

# Repurposing of Pipelines for Transportation of HCNG Blends through Pipelines

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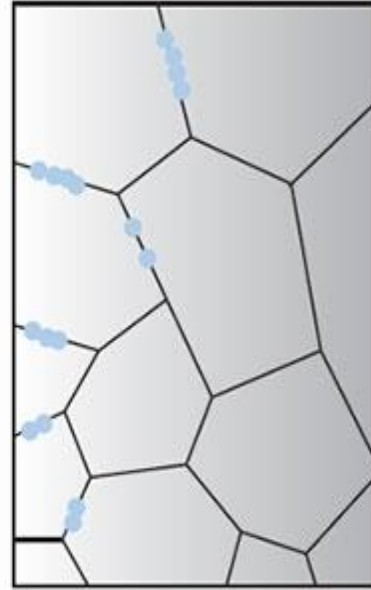
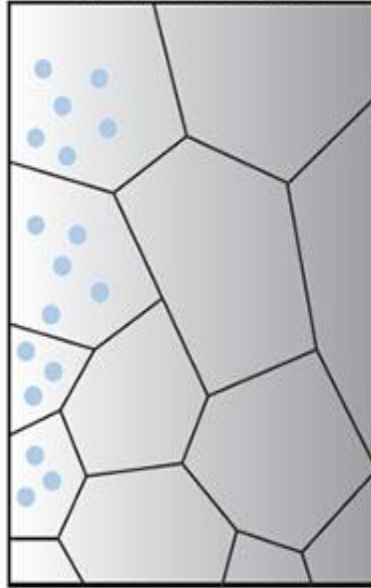
- Nascent 'H' diffuses into steel due to its atomic size, solubility and diffusivity
- Trapped at dislocations, point defects, grain boundaries, voids, precipitate-matrix interfaces
  - ✓ Entrapped hydrogen recombines at heterogeneities leading to swelling / **Blistering**
  - ✓ **High Temperature Hydrogen 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

Hydrogen

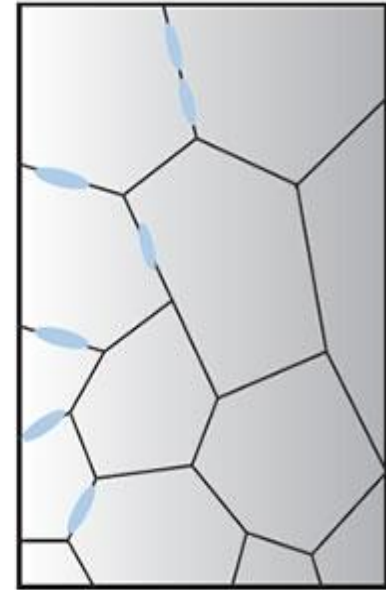


Hydrogen Absorption



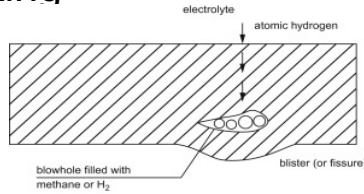
Hydrogen in preferential sites like grain boundaries, dislocations or impurities

Attack grows and leads to cracking under stress



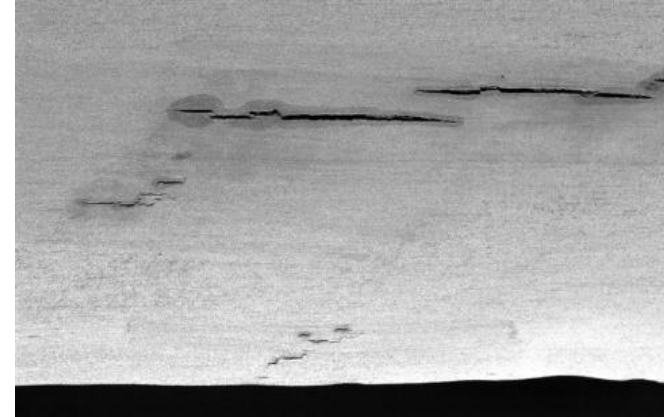
## Low Temperature

- Hydrogen Blistering
- Hydrogen Embrittlement
- Hydrogen Stress Assisted cracking
- Tolerant to lower levels of H<sub>2</sub>



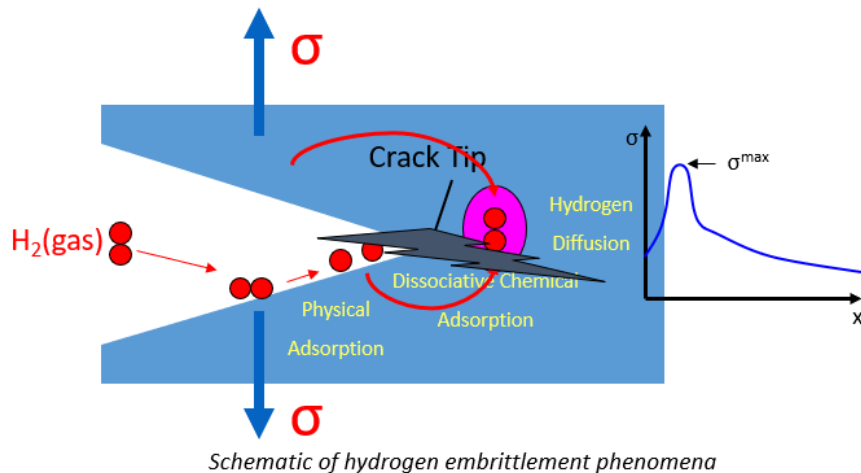
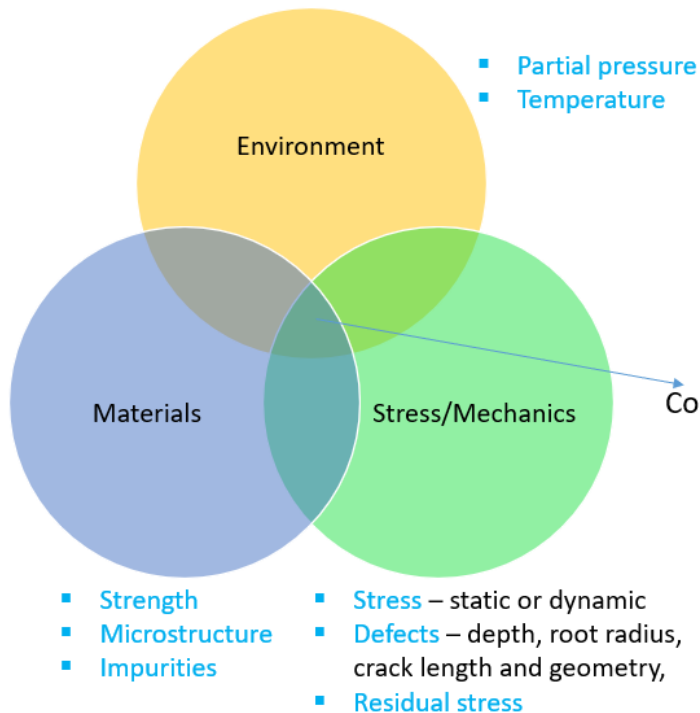
## High Temperature

