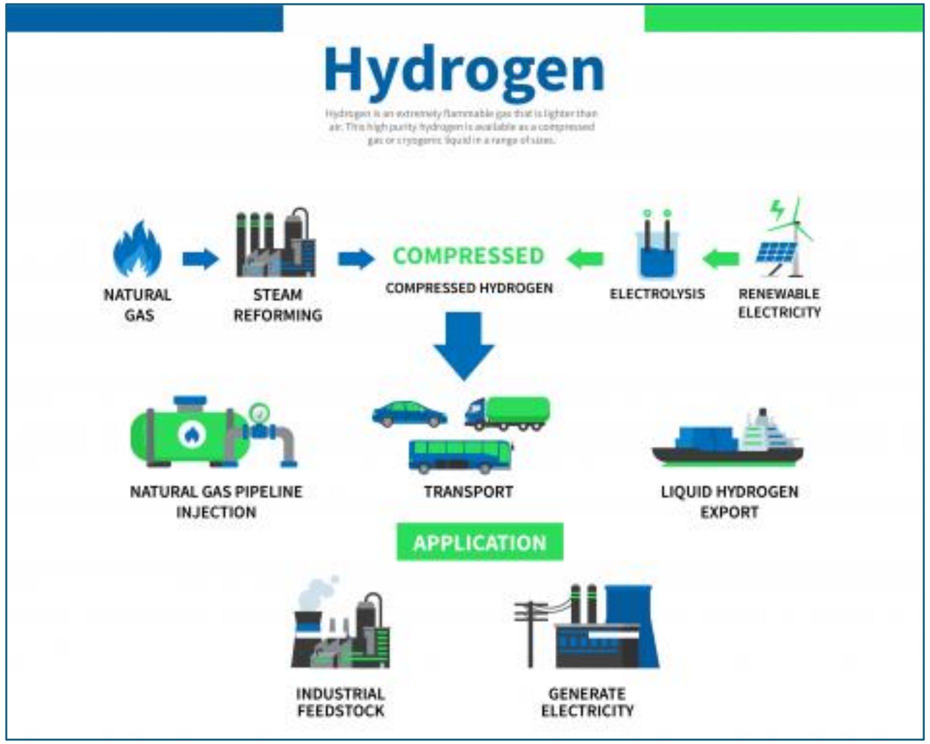
Repurposing of NG-Pipelines for Transportation of H_2+NG



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Indian Oil Corporation Limited

