



DOE Hydrogen Program

# Hydrogen Embrittlement of Structural Steels

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May 10, 2011

Project ID # PD025

This presentation does not contain any proprietary, confidential, or otherwise restricted information



# Overview

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## Timeline

- Project start date Jan. 2007
- Project end date Oct. 2011\*
- Percent complete 50%

## Budget

- Total project funding (to date)
  - DOE share: \$900K
- FY10 Funding: \$150K
- FY11 Funding: \$200K

\*Project continuation and direction determined annually by DOE

## Barriers & Targets

- Pipeline Reliability/Integrity
- Safety, Codes and Standards, Permitting
- High Capital Cost and Hydrogen Embrittlement of Pipelines

## Partners

- DOE Pipeline Working Group
  - Federal Labs: Sandia, Oak Ridge, Savannah River, NIST
  - Universities: Univ. of Illinois
  - Industry: Secat, industrial gas companies, ExxonMobil
  - Standards Development Organizations: ASME



# Objectives/Relevance

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- Why steel hydrogen pipelines?
  - Safety of steel pipelines well understood (e.g., third-party damage tolerance, vulnerability of welds)
  - Hydrogen pipelines safely operated under *static pressure*
- Demonstrate reliability/integrity of steel hydrogen pipelines for *cyclic pressure*
  - Address potential fatigue crack growth aided by hydrogen embrittlement, *particularly in welds*
- Enable pipeline design that accommodates hydrogen embrittlement
  - Ensure relevance to pipeline design code ASME B31.12
- FY10-FY11: measure fracture thresholds and fatigue crack growth laws for X52 steel in H<sub>2</sub> gas, emphasizing welds

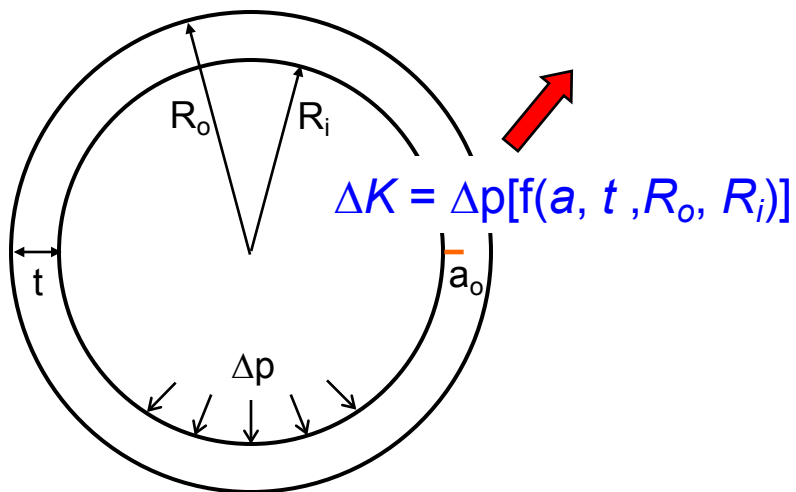
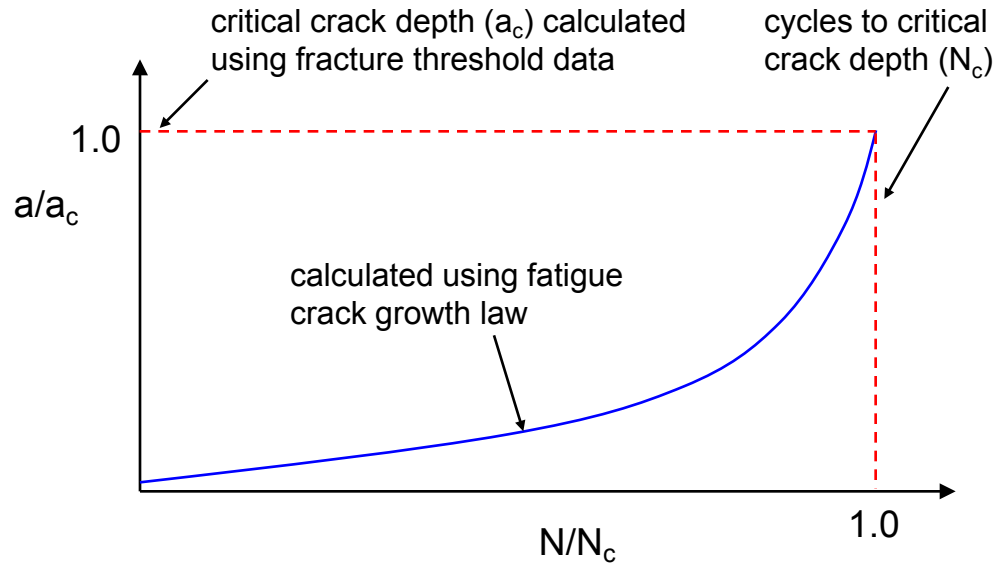
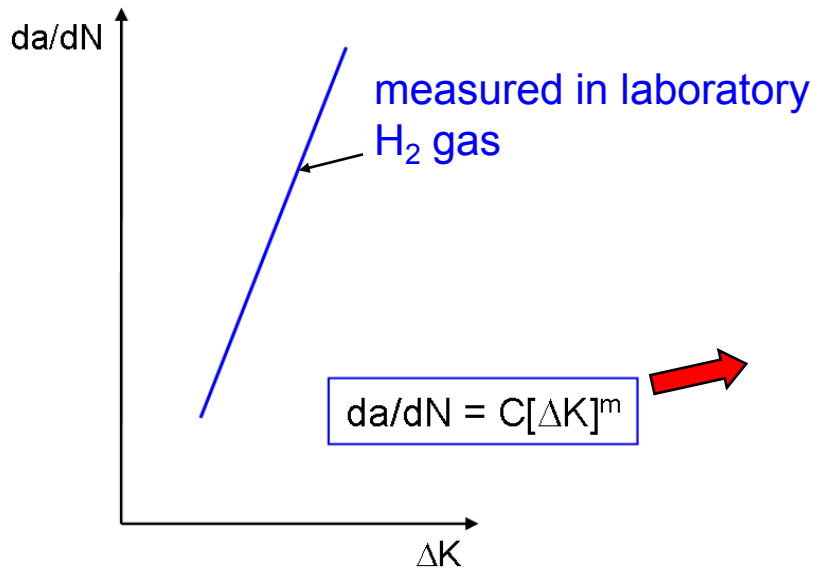