- High Temperature hydrogen attack (HTHA)
- Tolerance to higher levels of H<sub>2</sub>



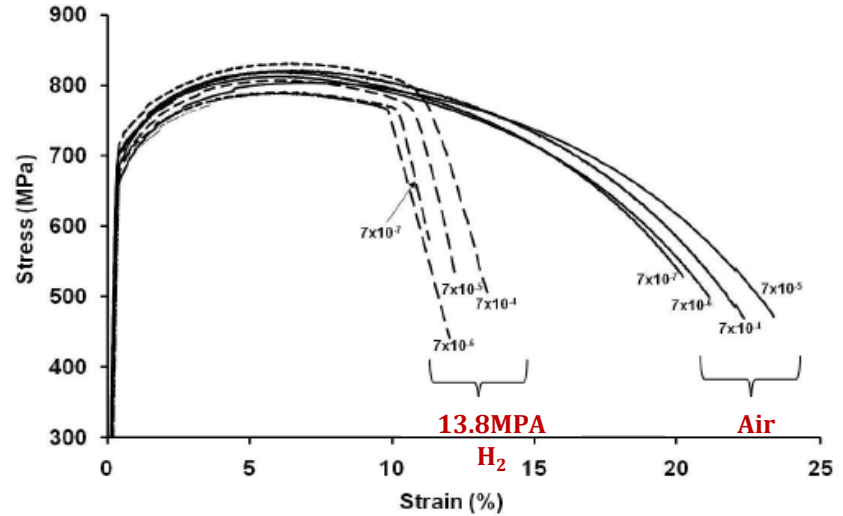
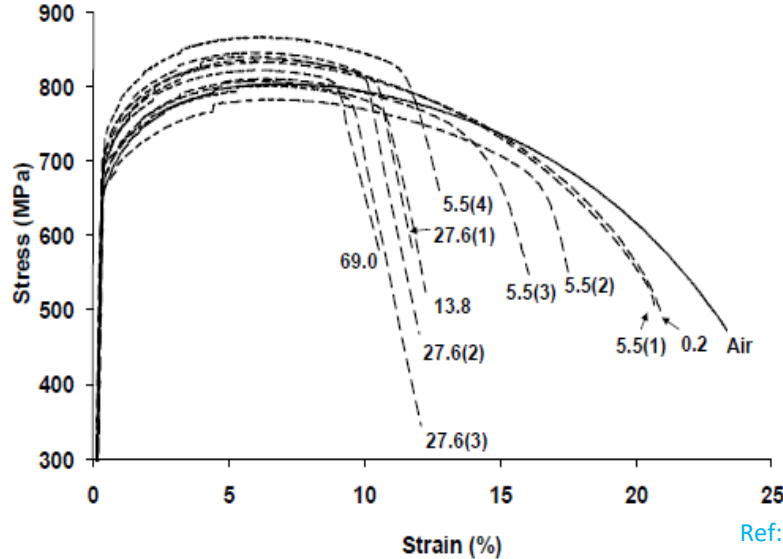
**Hydrogen Fissures / Blistering in Line pipe due to H<sub>2</sub> / wet H<sub>2</sub>S Corrosion**

## Interplay of three variables



## Factors affecting the entrapment of hydrogen

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



Ref: International Journal of Hydrogen Energy, Vol.59, Nicholas Nanninga et.al, NIST, 2012

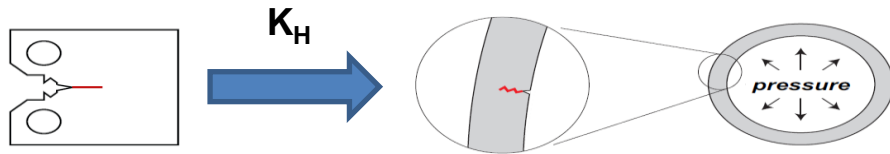
*Tensile Test X100 steel in hydrogen at different gas pressures (Strain rate -  $7 \times 10^{-5}$  /s)*

- ✓ Notch sensitivity & Strain rate sensitivity of Tensile properties to Hydrogen
  - Increasing  $H_2$  pressure significant vs. Increasing strain rate
- ✓ Revised properties for consideration in Design

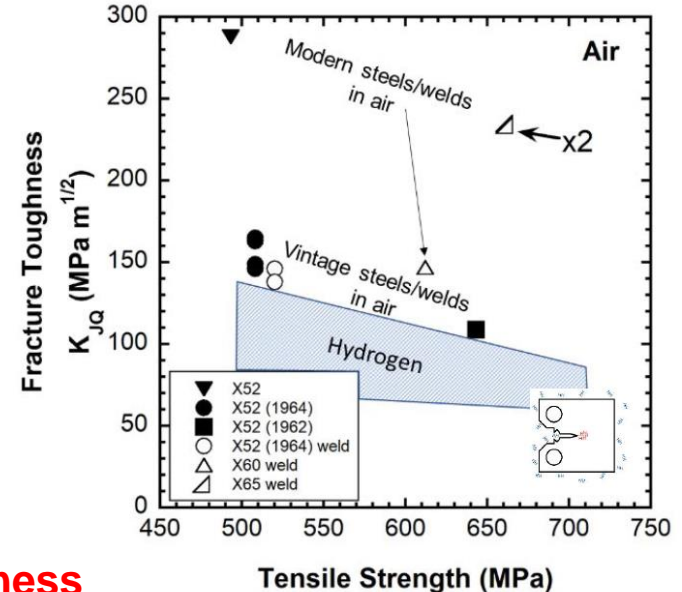
- **Fracture Toughness ( $K_{IC}$ )**– the most critical parameter for evaluation of the pipe grade steels
  - Dependant on Defect geometry & Strength (UTS) of the Pipeline grade
  - Fracture resistance behavior of welds vs parent metal
- ✓ *Residual stress, Local hard spots (HAZ) & Local microstructural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

## Stress Intensity Factor, K

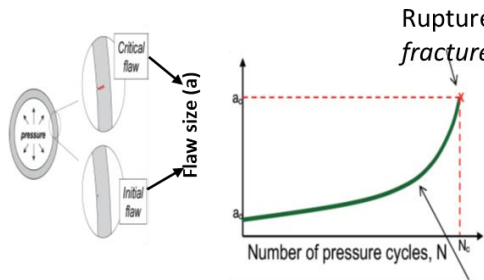
- K – defines stress state of crack
- $K = \sigma \sqrt{\Pi a} \times f(\text{geometry})$
- $\sigma = \text{Stress}$  ;  $a = \text{Crack size}$



