EPRG-PRCI-APGA
23rd Joint Technical Meeting
Edinburgh, Scotland • 6–10 June 2022

Paper 3: Fatigue Crack Growth Modelling for Safe and Efficient Hydrogen Pipeline Design

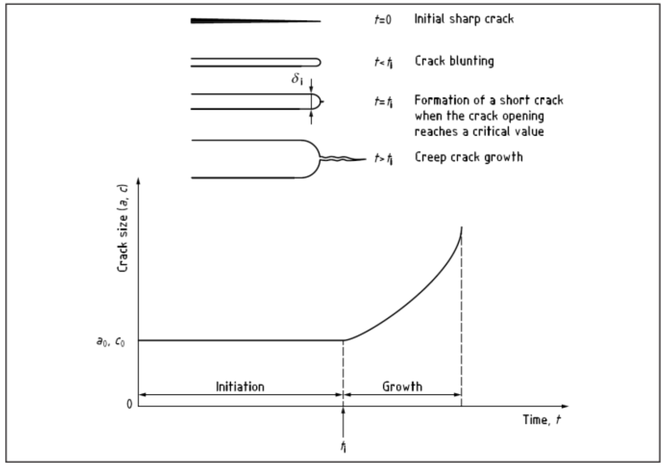
28 July 2022

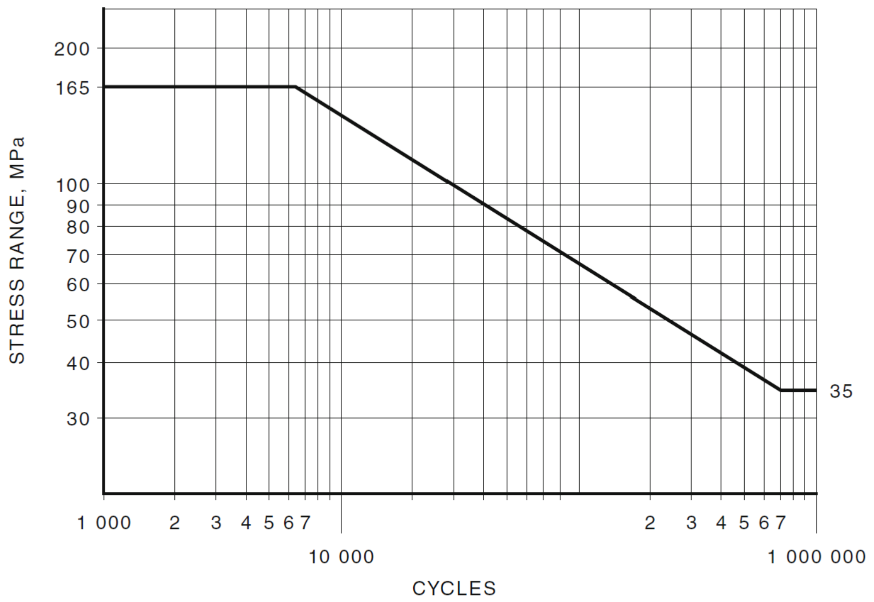
Overview

- Fatigue analysis in pipeline design
- Effect of Hydrogen on fatigue life of pipelines
- Parametric fatigue study of pipelines designed to ASME B31.12
- Results and discussion
- Conclusions