# Approach

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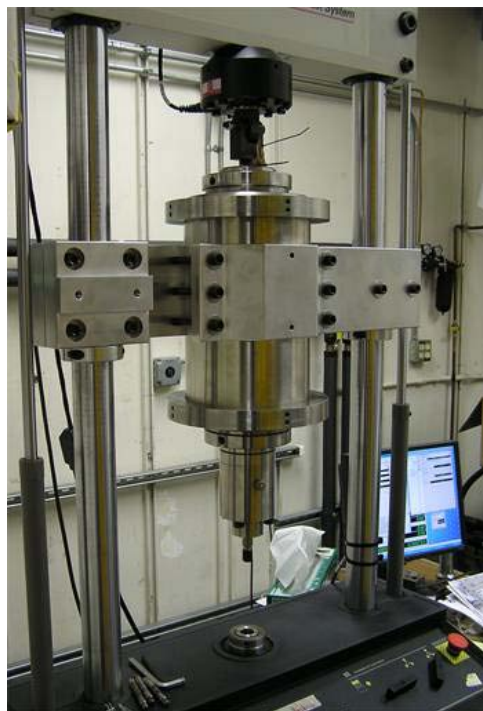
- Apply unique capability for measuring fracture properties of steels in high-pressure  $H_2$ 
  - Fracture properties serve as inputs into reliability/integrity assessment as specified in ASME B31.12 pipeline code
  - Milestone: Measure fracture thresholds for X52 steel base metal and seam weld (75% complete)
  - Milestone: Measure fatigue crack growth laws for X52 steel base metal and seam weld (75% complete)
    - Evaluate effect of load-cycle frequency on measurements
- Emphasize pipeline steels and their welds identified by stakeholders as high priority
  - Provide feedback to stakeholders through DOE Pipeline Working Group

# Reliability/integrity assessment framework in ASME B31.12 requires fracture data in H<sub>2</sub>

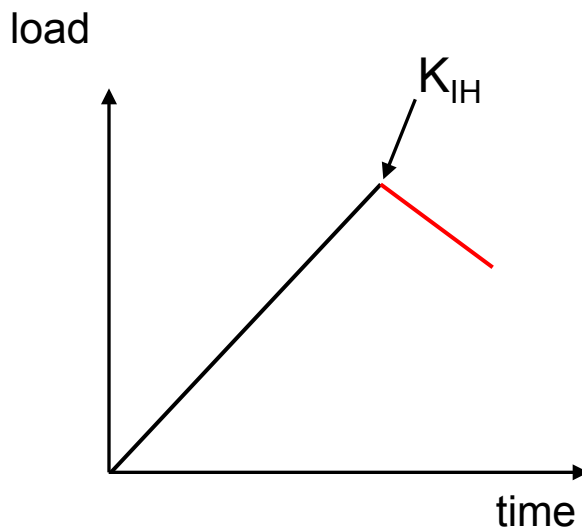
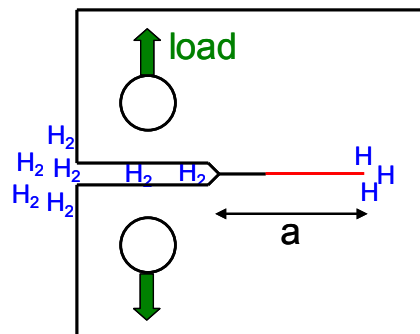


- Two fracture properties in H<sub>2</sub> needed
  - Fatigue crack growth law
  - Fracture threshold
- Reliability/assessment framework accommodates H<sub>2</sub> embrittlement

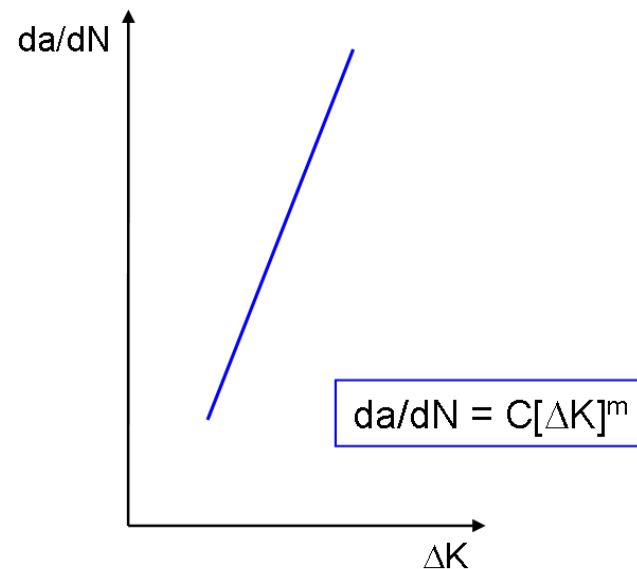
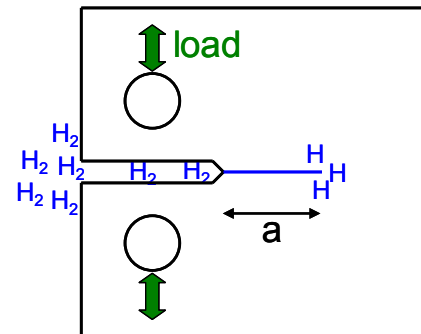
# Fracture data in H<sub>2</sub> measured using specialized laboratory capability