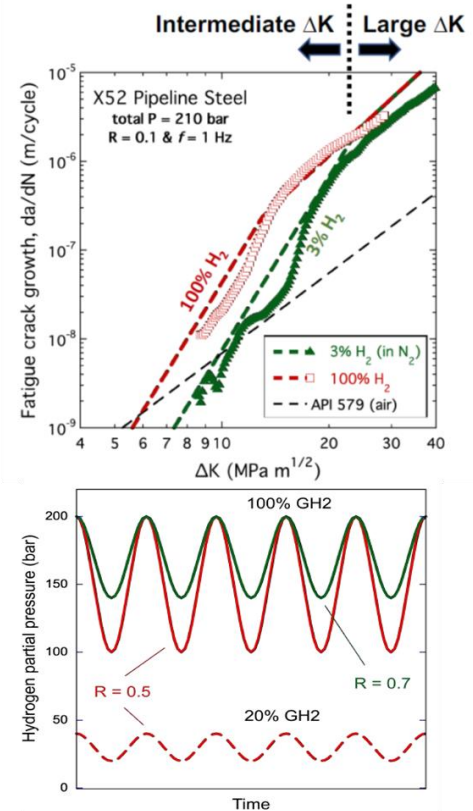
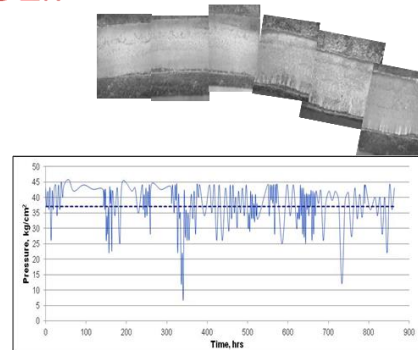
**Higher the strength Lower the Fracture Toughness**



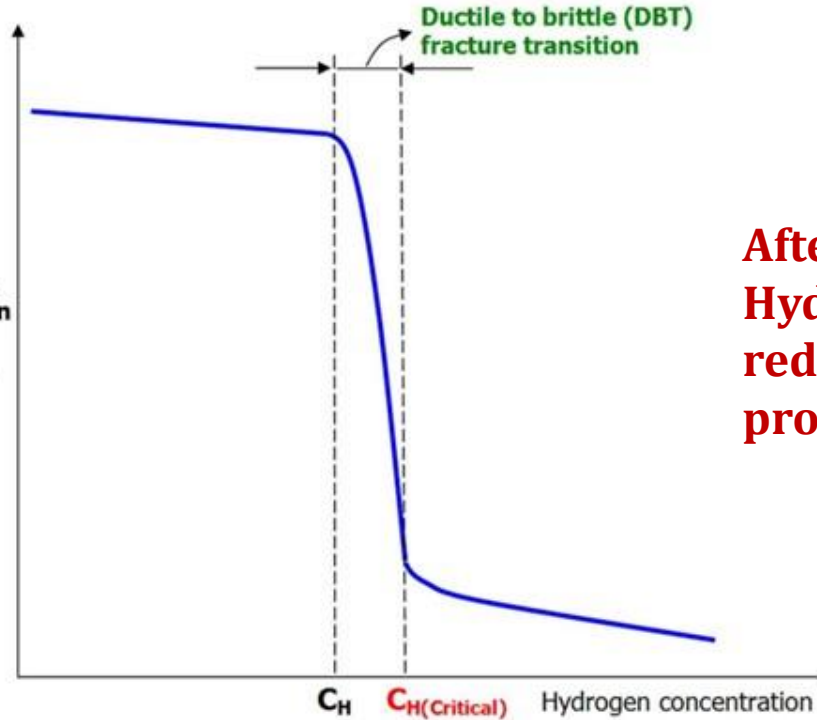
- ❖ *Fatigue Crack Growth Rate – Critical parameter in pipeline operations*
- ❖ Pressure cycling induces fatigue
- ❖ Partial pressure of hydrogen affects FCGR
- ❖ Hydrogen effects not seen under large  $\Delta K$



Evolution of flaw size determined by *Fatigue crack growth* ( $\Delta K$ - $da/dN$  data)

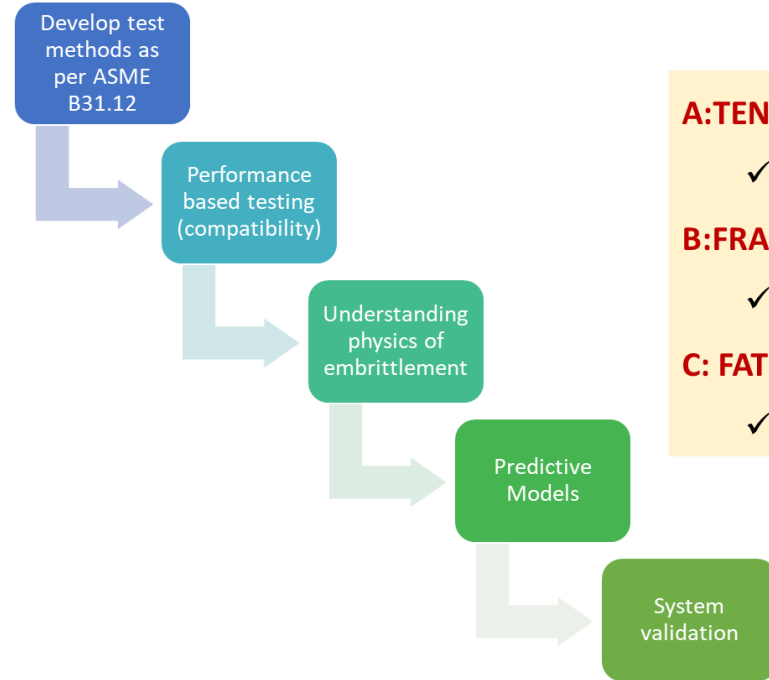


Macro mechanical properties:  
- UTS,  
- YS,  
- Ductility,  
- Plasticity,  
- Impact strength,  
- Crack propagation component of impact strength.



After critical concentration of Hydrogen in steel, drastic reduction in mechanical properties is observed

