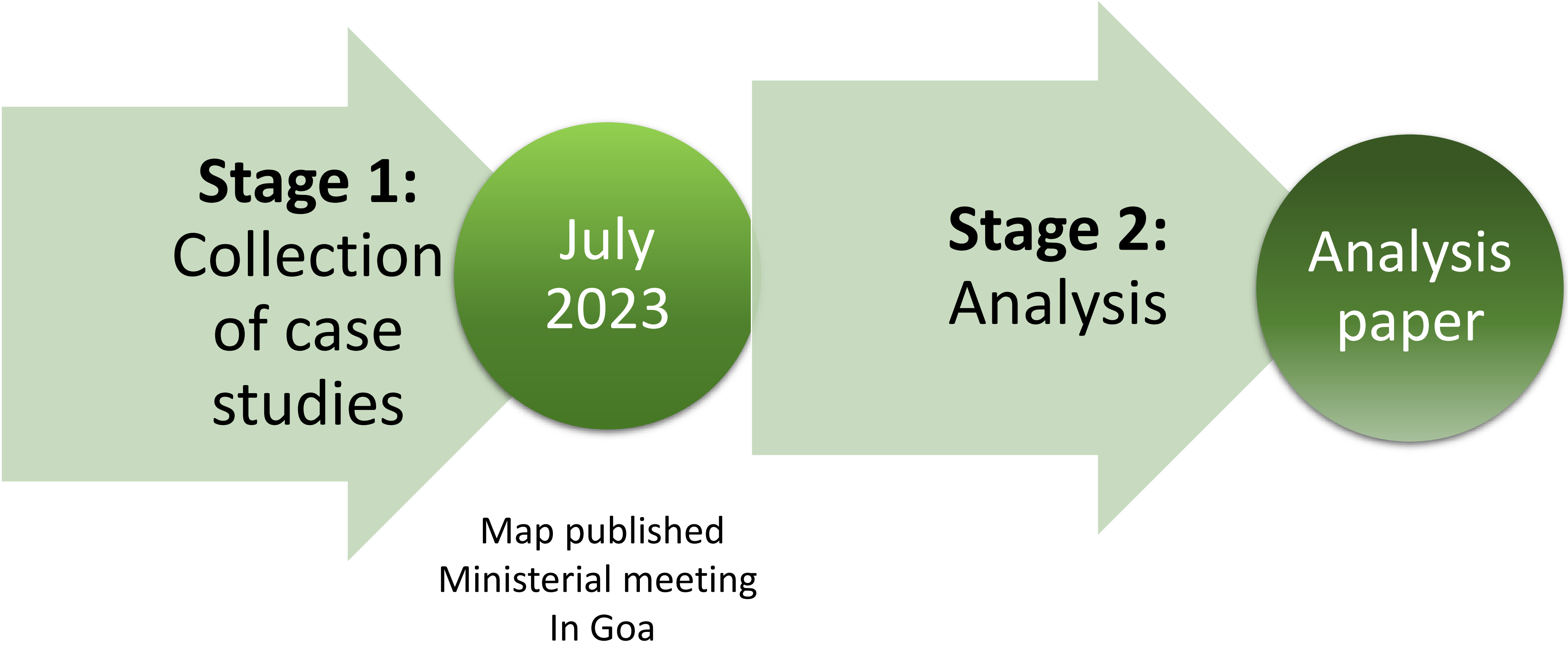
CLEAN HYDROGEN MISSION

Storage & Distribution Working Group

Hydrogen pipeline distribution workshop

Trevor Rapson, Canberra, Australia
Trevor.Rapson@csiro.au


Stage 1:
Collection of case studies
July 2023
Map published
Ministerial meeting
In Goa
Stage 2:
Analysis
Analysis paper

10 countries
45 case studies

26 demonstration projects
19 translational research projects

25 distribution focus
32 storage focus

Technology focus:
- 12 pipelines
- 10 liquid carriers
- 10 underground storage
- 5 liquid hydrogen

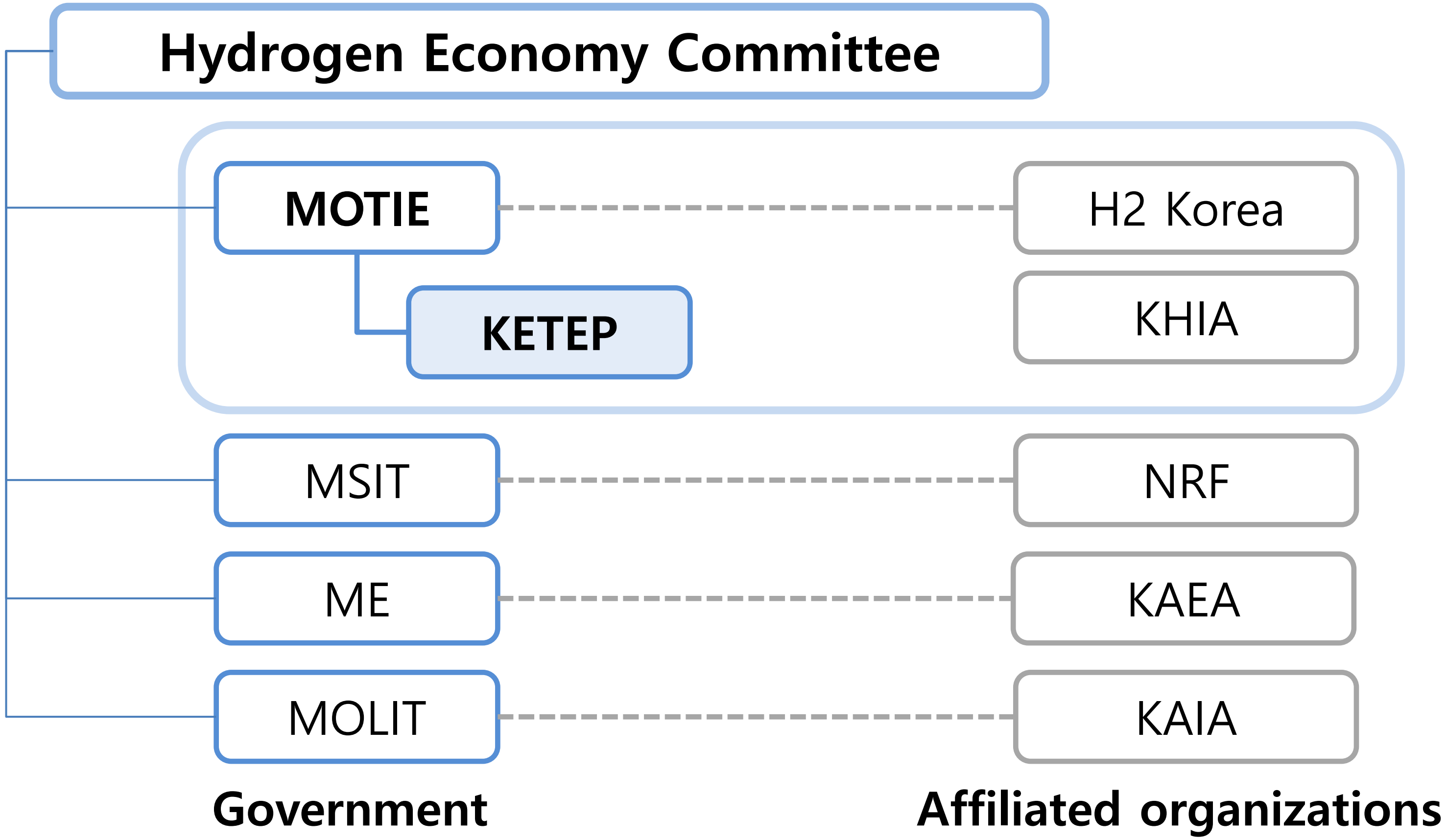
Status of Hydrogen Pipeline Transport in Korea

2023. 9. 27

Dr. Jin-Nam Park
Korea Institute of Energy Technology Evaluation and Planning

KETEP
한국에너지기술평가원
Korea Institute of Energy Technology Evaluation and Planning

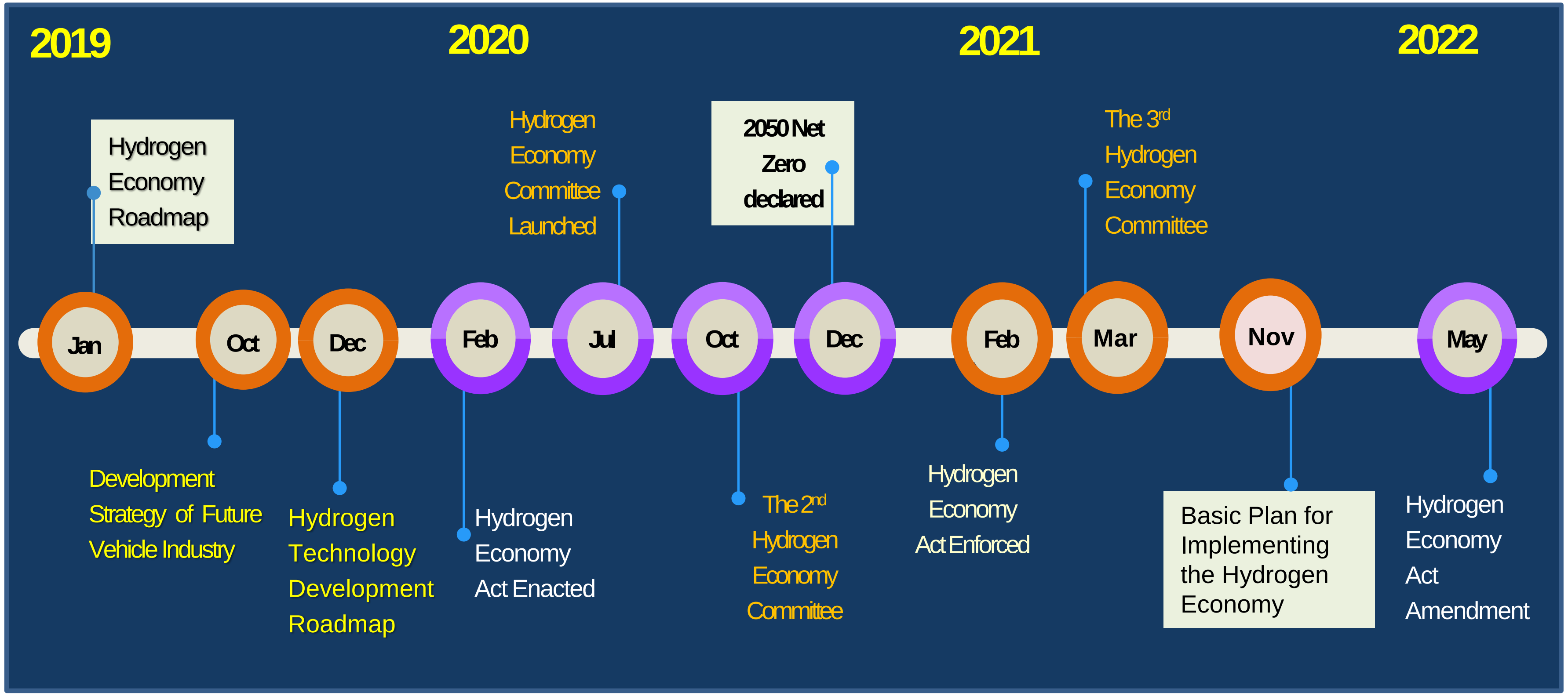
H_2 Related Organizations in Korea



MOTIE: Ministry of Trade, Industry and Energy, MSIT: Ministry of Science and ICT, ME: Ministry of Environment, MOLIT, Ministry for Land and Infrastructure, H2 Korea: Hydrogen Convergence Alliance, KHIA: Korean Hydrogen Industry Association, NRF: National Research Foundation, KAEA: Korea Automobile Environmental Association, KAIA: Korea Agency for Infrastructure Technology Advancement

Hydrogen History in Korea

- "Hydrogen Economy Roadmap('19.1)" is revised to "Basic Plan for Implementing the Hydrogen Economy('21.11)" to achieve "2050 Net Zero"



Korean Hydrogen Economy Roadmap('19.01)

Vision: World's Top-Class Country in H_2 Economy

		2018	2022	2040
Hydrogen vehicles(FCEV) (export) (domestic demand)		18,000 (900) (900)	81,000 (14,000) (67,000)	6,200,000 (3,300,000) (2,900,000)
Fuel Cells	Power Gen. (domestic demand)	307 MW (in total)	1.5 GW (1 GW)	15 GW (8 GW)
	Homes/Buildings	7 MW	50 MW	2.1GW
Hydrogen Supply		130,000t/year	470,000t/year	5,260,000t/year↑
Hydrogen Price		-	KRW 6,000/kg	KRW 3,000/kg

Strategies

'18 → '22 → '30 → '40

Preparation of hydrogen economy	Expansion of hydrogen economy	Leadership of hydrogen economy
▪Hydrogen industry eco-system ▪Infrastructure and legal/institutional basis	▪Increase in hydrogen use ▪Large-scale supply-demand system	▪Overseas hydrogen production and water electrolysis ▪CO2-free supply-demand system

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Korean Hydrogen Economy Roadmap('19.01)

HRS Deployment Plan

2018	2019	2022	2040
			
Establish 14 fueling stations mainly in hub cities.	Establish cumulative total of 86 fueling stations to form regional transportation networks.	Establish cumulative total of 310 fueling stations nationwide while expanding and connecting the regional networks.	Establish cumulative total of 1,200 fueling stations nationwide.

