Sandia National Laboratories

Exceptional service in the national interest

SAND2024-9864C

Technical basis for fatigue crack growth rules in gaseous hydrogen (B31.12 CC220 and BPVC VIII-3 CC2938-2)

Chris San Marchi,

Joseph A. Ronevich, Paolo Bortot,
Matteo Ortolani, Kang Xu, Mahendra Rana

Sandia National Laboratories
Livermore CA

ASME PVP Conference, Bellevue WA

July 28 – August 2, 2024

U.S. DEPARTMENT OF ENERGY

NNSA

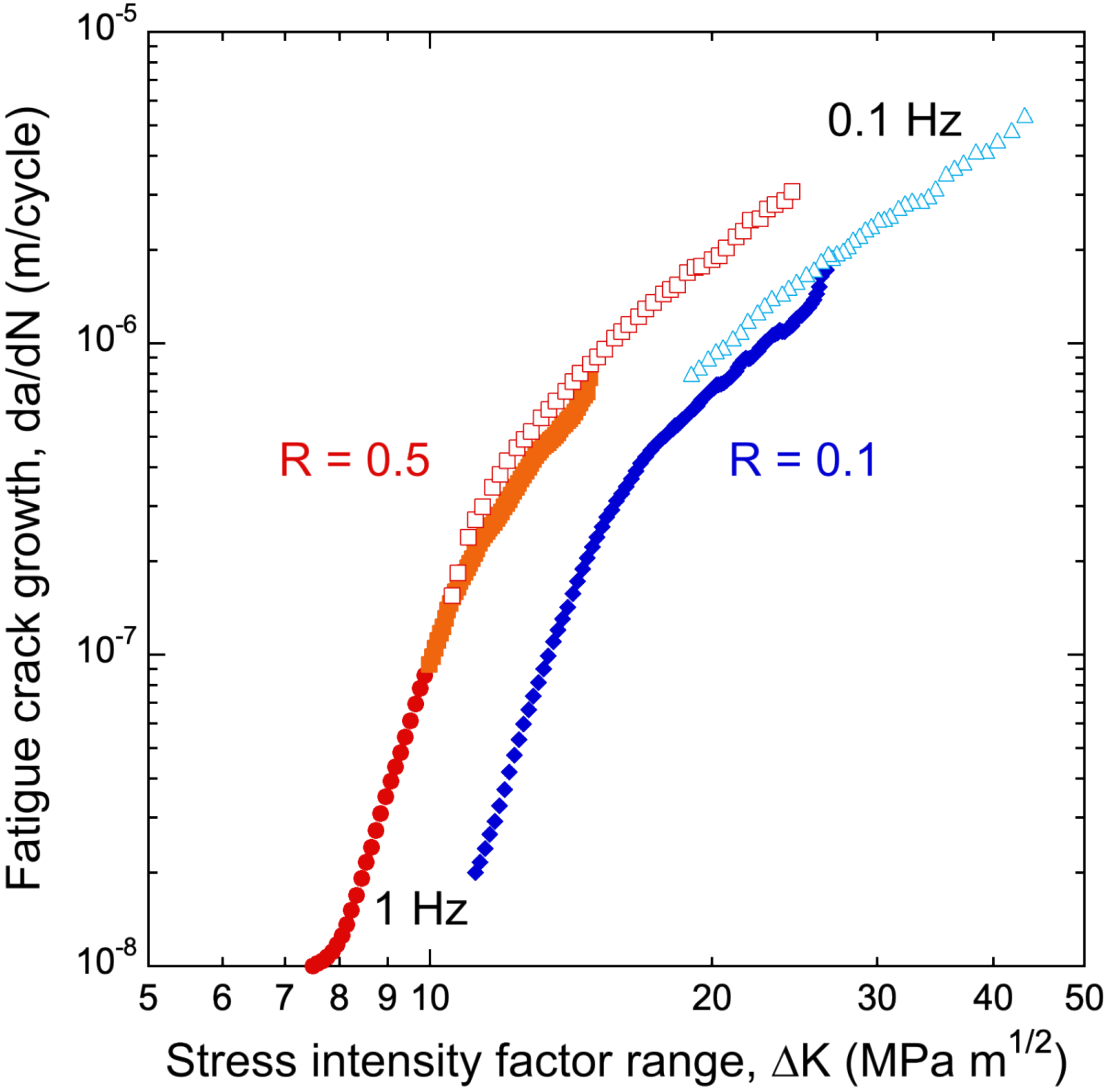
Background

- ASME BPVC uses a basic Paris Law (power law) formulation to characterize fatigue crack growth rate:

$$\frac{da}{dN} = \overbrace{\underset{\nearrow\,\textit{constant}}{C}\;\;\underbrace{f(R_k)}_{\textit{stress ratio dependence}}\;\;\underbrace{\Delta K^m}_{\textit{power law}}}^{\textit{Basic Paris Law form}}$$

Background

- In high-pressure gaseous hydrogen, a single power law formulation is insufficient to capture the observed fatigue crack growth behavior over relevant range of ΔK
- Additionally, a relatively large dependence on stress ratio (R) is observed



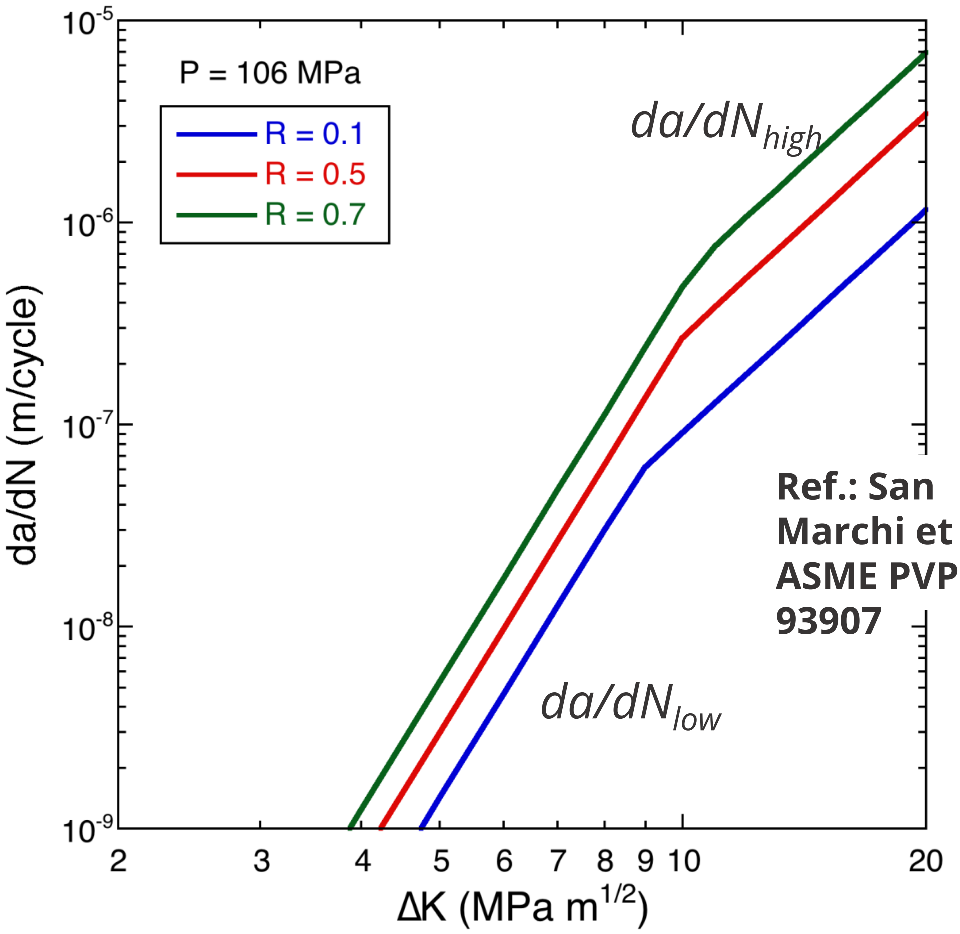
Background

- BPVC VIII-3 Code Case 2938 adopted a two-part power-law formulation to capture observed rate