## Fracture threshold



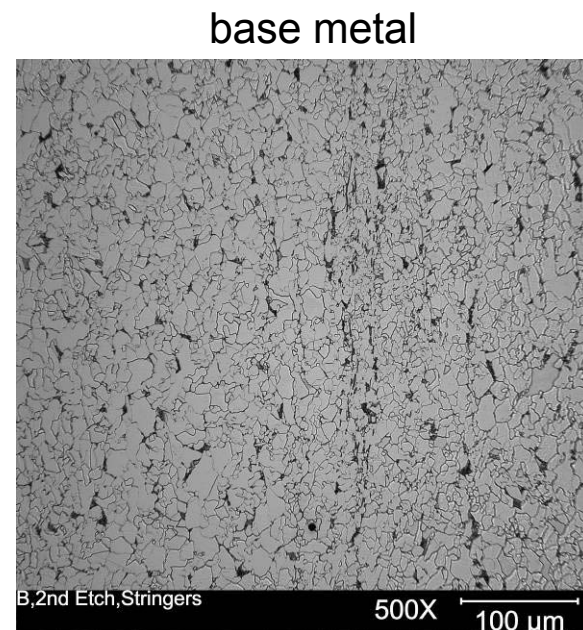
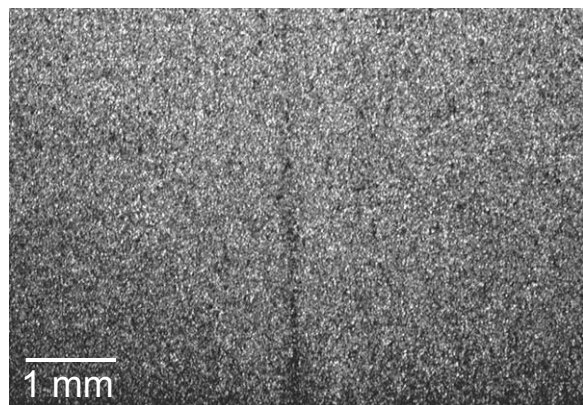
## Fatigue crack growth





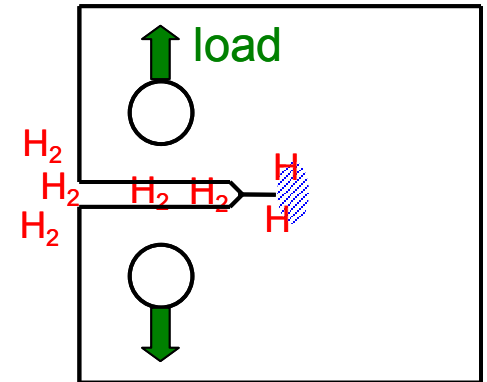
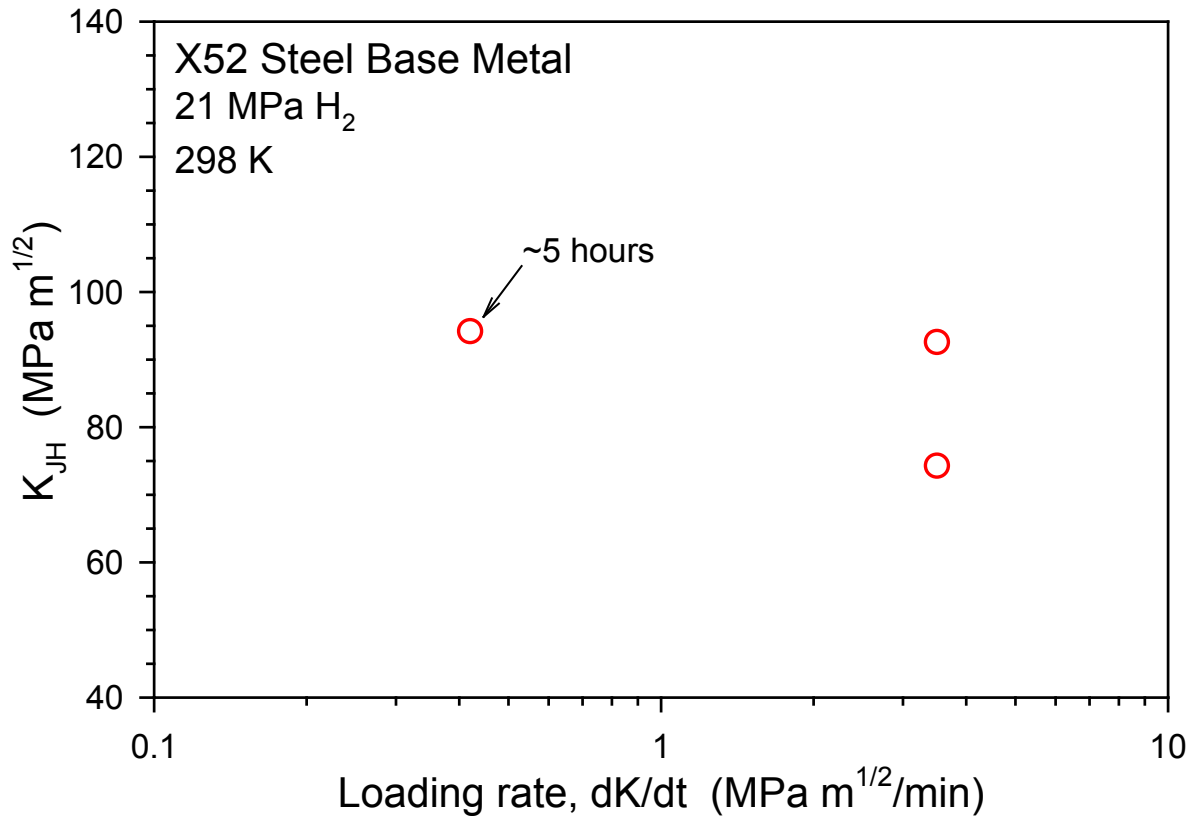
# Measured fracture properties of technologically relevant steel: API 5L X52