Korean Hydrogen Economy Roadmap('19.01)

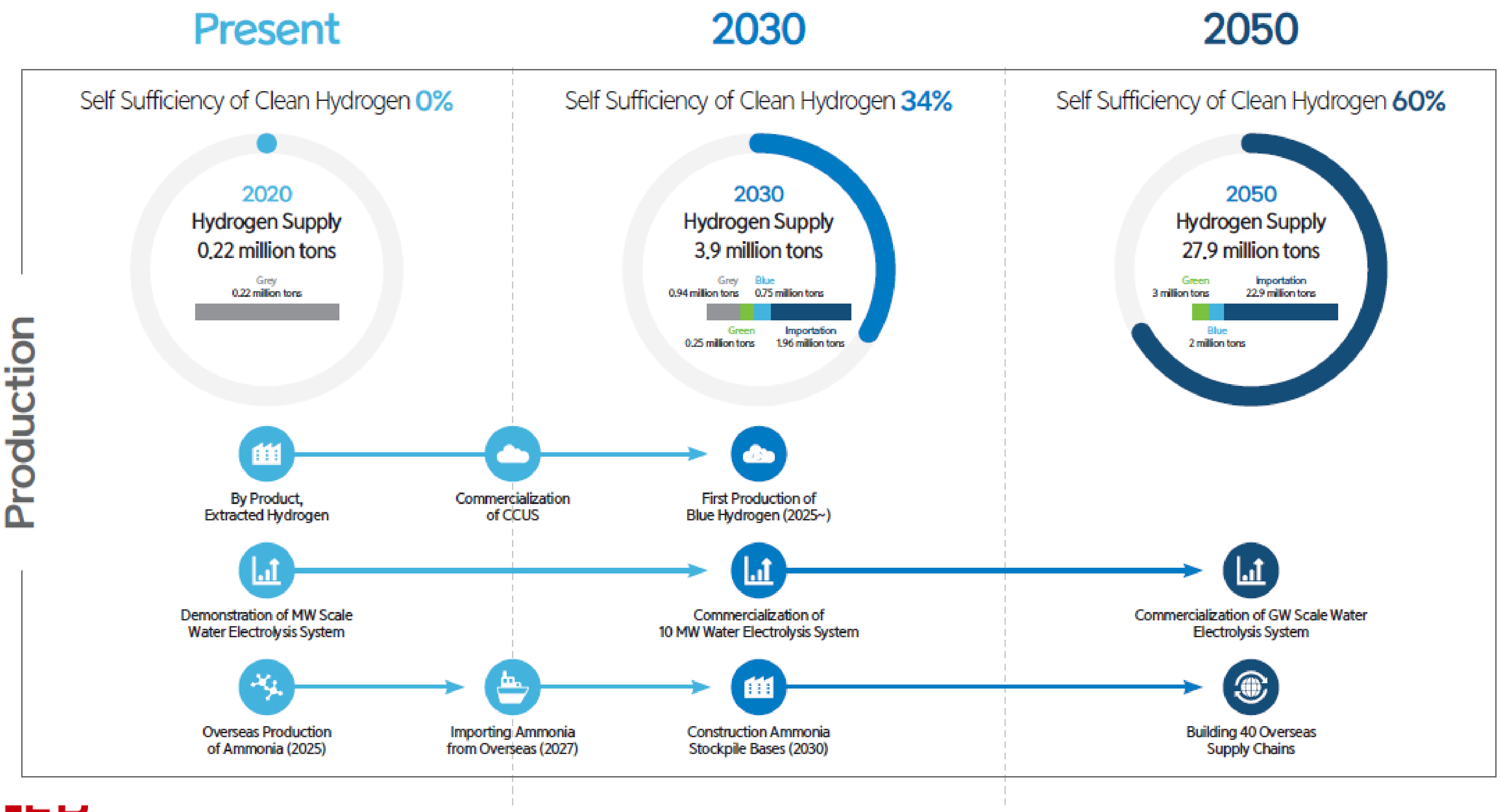
- Developing H_2 pipeline at a high pressure of 50 bar or more, and expanding it to include major sources of demand before making it a nationwide network

Main Goals of Hydrogen Storage and Transportation

	2019	2022	2030
Tube Trailers	500	Large-scale gas storage and transportation	Liquefaction and liquid and solid hydrogen storage and transportation
Pipeline	200km	Establish hydrogen pipelines near sources of by-product hydrogen production (Ulsan, Yeosu, and Daesan)	Consider the construction of high-pressure hydrogen pipelines nationwide
Core Issues	-	Establish base of supply centered on demand	Establish supply infrastructure nationwide

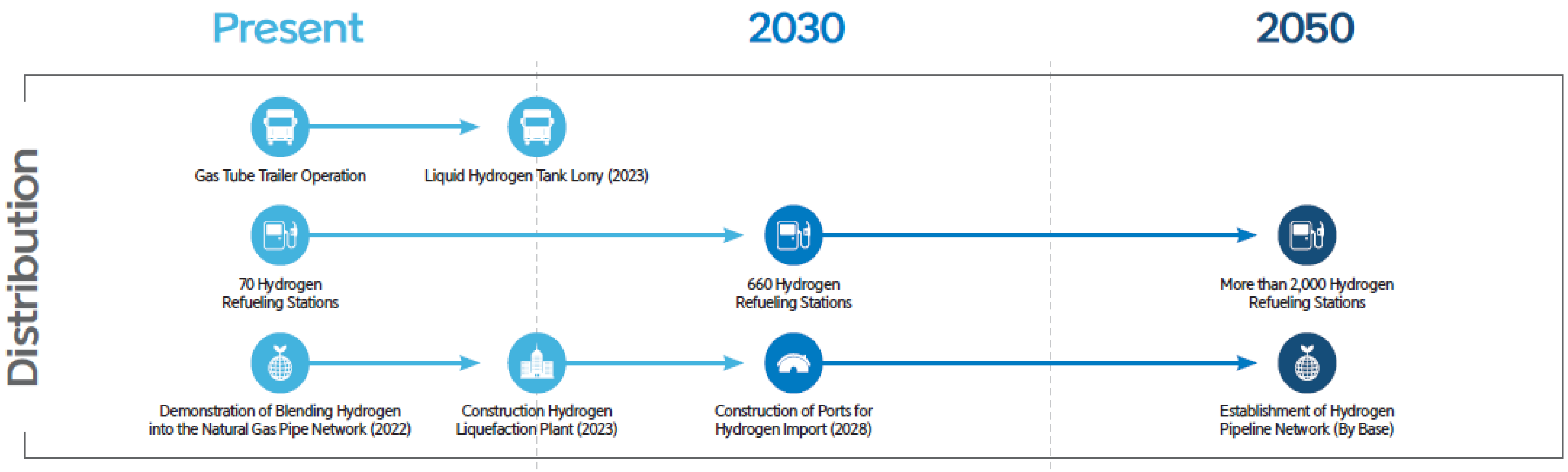
Basic Plan for Implementing H_2 Economy('21.11)

- **Green H_2**: 0.25 million ton/y('30) → 3 million ton/y('50)
- **Blue H_2**: 0.75 million ton/y('30) → 2 million ton/y('50)
- **No more Grey H_2** after '40
- **Imported Hydrogen** will be over 80%('50)



Basic Plan for Implementing H_2 Economy('21.11)

- **Transportation**: Tube Trailer → LH_2 Tank Lorry → H_2 Pipeline(Regional → National)
- **HRS**: H_2: 660('30) → 2,000('50)
- **Hydrogen import**: commence after '28



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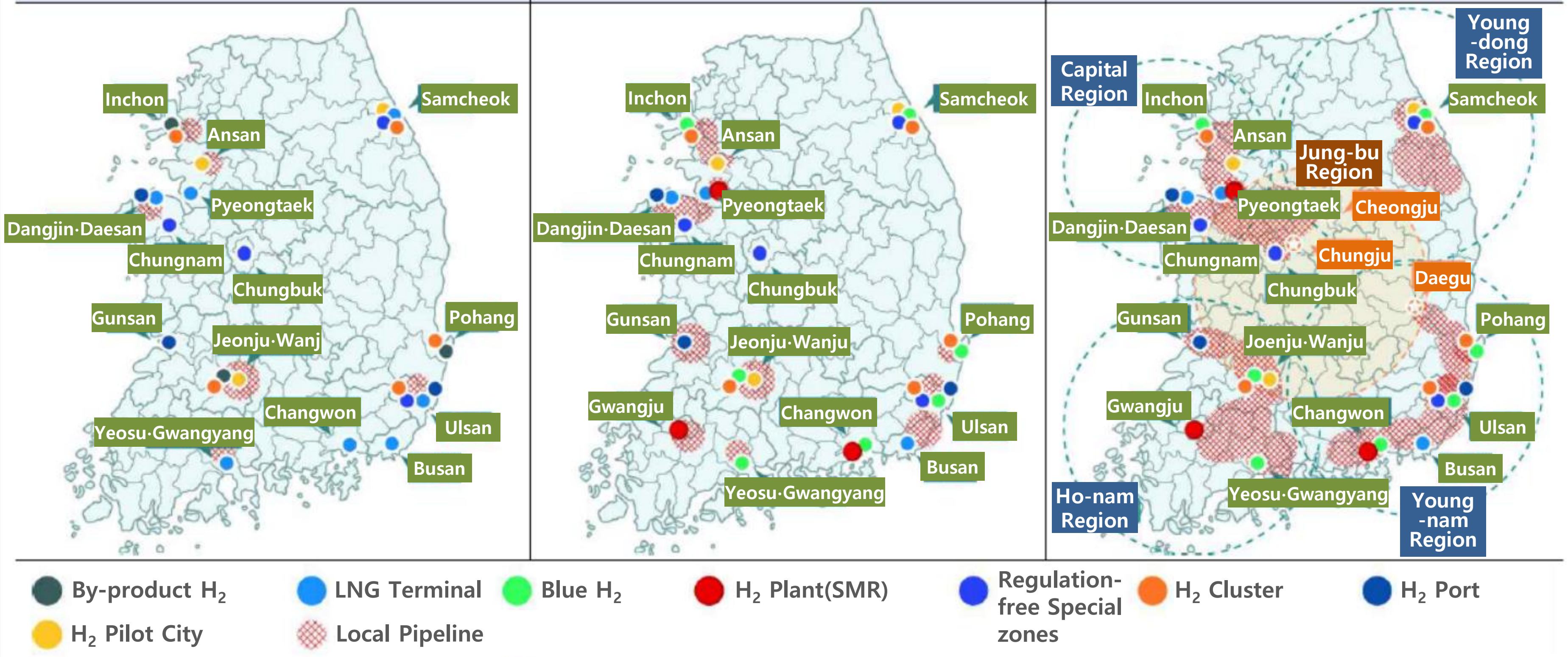
H_2 Pipeline Roadmap

< H_2 Pipeline Roadmap >

2025	2030	2050



Establishment of a base centered on H_2 ports, H_2 cities, industrial complexes, etc	Expansion of key regions Connection to LNG pipeline network	Construction of pipeline networks in five regions

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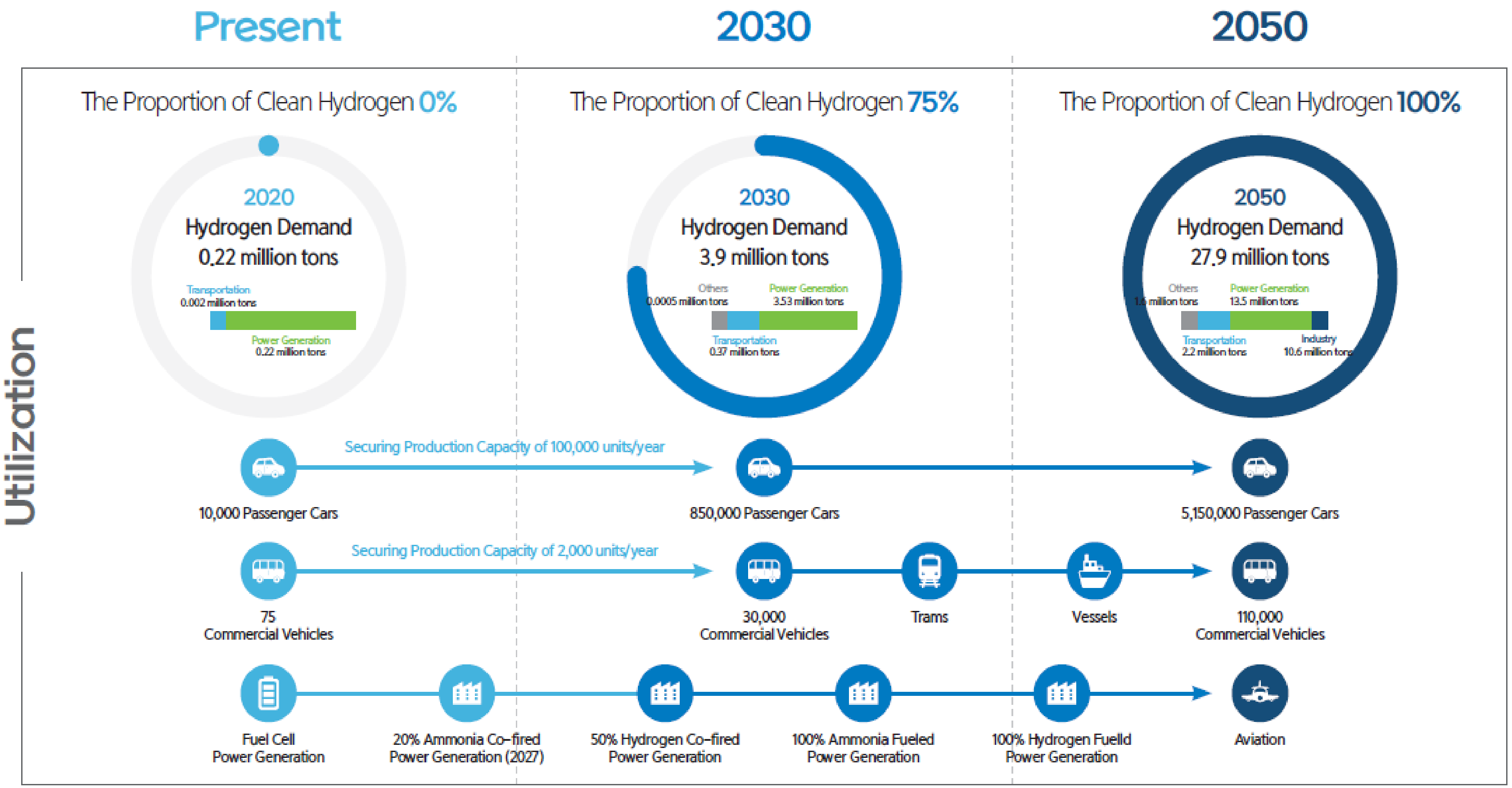
Basic Plan for Implementing H_2 Economy('21.11)