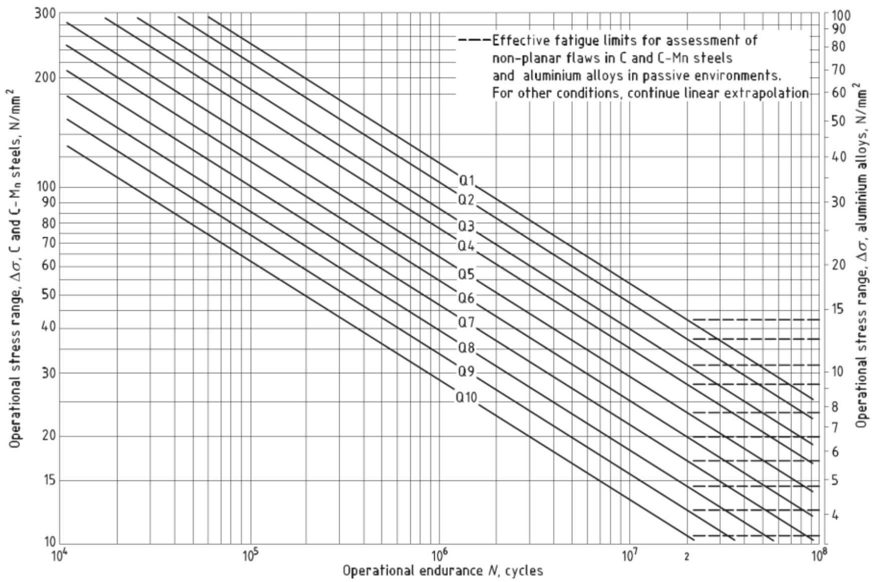
Background

- Fatigue life assessment in natural Gas pipeline:
  - S-N Curve (BS 7910, DIN 2413 etc.) -> Total Life
    - Simple (requires peak stress only)
    - Except DIN 2413-1993, no Linepipe specific curve
    - IGE/TD/1 and AS 2885.1, not a real S-N curve (Fracture Mechanics based of Hydrotest survive cracks)





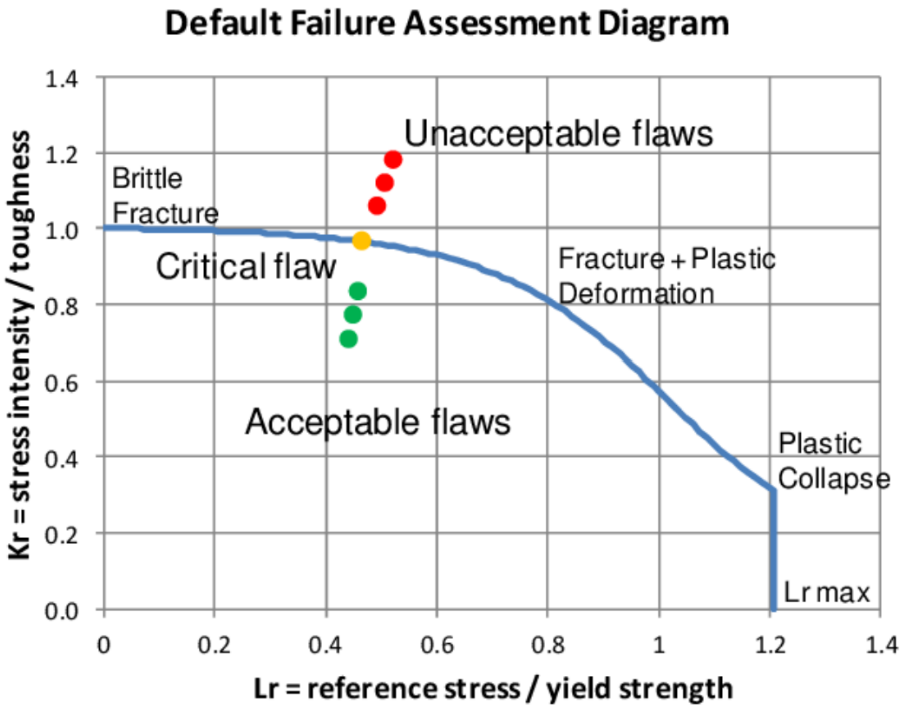
S-N Curve (IGE/TD/1 and AS 2885.1)



S-N Curve (BS 7910)