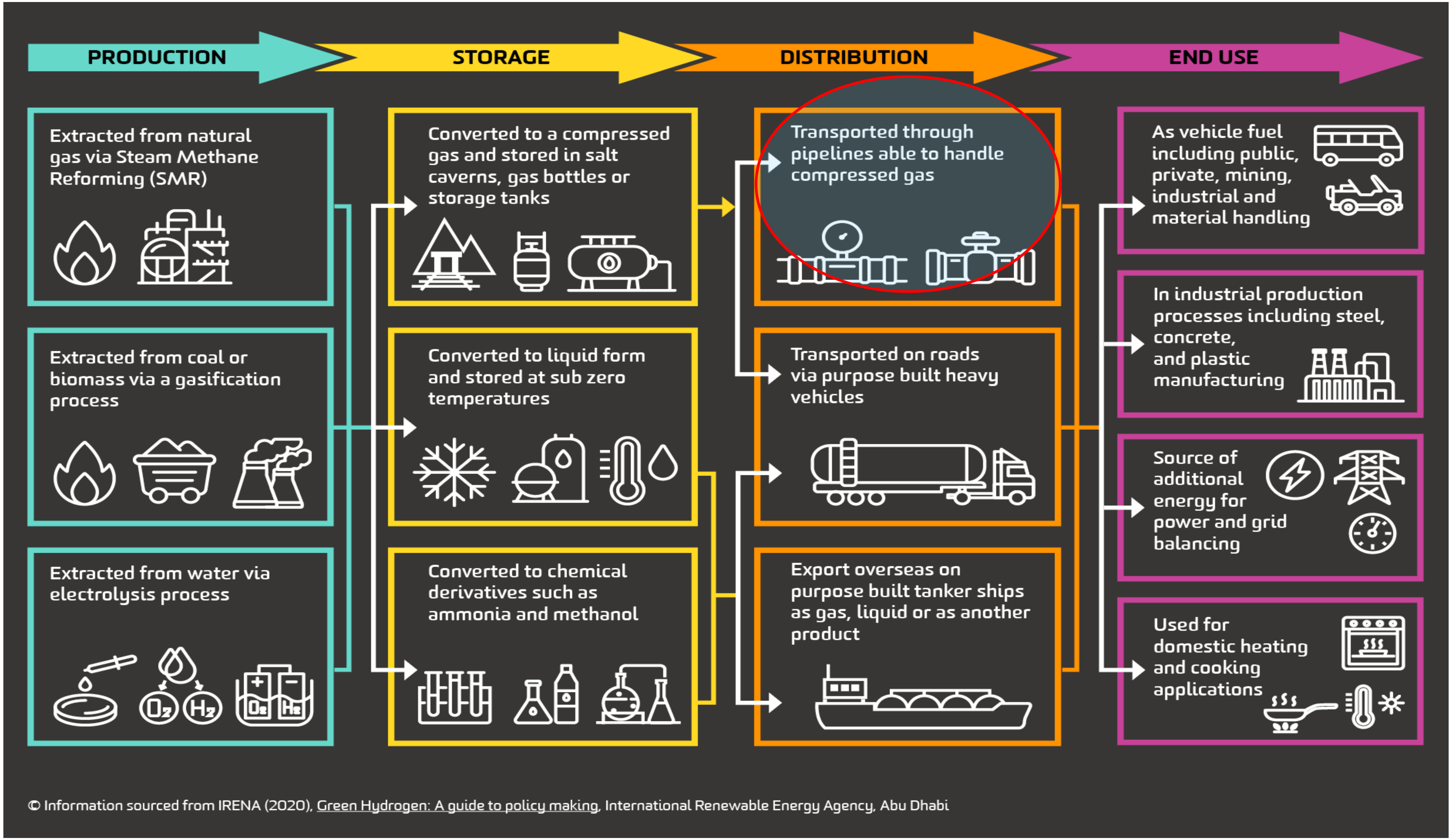
4th Nov. 2025

DISCUSSION AGENDA

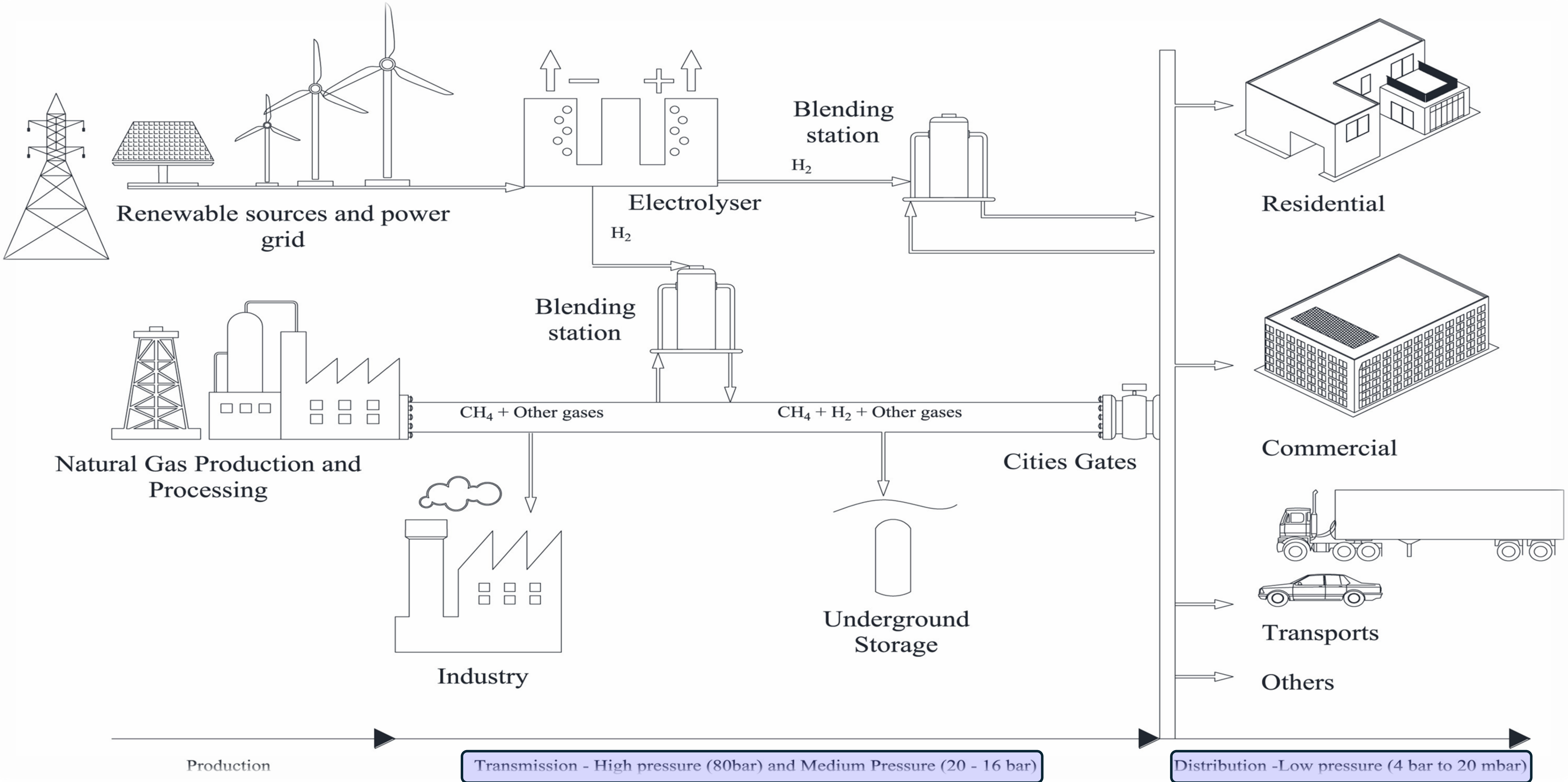
- Hydrogen Value Chain
- Challenges in Transportation of Hydrogen
- Damage Mechanisms of Hydrogen in Metals
- Evaluation of NG Pipeline for Transportation of H_2+NG
- Hydrogen Diffusion Mechanism in Pipeline
- Global Practices for repurposing NG PL for H_2+NG Transport
- Way Forward

Hydrogen Value Chain

Hydrogen Value Chain



Hydrogen Value Chain



Challenges in Transportation of Hydrogen

Challenges in Transportation of Hydrogen

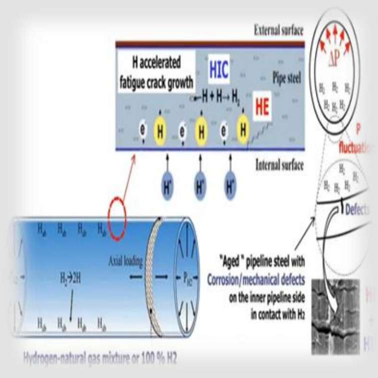
- **Low Energy Density**
  H_2 has very low energy density → Needs costly compression (700 bar) or liquefaction (−253 °C).
- **Liquefaction Challenges**
  Liquefying H_2 uses 30–40% of its energy and needs costly cryogenic tanks to limit boil-off.
- **Pipeline Issues**
  H_2 causes steel embrittlement → cracks/leaks; NG pipelines need retrofitting or replacement.
- **Conversion Alternatives**
  Converting H_2 to ammonia or liquid organic hydrogen carriers **(LOHCs)** for transport adds significant cost.
- **Infrastructure Cost**
  Building dedicated hydrogen pipelines or terminals requires massive capital investment.
- **Storage and Handling**
  High-pressure or cryogenic storage adds cost, complexity, and safety risks (flammability, leakage).

Challenges in Transportation of Hydrogen

Risk Category	Description
Material degradation	H_2-induced embrittlement, cracking, and failure in steel pipelines & components
Leak behavior	Higher leak risk, fast dispersion, harder detection, larger flammable clouds with H_2
Explosion hazard	Wide flammability, low ignition energy → Higher explosion/fire risk vs methane
Equipment compatibility	Risks to compressors, meters, valves, & use of H_2 blend in unmodified appliances

Key Pipeline Components Needing Testing

- Pipes (Steel and Plastic)
- Valves and Flanges
- Compressors
- Meters and Pressure Regulator
- Welds and Joints
- Sealing Materials and Gaskets
- Auxiliary Equipment and Controls