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 –  $(da/dN)$

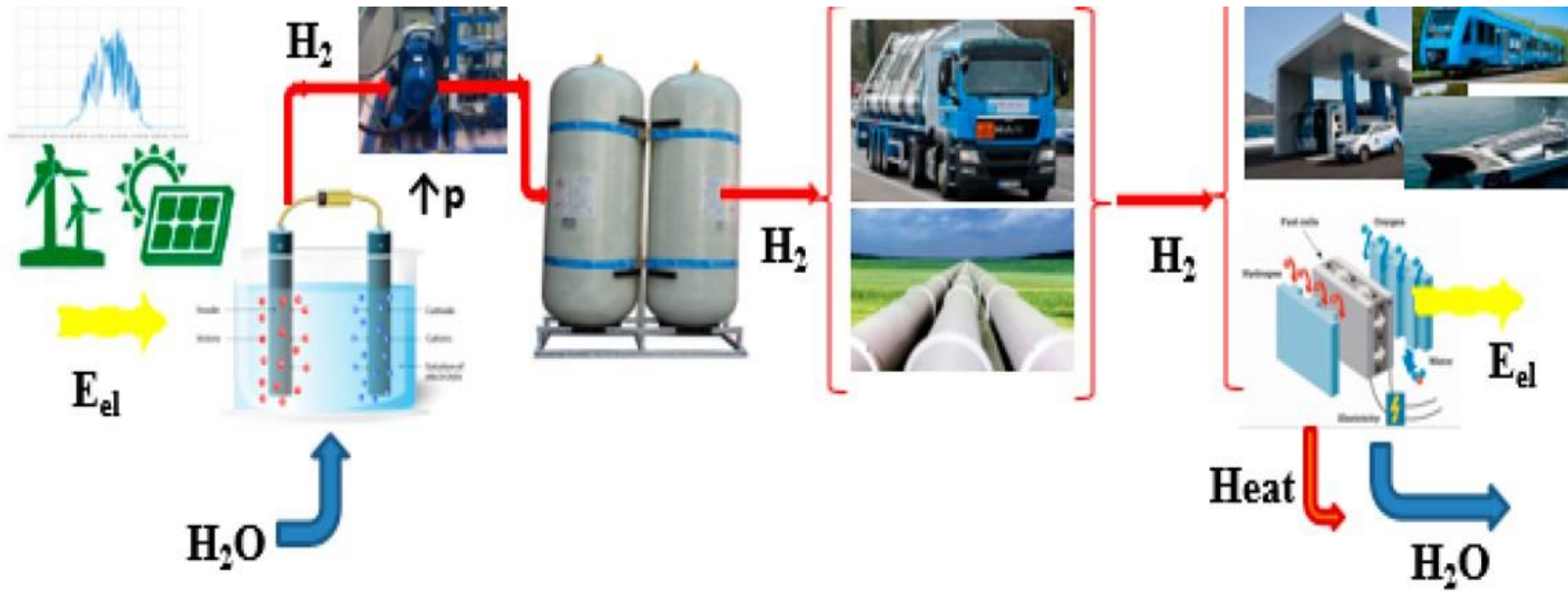
Structure integrity tool for quantitative risk assessment

– predictive models

Development of Indigenous Regulatory standards for

Repurposing

# Hydrogen Value Chain



Production & storage

Transportation & distribution

Utilization

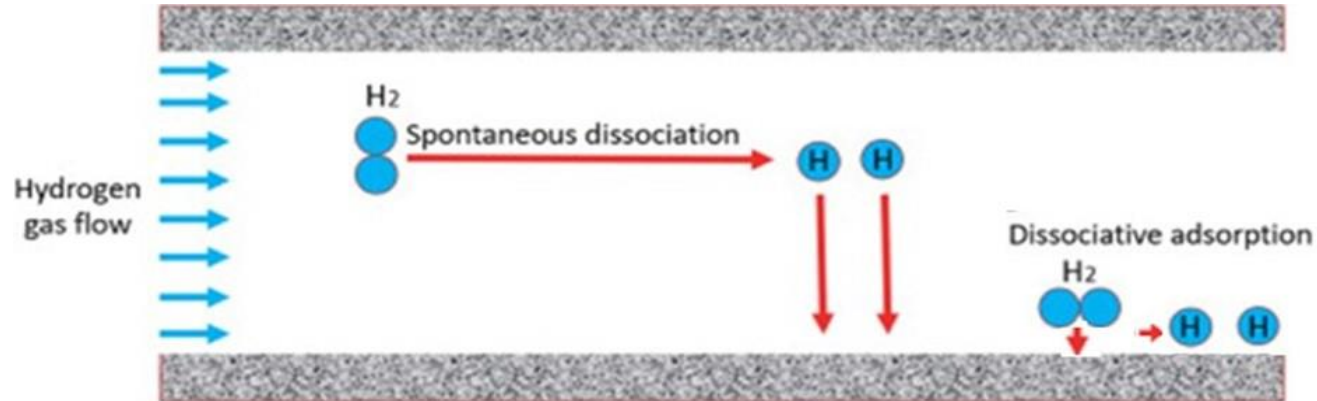
S.N.	Characteristic	ASME B31.12 Option A	ASME B31.12 Option B
1	Design Factor	Max 0.5	Max 0.72
2	Brittle fracture control	Min(0°C or min operating temp); Avg shear – 80% (full size); 85% (reduced size); 40% drop weight	Same as Option A
3	Ductile fracture control	$CVN \geq 0.008(RT)^{0.39} \sigma_h^2$	Same as Option A
4	Fracture toughness, $K_{IC}$ & $K_{IH}$	Not specified	$K_{IH} \geq 55 \text{ MPa} \sqrt{\text{m}}$
5	Yield strength	$\leq 70 \text{ ksi}$	$\leq 80 \text{ ksi}$
6	UTS	$\leq 100 \text{ ksi}$	$\leq 110 \text{ ksi}$
7	Steel composition	Not specified	$P \leq 0.015\%$ ; Inclusion shape control
8	Weld hardness	$\leq 235 \text{ HV}_{10}$	Same as Option A

- **From cathodic reaction**

- $2\text{H}^+ + 2\text{e}^- \rightarrow 2\text{H}_{\text{ads}} \rightarrow 2\text{H}_{\text{abs}} \rightarrow$  diffuses into steel
- Excessive charging of H in steel, not representative of pipeline conditions

- **Dissociation of gaseous  $\text{H}_2$**

- Spontaneous dissociation – Thermodynamically not feasible
- **Dissociative adsorption – Possible under pipeline operating conditions**



## Methane (CH<sub>4</sub>) - Competes

- CH<sub>4</sub> breaks into CH<sub>3</sub> & H
- Competitive absorption of CH<sub>4</sub> and H<sub>2</sub> molecules on steel

## Oxygen (O<sub>2</sub>), Sulfur dioxide (SO<sub>2</sub>) and Carbon monoxide (CO) - Inhibits

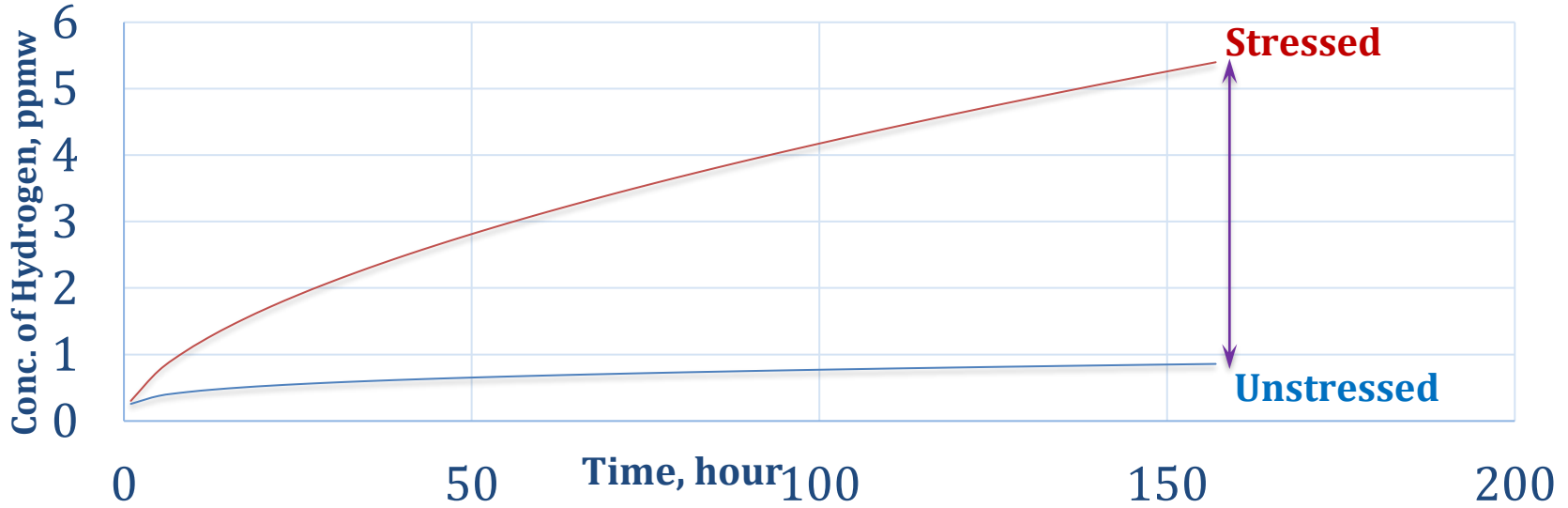
- Raises activation energy for H atom
- Impedes the kinetics of atomic H uptake

