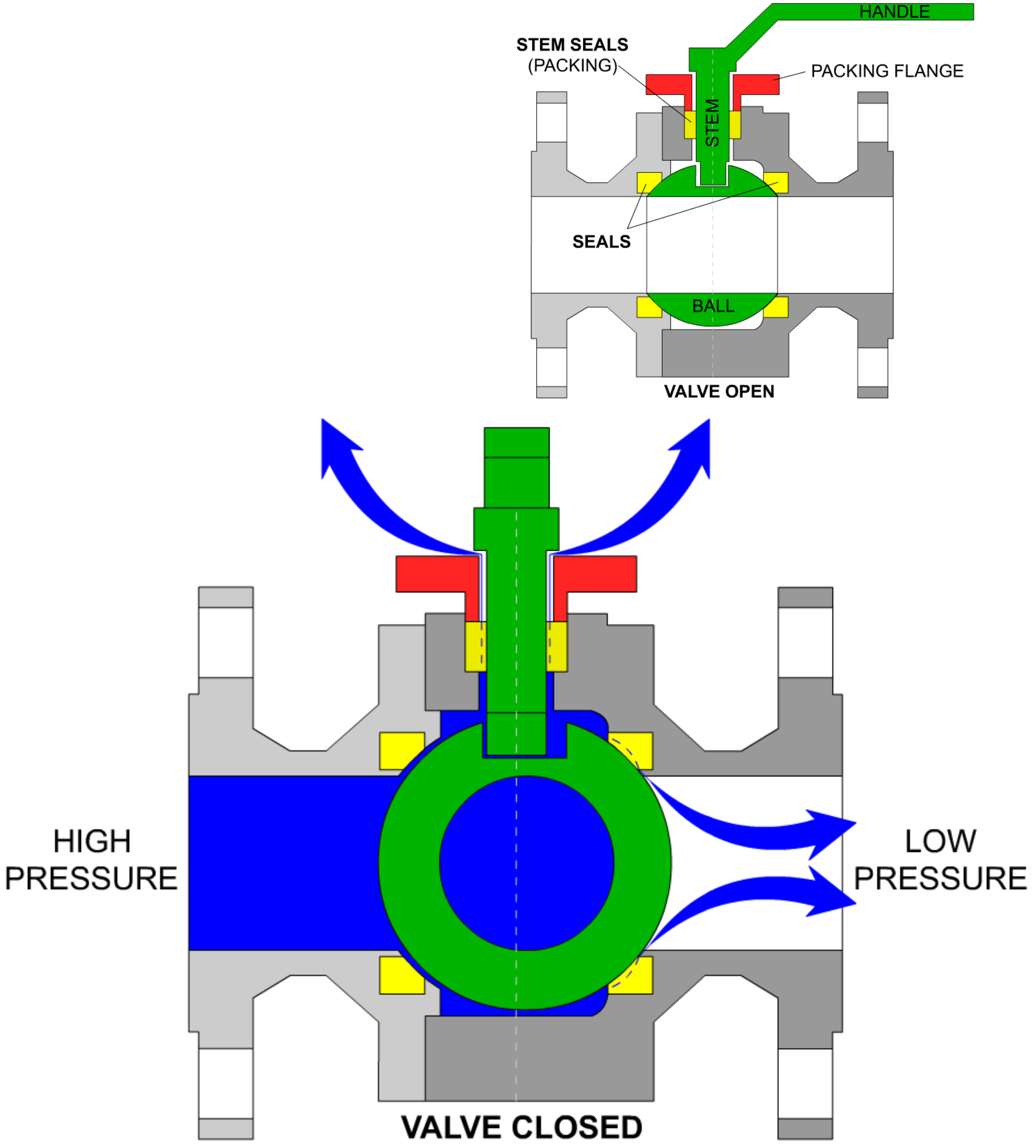
	Gaseous Hydrogen	Methane	
	343 Btu/ft^3	1089 Btu/ft^3	**Heating Value**
	2.55 g/ft^3	22.0 g/ft^3	**Density**

	Permeability ϕ mol H_2/(m s MPa) x10^9	
	20°C (68°F)	80°C (176°F)
Thermoplastics		
HDPE	0.8	
PTFE	3.2	
Elastomers		
NBR - Shore 50	2.0	17.0
NBR - Shore 70	1.5	12.1
FKM	1.5	18.6