- **Mobility**: 0.37 million ton/y('30) → 2.2 million ton/y('50)
- **Power Generation**: 3.53 million ton/y('30) → 13.5 million ton/y('50)
- **Industry**: no plan('30) → 10.6 million ton/y('50)



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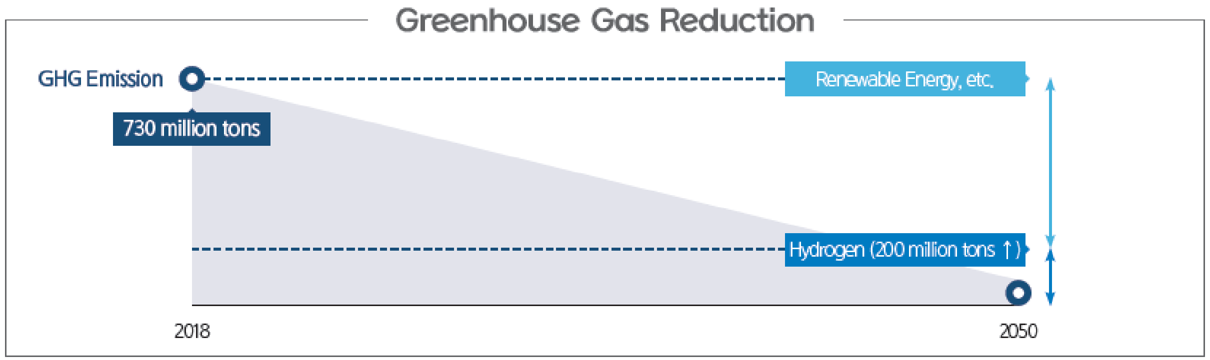
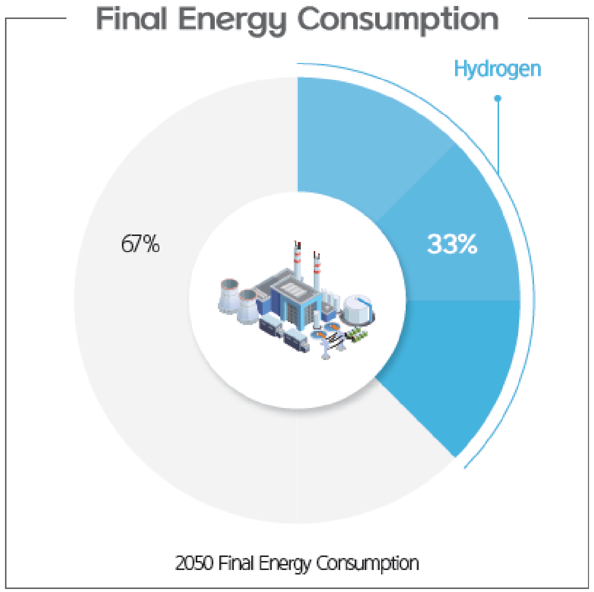
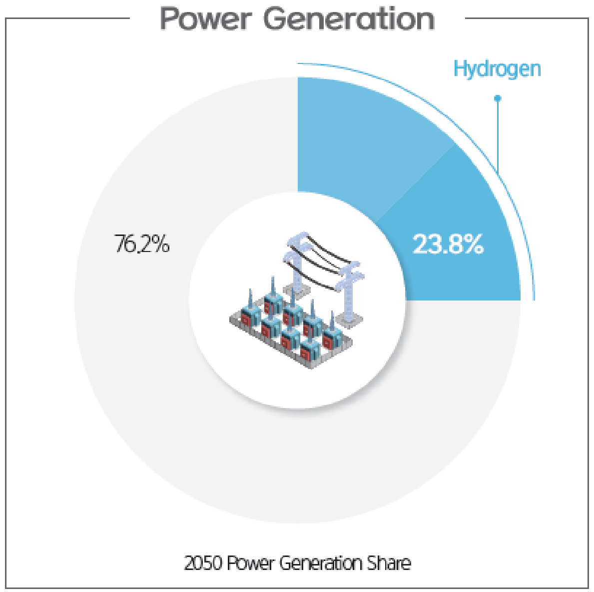
2050 Outlook

H_2 Economy will play a key role to accomplish Net Zero







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H_2 Pilot City

H_2 Pilot City ('20~'22, MOLIT)

Ansan: 10 km (Expanding)

- **H_2 Production**: Steam reforming of LNG
- **Pipeline**: diameter 20 cm, 1.65 Mpa
- **Usage**: H_2 town(heating, hot-water), 3 HRS

Ulsan: 12.5 km (Expanding)

- **H_2 Production**: by-product H_2
- **Pipeline**: diameter 20 cm, 2 Mpa
- **Usage**: H_2 fuel cell, 3 HRS

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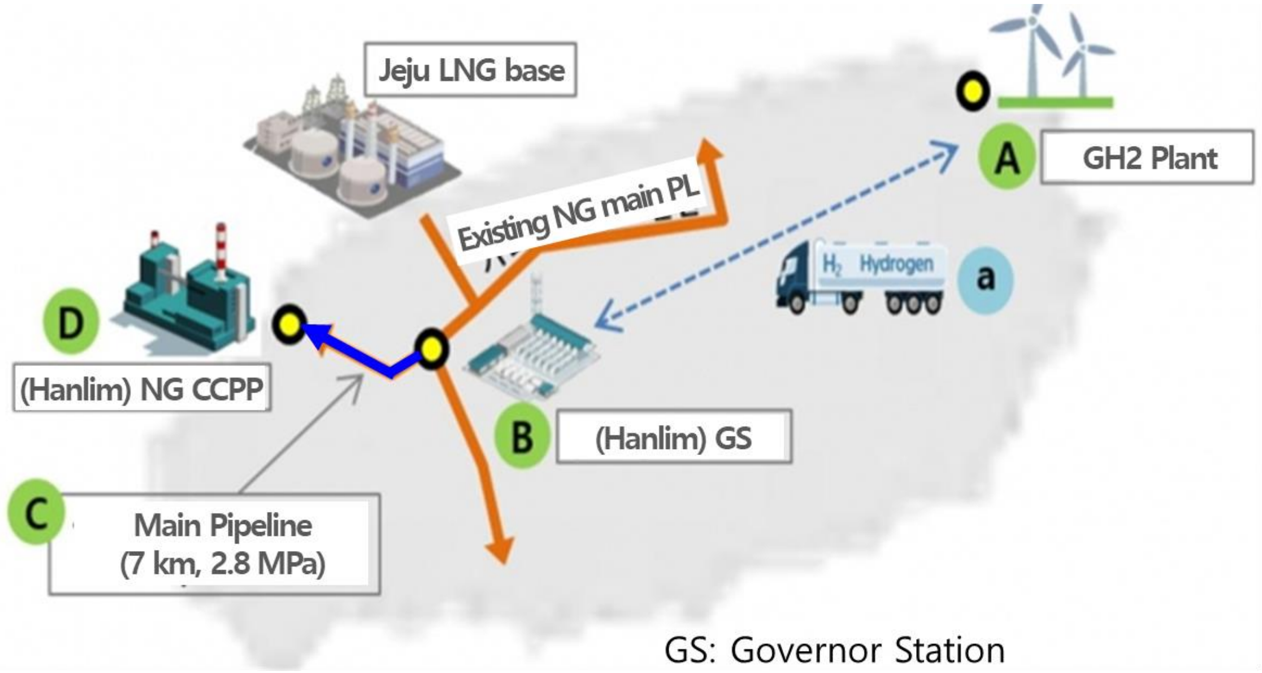
H_2 Blending Project

H_2 blending in NG pipeline(KOGAS, '23~'26)-

- **Site**: Jeju island
- **Blending**: 10~20 %
- **Application**: NG combined cycle power plant



GS: Governor Station
CCPP: Combined Cycle Power Plant

Thank You !

Dr. Jin-Nam Park
Hydrogen Program Director, KETEP, Republic of Korea
Contact: jnpark@ketep.re.kr, jnpark@kiu.kr

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한국에너지기술평가원
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European Research Institute for Gas and Energy Innovation

Hydrogen tolerance of natural gas infrastructure

Pipeline distribution of hydrogen workshop - Clean Hydrogen Mission Storage and Distribution working group 27.09.2023

Hans Rasmusson

Secretary General

rasmusson@erig.eu

+49 172 215 25 80

The ERIG working principle for research about *"the optimal exchange between electrons and molecules"*

- **Country Members bring in national research and industry connections to the ERIG Community**

- **The ERIG Community elaborate on topics of common interest, form consortia and generates EU funded projects**

- **The projects generate knowledge, facts and innovation**

- **The output serves the public and the EU**

ERIG Theses for the European Energy Future

Three overarching guiding principles

1. **Quality** - Suggestions for actions must be based on accountable research and realistic projections of possible developments
2. **Completeness** -Time, existing infrastructure, and overall systemic effects must be primary considerations
3. **Feasibility** - Disruption must be minimised for social acceptance and feasibility

Three theses for a successful energy transition

1. **Gas in the center**

   - Gas is the key factor in achieving an integrated energy system of electrons and molecules

2. **Multi-gas not Mono-gas**

   - All types of energy gas should be considered and deployed on the market based on their GHG reduction potential

3. **Gas is an R&D priority**

   - R&D efforts for gas solutions must be intensified

Overview of the ongoing projects with ERIG involvement

Projects and Studies

1. **HIGGS** - Hydrogen in Gas Grids
2. **LivingH2** – Living Laboratory Demonstration of Complete Pure Hydrogen Fuel Cell Cogeneration System
3. **MefHySto** - Metrology for Advanced Hydrogen Storage Solutions
4. **HEAVENN** - Hydrogen Energy Applications for Valley Environments in Northern Netherlands
5. **SuperP2G** - Synergies Utilising renewable Power Regionally by means of Power to Gas
6. **Hy2Market** - Helping regions in Europe develop H2 Business cases
7. **ReHaul** - Renewable Long Haul Road Transport Considering Technology Improvements and European Infrastructures

"The HIGGS project will help decarbonize the European gas grid by clearing the pathway for the admixture of hydrogen."

HIGGS Hydrogen in Gas Grids
www.higgsproject.eu

"Hydrogen will play a major role in energy storage systems – our project will secure correct metrology of hydrogen and hydrogen blends"

MefHySto Metrology for Advanced Hydrogen Storage Solutions
www.mefhysto.eu

"P2G is a key technology to bridge the major energy grids and consumers - our project will help stakeholders find and evaluate the beneficial regions"

SUPER P2G
www.superp2g.eu

HIGGS – Hydrogen In Gas GridS

Goals:

1. **Technical, legal and regulatory barriers** for admixing up to **100% H_2** in the high-pressure gas network

2. Setting up and operating a **test platform** and replicating all components of a high-pressure network

3. **Testing and evaluation** of different equipment and **materials** for different H_2/CH_4 blends

4. **Techno-economic modeling** for H_2/CH_4 blends in the high-pressure gas grid and equipment

- **6 Partner**
- **Start:** 01.01.2020
- **Duration:** 48 Months
- **Budget:** 2 Mio €

Source: all images belong to HIGGS project

Review of the potential of H_2 injection in European grids

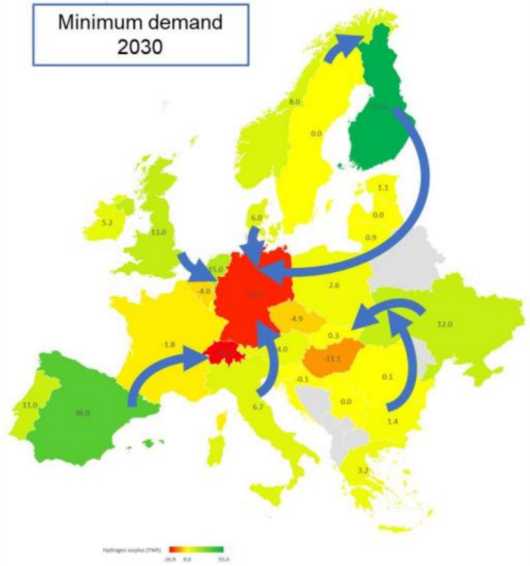
Objectives

- **Inventory of the European transport grid** with information from TSOs in the HIGGS network.
- Estimating the **ranges of hydrogen injection** which are potentially required due to future energy trends.
- Hydrogen injection in the European countries and **forecasting future trends** in the mid-term (**by 2030**) and long-term (**by 2050**), including possible flows of hydrogen among countries.