## Hydrogen Sulphide (H<sub>2</sub>S), Carbon dioxide (CO<sub>2</sub>); Methanethiol (CH<sub>3</sub>SH)- Assist

- Significantly increases H uptake in steel

Inhibit HE	Neutral	Promote HE
O <sub>2</sub> , SO <sub>2</sub> , CO	CH <sub>4</sub> , N <sub>2</sub>	H <sub>2</sub> S, CH <sub>3</sub> SH, CO <sub>2</sub> , H <sub>2</sub> O

# 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**

- There are pipelines (dedicated as well as repurposed) to transport gaseous hydrogen or hydrogen blend with NG
- Fracture toughness is the key parameter which is affected by hydrogen environment
- As per ASME B31.12, fracture control is not needed when hoop stress <40% of SMYS
- Further ASME B31.12 mentions **two** approaches
  - **Approach 1 (Prescriptive) :**
    - Fracture control based on Charpy impact values
    - **Max. design factor – 0.50**
  - **Approach 2 (Performance):**
    - Fracture control based on threshold stress intensity values,  $K_{IH}$
    - **Max design factor – 0.72**

- Pipeline MAOP calculations

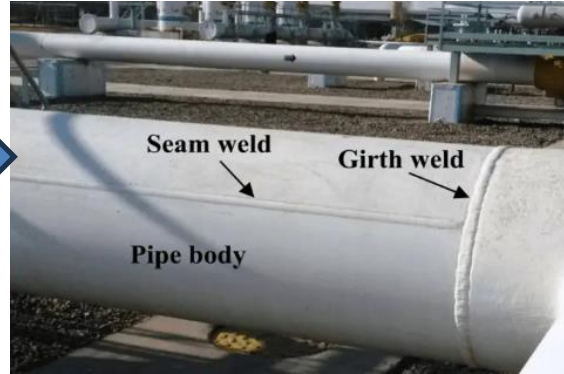
$$MAOP = \left( \frac{2St}{D} ET \right) FH_f$$

- 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 $\leq 69$ )	Factor $FH_f$	
		ASME B31.12 Option A (F=0.5)	ASME B31.12 Option B (F=0.72)
$\leq 52$	1	0.5	0.72
$\leq 60$	0.874	0.44	0.63
$\leq 70$	0.776	0.39	0.56
$\leq 80$	0.694	0.35	0.5

If we do not carry experimental study, then we may lose on capacity

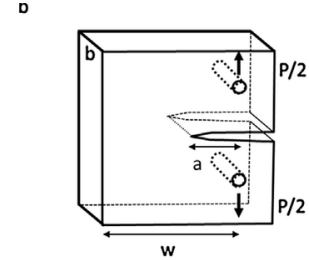
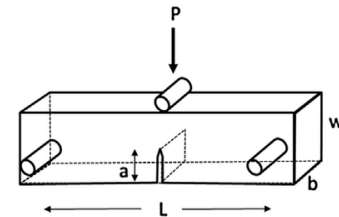
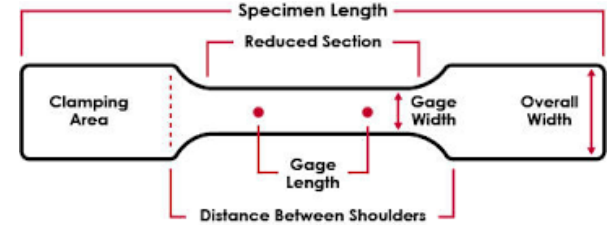
# Hydrogen Damage Assessment – Sampling



Fittings-Forged, Cast etc

Gaskets, Flanges, bends, Tee

Rotary meters, flow meters, Transmitters etc.



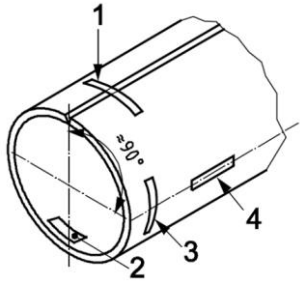
- Compositional Tolerances within the specified grade
- Steel making and Pipe manufacturing processes
- Workmanship & Quality control during fabrication
- Defect acceptance limits and the NDT adopted
- Operational aspects : Max.pressure , pressure cycles, temperature, fluid type etc.
- In-service stresses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

**Case to case assessment required for alteration of service**

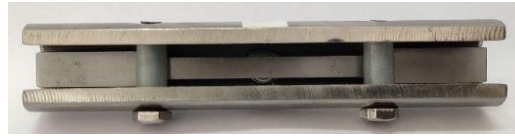
# Initiatives: Pre-Research Testing

- ✓ Study on weldments of service exposed Pipelines
  - ❖ Theoretical determination of  $H_2$  concentration in Pipeline steel using empirical equations
  - ❖ Finite Element Modelling for local stress field evaluation at various operating pressure
  - ❖ Micro-structural characterization
  - ❖ Autoclave Exposure in 18%, 36%, 50% (v/v)  $H_2$  blends in CNG and 100%  $H_2$  @ 35 kg/cm<sup>2</sup>
  - ❖ Slow Strain Rate Tensile testing

# Prestressed Three Point Bend samples



Weld sample as per API 5L Spec.