H_2 Effect on Elastomers in Transport/Distribution Systems

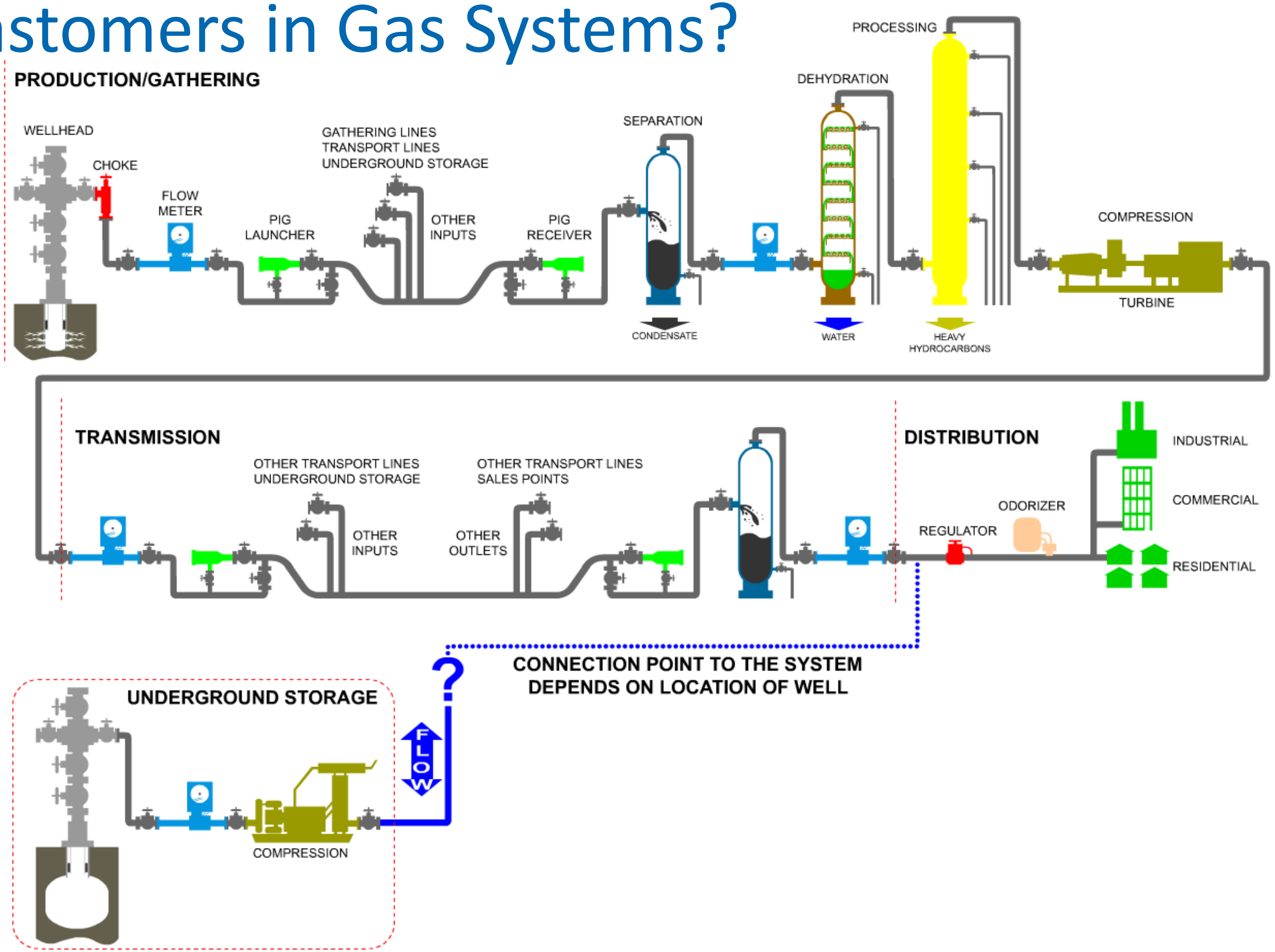
- Leakage
  - External seals: leak to environment
  - Internal seals: leak to lower pressure
- Rapid decompression failure
  - Rubbers get “the bends” if depressurized too quickly
  - Can likely control procedurally
    - Not many items that “blow down” quickly
    - Need protocols for slow bleeds
- Change in elastomer material properties
  - Increased compression set
  - Yield strength
  - Young’s modulus





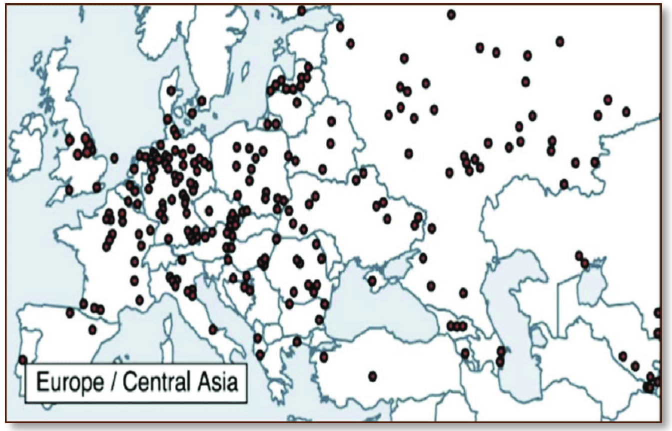
Where are the Elastomers in Gas Systems?

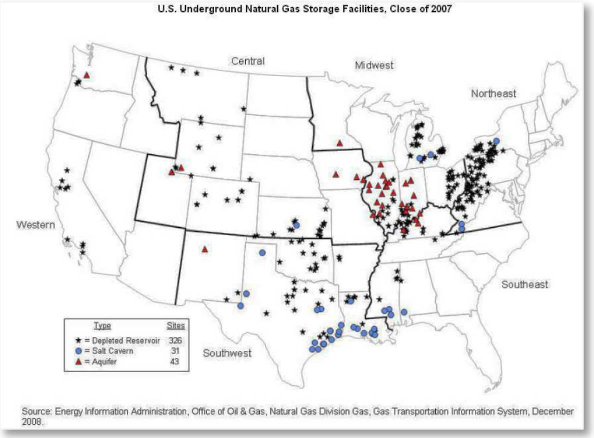
- *Hydrogen storage in/out can be anywhere in a given gas system*
    1. *Flange seals are likely okay*
    2. *Dynamic seals (valves) and "Jewelry" on system need to be reviewed*
        1. *Regulators*
        2. *Liquid level switches*
        3. *Sight glasses*
        4. *Valve seals, stem packing, diaphragms*
        5. *Relief valves*
        6. *Pig trap closure seals/pig signals*
        7. *Meter run orifice plate access ports*