Outlook

1. Rapidly changing H_2 market requires flexible solutions
2. Pathway and proposals summary to enable wider injection of H2 in EU gas Networks

   → will be published at the end of the project



The R&D platform: key parts

Platform Video

Testing platform
Exposure of testing materials

Purification prototype
H_2/CH_4 deblending at high pressure with membrane technology

Admixture system
Blending electrolytic hydrogen with “simplified” natural gas and injection at high pressure

Setting up and operating a test platform and testing

Platform Video

Objectives and Results

- Testplatform for exposure of NG grid materials steels (4pb, C-ring, CT-WOL), valves, flow meter, etc to H_2
- H_2/CH_4 blending at high pressure (80 bar)
- Tests with **20%, 30% (30% + contaminants)** and **100%** hydrogen
- No damage detected on the steel alloys **X42, X52, X60, and X70**
- **Valves remained tight** under the conditions tested, besides **screwed ball valves** which had a clear lack of tightness

Outlook

1. Test with **100% hydrogen** are still under evaluation.
   → **No embrittlement expected**, but has to be proven
2. **Shear force tests** under hydrogen atmosphere still pending

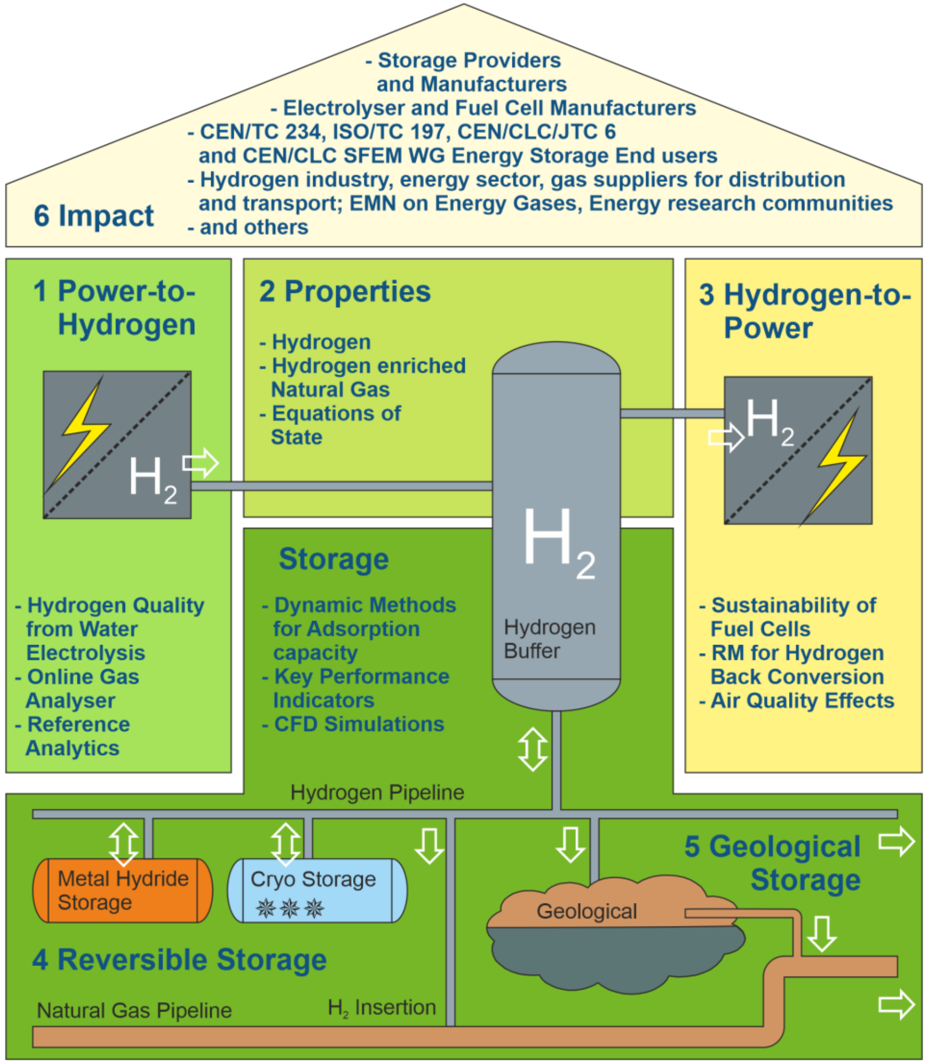
MefHySto – Metrology for Advanced Hydrogen Storage Solutions

Motivation

- EU energy target of 32% renewable energy by 2030
- Energy storage such as H_2 storage necessary
- The measurement technology is crucial for the implementation

Key Data

- Duration 2020-2023
- EU funding 2.3 M€
- Coordinator: BAM
- 14 partners



Thermophysical properties

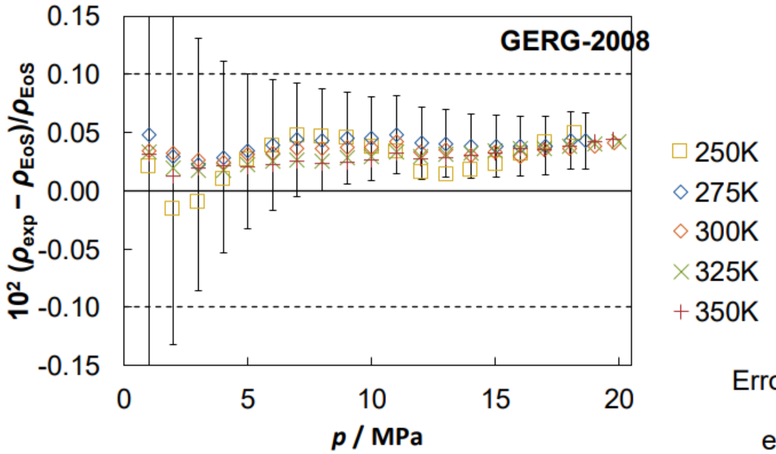
Goals and Objectives

- Develop reference equations of state (EoS) for **hydrogen-enriched natural gas mixtures** and hydrogen under geological storage conditions – ”GERG-Improved”
- To characterize the hydrogen-enriched natural gas mixtures with a **hydrogen content of up to 20 %**
- To tackle metrological and **thermodynamic issues** in the large-scale storage of hydrogen in **underground gas storages (UGS)**
- **How:** Gas density measurements with up to 20% H_2, and comparison between experiment and GERG-2008 EoS

Results

1. Most data are located within the assigned uncertainty boundary for density (0.03 – 0.05%)
2. “GERG-improved” works better than the classic GERG-2008 but not for the **low temperatures** (250 and 275 K)

EoS model **uncertainty** of the **density** ρ in the **gaseous** region: **0.10 %**



Error bars: Uncertainty (k = 2) of the experimental data

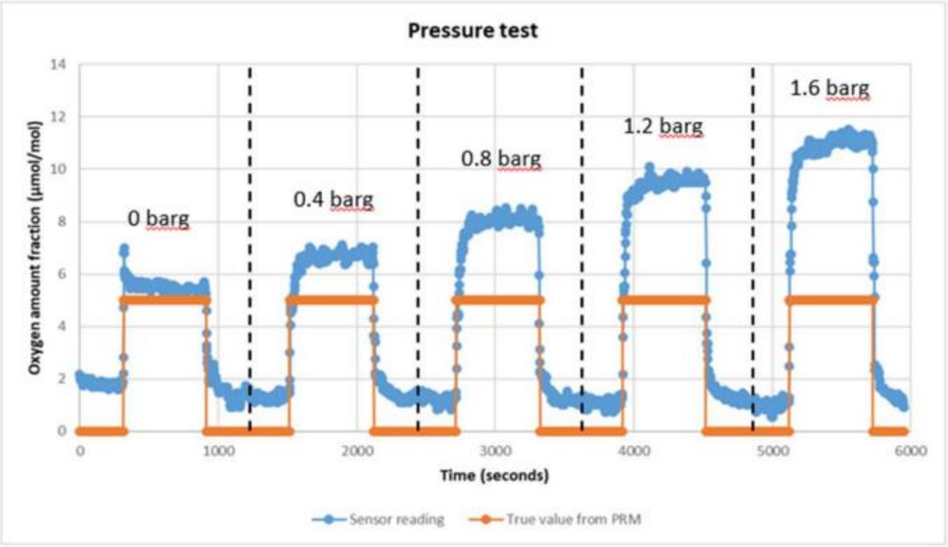
Online Gas Analysis for hydrogen quality measurement and reference analytics

Goals and Objectives

- Better understanding of the **parameters influencing water electrolysis** under process conditions.
- Testing and validation of instruments **for measuring key impurities in hydrogen**
- Go beyond the state of the art by investigating the **quality of hydrogen produced from PEM** water electrolysis during rapidly imposed transient use periods.
- Online gas analysers used for measuring key impurities such as water vapour and oxygen calibrated against standards developed by project partners.

Results

1. Some sensors showed drift with changed environmental conditions. (e.g. pressure or concentration of pollutants)
2. Results and accuracy highly dependent on contaminants concentration



HyDelta – a Dutch Public-Private Partnership Research Programm for the Hydrogen Transition

HyDelta was coordinated by the Dutch ERIG Country Member

Focus areas of HyDelta

- Hydrogen safety
- Hydrogen in the gas grid
- Value chain & hydrogen admixing
- Economic aspects of the hydrogen system
- Hydrogen & transport assets
- Social aspects of hydrogen

Source: https://hydelta.nl/

SyWeSt H2 – Investigation of Steel Materials for Gas Pipelines and Plants for Assessment of their Suitability with Hydrogen

Objective

- Examination of commonly used steel materials for hydrogen suitability according to ASME B 31.12 (2019)
- Testing of pipeline steels - approx. 200 tests including characterization of the material (chem. analysis, mechanic-technological data, hardness testing of welds)
- Validation of the ASME crack growth relationship for steels typically used for implementation in the German DVGW regulations

Results

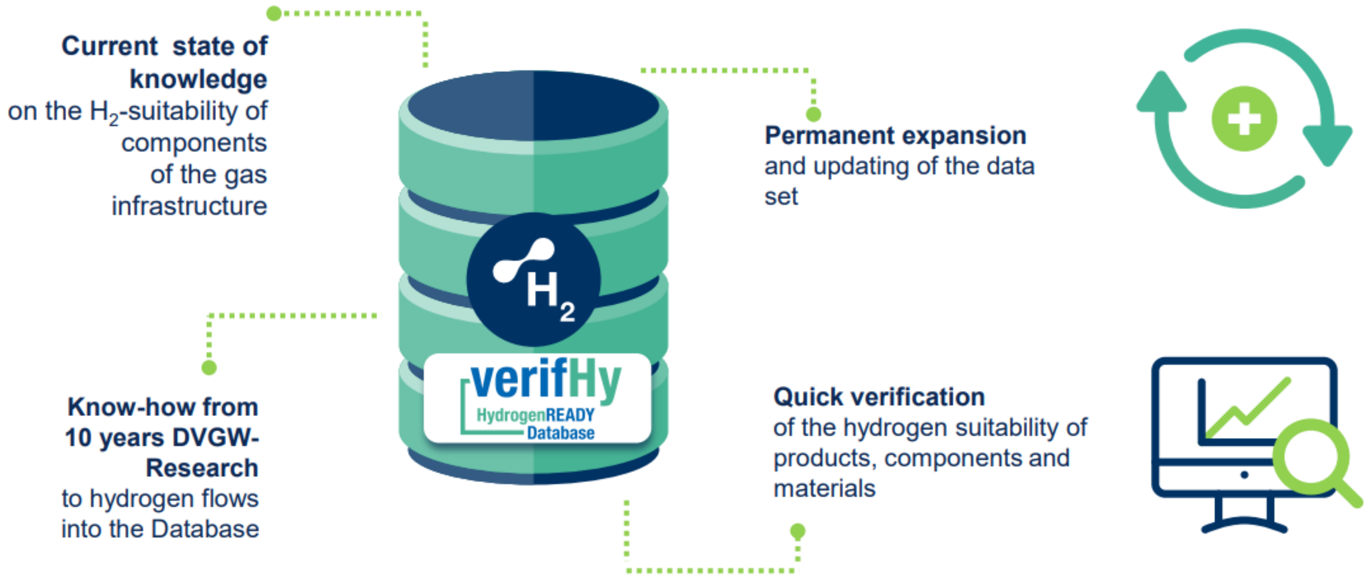
- 100% suitability proven for all steel materials typically used in Germany (and Europe)
- No relevant variance of test results for all tested pipeline materials, types and test locations
- Confirmation of the results from ASME B31.12 and addition of a bilinear and conservative model
- Results are transferable to distribution networks and admixtures

Source: g202006-sywesth2-steel-dvgw.pdf

VerifHy- Hydrogen Ready Database of DVGW and German Gas Institute (DBI)

Decade of research around the H2 acceptance of the NG grid

- Collected information and studied effects of hydrogen to natural gas grid in Germany since 2010
- Knowledge made available in „Gas Grid Transition Guideline“ in conjunction with commercial database „VerifHy“
- Validated in the national “Gas Grid Transformation Plan” in Germany (www.h2vorort.de/gtp)



Source: Hydrogen Readiness Database: DVGW verifHy

Outlook

ERIG Results

Please find results of ERIG-projects and activities under:

www.erig.eu

Upcoming HIGGS Closing Conference

ERIG

European Research Institute for Gas and Energy Innovation

Hydrogen tolerance of natural gas infrastructure

Pipeline distribution of hydrogen workshop - Clean Hydrogen Mission Storage and Distribution working group 27.09.2023

Hans Rasmusson
Secretary General

rasmusson@erig.eu
+49 172 215 25 80

Sandia National Laboratories

Exceptional service in the national interest

Fatigue and Fracture Behavior of Line Pipe Steels in Pressurized Gaseous Hydrogen

Joe Ronevich, Milan Agnani, Chris San Marchi

Sandia National Laboratories
Livermore, CA

Storage and Distribution Working Group – Clean Hydrogen Mission

27 September 2023

SAND2023-09750PE

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U.S. DEPARTMENT OF ENERGY

NNSA

Pipeline Blending CRADA

Objective - Provide scientific framework that enables blending of hydrogen into NG infrastructure