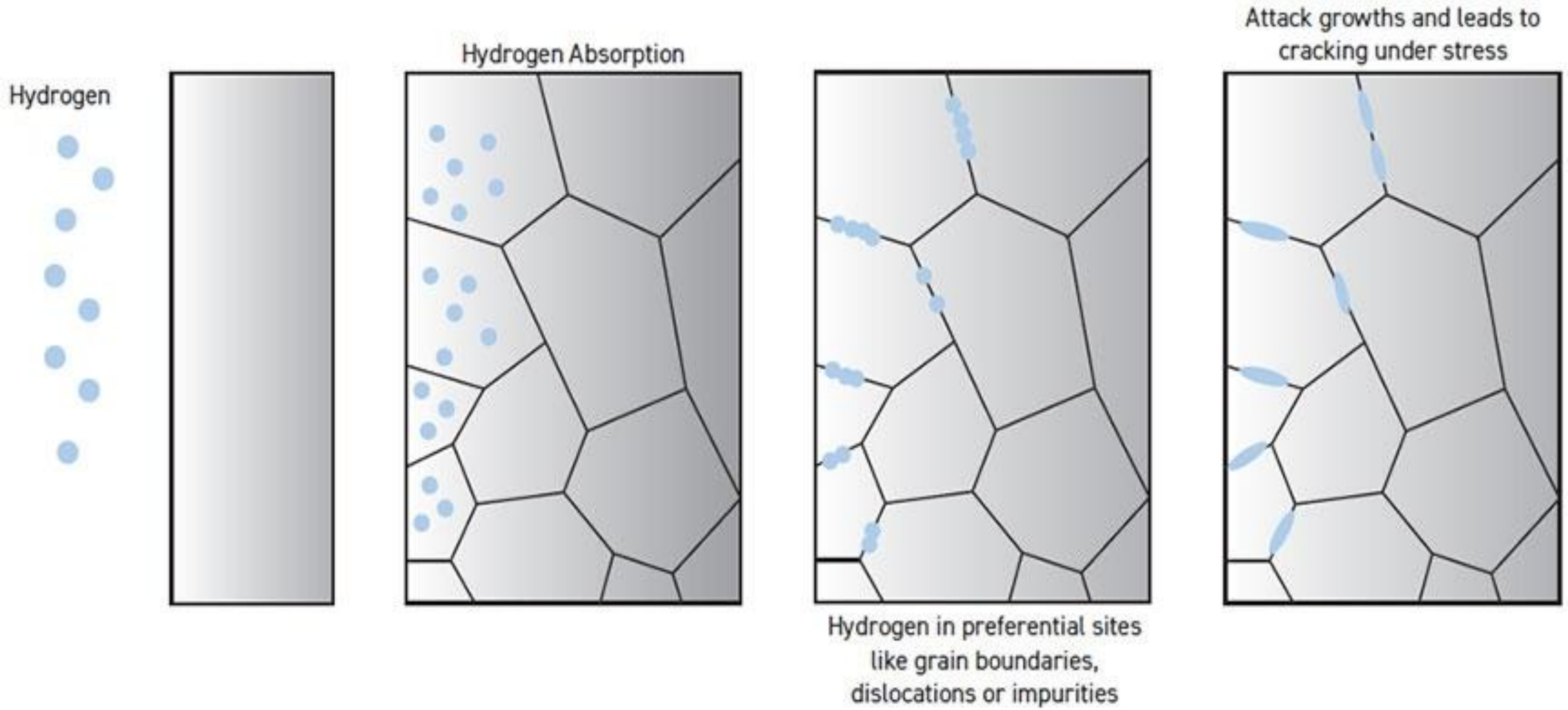


Damage Mechanisms of Hydrogen in Metals

Damage Mechanisms of Hydrogen in Metals

- Nascent 'H' diffuses into steel due to its atomic size, solubility and diffusivity
- Trapped at dislocations, point defects, grain boundaries, voids, precipitate-matrix interfaces
  - ✓ Entrapped hydrogen recombines at heterogeneities leading to swelling / Blistering
  - ✓ High Temperature Hydrogen Attack – reaction of trapped hydrogen with carbides leading to fissures
- Dissolved hydrogen migrates to triaxial stress sites causing time dependent static fatigue
- Dissolved hydrogen causes matrix Hydrogen Embrittlement
- Retardation of plastic deformation by locking of dislocation by trapped hydrogen

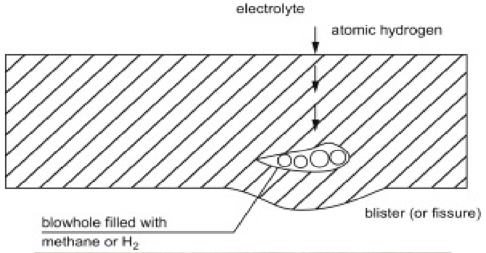
Damage Mechanisms of Hydrogen in Metals



Damage Mechanisms of Hydrogen in Metals

Low Temperature

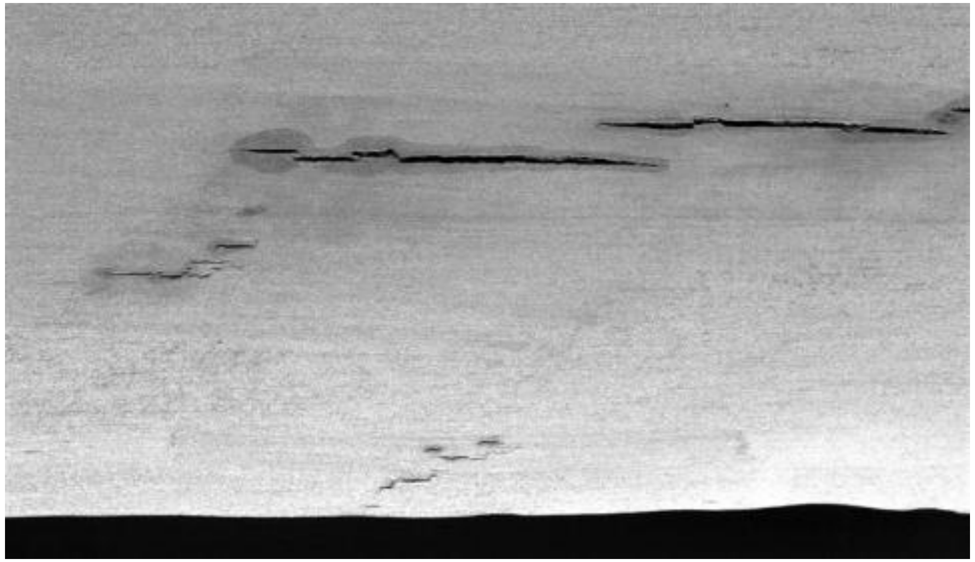
- Hydrogen Blistering
- Hydrogen Embrittlement
- Hydrogen Stress Assisted cracking
- Tolerant to lower levels of H_2