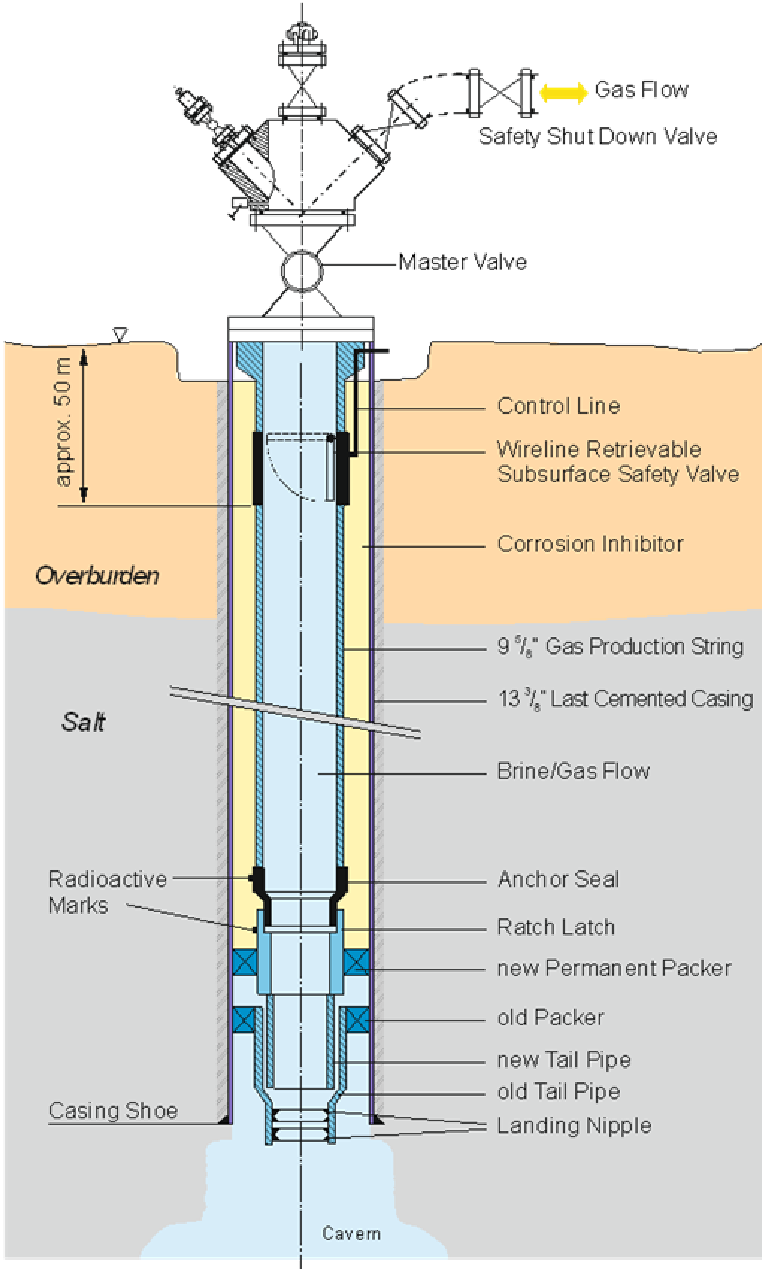


Subsurface Storage Facilities

- Accessing underground volumes
  - Casing and tubing: Pipe to get you deep underground
  - Compressors: Pumps to get gases in/out
- Pressure differences
  - Casing
  - Tubing
- Downhole packers seal between casing and tubing
  - Mechanically energized packer element
  - Static seals "O-rings"
  - Environment is hotter/higher pressure than distribution systems

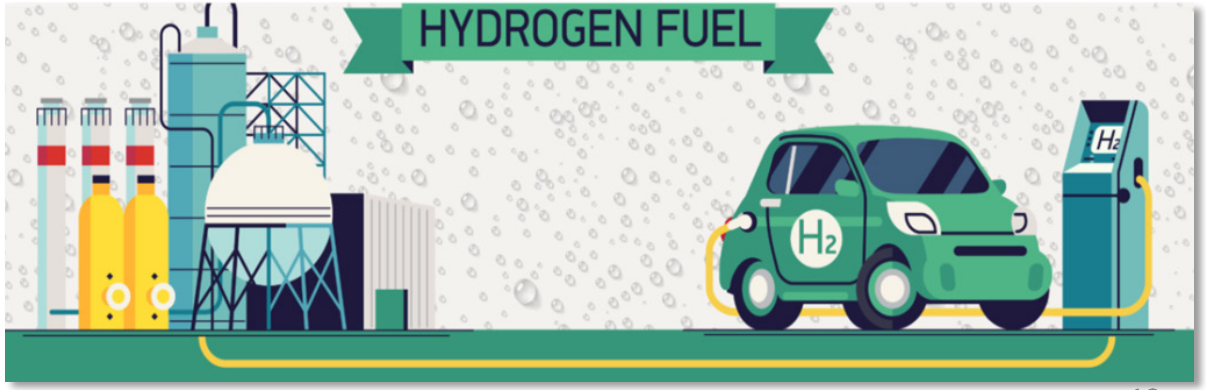






Summary

- Blended vs Pure Hydrogen
  - Putting H_2 into existing infrastructure can work as “energy battery”
  - Many studies show up to 30% hydrogen can be added
- May require different elastomers/polymers for different applications
  - There will be external residual hydrogen leakage
  - May have to shift away from elastomers toward plastics to reduce leakage
  - Plastics have their own installation and sealing issues
- Component-by-component review needed
- Long term effects show up later



Effect of Hydrogen on Metals

In Natural Gas Transmission and Storage Systems

Date: 11 March 2021

Prepared for: General Audience

Prepared by: Suresh Divi, PhD, PE

Taking on your toughest technical challenges.