- Tested same X52 steel from DOE Pipeline Working Group tensile property round robin
  - Stakeholders expressed interest in X52 steel
- Tensile properties
  - Yield strength: 62 ksi (428 MPa)
  - Ultimate tensile strength: 70 ksi (483 MPa)



Accomplishment:

# Crack initiation thresholds measured for X52 in H<sub>2</sub> as function of loading rate

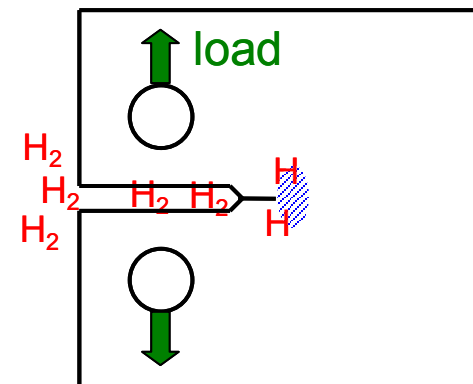
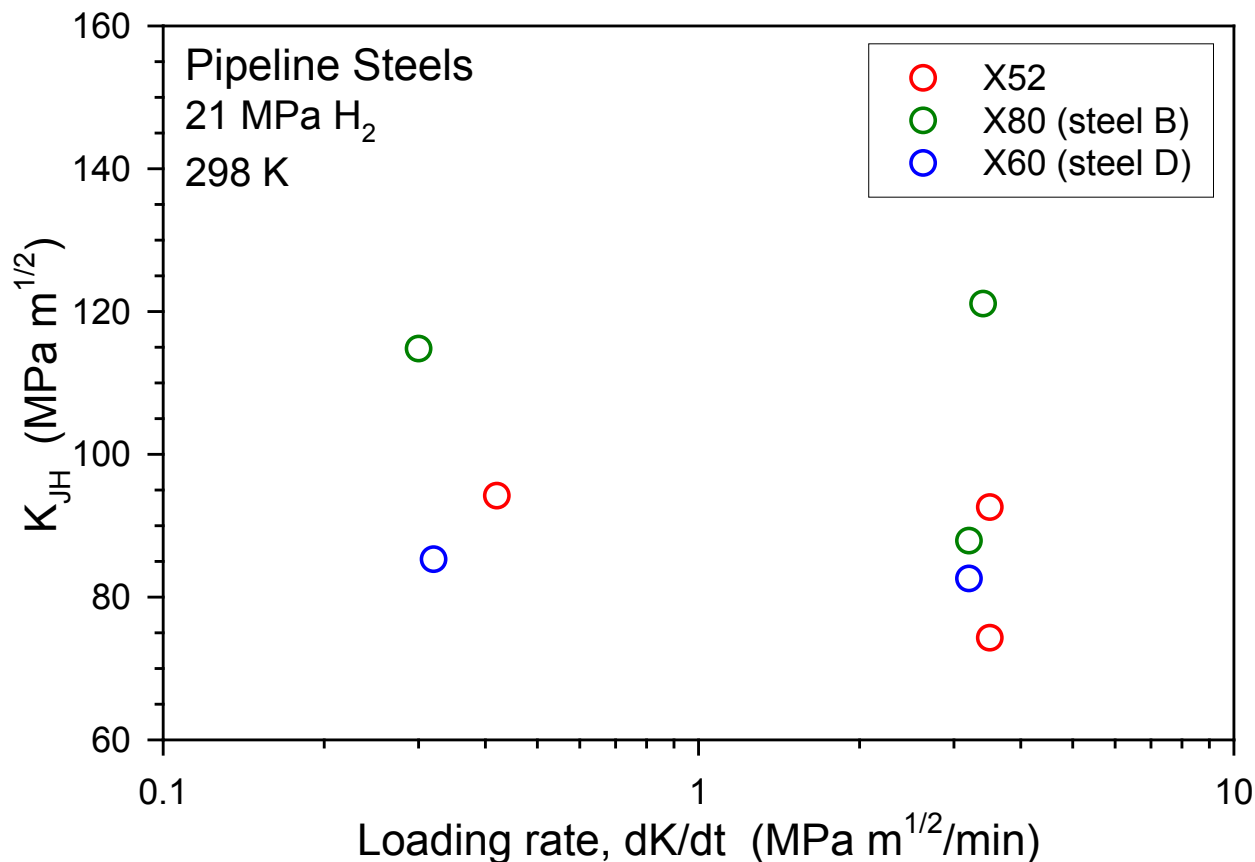


- Loading rate must be selected to balance test efficiency and data reliability
- Fracture threshold values ~80-100 MPa m<sup>1/2</sup> favorable for pipeline reliability/integrity