$$\frac{da}{dN} = \underset{\nearrow \atop \text{constant}}{C} \underbrace{\left[\frac{1+C_H R}{1-R}\right]}_{\text{stress ratio dependence}} \underbrace{\Delta K^m}_{\text{power law}}$$

	da/dN_{low}	da/dN_{high}
C (m/cycle)	3.5 x10^{-14}	1.5 x10^{-11}
C_H	0.4286	2.00
m	6.5	3.66

ΔK units: MPa $m^{1/2}$



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

Specifically developed for

- Pressure of 106 MPa
- Quenched and tempered, pressure vessel steels

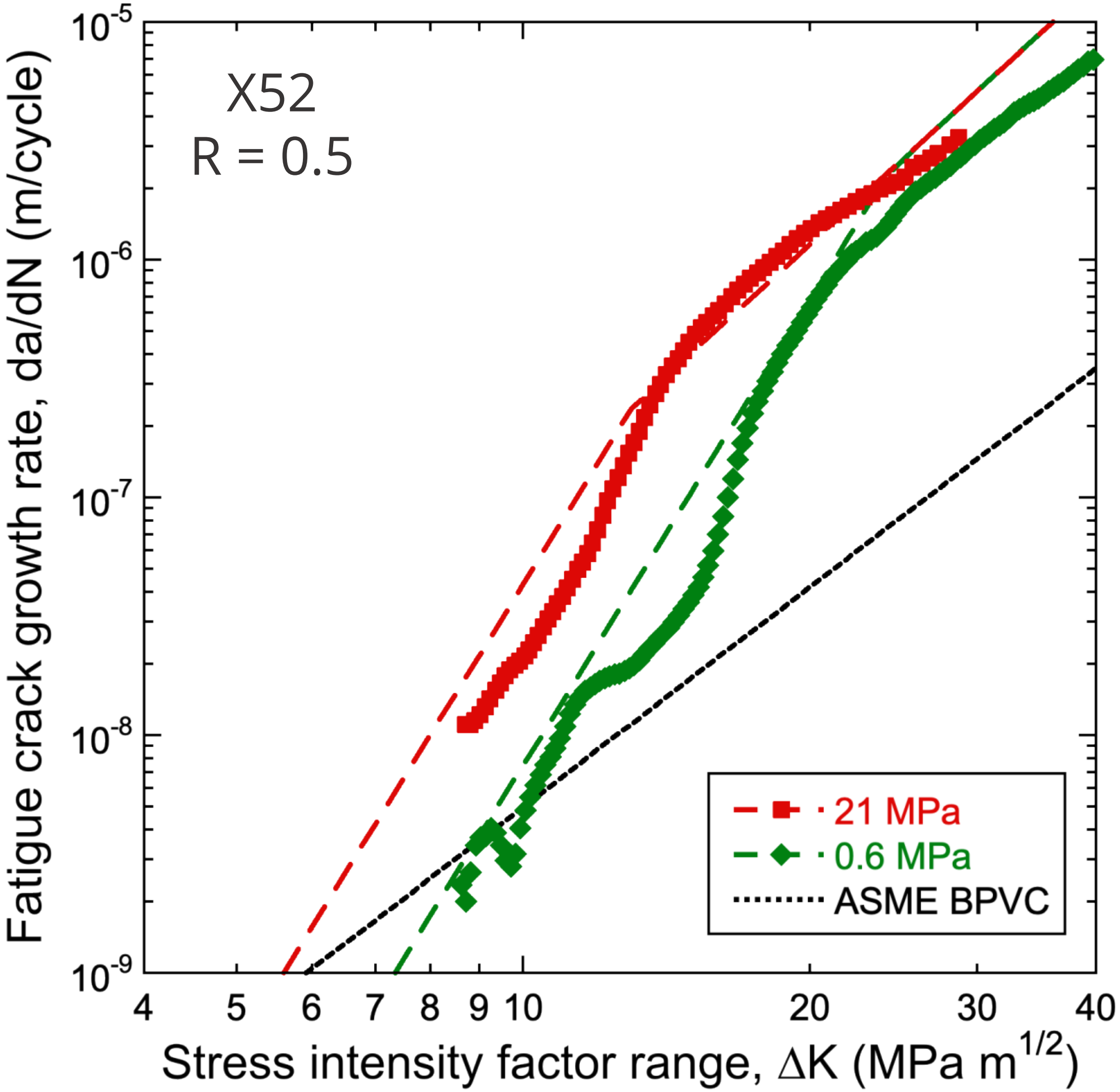
Background and Motivation

Two important observations from extensive testing in gaseous hydrogen

1. **Line pipe steels show similar behavior as PV steels**