SES Document No.: 03-11-2021 Effects of Hydrogen on Metals

STRESS ENGINEERING SERVICES INC.®

an employee-owned company

Natural Gas and Hydrogen in Gas Distribution System

Gas Distribution System

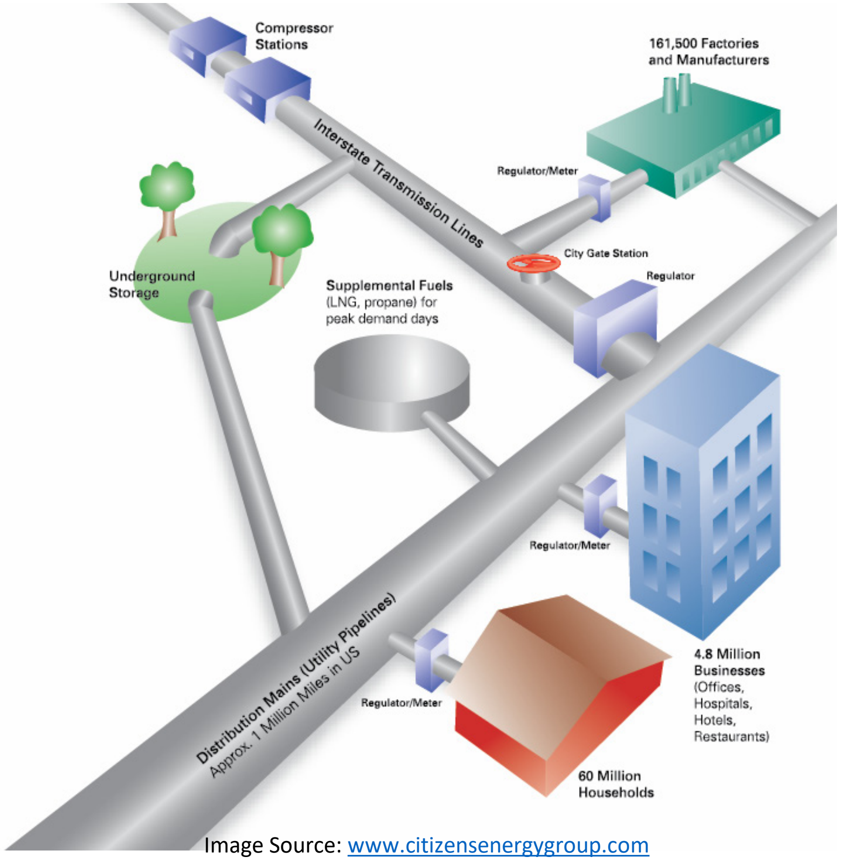


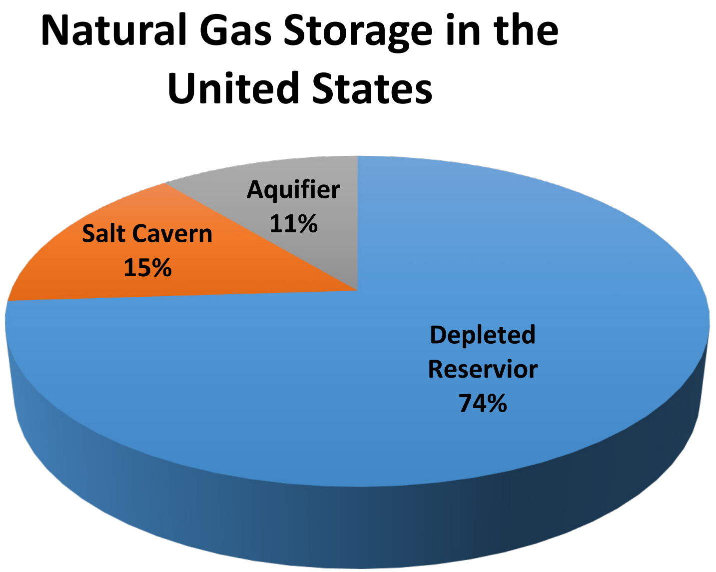
Image Source: www.citizensenergygroup.com

Interstate Transmission Lines

Image Source: www.orbitaleng.com

Underground Storage

- **United States uses three main types of natural gas underground storage facilities**
  - *Depleted natural gas or oil fields*
  - *Salt caverns*
  - *Aquifers*



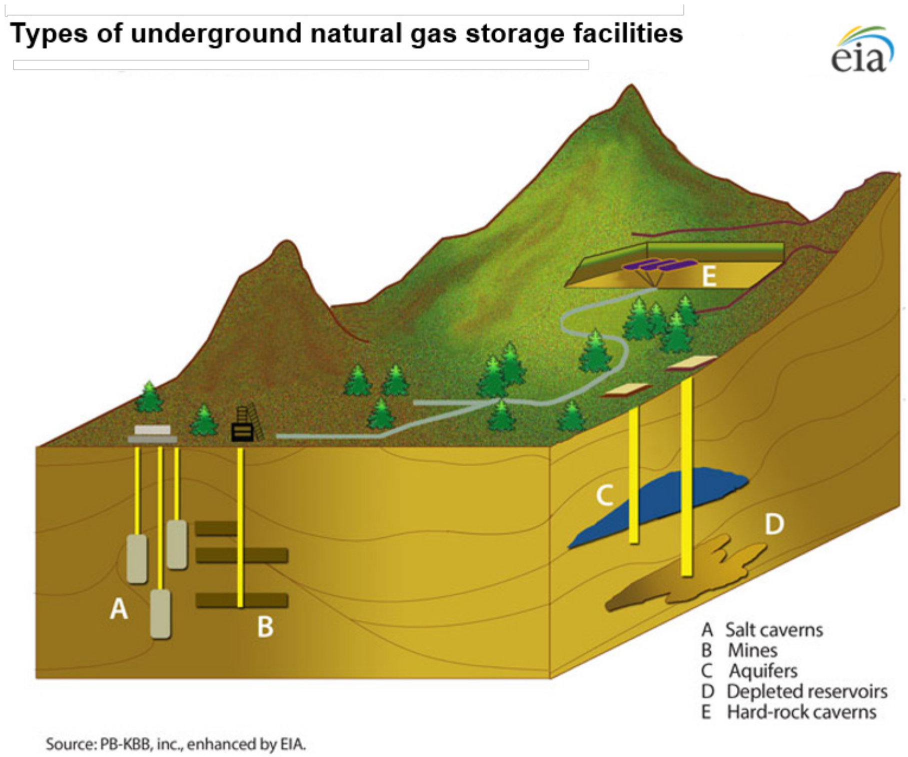
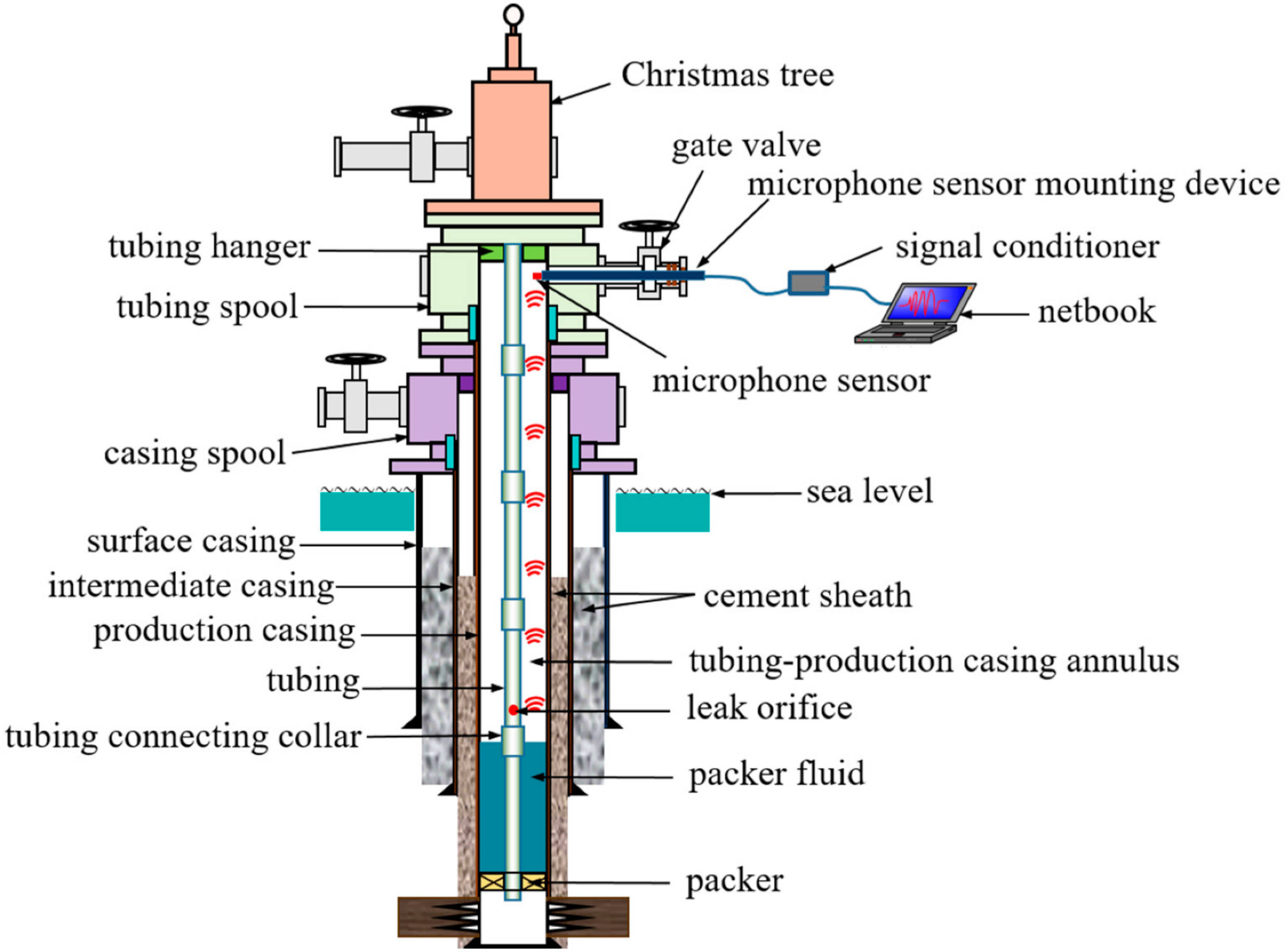