# Crack initiation thresholds similar for three different pipeline steels

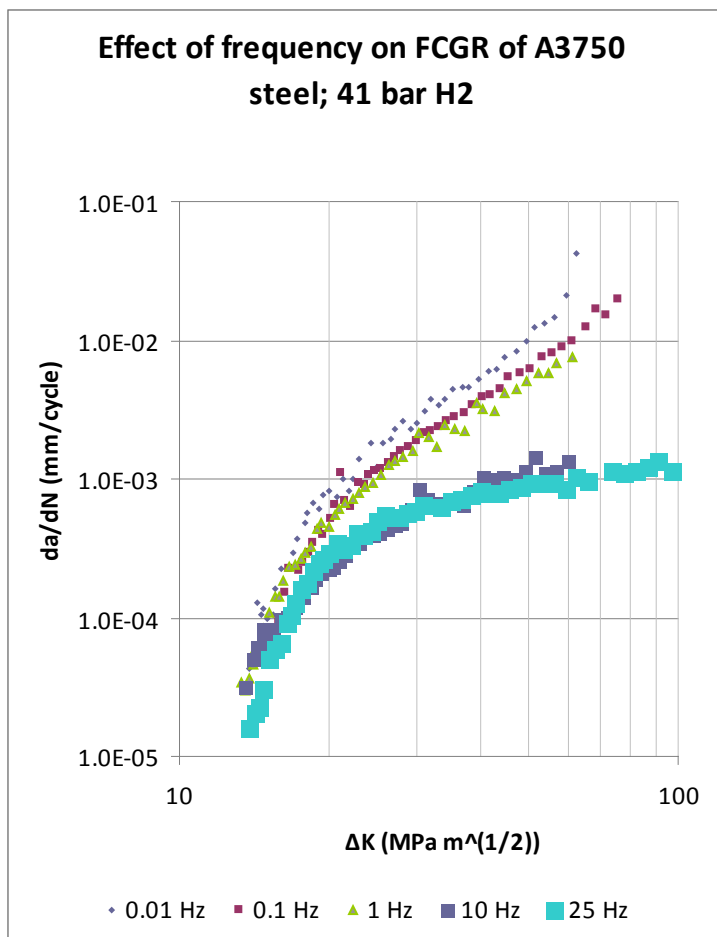
X60 and X80 data: C. San Marchi et al., ASME PVP2010-25825, 2010



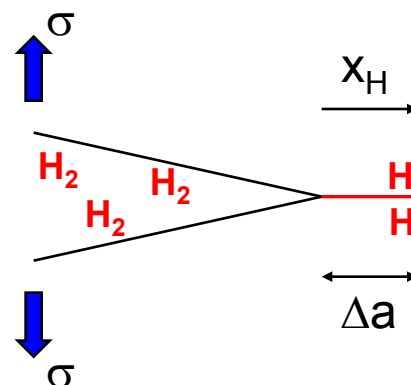
- Measurements for three steels conducted by participants in Pipeline Working Group

# Measurement of fatigue crack growth laws must consider effects of frequency

A.H. Priest, British Steel, EHC-(1)42-012-81UK(H), 1983



Condition for H penetration to affect crack growth:



$$x_H = (Dt)^{1/2}$$

$$\Delta a < x_H = (Dt)^{1/2}$$

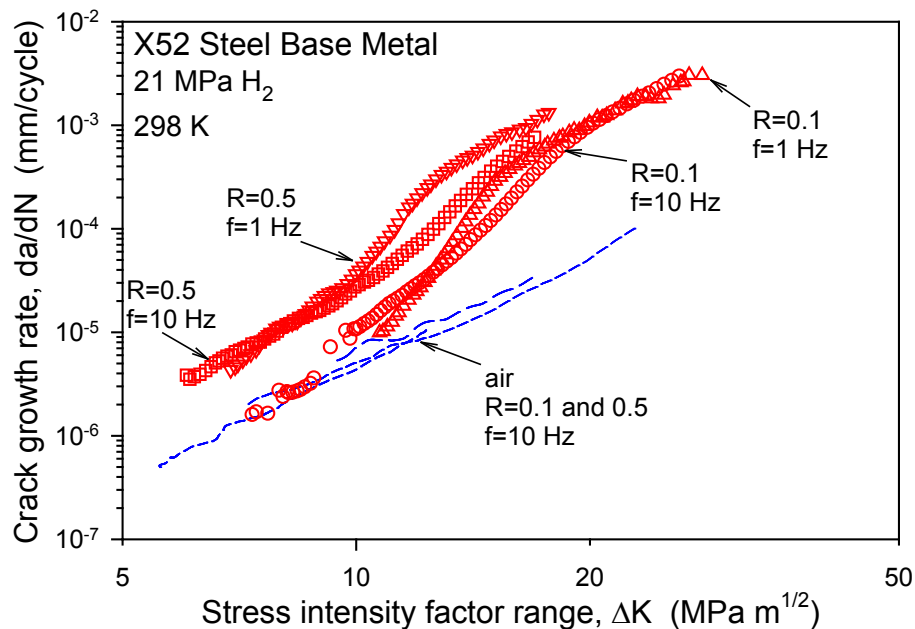
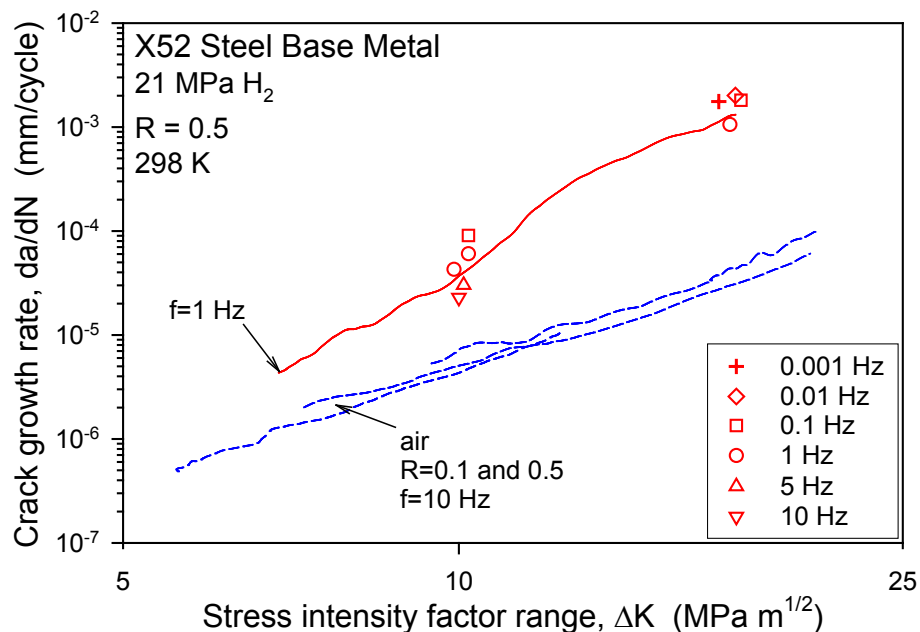
$$\Delta a < (D/f)^{1/2}$$