Hydrogen Fissures / Blistering in Line pipe due to H_2 / wet H_2S Corrosion

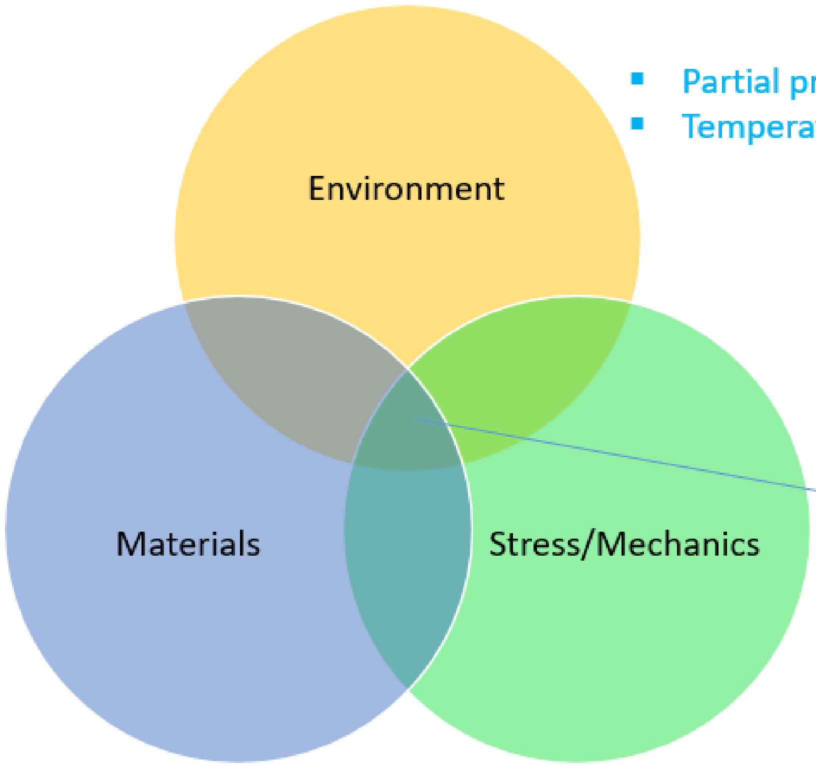
High Temperature

- High Temperature hydrogen attack (HTHA)
- Tolerance to higher levels of H_2



Damage Mechanisms of Hydrogen in Metals

Interplay of three variables

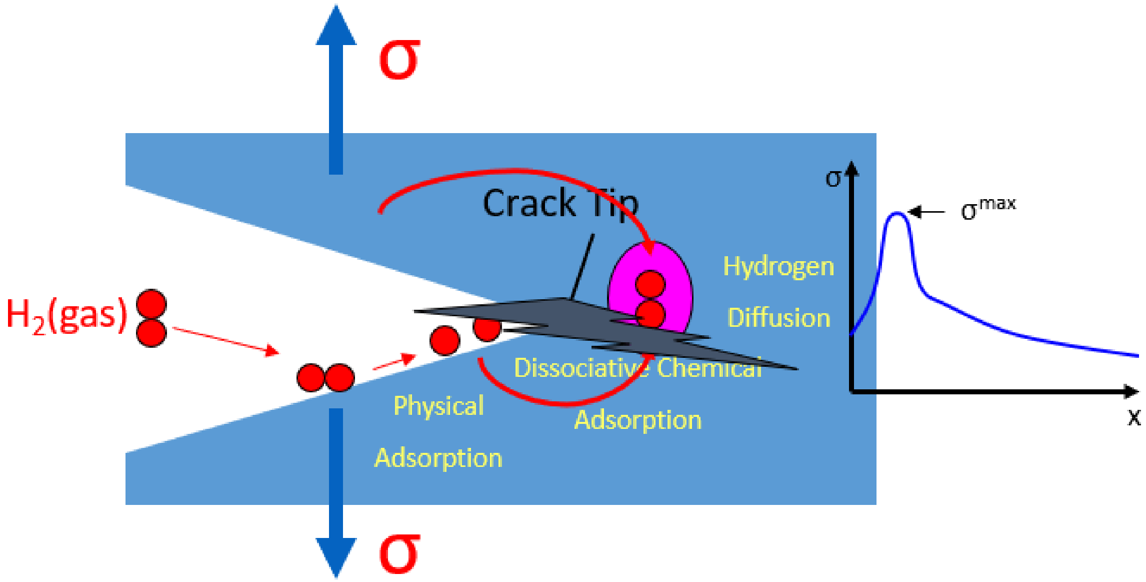


- Partial pressure
- Temperature

Confluence of the three conditions for HE

- Strength
- Microstructure
- Impurities

- Stress – static or dynamic
- Defects – depth, root radius, crack length and geometry,
- Residual stress



Schematic of hydrogen embrittlement phenomena

Factors affecting the entrainment of hydrogen

- T, P, k (kinetics driven by T, P and other catalytic activity)
- Solubility and Diffusivity
- Microstructures (Normalised; Q&T)
- Composition & Phases

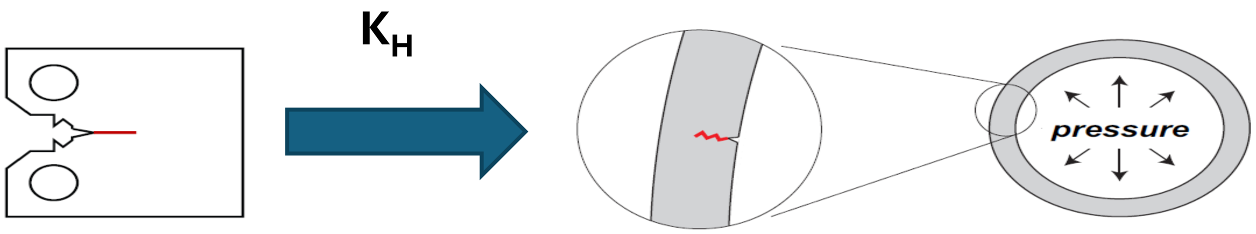
Evaluation of NG Pipeline for Transportation of H_2+NG

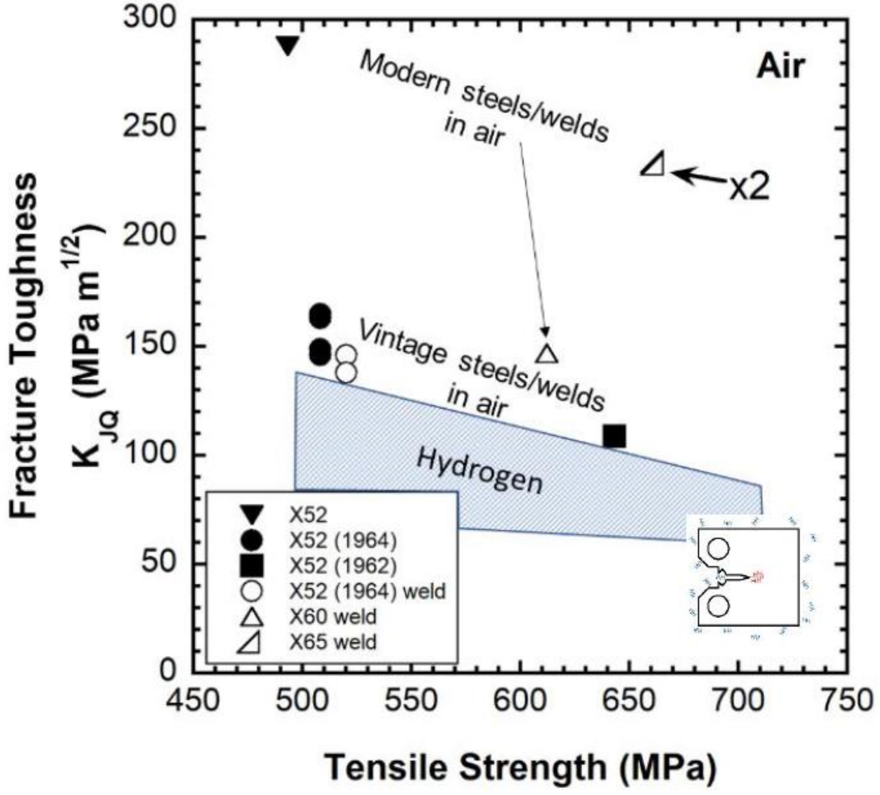
Fracture Resistance

- *Fracture Toughness* (K_{IC})– the most critical parameter for evaluation of the pipe grade steels
- Dependant on Defect geometry & Strength (UTS) of the Pipeline grade
- Fracture resistance behavior of welds vs parent metal
  - ✓ *Residual stress, Local hard spots (HAZ) & Local microstructural inhomogeneity*

Stress Intensity Factor, K

- K – defines stress state of crack
- $K = \sigma \sqrt{\Pi a} \times f(\text{geometry})$
- σ = Stress ; a = Crack size



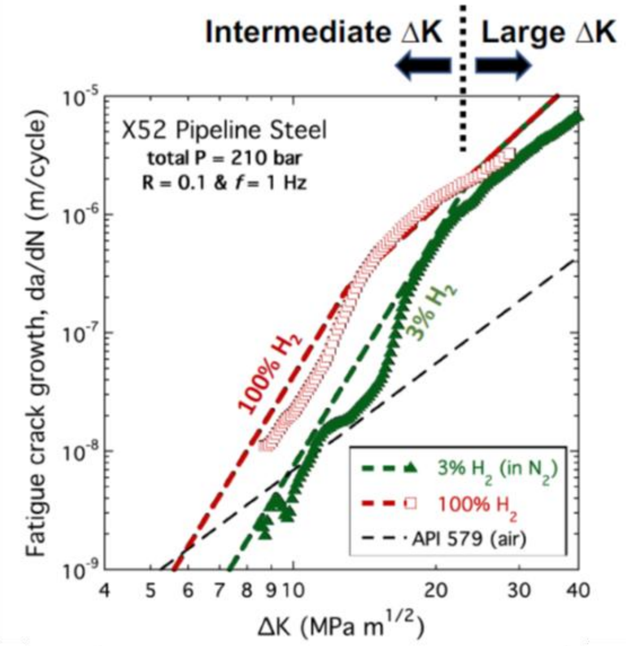


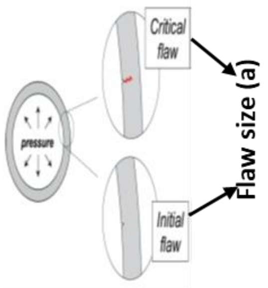
Higher the strength Lower the Fracture Toughness

Ref.: Ronevich et al, Intern Conf Metals and Hydrogen (2022)