Image Source: http://naturalgas.org/wp-content/uploads/2013/09/storage_graph2.gif

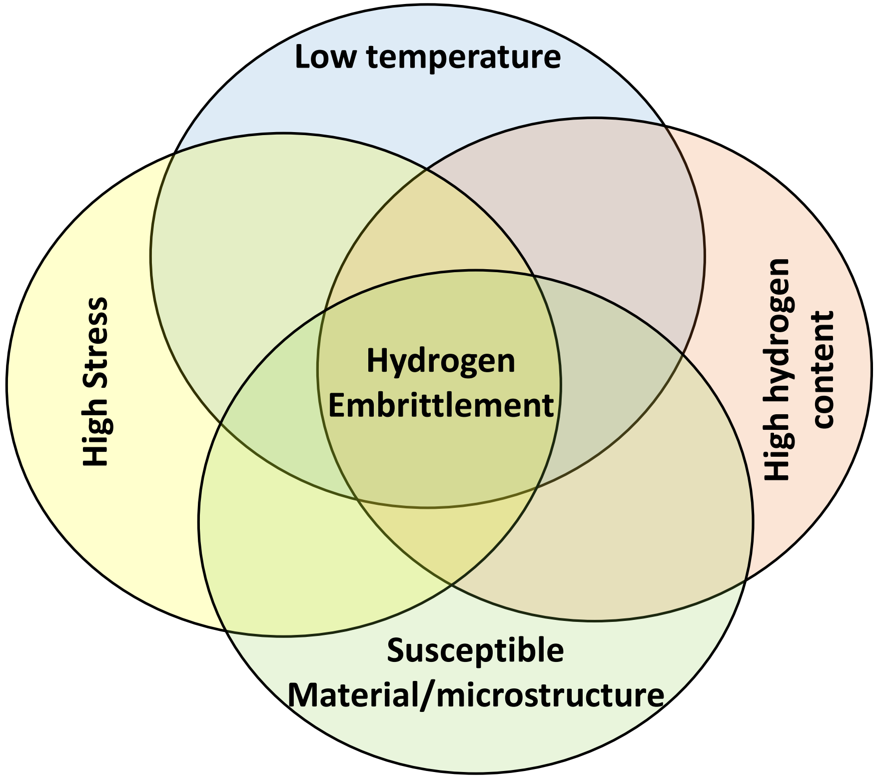
STRESS ENGINEERING SERVICES INC.® an employee-owned company

Metal Casing and Tubing



Challenges

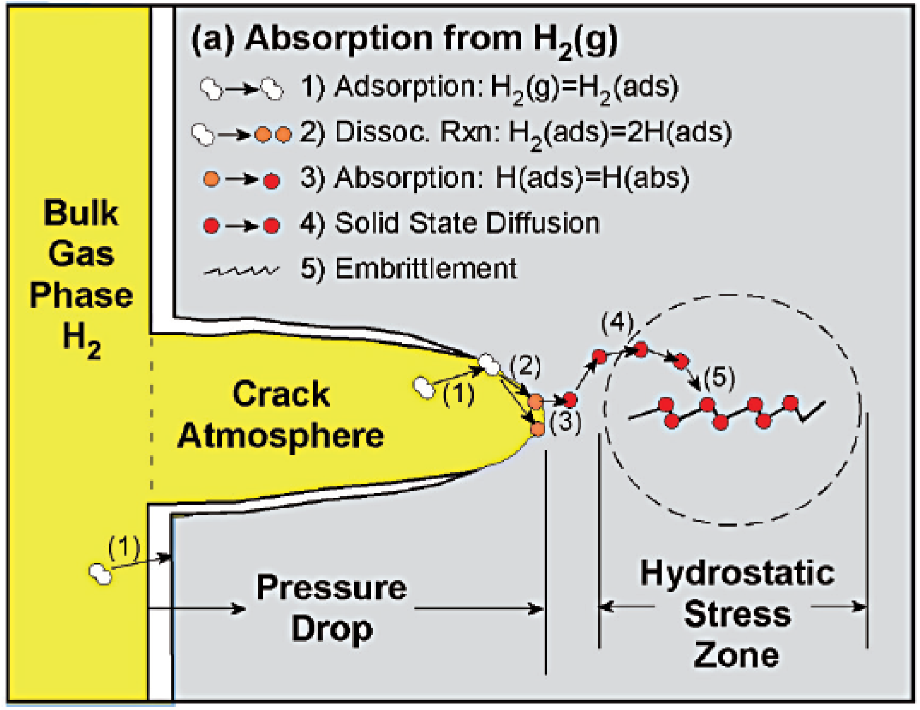
- Natural gas with blended hydrogen under the operating pressure and stress levels (residual or applied), hydrogen-induced embrittlement (HE) could be a concern for steel pipes/tubes



HE Mechanism

- Hydrogen embrittlement (HE) is also known as hydrogen induced cracking or hydrogen attack. Materials that are most vulnerable are high-strength steels

- Hydrogen enters and diffuse through a metal surface. Hydrogen pressure builds at crystallographic defects (dislocations and vacancies) or discontinuities (voids, inclusion/matrix interfaces) causing minute cracks to form and eventually lead to metal embrittlement