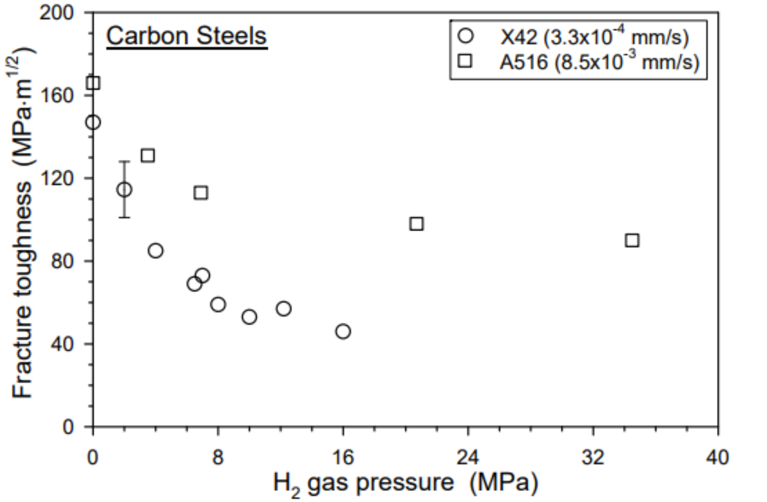
Background

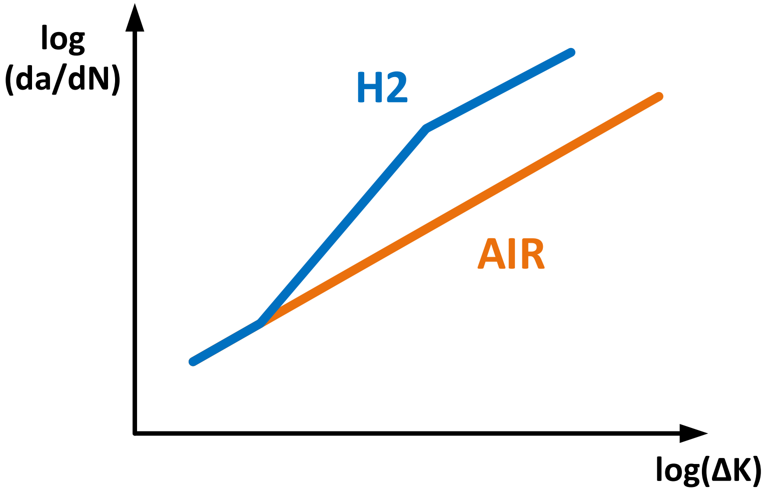
- Fracture Mechanics based -> Crack Growth Life
  - Complex calculations, step-by-step crack growth
  - Requires Stress Intensity Factor and FCGR equation
- Types of Fracture Mechanics based analysis
  - Identified/detected crack
    - Crack dimensions and geometry features are measured
    - Crack dimensions are assumed features are assumed
  - Workmanship based cracks
    - Crack dimensions and geometry features can have a range
    - Assumption of having simultaneous geometry feature can lead to stresses above Yield Strength.
    - Best approach is probabilistic analysis, not suitable for present study (billions of cases)
  - Hydrotest survived cracks
    - Can be very conservative specially for low design factor pipelines

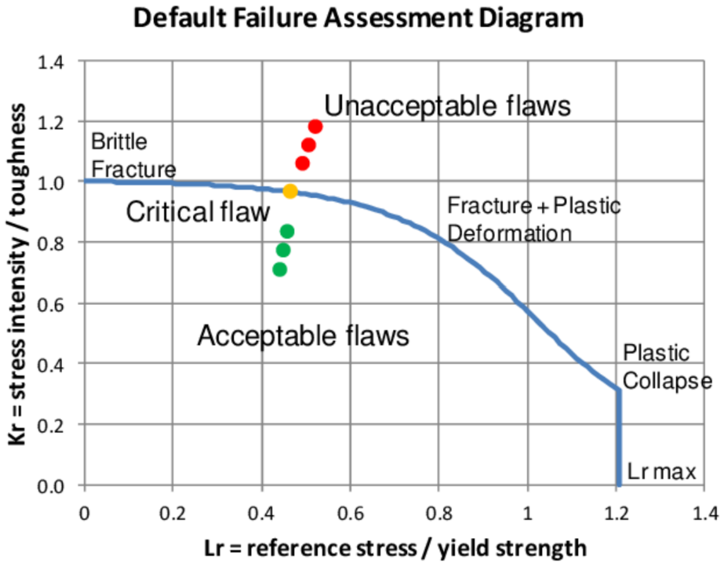


Effect of Hydrogen on fatigue life of pipelines

- Fracture behavior
  - Formation, initiation, propagation
  - Reduction in effective toughness (Hydrogen Embrittlement)
  - Accelerated fatigue Crack Growth rate (FCGR)
- Fatigue:
  - Applies even at low pressures, though worse at increasing fugacity
  - Larger impact at high ΔK_{IC}
  - Larger impact at high R-ratios