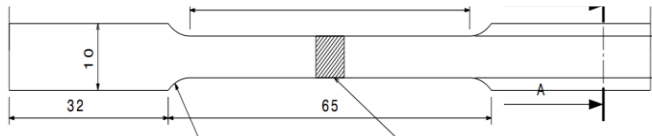


Three point bent beam fixture

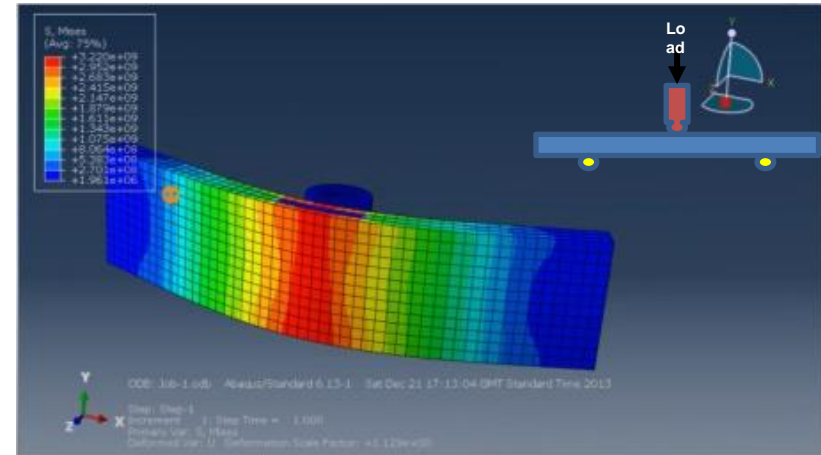


Deflection measurement with LVDT

- Prestressed Three Point Bend specimens considered
- Deflection generates bending tensile stress **equivalent to Hoop stress**
- Deflection estimated at MAOP (72% SMYS)



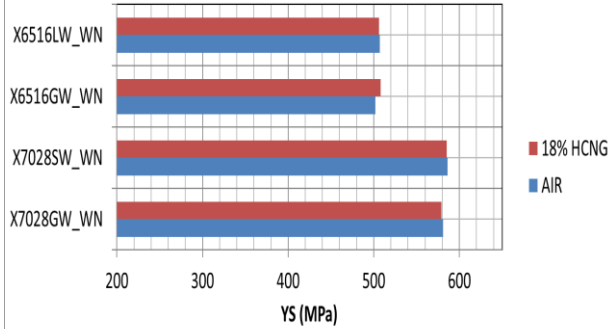
- ❖ Samples extracted from weldments of API X65 & X70 as per *API 5L*
- ❖ Subsize tensile samples were fabricated as per *ASTM E8*
- ❖ Subjected to stress using a bent beam fixture at MAOP
- ❖ Post exposure, tensile property evaluated



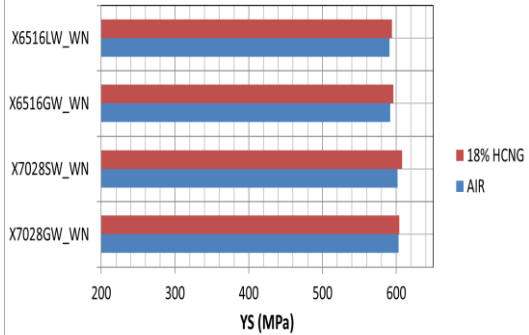
FEM based Applied Stress vs. Deflection plots

# Tensile Test Data (Normal strain rate)

Average YS over three samples



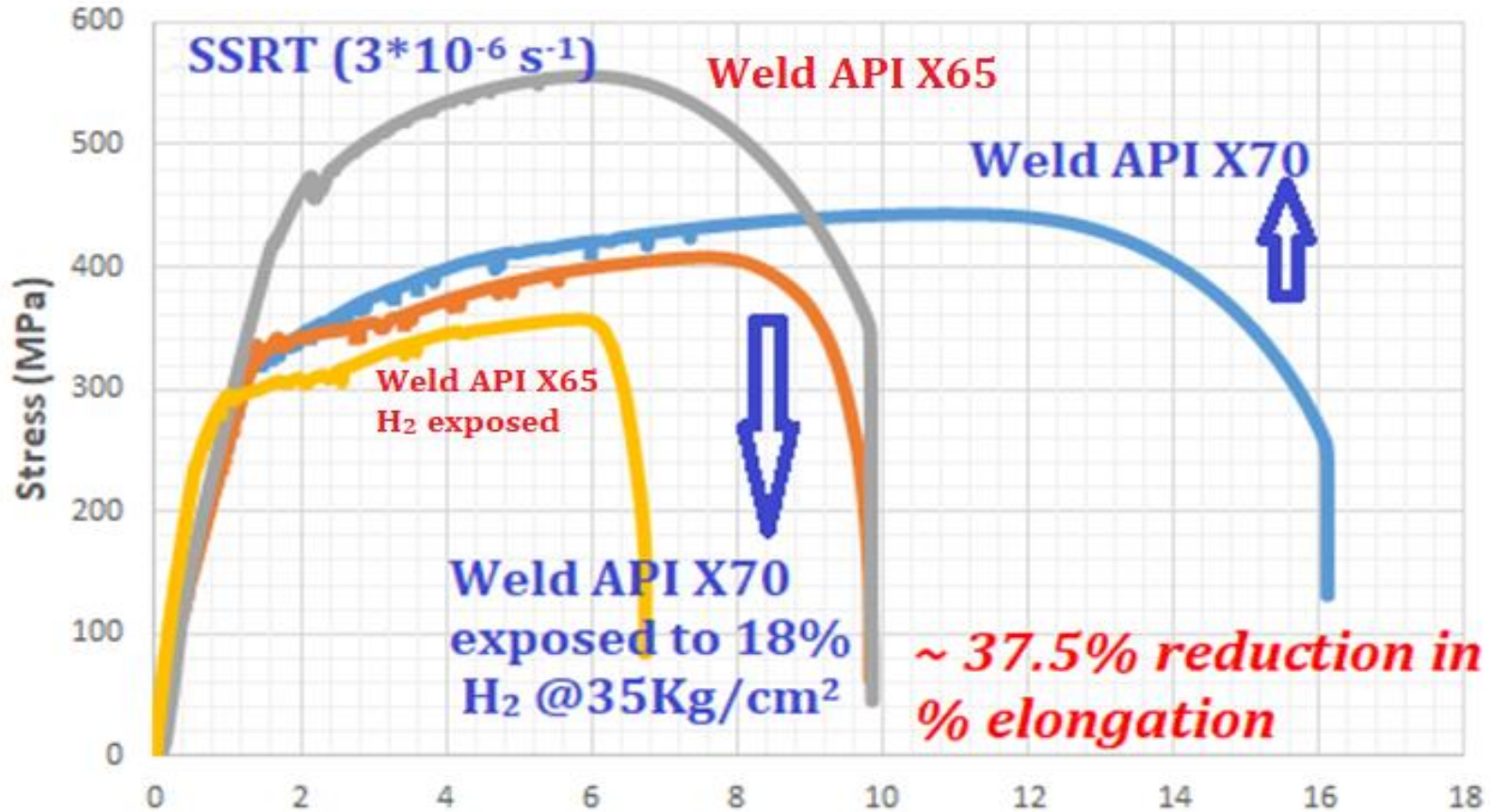
Average UTS over three samples

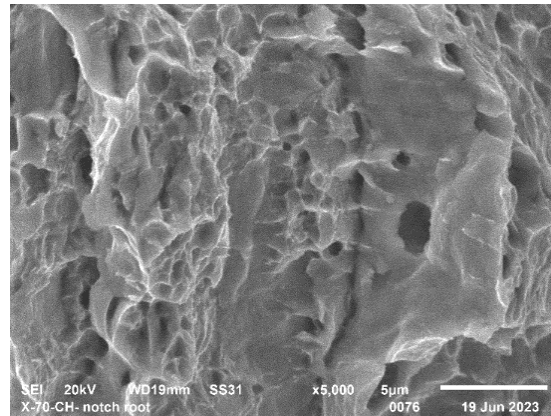
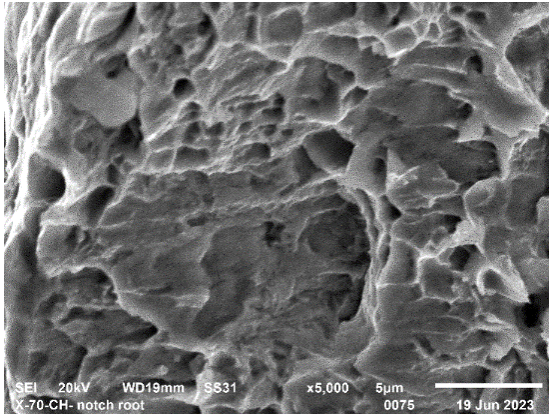