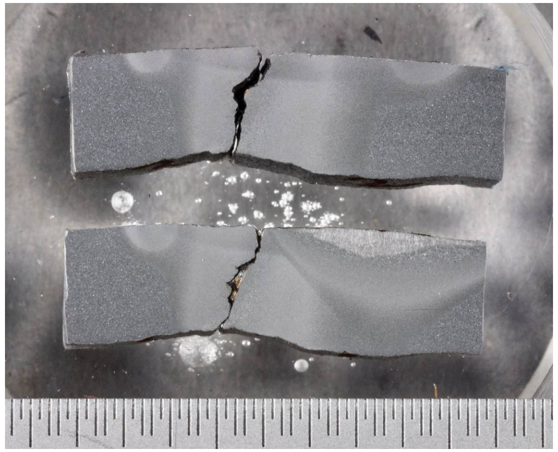
Sources of images: http://www.heat-treat-doctor.com/

HE Factors

- The severity and mode of the hydrogen damage depends on many factors including
  - Hydrogen source (either direct or indirect exposure)
  - Exposure time
  - Temperature
  - Pressure
  - Type of metal/alloy
  - Metallurgy/Metal Processing
    - defects/discontinuity in microstructure
    - surface conditions
    - heat treatment
    - residual stress
    - applied stresses

STRESS ENGINEERING SERVICES INC. an employee-owned company

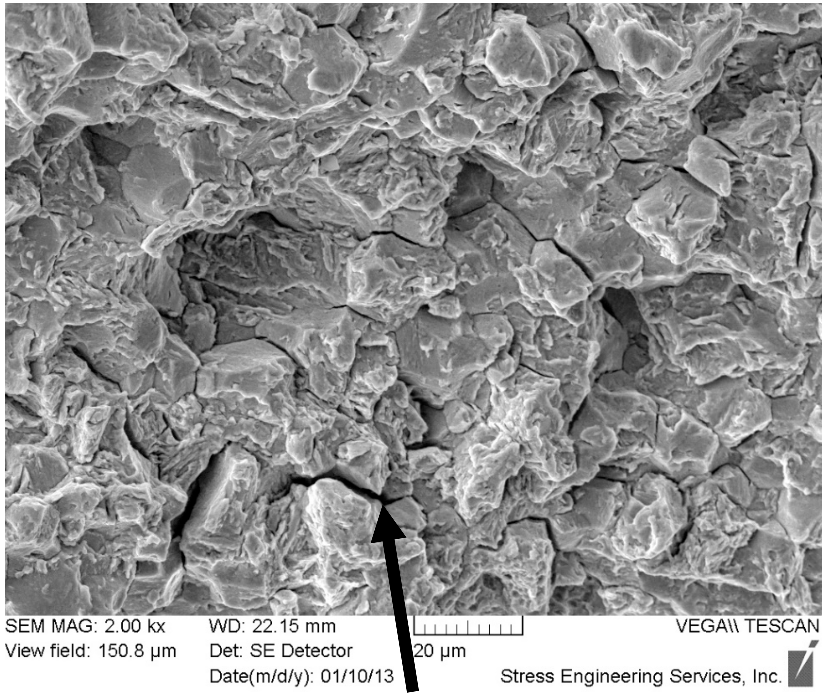
HE of Steel



- Hydrogen embrittlement (HE) of steel tube/pipe is subjected to concurrent hydrogen invasion with mechanical loading while being exposed to natural gas/hydrogen mixtures

- Susceptibility of steels to HE depends on the steel process history, hydrogen concentration, metallurgy, etc.

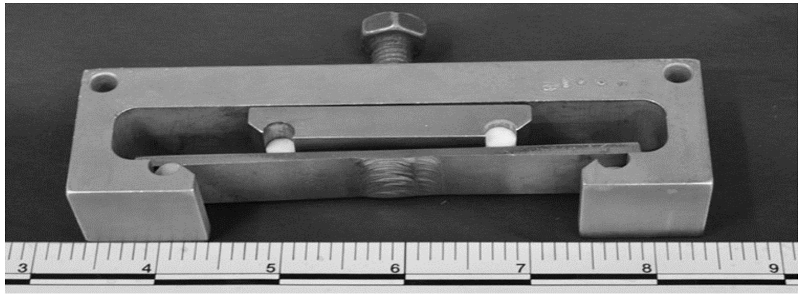
- Often the HE failure mode of steel is brittle (intergranular) in nature, which is catastrophic



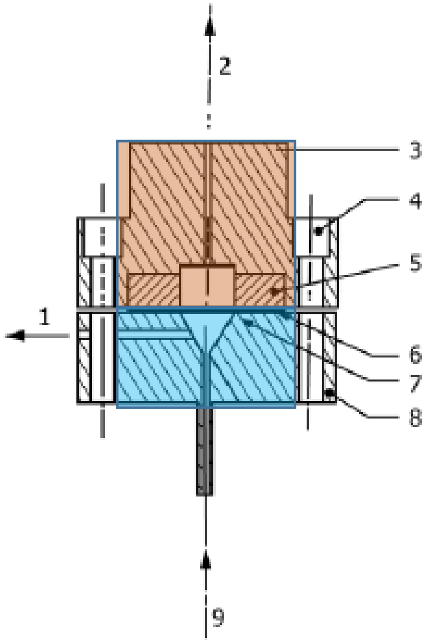
Intergranular fracture due to hydrogen Embrittlement (HE) (image magnification: 2000X)

HE Testing

- **SES Hydrogen Embrittlement Test Methods (Lab Scale)**
  - Disk Pressure Test (ASTM F1459)
  - Constant Load test
  - Electrochemical Hydrogen Charging
  - Four-Point Bend Test
  - High Pressure Tubular Test



Four-point bend test jig



1. Port for evacuation and flow adjustment
2. Discharge Port
3. Upper flange
4. Bolt
5. High strength steel ring
6. Disk
7. O-ring
8. Lower Flange
9. Gas Inlet