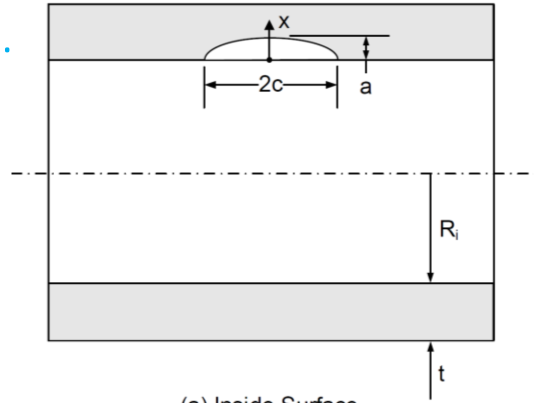






Parametric fatigue study of Hydrogen pipelines

- Objective
  - Develop simplified S-N curves for Hydrogen like existing curve in IGE/TD/1 and AAS 2885.1
- Analysis parameters
  - Crack type: Inside surface Semi-Elliptical crack
  - Crack size: Depth=Thickness/4, Length=1.5xThickness (assumed crack dimensions)
  - Diameter, D – DN100 to DN1050 (4” to 42”)
  - Pressure, P – ASME B16.5 pressure ratings: 1.96, 5.11, 6.81, 10.21 and 15.32 MPa
  - Thickness, t – Calculated based Design Factors 0.3, 0.4, 0.5, 0.6, 0.67, and 0.72.
  - Cycling pressure, ΔP – 10 to 90% of the P with R-ratio of:
  - R-Ratio $R = \frac{P-\Delta P}{P}$
  - Material – API 5L Grades B to X70 (70ksi).
  - Flow stress: (SMYS+SMTS)/2



(a) Inside Surface

Parametric fatigue study of Hydrogen pipelines

- ASME B31.12 design options:
  - Option B: Maximum Design Factor 0.72, Material Performance Factor =0.72, K_{IH}=55 MPa*m^0.5
  - Option A: Maximum Design Factor 0.5, Material Performance Factor to B31.12

    K_{IH} Converted from CVN=10J, 27J and 57J using Rolfe-Novak equation divided by 2

- Fatigue Crack Growth Rate (FCGR):
  - ASME B31.12 (developed by NIST)

$$\frac{da}{dN} = a1\Delta K^{b1} + \left[\left(a2\Delta K^{b2}\right)^{-1} + \left(a3\Delta K^{b3}\right)^{-1}\right]^{-1}$$

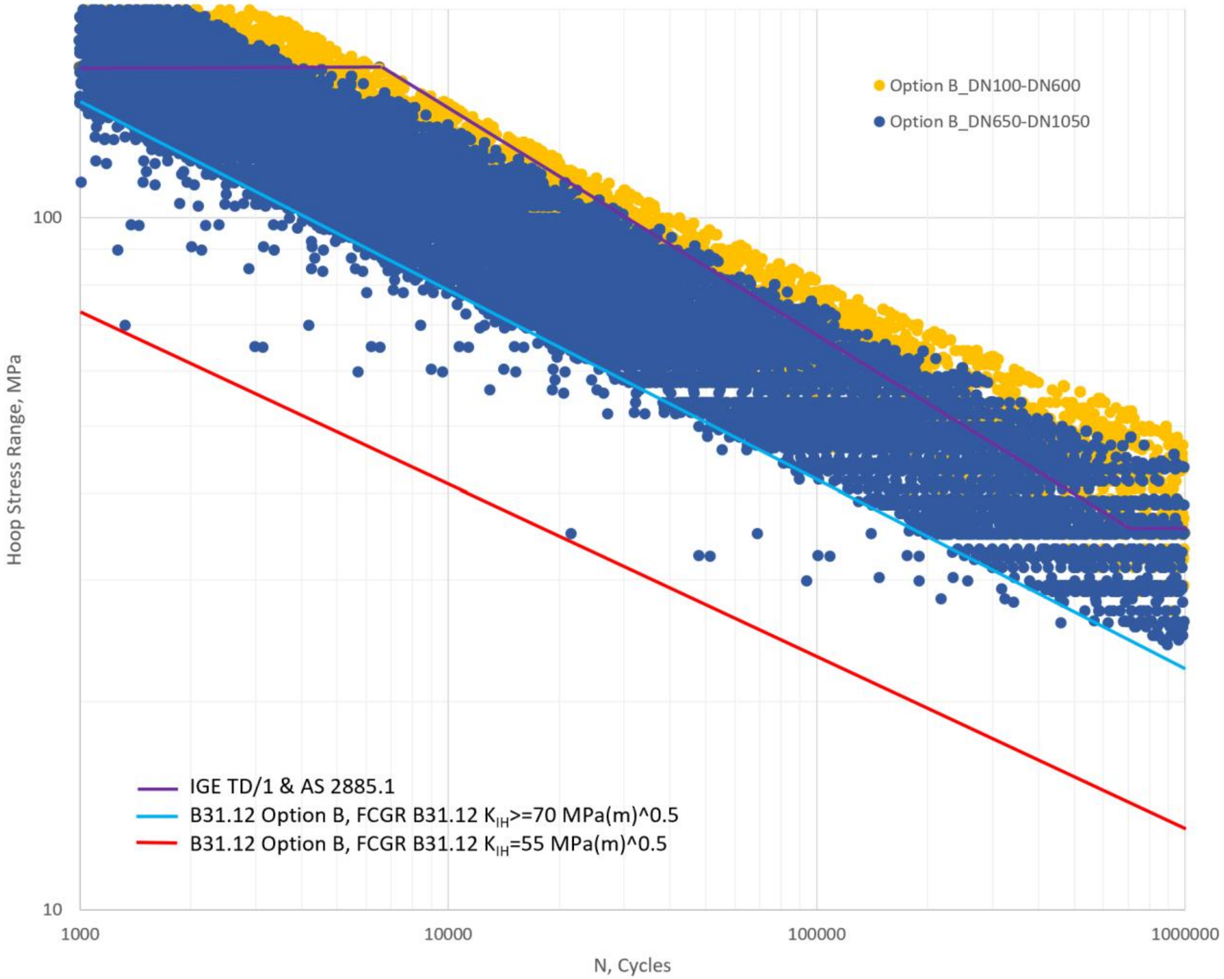
  - ASME BPVC Code Case 2938 (developed by Sandia Lab)