$$f \leq \frac{D}{(da/dN)^2}$$

- Frequency effects most pronounced at high  $da/dN$

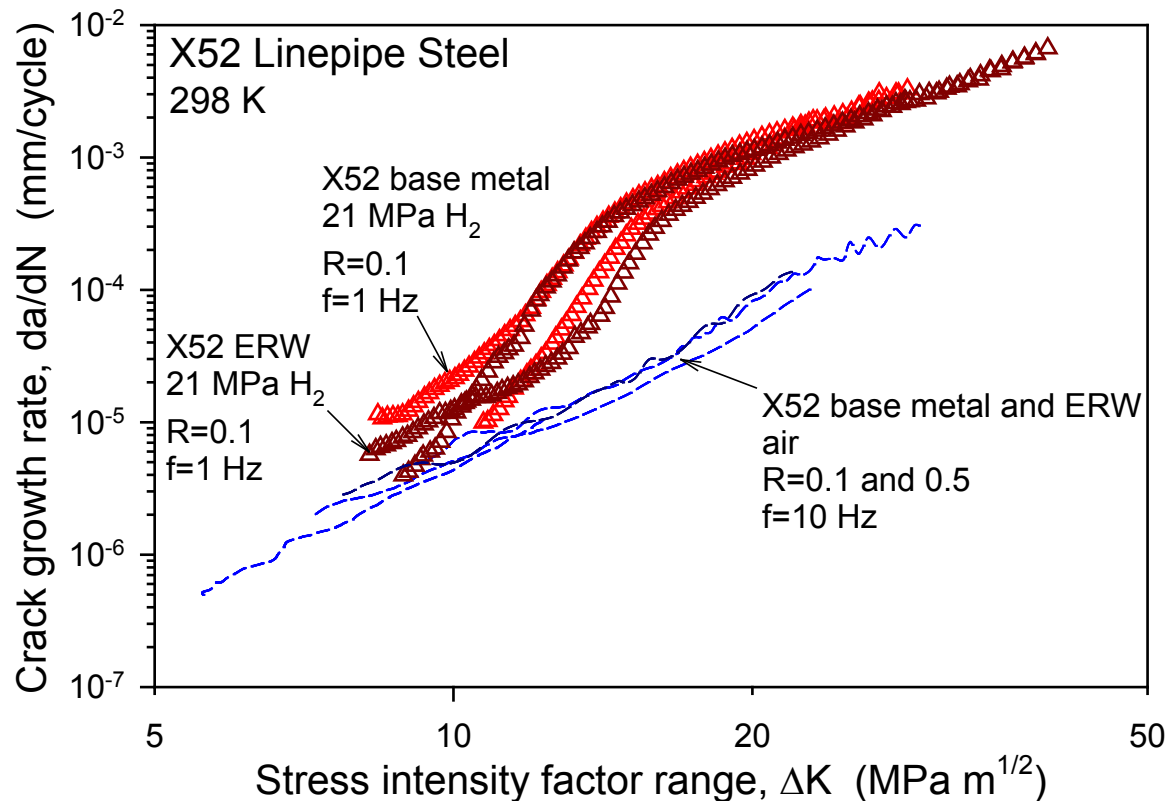
## Accomplishment:

# Measured effects of frequency on fatigue crack growth laws for X52 base metal



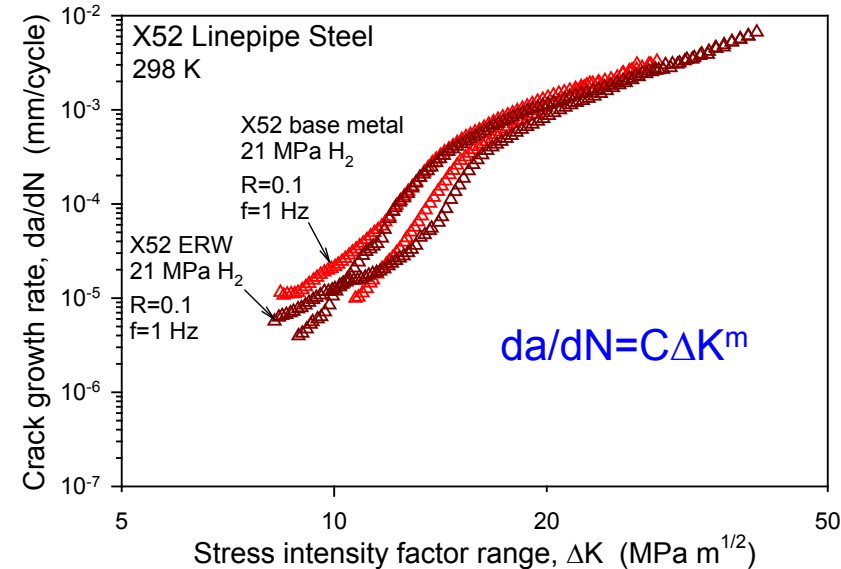
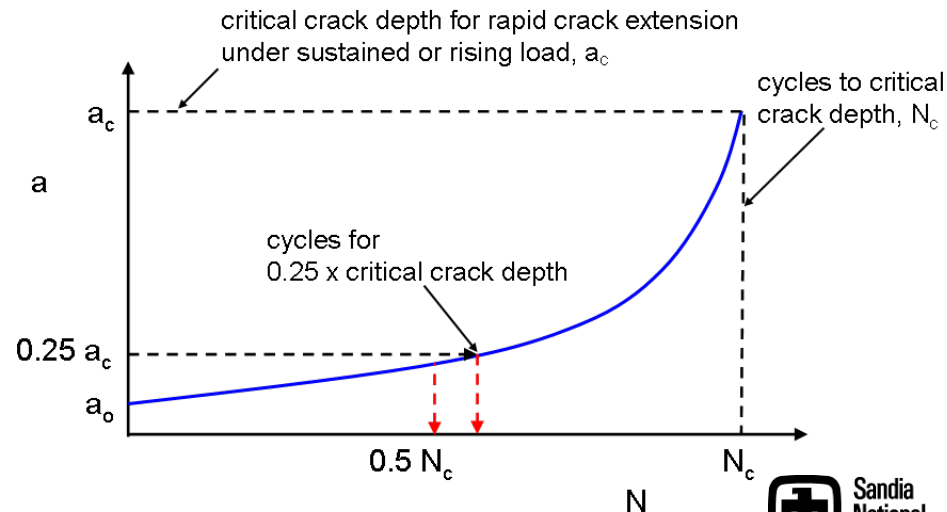
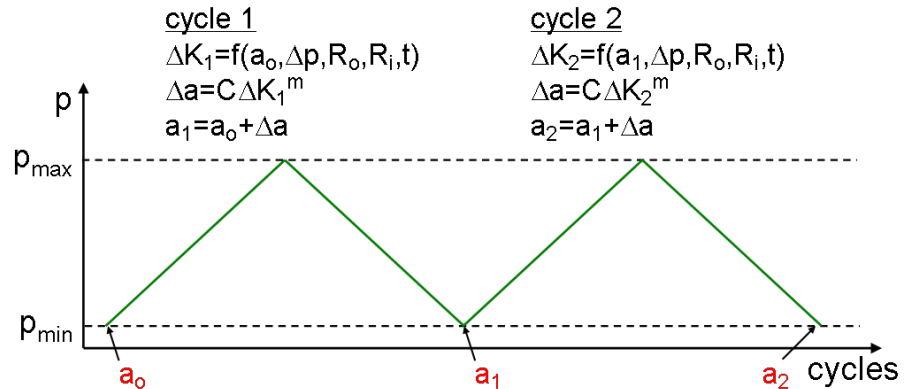
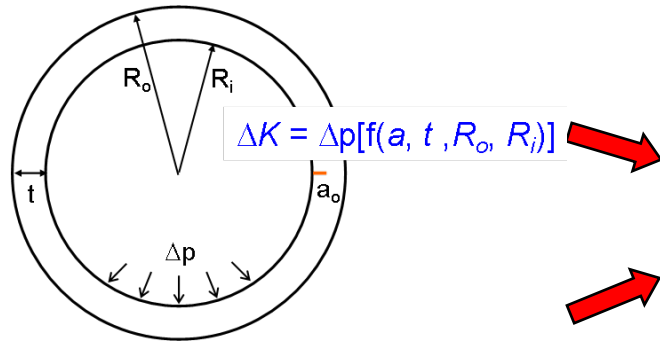
- Tests at higher frequency (> 1 Hz) yield non-conservative data at high crack growth rates
- Frequency selected must balance test efficiency (i.e., duration) and data reliability
  - Tests for comparing different materials (e.g., base metal vs welds) conducted at 1 Hz