4 national laboratories

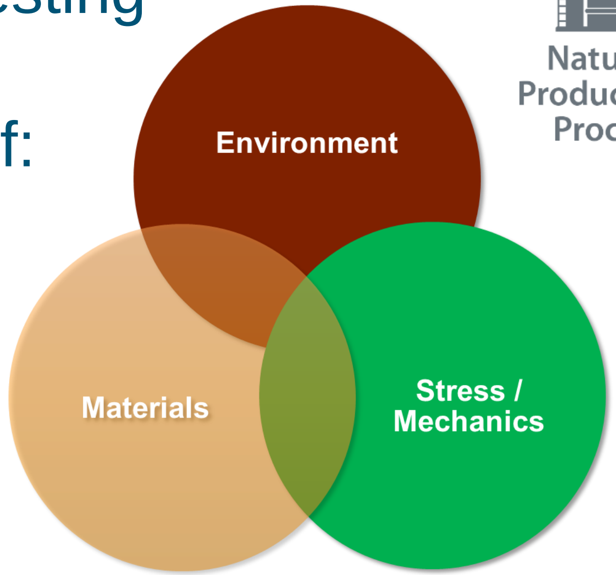
31 total industry and academia partners

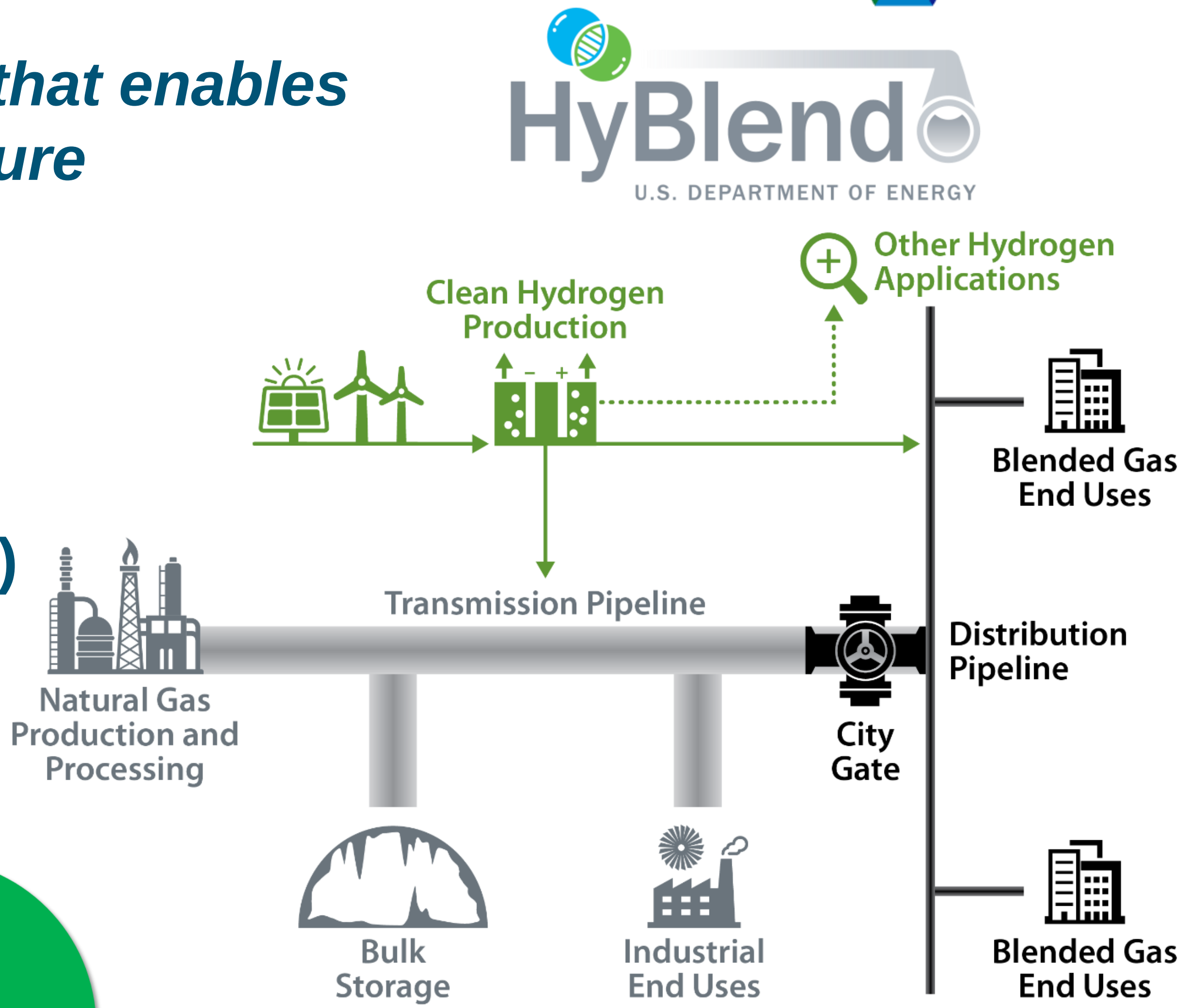
Structural Materials Task: Metals (Sandia)

→ Fatigue and Fracture Testing of Vintage pipe / welds

→ Understand influence of:

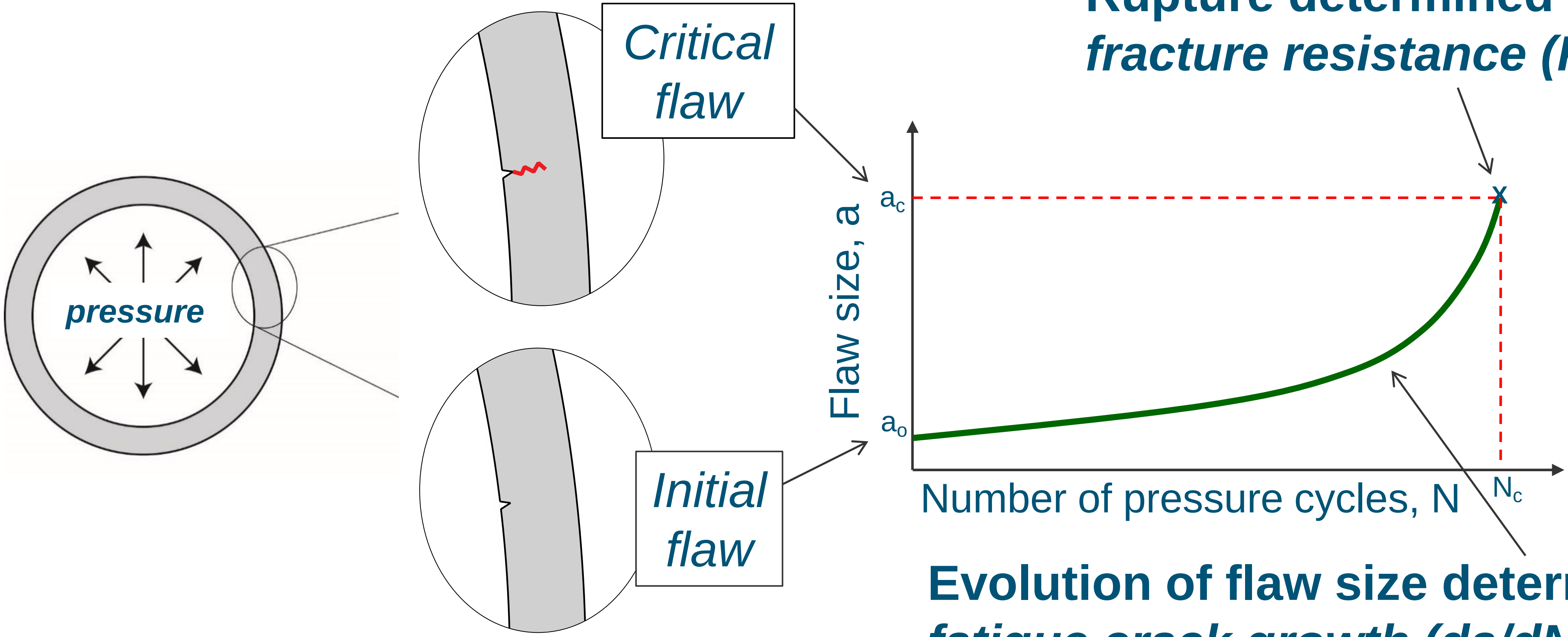
- Pressure
- Microstructure
- Rate / Frequency
- Strength





Oct 2021 – Sept 2023 (2 yr project)
Phase 2: Oct 2023 start (3 yr project)
To get involved: email HyBlend_CRADA@nrel.gov

Fracture mechanics-based analysis used for structural integrity assessment

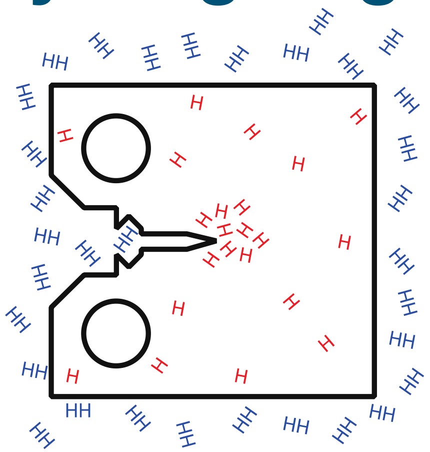


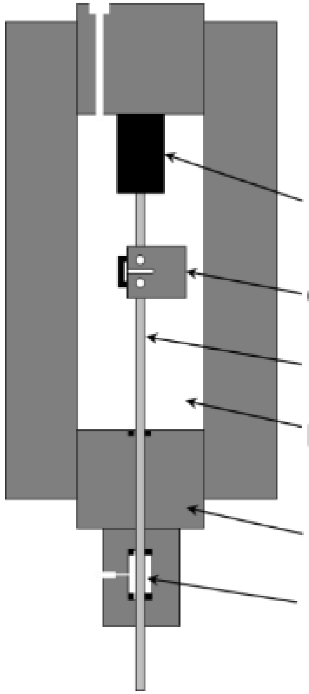
Rupture determined by *fracture resistance (K_{IC})*

Evolution of flaw size determined by *fatigue crack growth (da/dN - ΔK data)*

ASME BPVC Section VIII, Division 3, Article KD-10 provides guidance on fracture mechanics design

Fatigue crack growth rate testing performed in high-pressure hydrogen gas





Instrumentation

- Internal Load cell
- Clip gauge
- Direct Current Potential Difference (DCPD)

Fatigue: ASTM E647

- Load ratios (R) 0.1 to 0.8
- Frequency: 0.01 → 10 Hz
- Constant load or K-control

Fracture: ASTM E1820 (Elastic-Plastic)

- Loading rates (0.1→1 MPa $m^{1/2}$/min)
- Crack length monitor (DCPD)

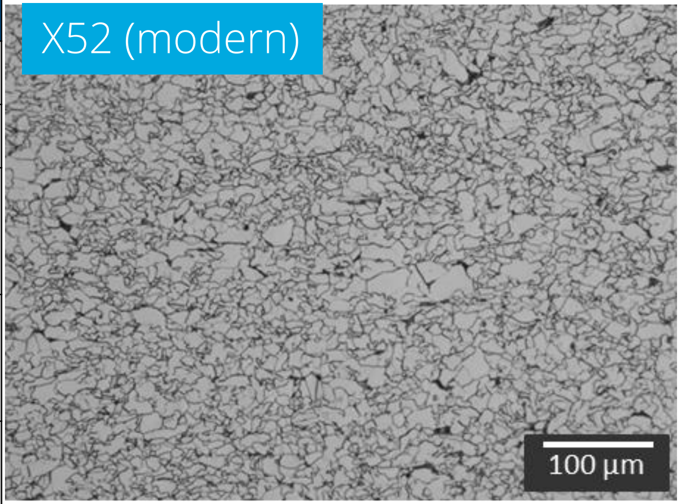
Environment

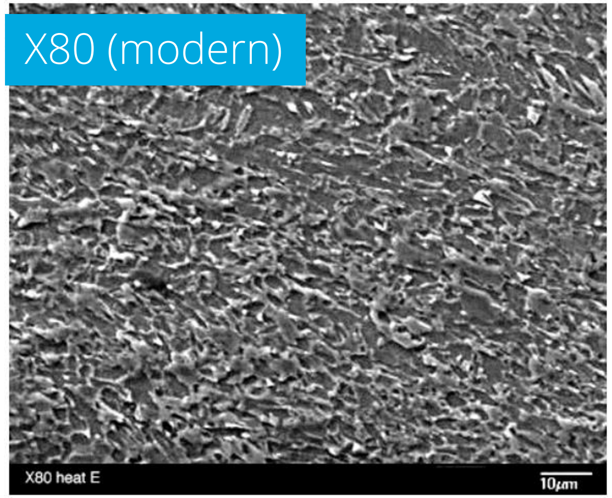
- Air
- Pure H_2
- Gas blends, e.g. N_2 – 3%H_2
- Gas impurity mixtures:
  e.g. H_2 + 10-1000 ppm O_2

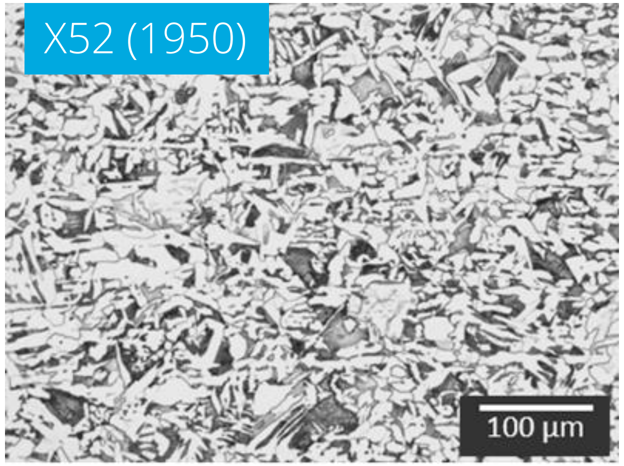
Pipeline steels examined have range of microstructures, strengths, ages

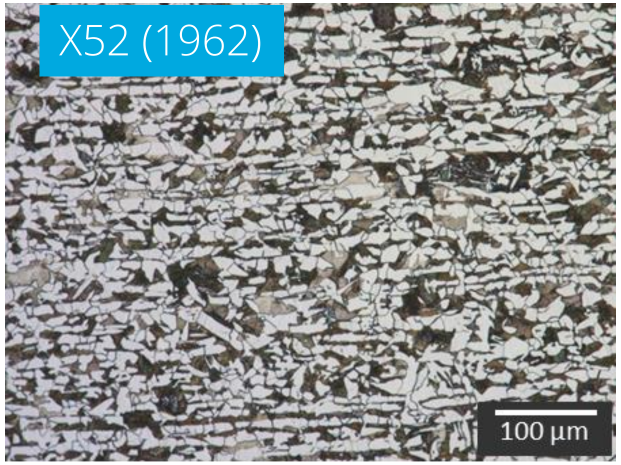
	Material	Microstructure	σ_{ys} (MPa)
Modern	X52	Ferrite / pearlite	429
Modern	X65	Banded ferrite / pearlite	478
Modern	X65 (E18)	Awaiting characterization	517
Modern	X65 (J22)	Awaiting characterization	558
Modern	X80 (B)	90% PF + 10% AF (coarse)	565
Modern	X80 (E)	AF (fine)	593
Modern	X80 (F)	70% AF + 30% PF	552
Vintage	X52 (1950)	Ferrite / pearlite	416
Vintage	X52 (1952)	Ferrite / pearlite	424
Vintage	X52 (1959)	Ferrite / pearlite	424
Vintage	X52 (1962)	Banded Ferrite / pearlite	490
Vintage	X52 (1964)	Ferrite / pearlite	334