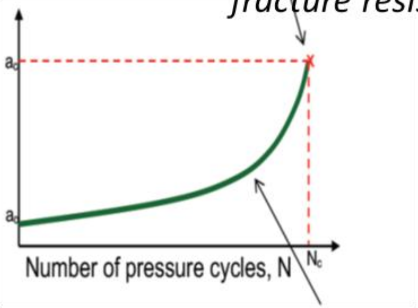
Fatigue Resistance

- *Fatigue Crack Growth Rate – Critical parameter in pipeline operations*
- Pressure cycling induces fatigue
- Partial pressure of hydrogen affects FCGR
- Hydrogen effects not seen under large ΔK

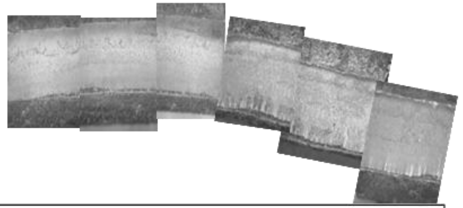


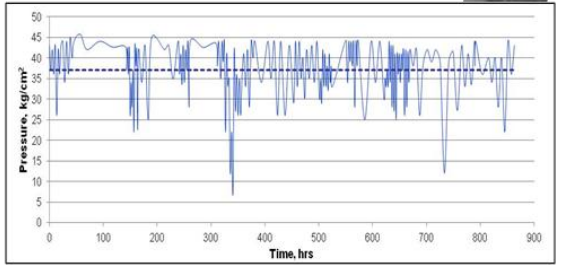


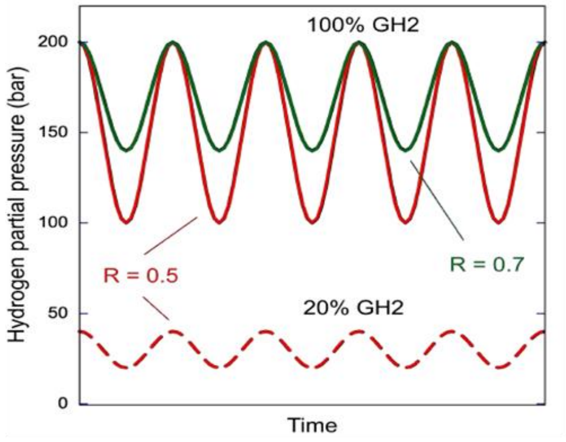
Rupture determined by *fracture resistance* (K_{IC})