$$\frac{da}{dN} = C\left[\frac{1 + C_H R}{1 - R}\right]\Delta K^m$$

  - Original model developed by Sandia (Pressure modified version of CC 2938)

$$\frac{da}{dN_{low}} = C\left[\frac{1 + C_H R}{1 - R}\right]\Delta K^m \left(\frac{f}{f_{ref}}\right)^{1/2}$$

Results and Discussion



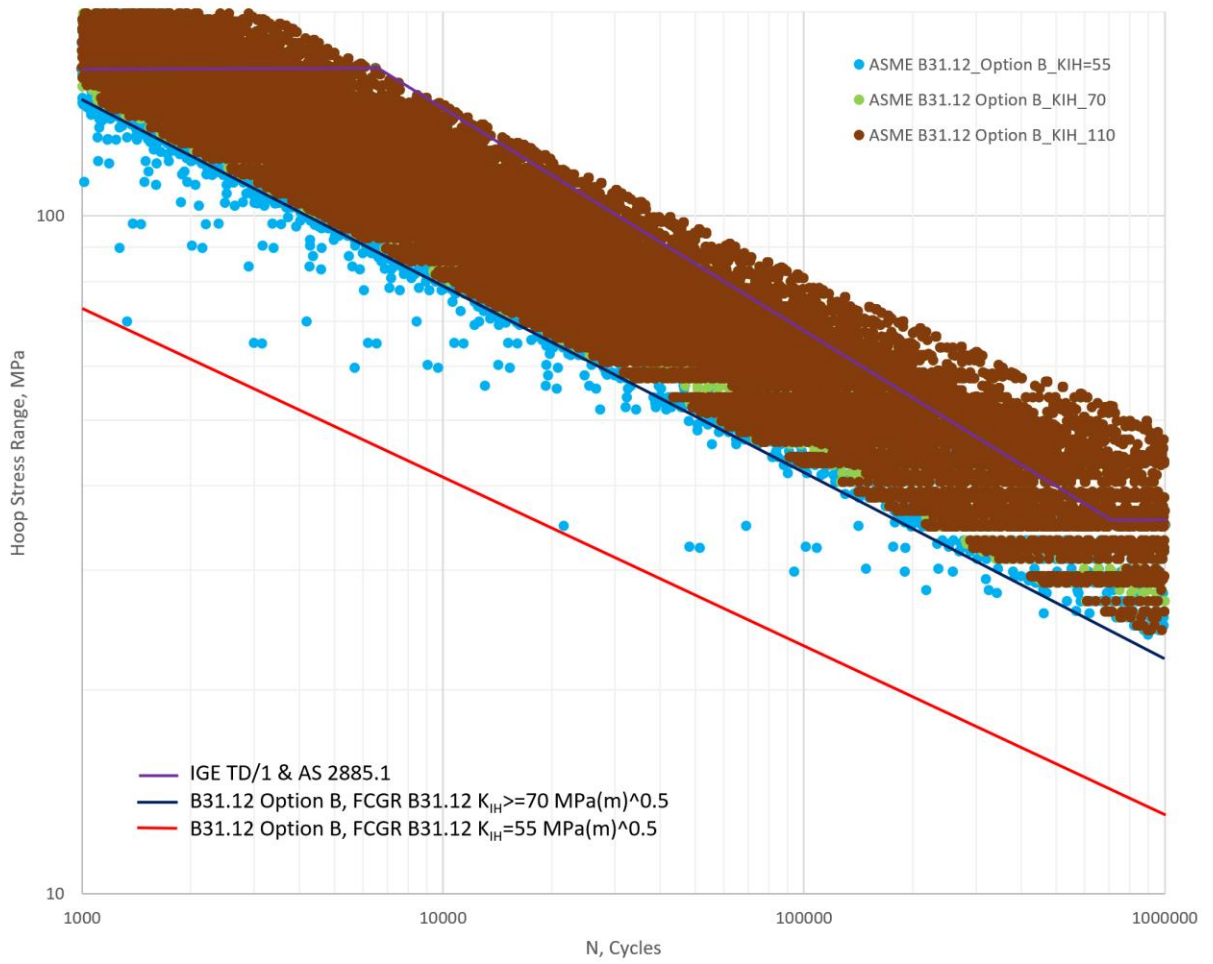
ASME B31.12, Option B, K_{IH}=55 MPa*m^0.5