AF = acicular ferrite: PF = polygonal ferrite









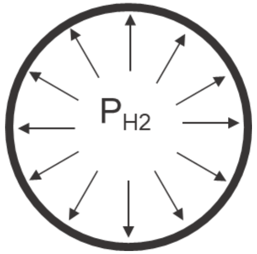
Higher carbon, higher sulfur

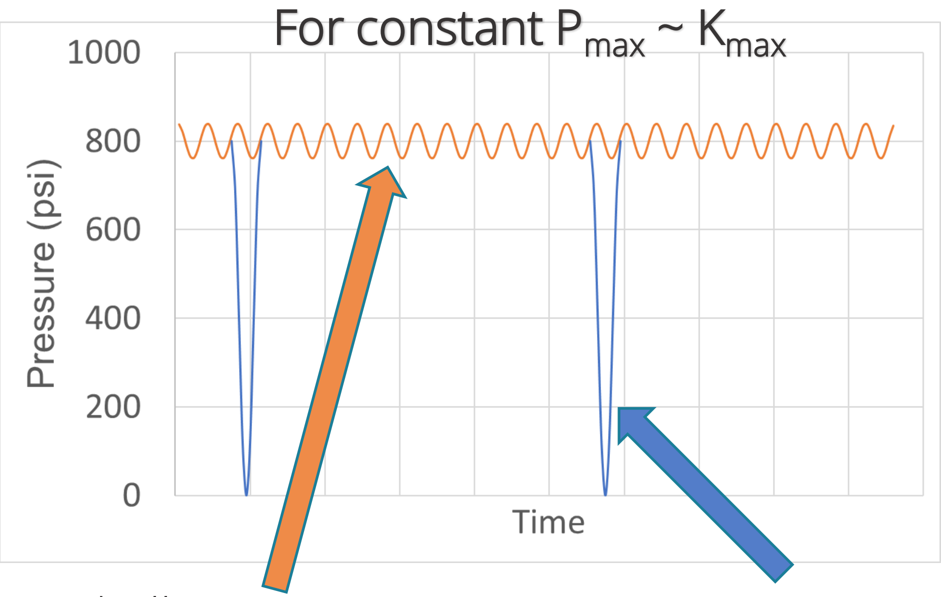
Trends in Fatigue Crack Growth Rates in H_2

Background: Hydrogen Assisted Fatigue

Fatigue: Loading of pipe or vessel caused by **fluctuations in operating pressure**

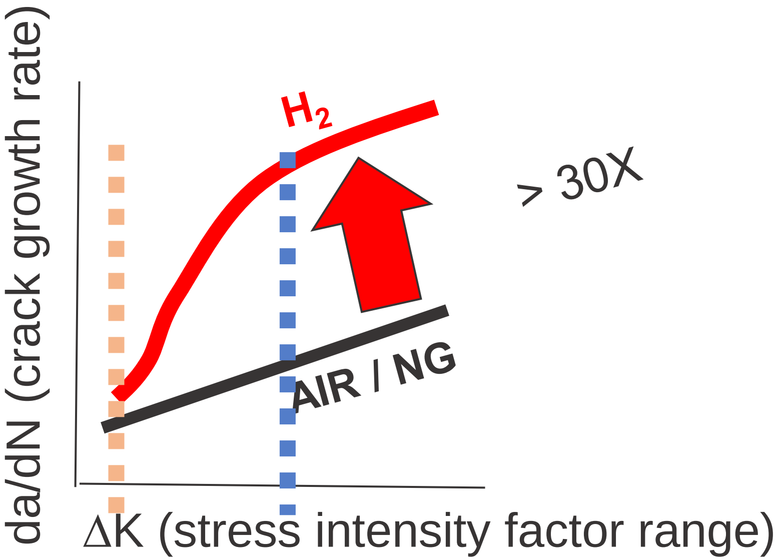
$$R = \frac{P_{min}}{P_{max}}$$





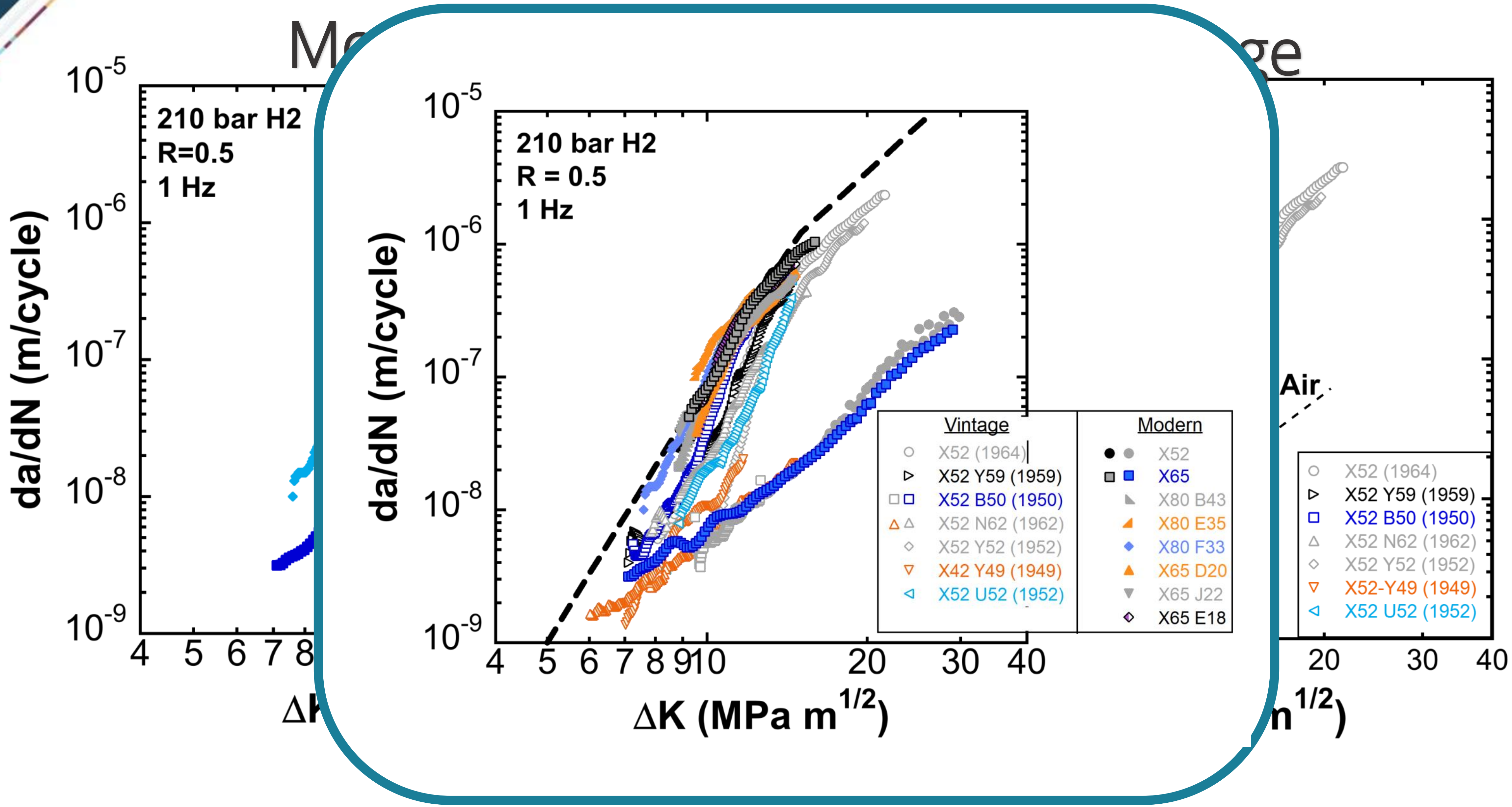
Shallow pressure cycles (high R, low ΔK)

Deep pressure cycles (low R, high ΔK)



Hydrogen-assisted fatigue does not preclude material from use but necessitates proper design.

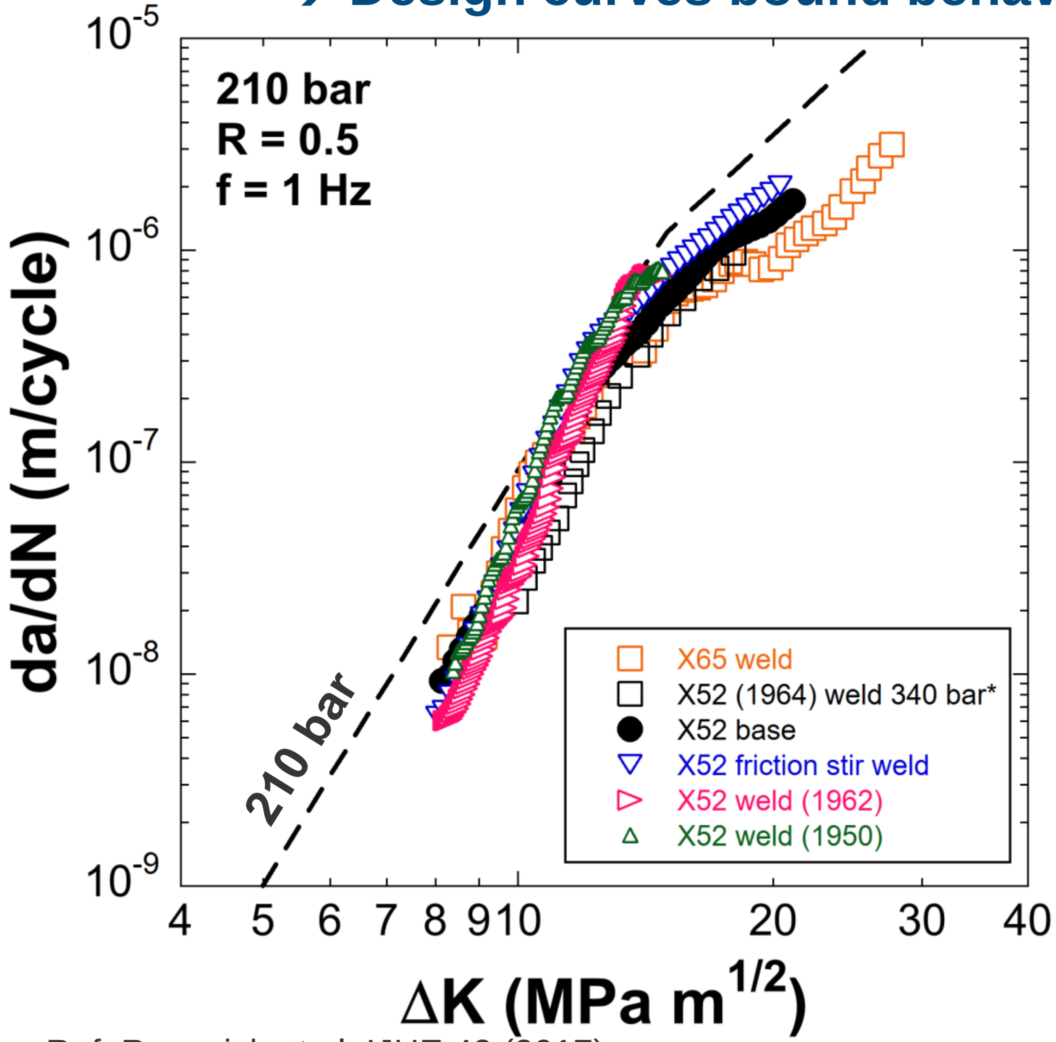
Variety of grades show similar behavior in gaseous H2

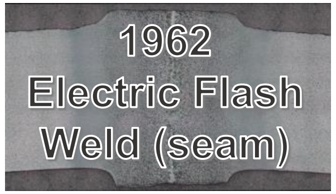


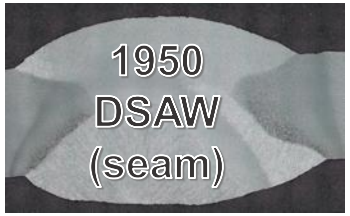
Weld material and base material exhibit similar FCGR