Autoclave exposure to 18 Vol.% H<sub>2</sub>



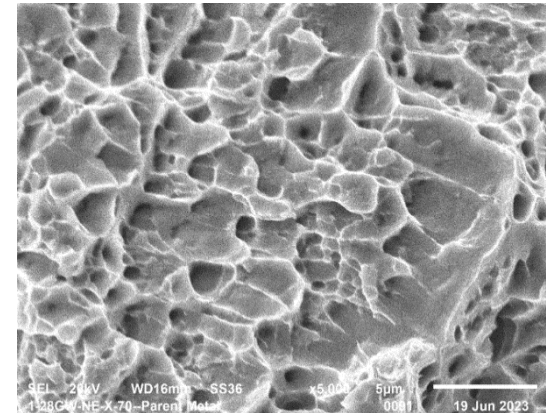
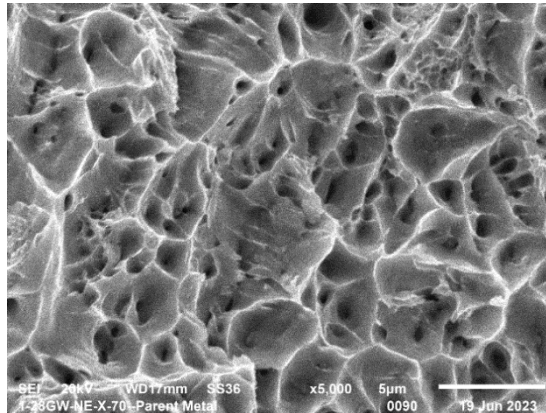
# Testing Property after exposure



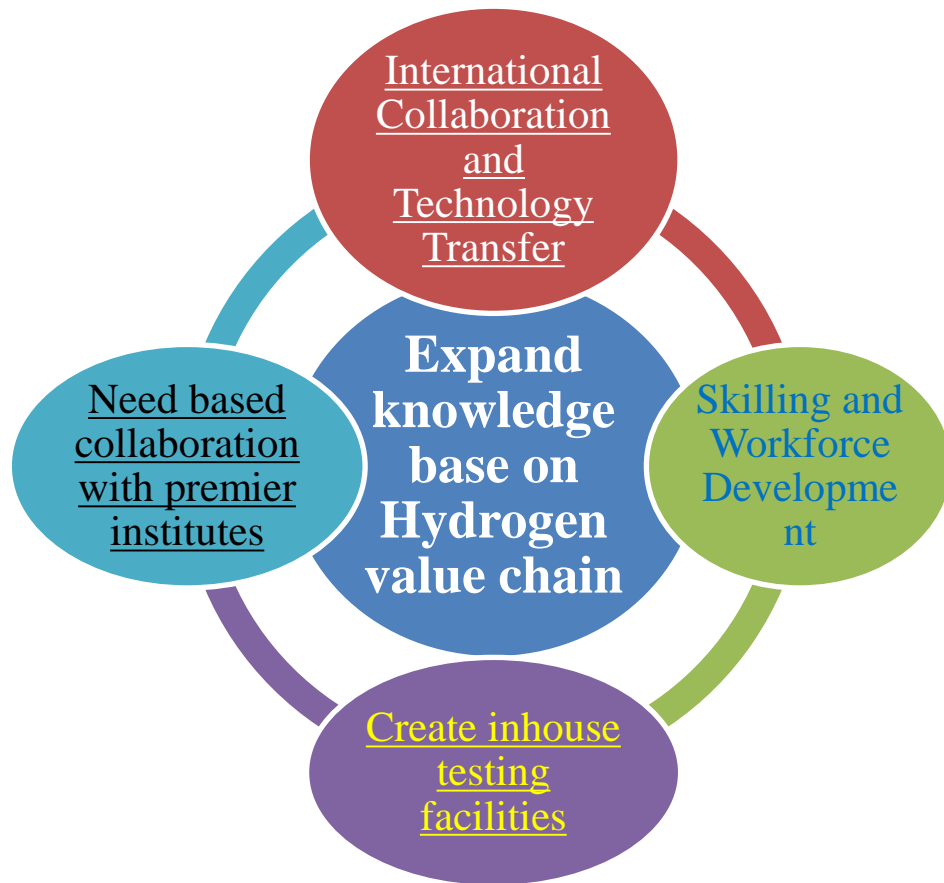


**H Charged sample showing a mixed mode (Ductile dimples & cleavage) fracture**

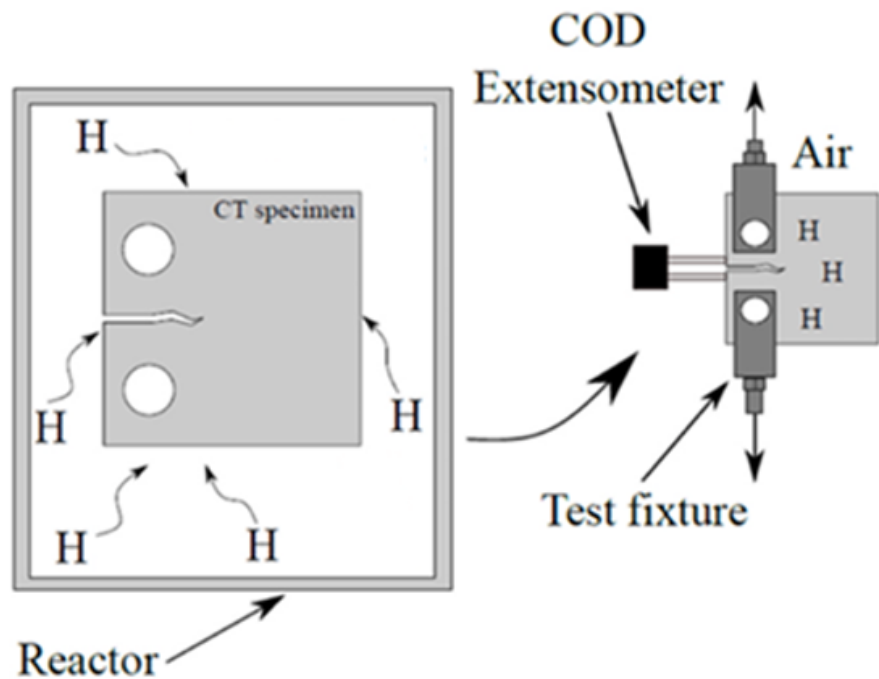
**Uncharged sample showing a ductile dimple fracture**