2. **Pressure affects lower domain of crack growth but not upper domain**

Motivation: can formulation be adapted to capture:

1. **other steels and**
2. **pressure effects?**



Formulation of Fatigue Design Curves (FDCs) for steels in hydrogen service

Proposed generic form to include pressure dependence:

$$\frac{da}{dN} = \underbrace{C\ f(R_k)\ \Delta K^m}_{\textit{basic ASME form}} \boxed{f(P)}$$

Pressure term

	da/dN_{low}	da/dN_{high}
C (m/cycle)	3.5 x10^{-14}	1.5 x10^{-11}
C_H	0.4286	2.00
m	6.5	3.66
$f(P)$	$g(P)$	1

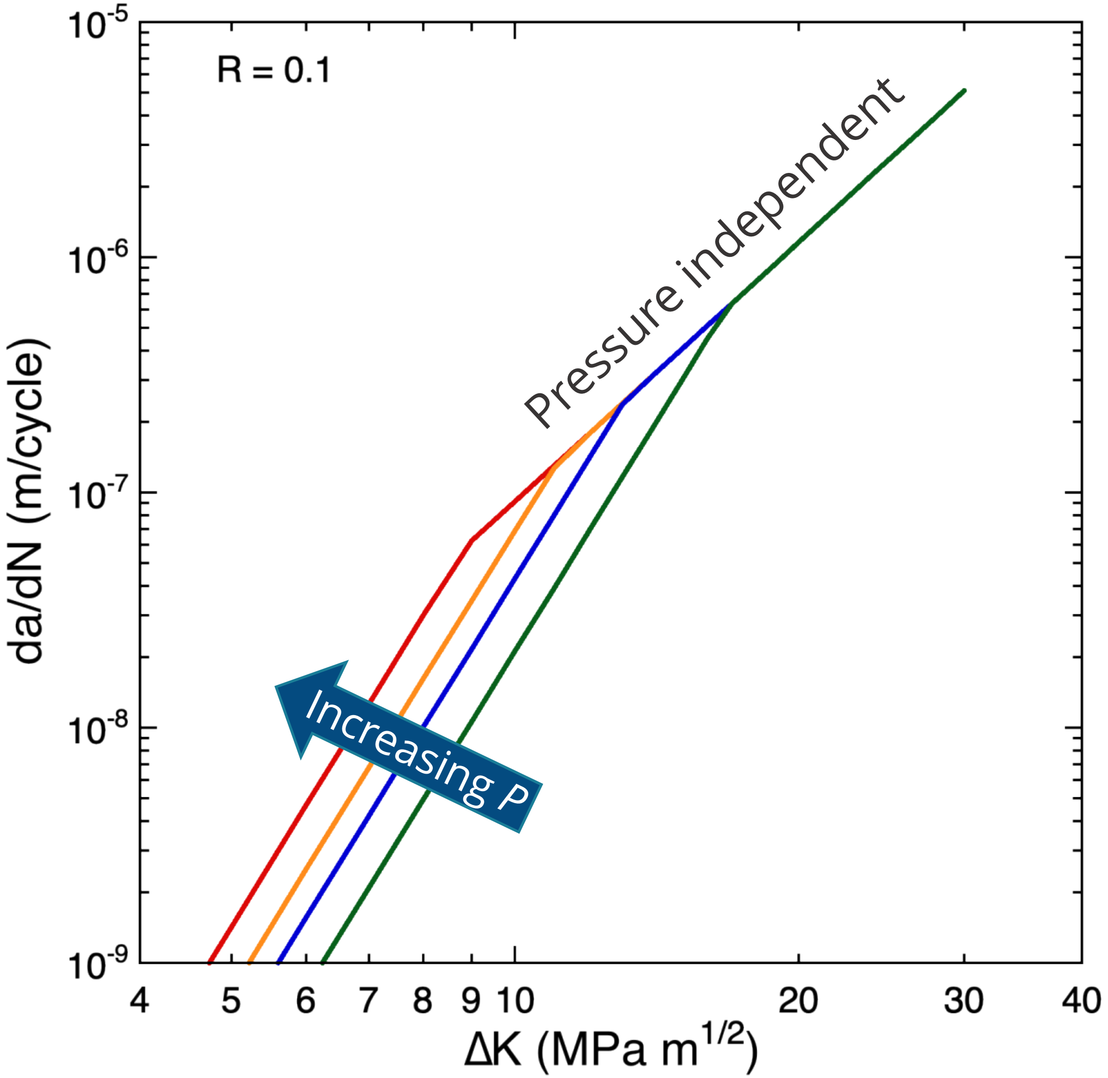
$$f(R_k) = \left[\frac{1 + C_H R}{1 - R}\right]$$