Results and Discussion

ASME B31.12, Option B, DN100-DN600

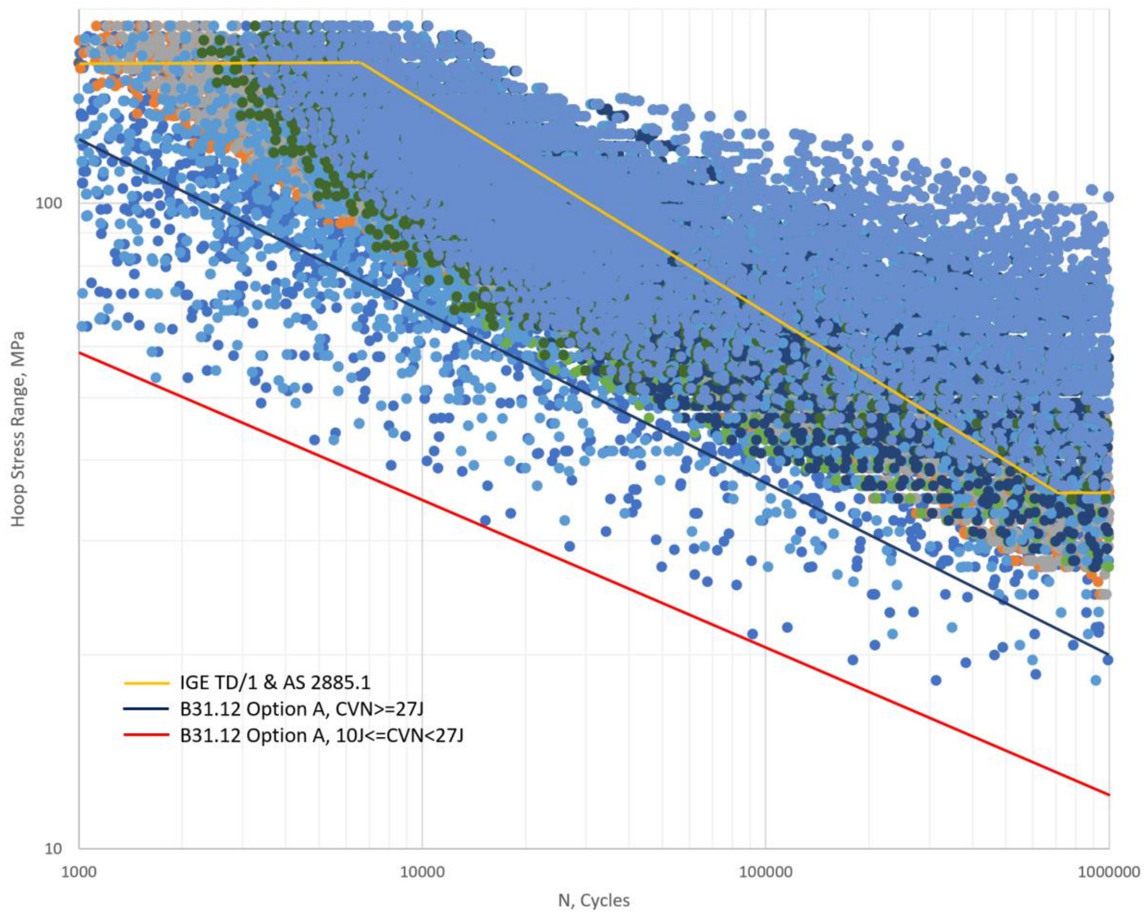
ASME B31.12, Option B, DN650-DN1050

Results and Discussion

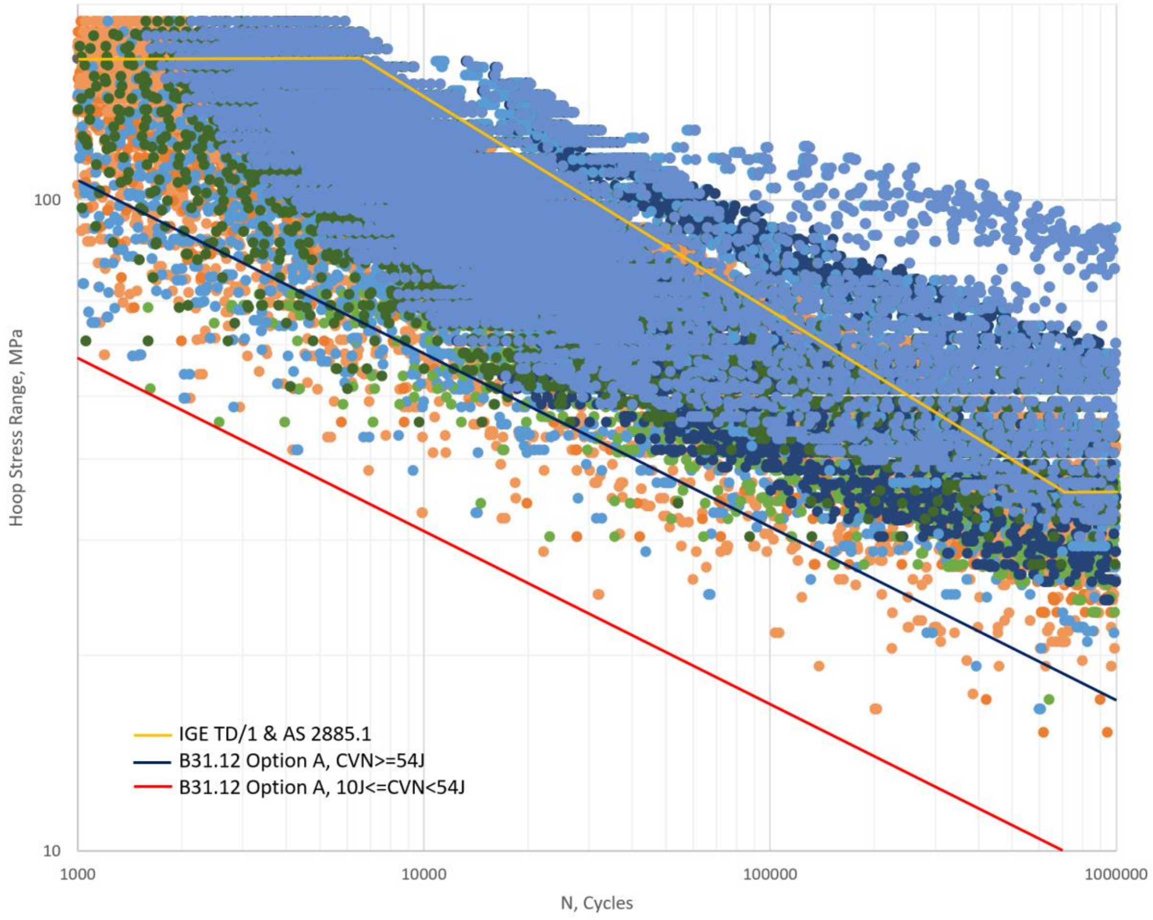


ASME B31.12, Option B, DN100-DN1050, K_{IH}=55 MPa*m^0.5 and K_{IH}>=70MPa*m^0.5

Results and Discussion

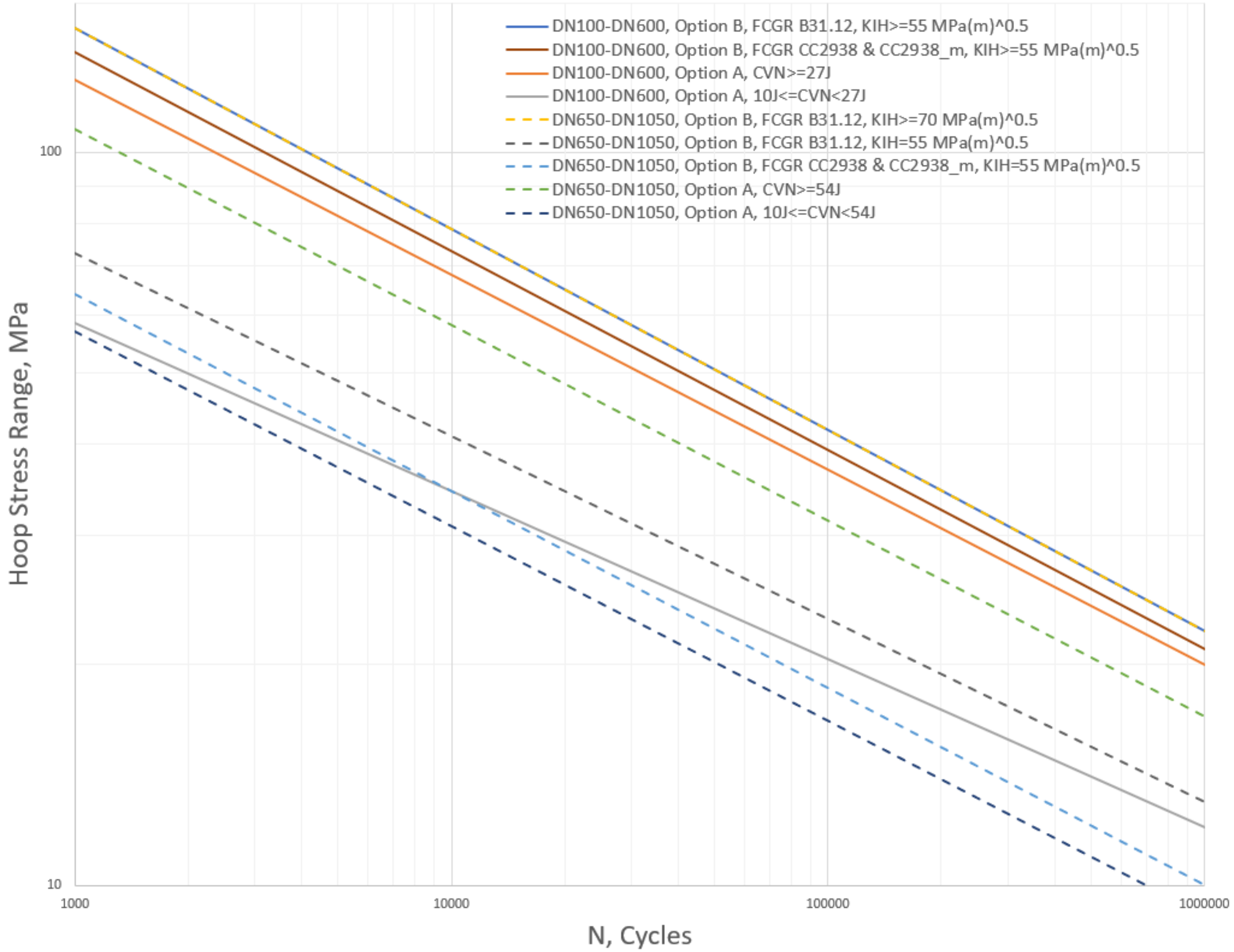


ASME B31.12, Option A, DN100-DN600



ASME B31.12, Option A, DN650-DN1050

Results and Discussion



ASME B31.12, S-N Curves

Conclusion

1. Analysis of more than 216,000 cases (base cases) with three different FCGR equations show that results are scattered, and a single lower bound S-N curve leads to a conservative equation with limited usefulness.
2. Individual results of three FCGR equations are different, but the overall and lower bound S-N is not influenced by the choice of FCGR equation.