# Measured fatigue crack growth laws for X52 steel base metal and ERW (seam weld)



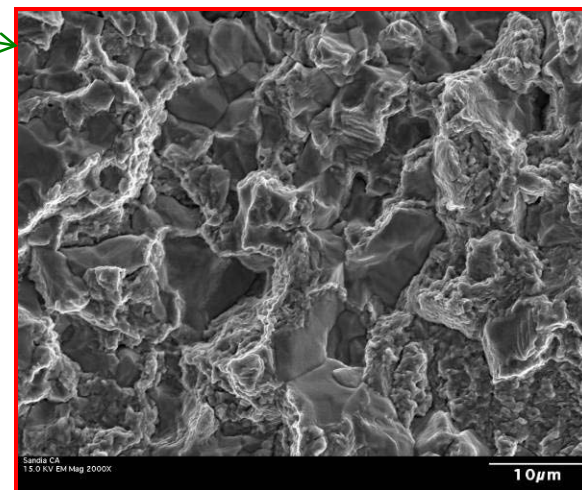
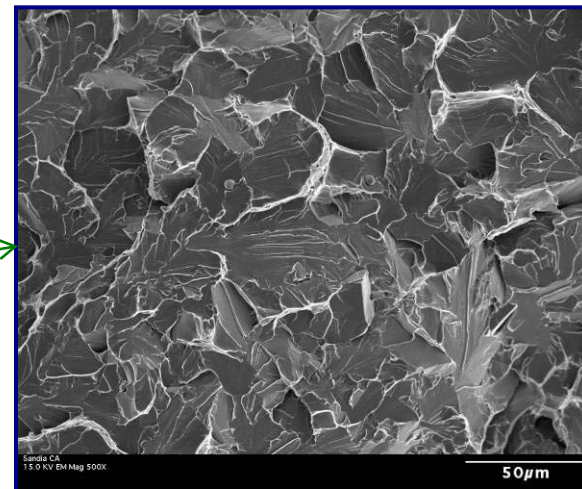
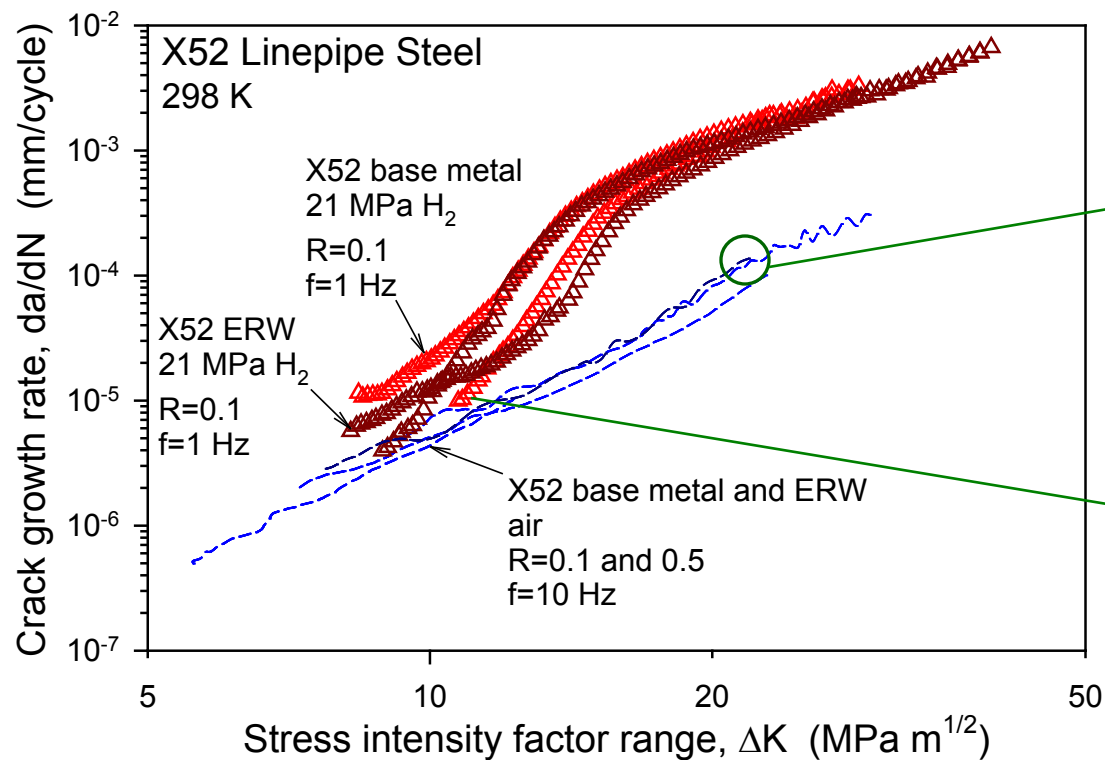
- Fatigue crack growth laws for X52 base metal and ERW similar in  $\text{H}_2$
- Notable variability in data from replicate tests for both base metal and ERW in  $\text{H}_2$

# Fatigue crack growth laws can be used to evaluate reliability/integrity of X52 H<sub>2</sub> pipelines



Accomplishment:

# Examined fracture surfaces from fatigue crack growth specimens



- Base metal in H<sub>2</sub> exhibits intergranular fracture at low  $\Delta K$
- ERW in air (R=0.5) exhibits unstable fracture at  $K_{\max} \sim 40$  MPa m<sup>1/2</sup> → cleavage





# Collaborations

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- DOE Pipeline Working Group (PWG)
  - Participants funded by DOE FCT Program
    - Federal Labs: Sandia, Oak Ridge, Savannah River
    - Universities: Univ. of Illinois
    - Industry: Secat
  - Participants not funded by DOE FCT Program
    - Federal Labs: NIST
    - Industry: industrial gas companies, ExxonMobil
    - Standards Development Organizations: ASME
  - Extent of collaborations include:
    - PWG meetings (up to 2 times/year) for participants to report results and receive feedback
    - Leveraging resources for testing (e.g., Secat-Sandia)
    - Supplying materials (e.g., ExxonMobil-Sandia)
    - Coordinating testing (e.g., NIST-Sandia)

# Proposed Future Work

## Remainder of FY11

- Expand evaluation of X52 seam weld to understand implication of cleavage fracture
- Determine threshold level of  $O_2$  to inhibit accelerated fatigue crack growth of X52 steel in 21 MPa  $H_2$  gas
- Measure fatigue crack growth law of girth weld fusion zone in  $H_2$  gas



## FY12

- Measure fatigue crack growth law of girth weld heat-affected zone (HAZ) in  $H_2$  gas
- Evaluate effects of load-cycle frequency on  $O_2$  inhibition of  $H_2$ -accelerated fatigue crack growth



# Summary

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- Measured fracture thresholds and fatigue crack growth laws allow evaluation of reliability/integrity of steel H<sub>2</sub> pipelines
  - Hydrogen embrittlement accommodated by measuring fracture properties in H<sub>2</sub> following ASME B31.12 design standard
- Measurements on X52 steel reveal the following trends:
  - Fracture thresholds of base metal in H<sub>2</sub> (~80-100 MPa m<sup>1/2</sup>) are favorable for pipeline reliability/integrity
  - Fatigue crack growth laws for base metal and seam weld are similar in H<sub>2</sub>
  - Unstable cleavage fracture observed in seam weld at  $K_{\max} \sim 40$  MPa m<sup>1/2</sup> during fatigue crack growth testing in air