from BPVC VIII.3 CC 2938

$$g(P) = \left(\frac{f}{f_{ref}}\right)^{1/2}$$

Phenomenological form based on thermodynamics

Idealized framework to capture pressure effect



Low ΔK: *pressure dependent*

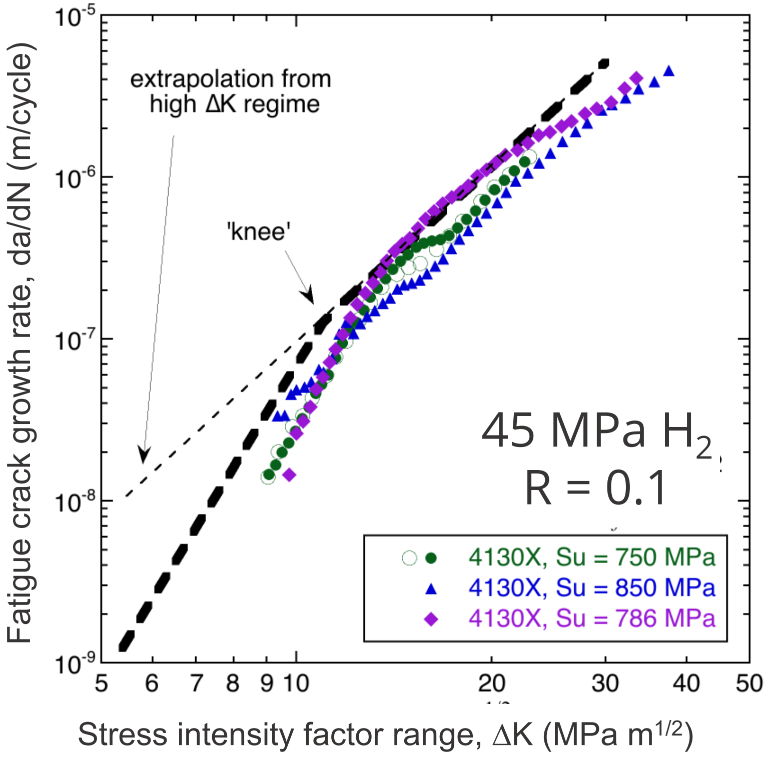
$$\frac{da}{dN} = C\left[\frac{1+C_H R}{1-R}\right]\Delta K^m g(P)$$