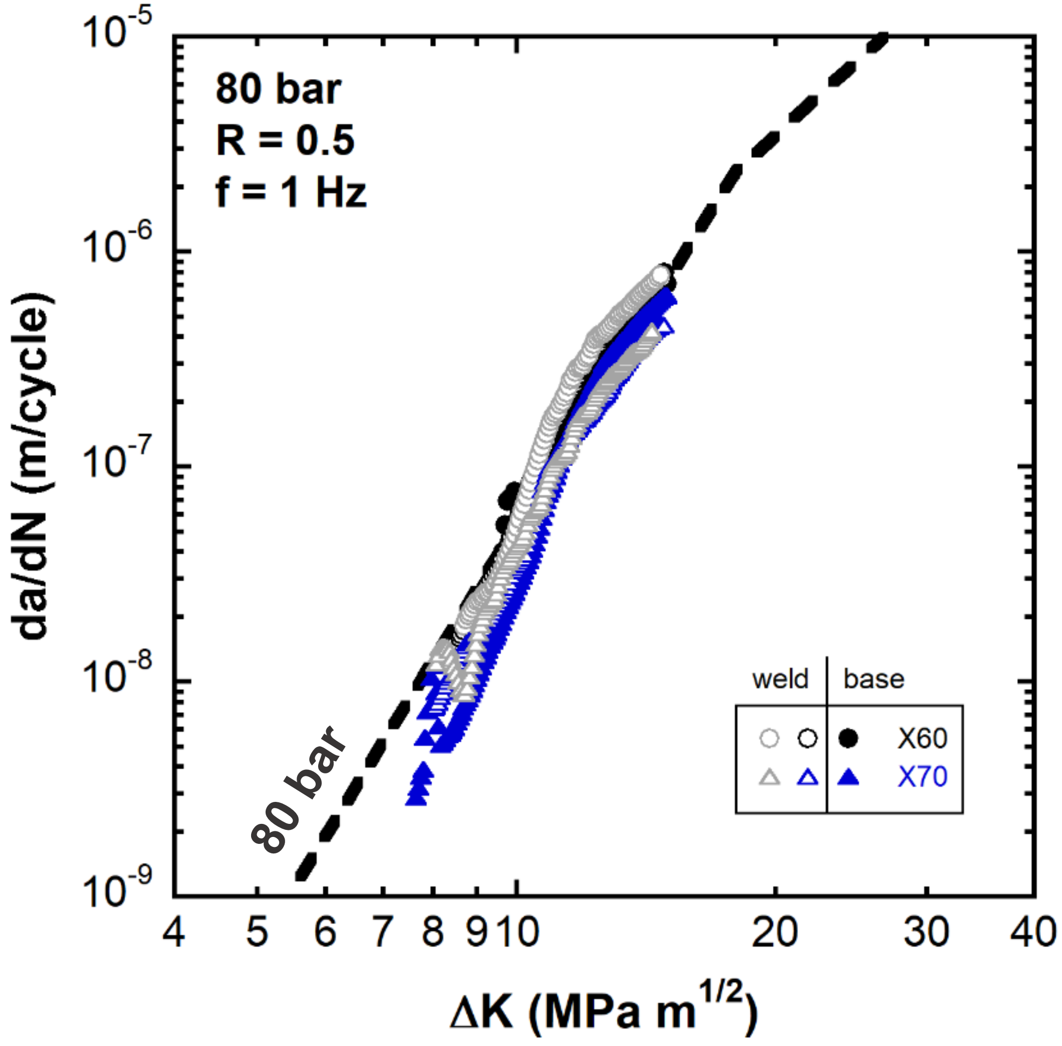
Similar trends have been observed for a variety of weld processes

→ Design curves bound behavior



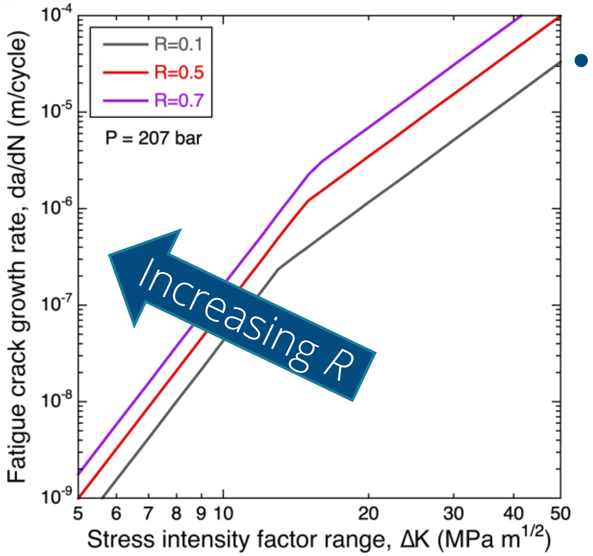


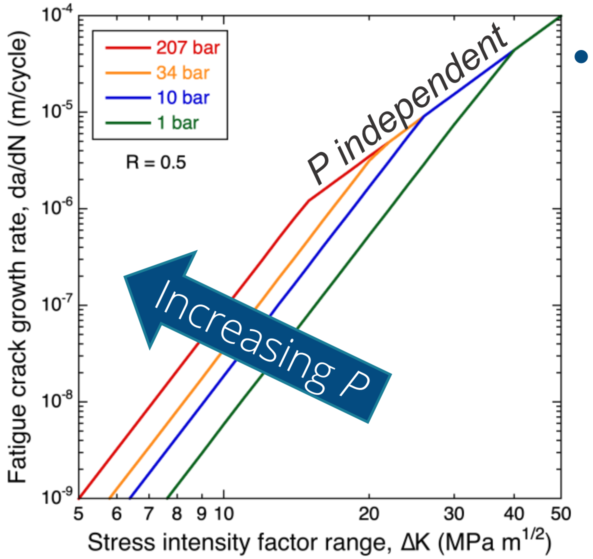




Ref: Ronevich et al. IJHE 42 (2017)
Slifka, PVP2015-45242

Design curves enable upper bound prediction for fatigue crack growth as function of loading and pressure





- **The effects of pressure and load ratio on fatigue crack growth are captured in conventional power law formulation :**

-At high ΔK $$\frac{da}{dN} = 1.5x10^{-11}\left[\frac{1+2R}{1-R}\right]\Delta K^{3.66}$$

-At low ΔK $$\frac{da}{dN} = 3.5x10^{-14}\left[\frac{1+0.4286R}{1-R}\right]\Delta K^{6.5} g(P)$$

From 0 to 210 bar: $g(P) = 0.071P^{0.51}$ units in MPa

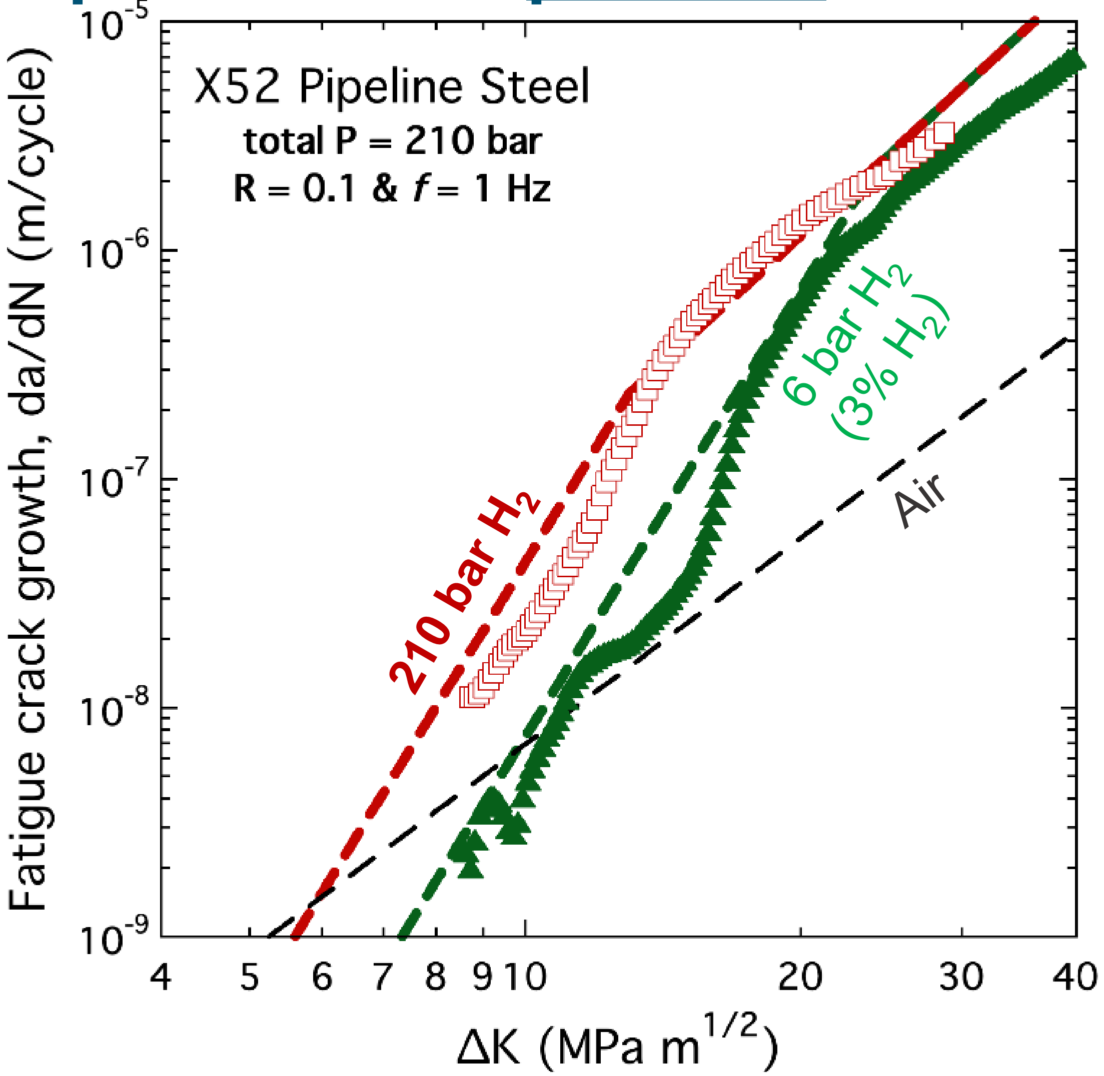
- **Master Design Curves appear to be effective for a wide range of pipeline steels – B31.12 Code Case 220 (approved July 2023)**

Ref.: San Marchi et al., PVP2019-93907

Outcome:

- **Master Design Curves provide a simple framework to bound the fatigue crack growth of steels in gaseous H_2**

Master design curves bound pipeline steel data & are sensitive to observed dependence on pressure



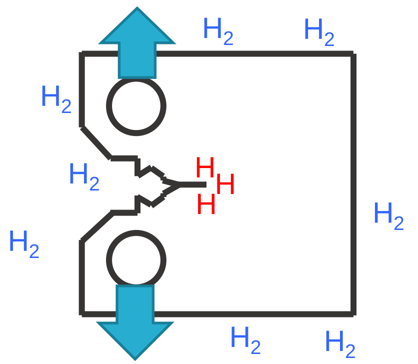
Ref.: San Marchi et al, PVP2021-62045

Even low partial pressures can exhibit accelerated FCGR

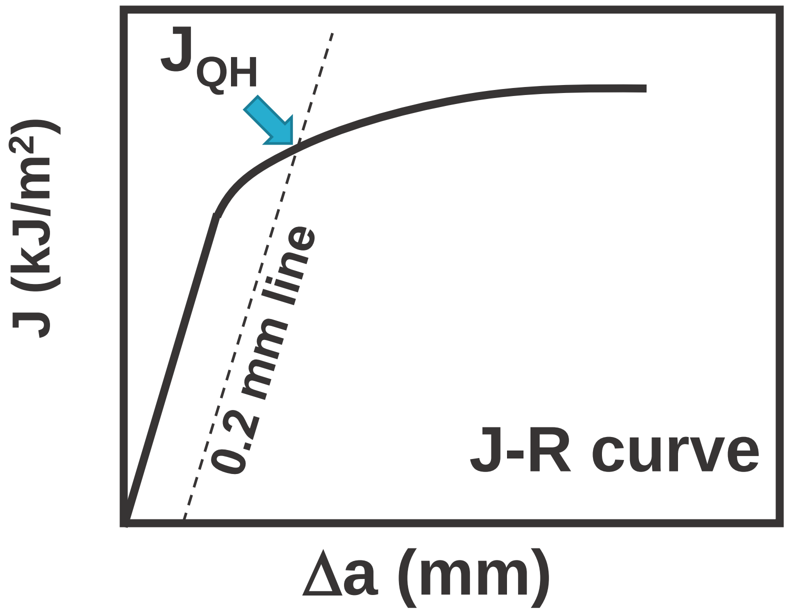
Trends in Fracture Toughness in Gaseous H_2