- Equip with all testing facilities
- Evaluate material compatibility
- Monitor and predict H2 damage
- H2 Risk Assessment
- Fitness for Service assessment of H<sub>2</sub> pipelines

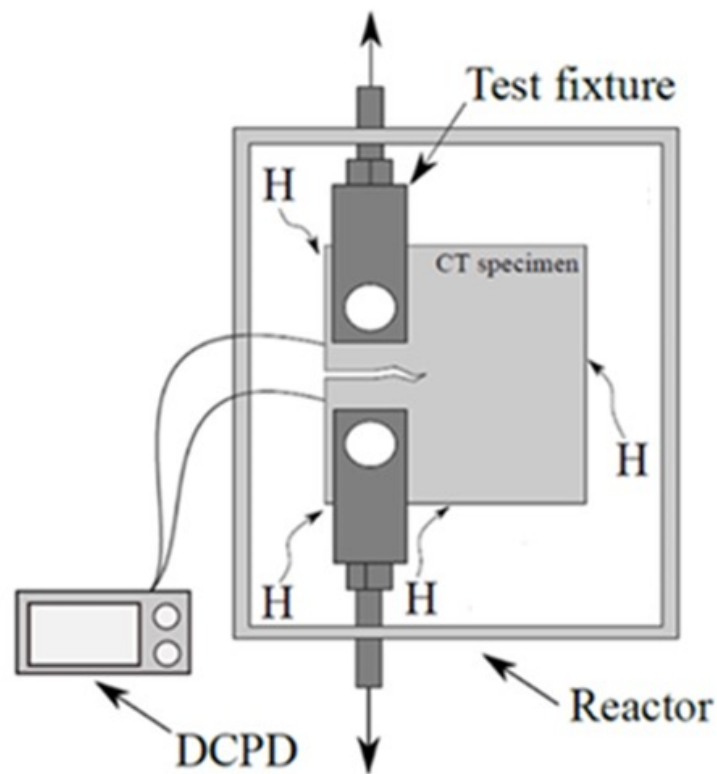


# Ex-situ vs In-situ testing



**Ex-situ Testing**  
Charging in H<sub>2</sub>, testing in air

## In-situ Testing Charging & testing in H<sub>2</sub>



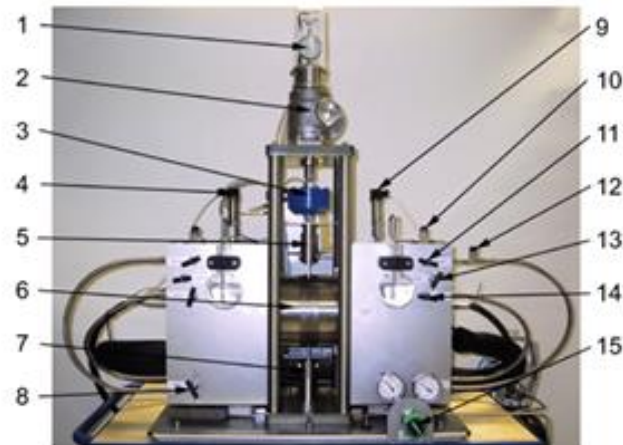
## Create testing facility



**High Pressure  
Mechanical Load Frame  
Test System**



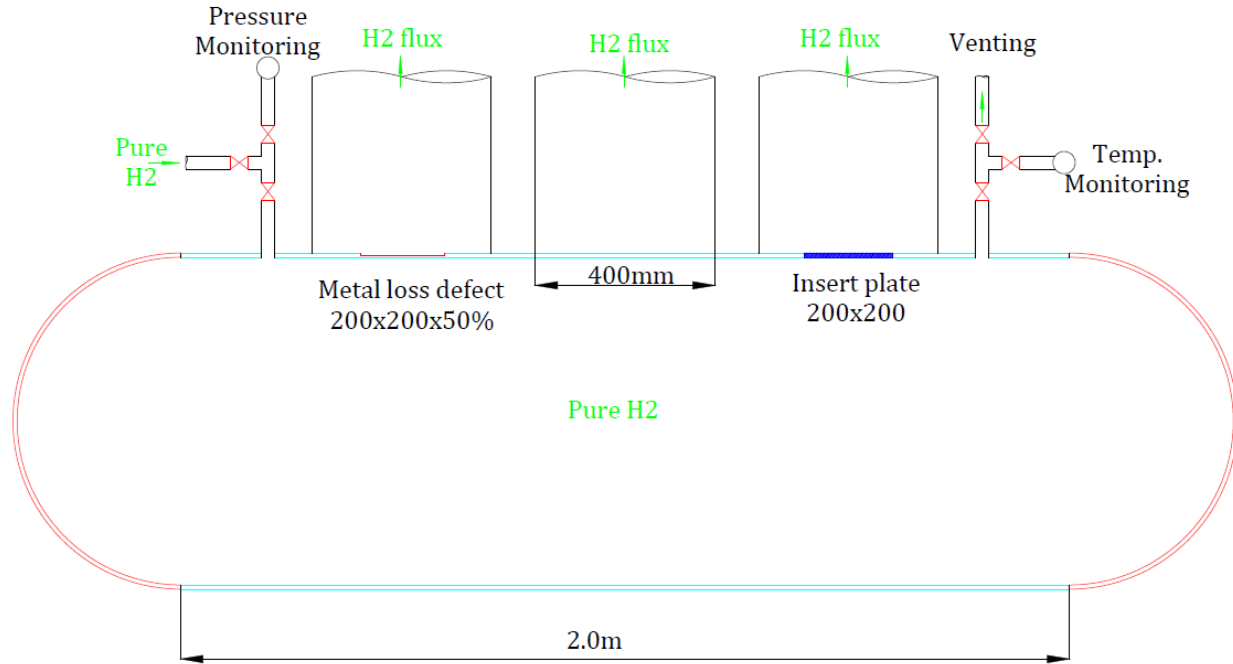
**High Pressure  
Non-Stirred  
Autoclave (10nos)**



1	Dial indicator and limit switches	9	Pressure sensor
2	Gear box with worm gear	10	Gas outlet valve 2
3	Load cell	11	Gas outlet valve 1
4	Pressure sensor	12	Connection valve of gas outlet lines
5	Upper specimen holder	13	Water inlet valve
6	Autoclaves	14	Gas inlet valve
7	Lower specimen holder	15	Gas inlet pressure reducer

**Devanathan-Stachurski  
Hydrogen Permeation Cell**

## Evaluation of Hydrogen Uptake by Components



(i) API 5L X70, 30" OD & (ii) API 5LX52, 24" OD,

2m long pipe spool of each of above grade to be exposed to H<sub>2</sub> environment

- “Joint Industry Program” on Repurposing of in-service Pipelines for Transportation of Hydrogen blends from all grades
  - ✓ 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**