Disk pressure test cell

Summary

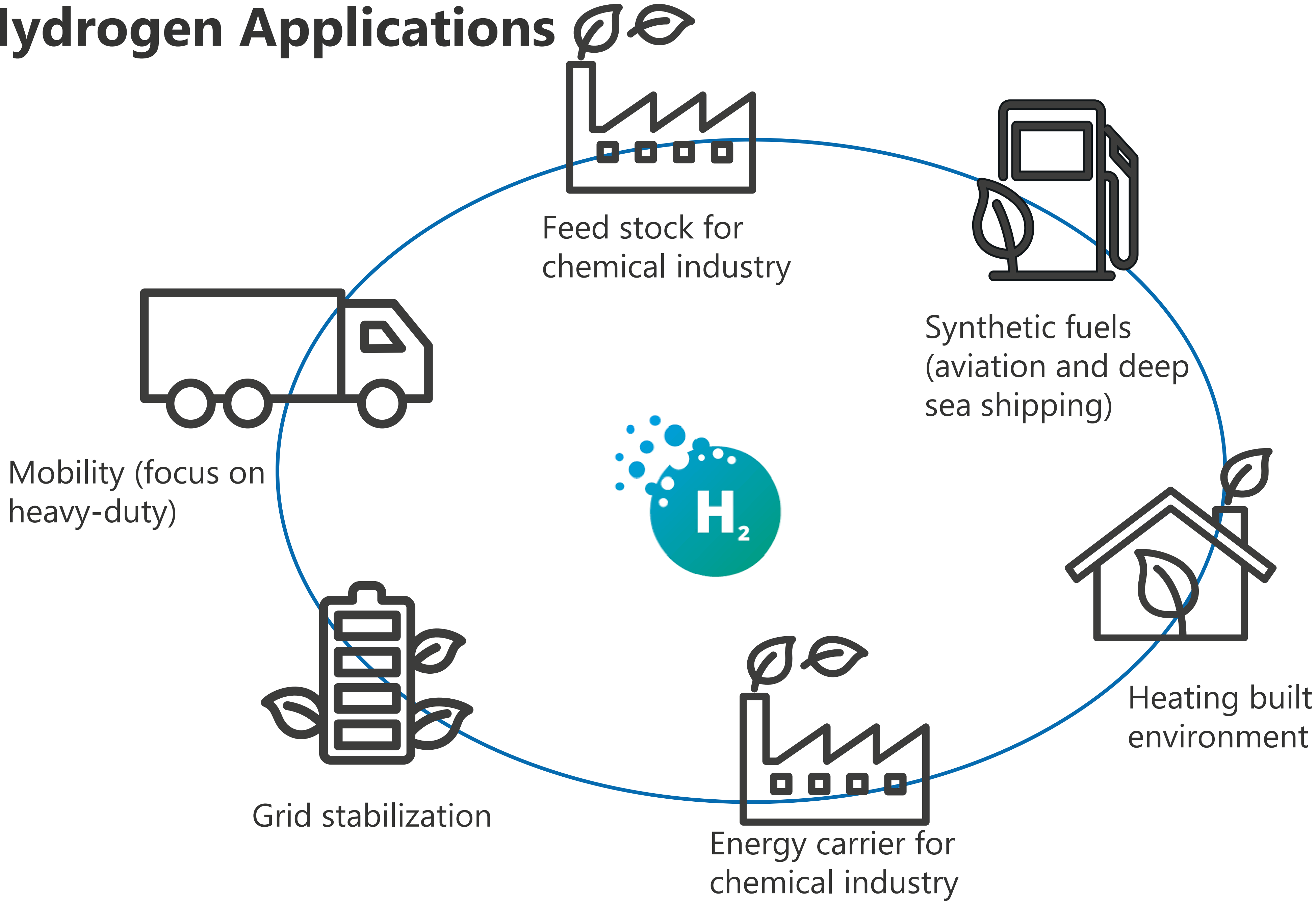
- **Blending hydrogen** into the existing natural gas pipeline network and underground storage has been proposed as a means of increasing the output of renewable energy systems such as large wind farms
- Natural gas with blended hydrogen under the operating pressure and stress levels (residual or applied), hydrogen-induced embrittlement (HE) could be a concern for steel tubing and pipes
- Hydrogen embrittlement (HE) of the steel may occur when steel is subjected to concurrent hydrogen invasion with mechanical loading while being exposed to natural gas/hydrogen mixtures
- HE testing and understanding the metallurgy and other factors are necessary to address the effects of natural gas/hydrogen mixtures on HE mechanism

Challenges for Hydrogen Infrastructure

Experience from Hydrogen Bus Implementation

AEBEL

Hydrogen Applications



Hydrogen Mobility in the Netherlands

- H2Bus Europe: 600 buses
- JIVE2: 60 in the Netherlands

- Inland Waterway Transport (NPRC, Nouryon, Nedstack)

- VDL/DAF development of H2 trucks in the Netherlands
- Hyzon
- Hyundai and Toyota
- HyTruck 1.000 truck project (AirLiquide)

Cars and taxi's:
- NL: 367 cars
- Paris: 600 by end 2020

- Trains: experiments with fuel cell trains in north part of the Netherlands

JIVE-2 project – FCH-JU funded

Objectives

- Deploy 152 FC buses across 14 cities
- Achieve a maximum price of €625k for a standard fuel cell bus
- Operate buses for at least three years / 150,000 km
- Validate large scale fleets in operation
- Enable new entrants to trial the technology
- Demonstrate routes to low cost renewable H_2
- Stimulate further large scale uptake

Benelux cluster
(60 FC buses)

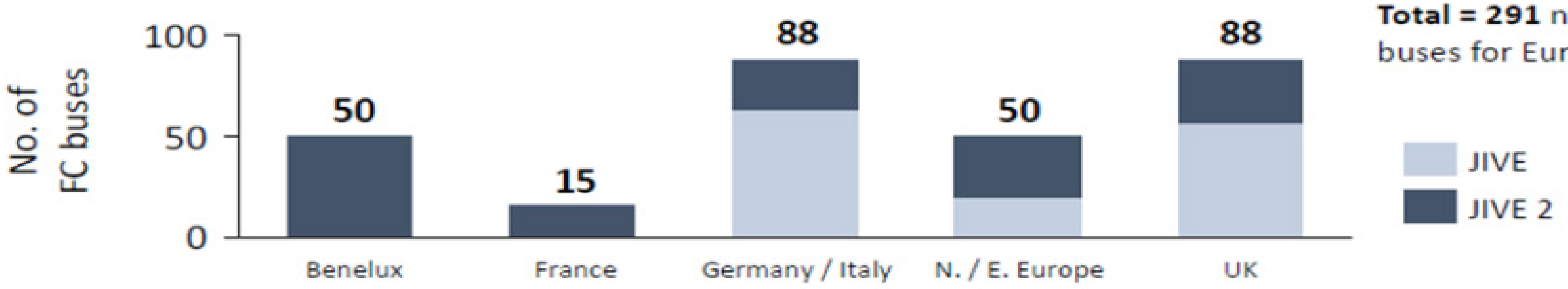
France Cluster
(15 FC buses)