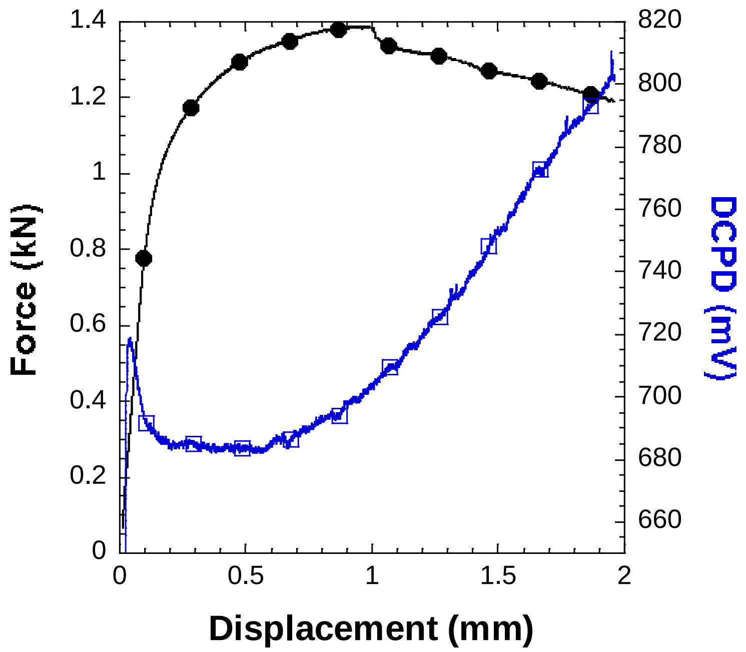
Hydrogen Assisted Fracture Testing

Fracture: subcritical crack extension as defined in ASTM E1820



- Monotonically load sample until crack extension
- Instrumented with DCPD



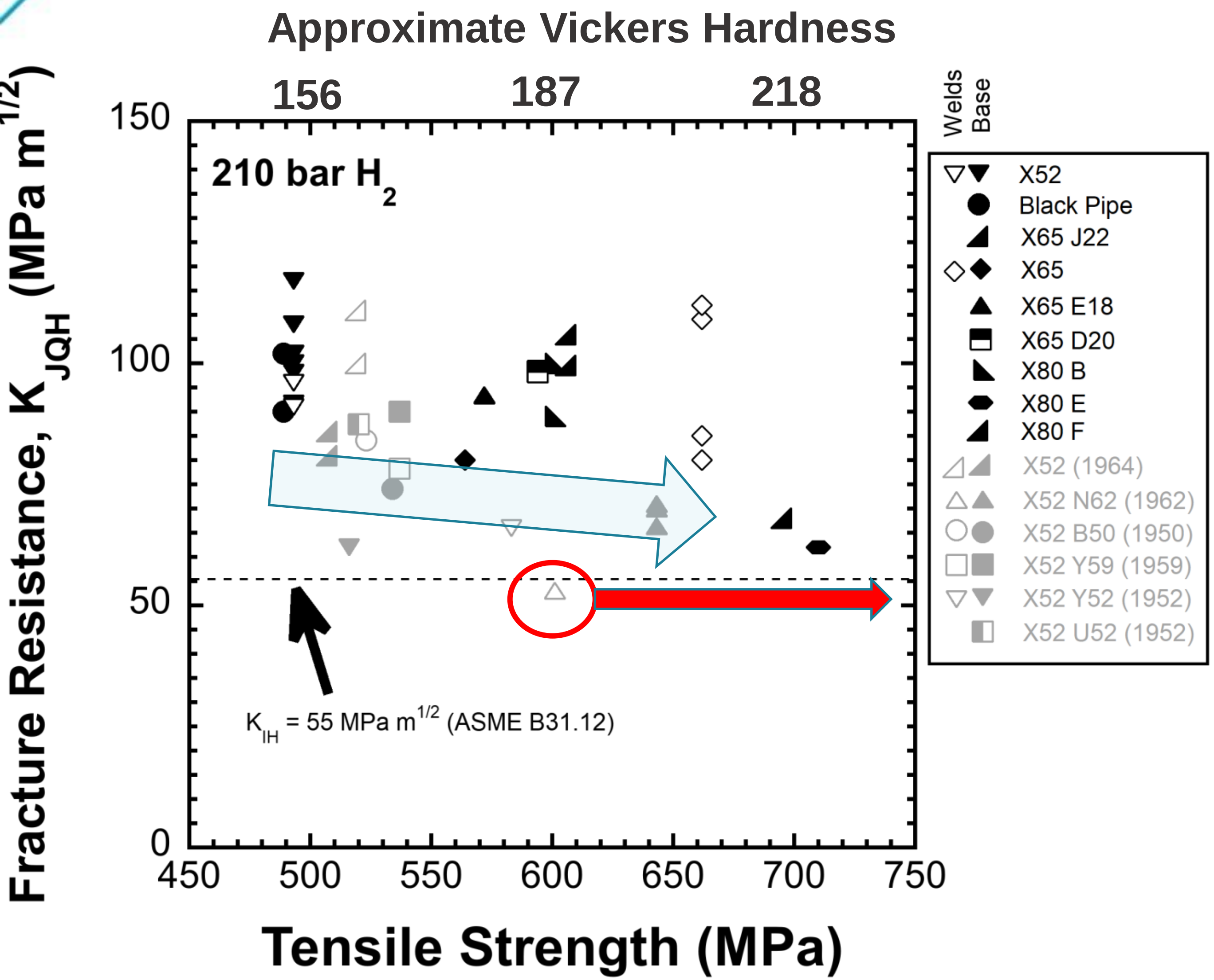


$$K_{JQH} = \sqrt{\frac{E J_{QH}}{(1-\nu^2)}}$$

In Hydrogen, K_{JQ} is referred to as K_{JQH} as it is hydrogen dependent

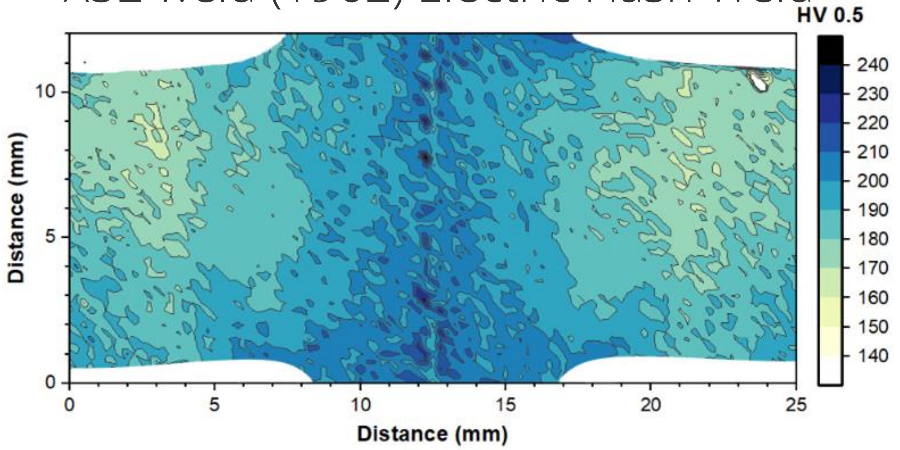
Fracture resistance, K_{JQH}, is environmentally dependent (e.g. pressure, rate)

Fracture resistance trends for pipeline welds and base metals are similar in H_2

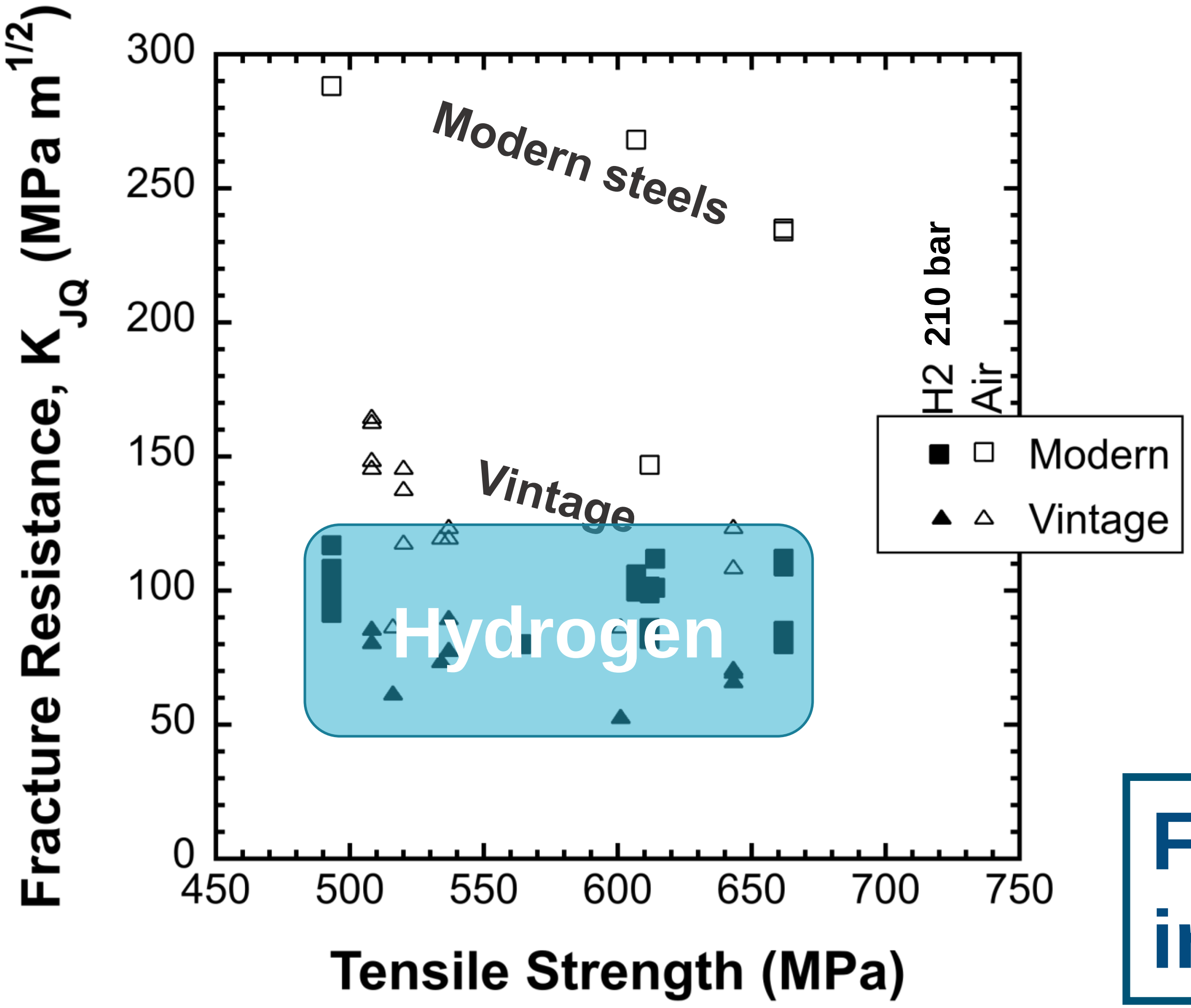


- K_{JQH} is generally greater than 55 MPa $m^{1/2}$
- Strength has only minor effect on lower bound K_{JQH} for steels with tensile strength < 650 MPa
- Local hard spots might account for lower toughness of welds

X52 weld (1962) Electric Flash Weld



Older pipeline steels tend to have poorer fracture toughness in air



- **Modern steels have greater percent drop in fracture resistance than vintage steel**

→ Broad knock-down factors may be non-conservative

Fracture in air is not a great indicator of performance in H_2

Ref: Ronevich et al. 4th Int Conf on Metals and Hydrogen

Summary of Pipeline Behavior in Hydrogen Gas

Fatigue crack growth rate (FCGR) accelerates by 10X in H_2

- Similar behavior among grades, age, strength, microstructure, weld
- Pressure sensitive in low ΔK regime
- Design curves capture FCGR relationship with pressure and R

Fracture resistance decreases in gaseous H_2

- Pressure dependent and non-linear
- Welds exhibit similar behavior for same hardness
- No significant influence of strength on lower bound fracture behavior for tested X52-X80
- Fracture in air is not a great indicator of performance in H_2

Gaps Remaining:

- Role of hard spots, HAZ, dents, bends
- How do we define bounding fracture behavior
- Anomalies to trends identified

Thank you for your attention!

Joe Ronevich
jaronev@sandia.gov

Chris San Marchi
cwsanma@sandia.gov

Milan Agnani
magnani@sandia.gov

HEML Team Members
Brendan Davis
James McNair
Keri McArthur
Tanner McDonnell
Robert Wheeler
Fernando Leon Cazares

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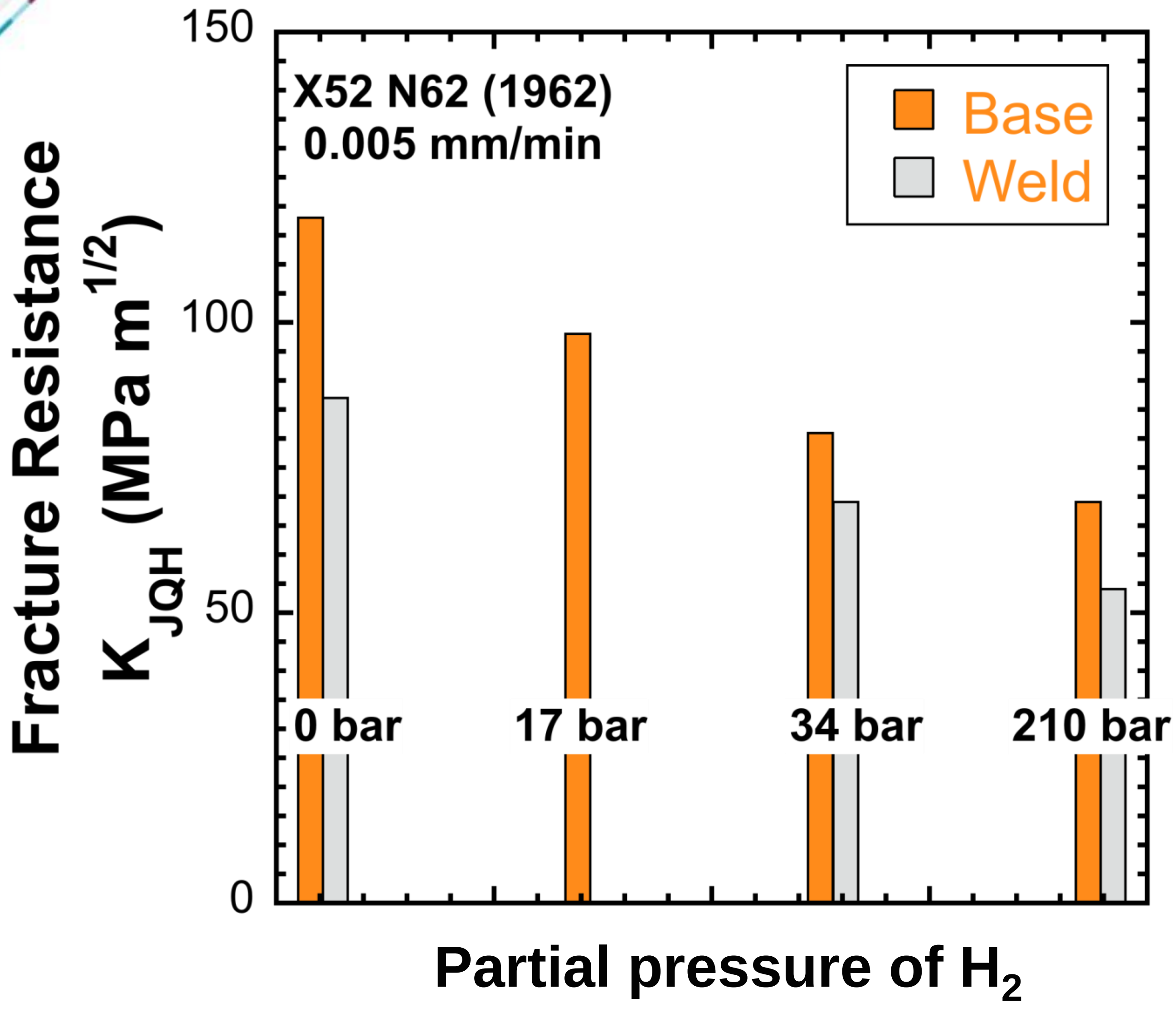
Fracture resistance decreases with increasing hydrogen pressure



- Significant reduction of fracture resistance (K_{JQH}) is apparent at low pressure
- Further reduction of K_{JQH} at higher pressure is non-linear

CLEAN HYDROGEN MISSION

Workshops planned

August – blended hydrogen pipeline distribution

September – pure hydrogen pipeline distribution

October – underground storage

Workshops planned

25th October – Underground Storage