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

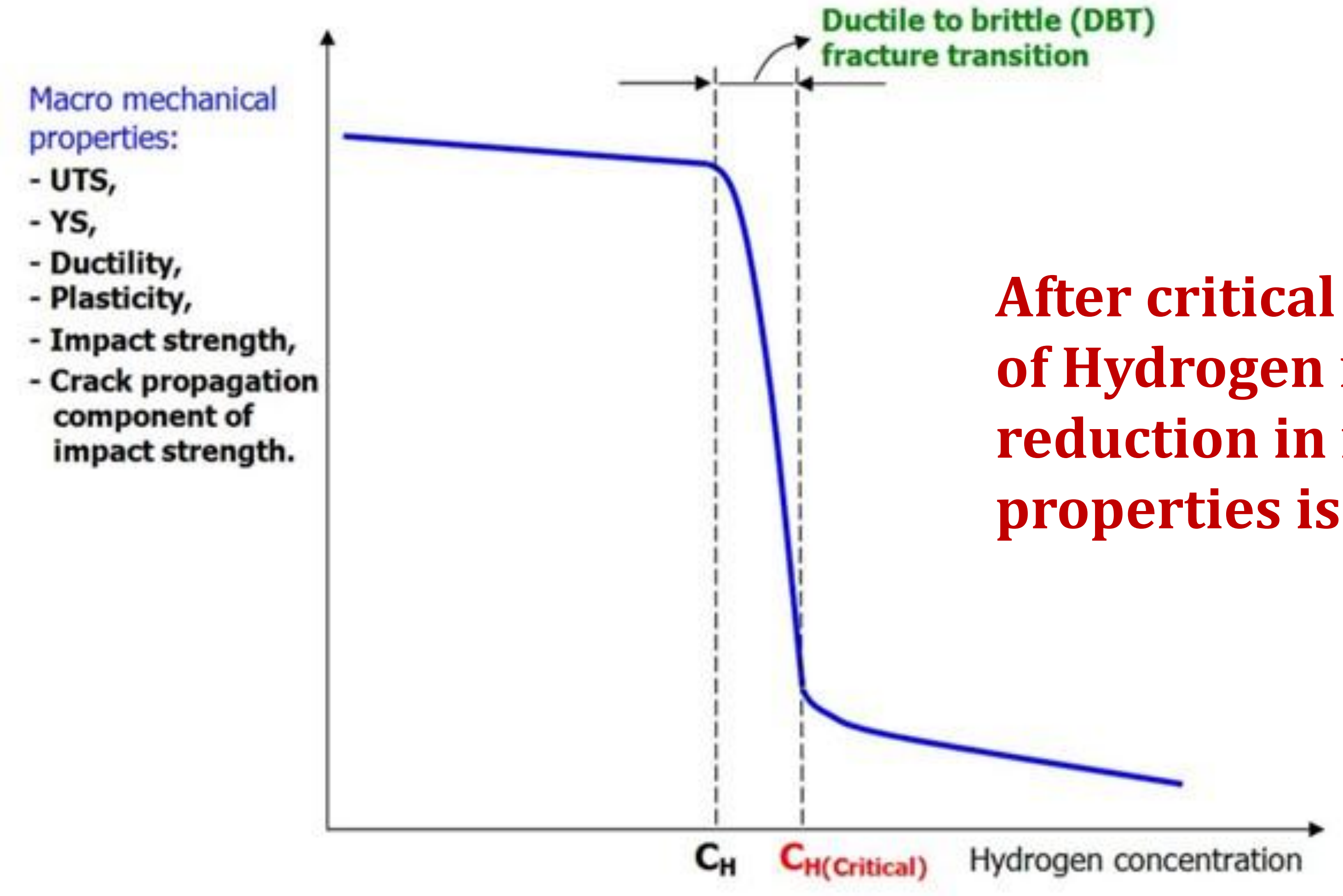






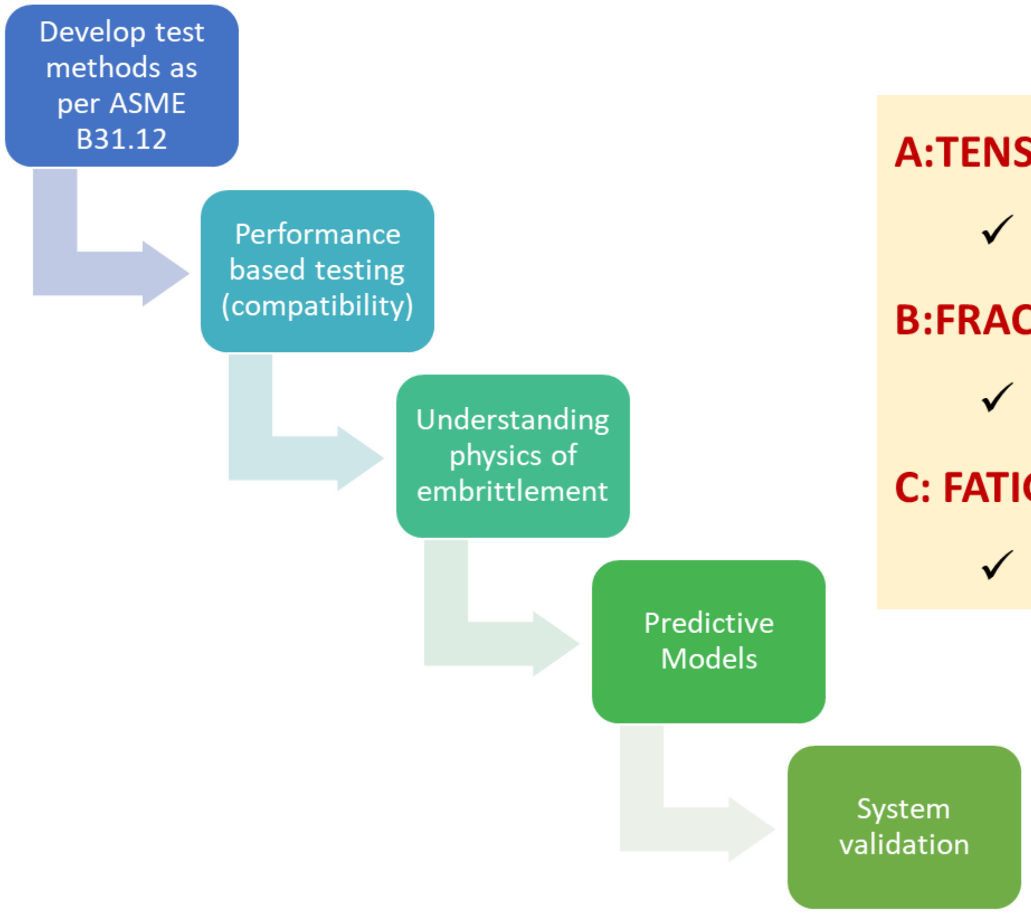
Ref.: San Marchi et al, PVP2021-62045

Hydrogen Embrittlement (HE)



After critical concentration of Hydrogen in steel, <u>drastic</u> reduction in mechanical properties is observed

Fitness Assessment



ASME B31.12 – Rules for hydrogen pipelines with reference to ASME BPVC Section VIII, Div. 3, Article KD-10

A:TENSILE DEFORMATION & FRACTURE BEHAVIOR

- ✓ Strain rate dependence & Notch sensitivity

B:FRACTURE RESISTANCE

- ✓ Fracture Mechanics based analysis – J_{IC} , J_{IH}, J-R curve

C: FATIGUE RESISTANCE

- ✓ Fatigue Crack Growth Rates – (da/dN)

Structure integrity tool for quantitative risk assessment – predictive models

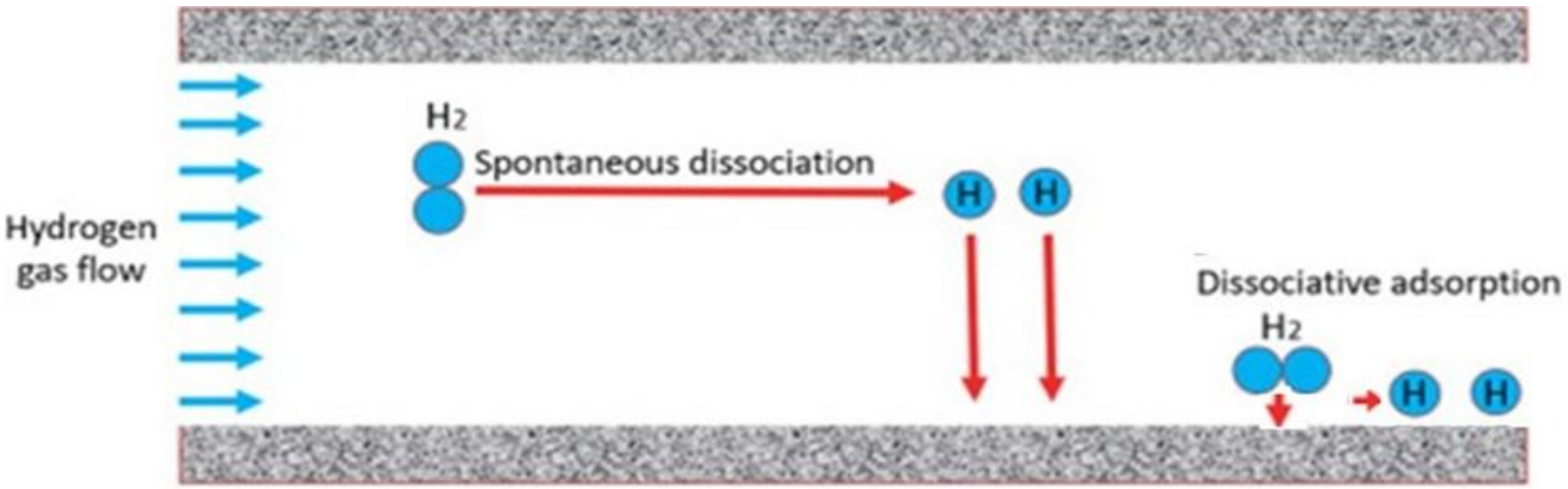
Development of Indigenous Regulatory standards for Repurposing

ASME B31.12 Extract

S.N.	Characteristic	ASME B31.12 Option A	ASME B31.12 Option B
1	Design Factor	Max 0.5	Max 0.72
2	Brittle fracture control	Min(0°C or min operating temp); Avg. shear – 80% (full size); 85% (reduced size); 40% drop weight	Same as Option A
3	Ductile fracture control	$CVN \geq 0.008(RT)^{0.39}{\sigma_h}^2$	Same as Option A
4	Fracture toughness, K_{IC} & K_{IH} (ASTM E399)	Not specified	$K_{IH} \geq 55$ MPa $\sqrt{m}$
5	Yield strength	≤70000 psi	≤80000 psi
6	UTS	≤100000 psi	≤110000 psi
7	Steel composition	Not specified	P ≤0.015%; Inclusion shape control
8	Weld hardness	≤235HV10	Same as Option A

Hydrogen Diffusion in PL

- **From cathodic reaction**
  - $2H^+ + 2e^- \rightarrow 2H_{ads} \rightarrow 2H_{abs} \rightarrow$ diffuses into steel
  - Excessive charging of H in steel, not representative of pipeline conditions
- **Dissociation of gaseous H_2**
  - Spontaneous dissociation – Thermodynamically not feasible
  - **Dissociative absorption – Possible under pipeline operating conditions**



Hydrogen Diffusion in Pipeline

Methane (CH_4) - Competes

- CH_4 breaks into CH_3 & H
- Competitive absorption of CH_4 and H_2 molecules on steel