3. A lower bound curve to cover all pipe diameters (DN100-DN1050) leads to a conservative S-N curve, but if the diameter range is split into two ranges i.e., DN100-DN600 and DN650-DN1050, unnecessary conservatism for the smaller diameter range can be avoided.
4. In the small diameter range (DN100-DN600), for pipe designed to ASME B31.12 Option A, the fatigue life is less sensitive to material toughness than the large diameter range (DN650-DN1050). Additionally, an API 5L PSL2 compliant pipe in small diameter range has a similar lower bound S-N curve than a pipe designed to ASME B31.12 option B with the same Design Factor.
5. For ASME B31.12 Option B designs in the small diameter range (DN100-DN600), the minimum specified K_{IH}= 55 MPa(m)^0.5 guarantees to meet a toughness-independent lower bound S-N curve.
6. In order to achieve toughness independence state for the large diameter range (DN650-DN1050), the material toughness in Hydrogen needs to be increased to K_{IH}= 70 MPa(m)^0.5.

FUTURE FUELS CRC

Future Fuels CRC is supported through the Australian Government's Cooperative Research Centres Program. We gratefully acknowledge the cash and in-kind support from all our research, government and industry participants.

Australian Government
Department of Industry, Science, Energy and Resources

AusIndustry
Cooperative Research Centres Program

Co-authors

- **GPA, Australia**
  - Nick Kastelein

- **University of Wollongong, Australia**
  - Dr Guillaume Michal

Thank you