Germany / Italy Cluster
(88 FC buses)

Northern / Eastern Europe Cluster
(50 FC buses)

UK Cluster
(88 FC buses)

Total = 291 new FC buses for Europe



Overview Benelux Cluster & Current Buses (in delivery)

Total of 60 buses in 4 project sites (start operation in 2021):

A Zuid-Holland: 20 buses (Solaris) + 1 HRS
PTA: Province Zuid-Holland
PTO: Connexxion
H2 infrastructure supplier: Everfuel/NEL
Start operation: December 2021

B Groningen-Drenthe: 20 (Groningen) +10 (Emmen) buses (Van Hool)
HRS: 2 (Groningen and Emmen)
PTA: OV-Bureau Groningen-Drenthe
PTO: (QBUZZ)
H2 Infrastructure supplier: Shell
Start operation: asap (delay due to Covid19)

C Gelderland: 10 buses (Solaris)
PTA: Province of Gelderland
PTO: Arriva
H2 infrastructure supplier: TBD
Start operation: December 2021

Province of Zuid-Holland

- Public transport concession Hoeksche Waard Goeree Overflakkee
- Operator Connexxion (Transdev)
- 4 H2 buses already in operation > fueling at HRS Rhoon

<u>JIVE2-project: split procurement</u>

- 20 buses ordered by Public Transport Operator at Solaris
- HRS procured by Province (PTA) using competitive dialogue

Challenge: Business Case

Main cost drivers for bus public transport:

- Investment costs of vehicle
- Maintenance costs
- Energy costs
- Personnel costs

Cost drivers	Diesel	Hydrogen	Battery electric
Investment costs	€ 225K (8-10 years)	€ 550K – € 625K (12-15 years)	€ 350K – € 425K (12-15 years)
Maintenance costs	€ 0,23 / km	€ 0,35 (including FC refurbishment)	€ 0,18 / km
Energy costs	€ 0,50 /km	€ 0,65 / km	• Electricity costs (€0,10/kWh) • Charging type • Country specific • Green/grey • Available net capacity

However, there are a number of opportunities for FCB's:

- Public push for ending tailgate emissions
- Easier in operation (faster refilling, more autonomy, less infrastructure issues)
- Integration of charging infrastructure is not always possible due to limited available grid capacity / insufficient space
- FCB's are lighter (specifically compared to overnight charging BEB's). Less energy loss and more passengers
- Costs for BEB increase for longer autonomous range (>300 km/d). Either due to larger batteries or due to charging infrastructure costs
- Less additional buses required due to limited range and long charging times

5 Challenges for Hydrogen Refilling Stations

Challenge 1: Increase Flexibility of HRS Stations

- Expectation is that usage will increase over coming years
- Current HRS solution engineered on ‘fit for very specific purpose and location’
- High engineering costs and limited standardization in components

- ⊳ Scalable solutions: possibility to adapt to increase of volume with minimal additional cost
- ⊳ Modular solutions: increase standardization, reduce engineering costs, limit construction time

5 Challenges for Hydrogen Refilling Stations

Challenge 2: Separate Procurement Procedures Bus and HRS

- Currently, HRS and bus often procured separately (buses by PTO, HRS by PTA)
- Introduces risks on interfaces (who is responsible for issues)
- Requires knowledge at PTA that is often not available (not core competence)

- ⊳ Responsibility for bus and HRS in hand (compared to battery electric in the Netherland)
- ⊳ Make arrangements for transfer at end of public transport service contract in order to use assets over full technical life

5 Challenges for Hydrogen Refilling Stations

Challenge 3: Gain Operational Experience for Larger (bus) Fleets

- Lack of experience on operation of larger bus fleets (10+)
- Lack of long-term operational data (up-time, maintenance, spare parts, etc.)
- Many ideas, dogma’s, assumptions on FCB’s around that reduce uptake speed (e.g. at PTA’s and PTO’s)

⊳ Develop and share fact based knowledge based on operational experience

5 Challenges for Hydrogen Refilling Stations

Challenge 4: Insufficient Hydrogen Knowledge at Permitting Organizations (specifically on safety issues)

- Hydrogen in mobility is new and requires specific knowledge for permitting organizations (municipalities)
- Lack of specific knowledge and standards
- Permitting processes are often long (1 – 2 years) and require perseverance, time and money
- Hindenburg still casts a shadow on current developments

⊳ Develop shared knowledge base at permitting organizations

⊳ Develop standards for permitting, safety regulations, risk management, incident response, etc.

5 Challenges for Hydrogen Refilling Stations

Challenge 5: Lack of Availability of Green Hydrogen

- Insufficient green energy available for total demand in Europe
- Additional disadvantage in energy loss due to conversion from green electrons to green molecules
- Demand for hydrogen in industry expected to rise fast

⊳ Investments in green energy necessary

⊳ Transparent certification schemes (e.g. CertifHY) necessary for accountability

But maybe the most persistent challenge……

Hydrogen and battery electric are no competitors!

Both have different applications and both will be necessary in order to meet the climate goals of the future.

Marc van der Steen
+31 6 10 32 51 00
Marc.vanderSteen@rebelgroup.com

Frederik de Vries
+31 6 13 77 32 49
Frederik.deVries@rebelgroup.com

Wijnhaven 23
3011 WH Rotterdam
Nederland
+31 10 275 59 90

info@rebelgroup.com
www.rebelgroup.com

Infrastructure Challenges

- Relative young market: no desire for system responsibility (integration of bus and HRS) within private sector > interface responsibility issues
- TCO for FCEV is significantly higher than for diesel. Both CAPEX and OPEX are more expensive. Main driver is energy part of OPEX
- No / limited standardized solutions for large scale HRS.
- Different options for transportation of hydrogen to stations (trucking, pipeline)
- High pressure (350 bar) for refueling is demanding on compressors
- Specifications on purity difficult to meet
- Definition of ‘green’ hydrogen is complicated.
- Green hydrogen import from neighboring counties (e.g. Belgium, Germany)
- Permitting and external safety are challenging > new and specialized topic for municipalities


Q&A

GT Contact Details

- Bill Garner: GarnerW@gtlaw.com
- Martin Borning: Martin.Borning@gtlaw.com
- Marijn Bodelier: BodelierM@gtlaw.com