Oxygen (O_2), Sulfur dioxide (SO_2) and Carbon monoxide (CO) - Inhibits

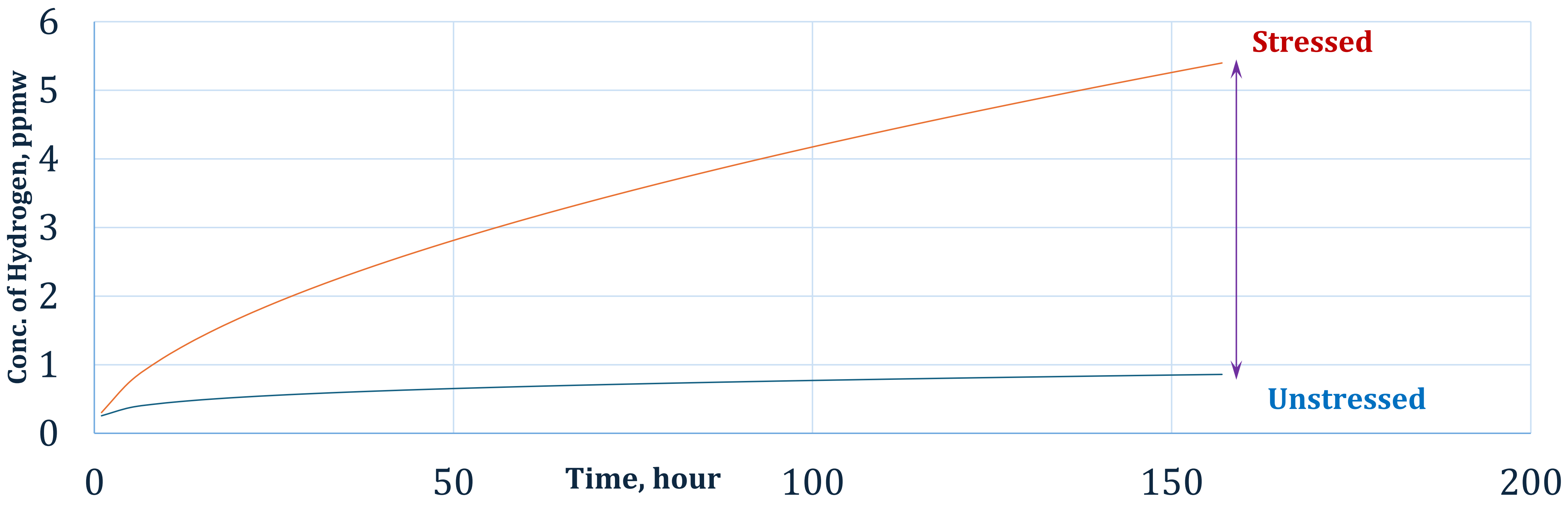
- Raises activation energy for H atom
- Impedes the kinetics of atomic H uptake

Hydrogen Sulphide (H_2S), Carbon dioxide (CO2); Methanethiol (CH_3SH)- Assists

- Significantly increases H uptake in steel

Inhibit HE	Neutral	Promote HE
O_2, SO_2, CO	CH_4, N_2	H_2S, CH_3SH, CO_2, H_2O

Hydrogen Diffusion in Stressed Condition



- Under stressed (loaded) condition, H uptake is multi-fold as compared to unloaded condition
- **Hence, testing should be considered under stressed condition**

Maximum Allowable Operating Pressure

- Pipeline MAOP calculations

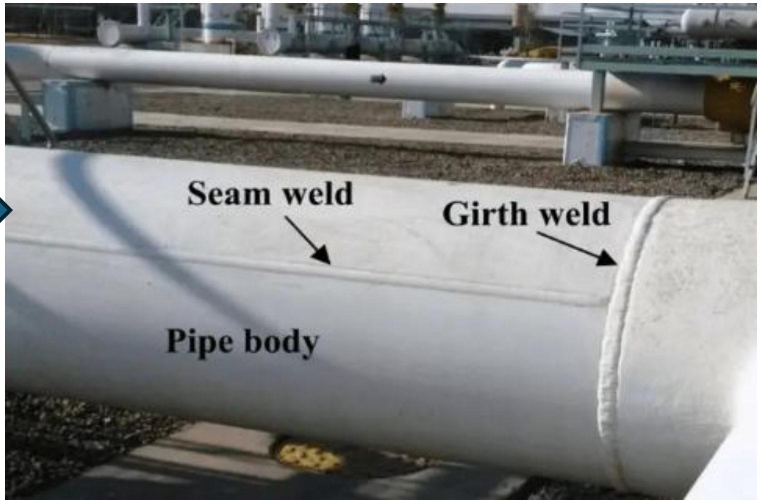
$$MAOP = \left(\frac{2St}{D}ET\right)FH_f$$

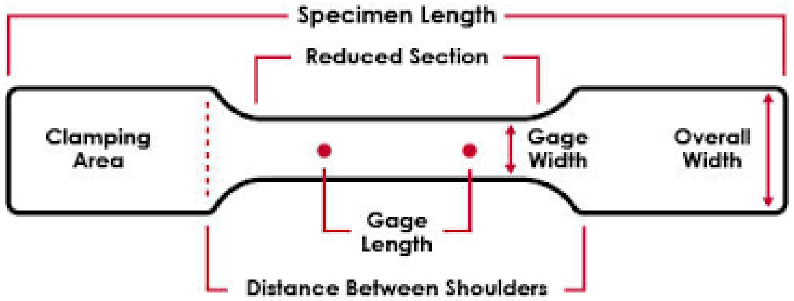
- MAOP – Maximum Allowable Operating Pressure
- S – SMYS
- t – Wall thickness
- D – Pipe outer dia
- F – Design factor
- E – Longitudinal weld joint factor
- T – Temperature derating factor
- H_f – Material Performance factor

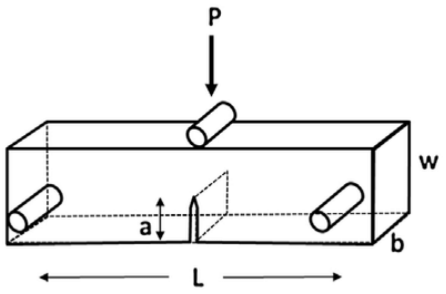
SMYS	H_f (for Opn press ≤69)	Factor FH_f	
		ASME B31.12 Option A (F=0.5)	ASME B31.12 Option B (F=0.72)
≤52	1	0.5	0.72
≤60	0.874	0.44	0.63
≤70	0.776	0.39	0.56
≤80	0.694	0.35	0.5

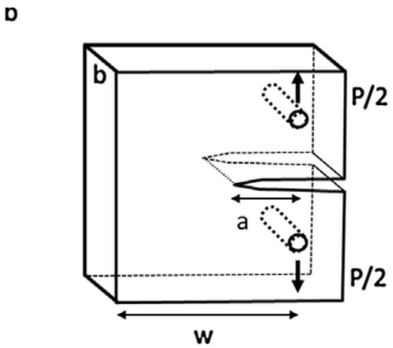
Experimental study required to avoid lose on capacity.

Hydrogen Damage Assessment – Sampling









Fittings- Forged, Cast, etc.

Gaskets, Flanges, bends, Tee.

Rotary meters, flow meters, Transmitters etc.

NACE, HIC, H_2 service

Sl. No.	Piping Class	Rating	C.A	Spl. Reqt.	Basic Material	Service Remarks
1	A5A	150	1.5	HYDROGEN SERVICE	CARBON STEEL	HYDROGEN AND HYDROGEN BEARING HYDROCARBONS
2	A65A	150	3	NACE+H2 SERVICE	CARBON STEEL	NACE,CORROSIVE PROCESS SERVICE,H2 SERVICE WITH WET H2S, MAXIMUM TEMPRATURE 260 DEG C.
3	A66A	150	3	NACE+HIC	CARBON STEEL	NACE, SOUR WATER CONTAINING H2S AND/OR AMMONIUM SALT, RICH/LEAN AMINE WITH H2S NON-LETHAL+HIC
4	A67A	150	3	NACE+HIC+H2	CARBON STEEL	NACE,HYDROGEN+HIC, CORROSIVE PROCESS SERVICE, SOUR GAS-FLAMMABLE, NON-LETHAL, MAXIMUM TEMPERATURE 260 DEG
5	B5A	300	1.5	HYDROGEN SERVICE	CARBON STEEL	HYDROGEN AND HYDROGEN BEARING HYDROCARBONS
6	B5D	300	1.5	HYDROGEN SERVICE	1.25Cr + 0.5Mo	HYDROGEN, HYDROGEN & HYDROCARBONS ABOVE 230 DEG C
7	B65A	300	3	NACE+H2	CARBON STEEL	NACE,CORROSIVE PROCESS SERVICE, HYDROGEN SERVICE WITH WET H2S, SOUR GAS - MAXIMUM TEMPERATURE 230 DEG. C
8	B65D	300	3	NACE+H2	1.25Cr + 0.5Mo	HYDROCARBON FEED AND HYDROGEN WITH WET H2S
9	B66A	300	3	NACE+HIC	CARBON STEEL	NACE, SOUR WATER CONTAINING H2S AND/OR AMMONIA SALT, RICH/LEAN AMMINE WITH H2S, NON-LETHAL+HIC
10	B67A	300	3	NACE+HIC+H2	CARBON STEEL	NACE,HYDROGEN SERVICE, CORROSIVE PROCESS SERVICE, SOUR GAS- FLAMMABLE, NON LETHAL+HIC

NACE, HIC, H_2 service

Sl. No.	Piping Class	Rating	C.A	Spl. Reqt.	Basic Material	Service Remarks
1	D5A	600	1.5	HYDROGEN SERVICE	CARBON STEEL	HYDROGEN AND HYDROGEN BEARING HYDROCARBONS
2	D5D	600	1.5	HYDROGEN SERVICE	1.25Cr + 0.5Mo	HYDROGEN AND HYDROGEN BEARING HYDROCARBONS ABOVE 230 DEG C.
3	D65A	600	3	NACE+H2 SERVICE	CARBON STEEL	CORROSIVE PROCESS SERVICE, HYDROGEN SERVICE WITH WET H2S, SOUR GAS NON-LETHAL. MAXIMUM TEMP. 230 DEG. C
4	D66A	600	3	NACE+HIC	CARBON STEEL	NACE, SOUR WATER CONTAINING H2S AND/OR AMMONIUM SALT, RICH/LEAN AMINE WITH H2S NON-LETHAL+HIC
5	D67A	600	3	NACE+HIC+H2	CARBON STEEL	NACE,H2 SERVICE+HIC, CORROSIVE PROCESS SERVICE, SOUR GAS-FLAMMABLE, NON LETHAL MAXIMUM TEMP. 230 DEG.C
6	E5E	900	1.5	HYDROGEN SERVICE	2.25Cr + 1.0Mo	HYDROGEN CONTAINING PROCESS LIQUID, VAPOUR & GAS.
7	E25M	900	1.5	HYDROGEN SERVICE	SS321H	HIGH TEMPERATURE HYDROGEN, HYDROGEN + CORROSIVE HYDROCARBONS. FLAMMABLE, TOXIC BUT NON LETHAL.
8	F5A	1500	1.5	HYDROGEN SERVICE	CARBON STEEL	HYDROGEN AND HYDROGEN BEARING HYDROCARBONS -FLAMMABLE, TOXIC/NON-TOXIC BUT NONLETHAL.

In a refinery, piping suitable for H2 service is used at various pressures. E.g. 20, 40, 100 kg/cm2(g), and Recycle gas upto 170-180 Kg/cm2(g) pressure.

NACE, HIC, H_2 service

H2 SERVICE:

- FOR HYDROGEN SERVICE, CARBON STEEL PIPING MATERIALS WITH WALL THICKNESS 3/8 INCH AND OVER SHALL BE NORMALISED.
- ANY MEDIUM CONTAINING HYDROGEN GAS WITH A PARTIAL PRESSURE OF 100 PSI & ABOVE SHALL BE CONSIDERED AS HYDROGEN SERVICE.
- NDT REQUIREMENTS AS PER EIL STANDARD A882-6-44-0016.

NACE SERVICE:

- MAXIMUM HARDNESS IN WELD JOINTS SHALL BE LIMITED TO 200 BHN.
- ALL GIRTH WELD JOINTS SHALL BE 100% RADIOGRAPHED & ALL TYPES OF WELDS INCLUDING GIRTH WELDS SHALL
- BE WET FLOURESCENT MP TESTED.
- NACE REQUIREMENT OF MR0103 SHALL BE MET.
- NDT REQUIREMENTS AS PER EIL STANDARD A882-6-44-0016.

NACE + HIC SERVICE:

- MAXIMUM HARDNESS IN WELD JOINTS SHALL BE LIMITED TO 200 BHN.
- ALL GIRTH WELD JOINTS SHALL BE 100% RADIOGRAPHED & ALL TYPES OF WELDS INCLUDING GIRTH WELDS SHALL
- BE WET FLOURESCENT MP TESTED.
- NDT REQUIREMENTS AS PER EIL STANDARD A882-6-44-0016.
- ALL WELDS SHALL BE PWHT IRRESPECTIVE OF THICKNESS.
- ALL REQUIREMENTS OF NACE MR 0103 SHALL BE MET.
- FOR ALL WELDED PIPES ,THE PLATE SHALL MEET HIC RESISTANT REQUIREMENTS.
- COMPLIANCE TO SPECIAL REQUIREMENTS OF HIC. REFER EIL SPEC 6-79-0013.

Uniqueness of Pipeline Transportation systems

- Compositional Tolerances within the specified grade
- Steel making and Pipe manufacturing processes
- Workmanship & Quality control during fabrication
- Defect acceptance limits and the NDT adopted
- Operational aspects : Max. pressure , pressure cycles, temperature, fluid type etc.
- In-service stresses , damages, defects, repair techniques

Case to case assessment is required for alteration of service.

Pipeline Suitability Checking

- Equip with all testing facilities
- Evaluate material compatibility
- Monitor and predict H_2 damage
- H_2 Risk Assessment
- Fitness for Service assessment of H_2 pipelines

Global practices for repurposing NG Pipelines for H_2 blending & Transport

Hydrogen Transportation Thru' NG Pipeline in EU & USA

IndianOil 2025 IGNITE PASSION, PROPEL THE CORE

SPRINT A Transformational Project

Aspect	Europe (EU)	USA
Infrastructure Strategy	Repurposing existing NG pipelines (e.g., Gasunie)	Utility-led pilot blending projects (e.g., SoCalGas, PG&E)
Blending Ratio	Typically, ≤20% in pilots; full H_2 transport planned in future	≤15% H_2 blending in most pilots; some legacy systems (e.g., Hawai'i Gas)
Regulatory Framework	EU Hydrogen & Gas Directive (2024); mandates network separation, tariffs, etc.	DOE-led initiatives; state-level approvals (e.g., CPUC in California)
Standardization Efforts	CEN/CENELEC developing hydrogen transport standards	National Labs (NREL, ANL, PNNL) developing tools & guidelines
Safety & Material Research	Fraunhofer, JRC studies on embrittlement, welding, permeability	HyBlend initiative: HELPR, BlendPATH, PPCT tools for integrity & economics
Cross-border Coordination	European Hydrogen Backbone (EHB) initiative for pan-EU pipeline network	No national backbone yet; focus on regional pilots
Technology Deployment	Modular retrofits, low-stress designs, weld control	Injection systems, modular designs, leak detection instrumentation
Scale & Ambition	~50,000 km proposed hydrogen-ready pipelines	>20 pilot projects; scaling depends on regulatory and technical readiness
Public Tools & Models	EU-funded techno-economic models under Horizon Europe	DOE open-source tools for lifecycle, cost, and integrity modeling

Way Forward

- Repurposing of in-service Pipelines for Transportation of Hydrogen blends from all grades for various % of H_2 - 5%, 10%, 15%, 20%, etc.
  - ✓ Research labs & Academic Institutes
  - ✓ Pipeline Operators
  - ✓ Manufacturers of steel / pipe / pipe components / others
- Frame guidelines on Fitness For Purpose, Integrity, Risk assessment repair procedures, Inspection practices etc.
- Development of suitable NDT techniques to detect the allowable sizes of defects under Hydrogen service.


THANK YOU!