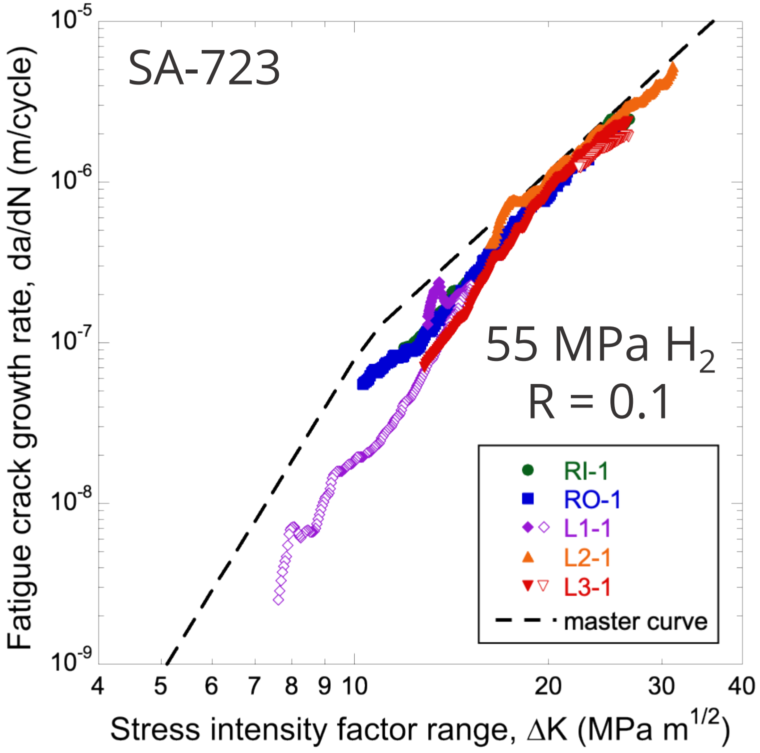
High ΔK: *pressure independent*

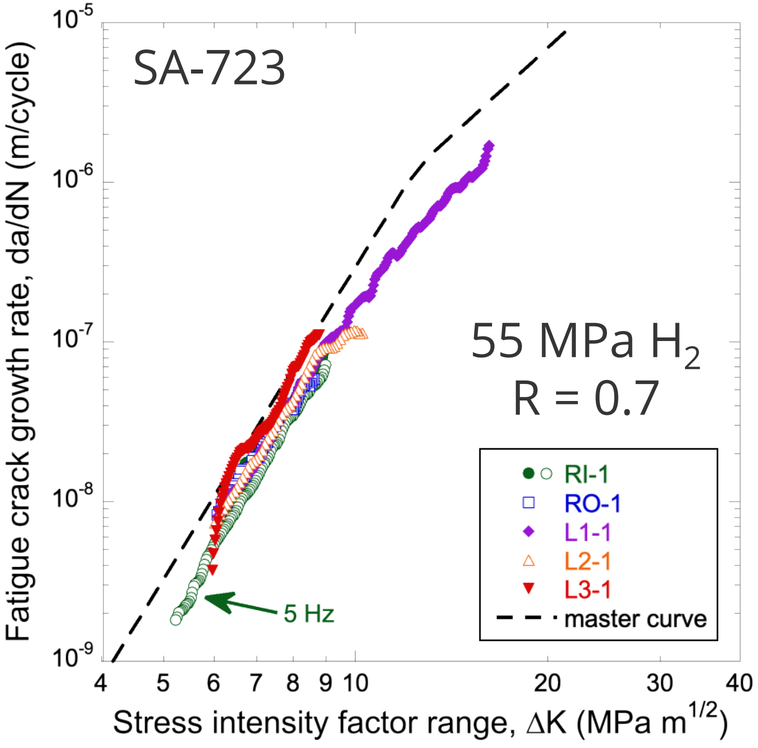
$$\frac{da}{dN} = C\left[\frac{1+C_H R}{1-R}\right]\Delta K^m$$

Fatigue crack growth for PV steels

- **Note capturing the transition region (*i.e.*, 'below' the knee) is important for design in the low ΔK regime**
- **SA-723 designations (RI, RO, L) represent different positions and orientations**



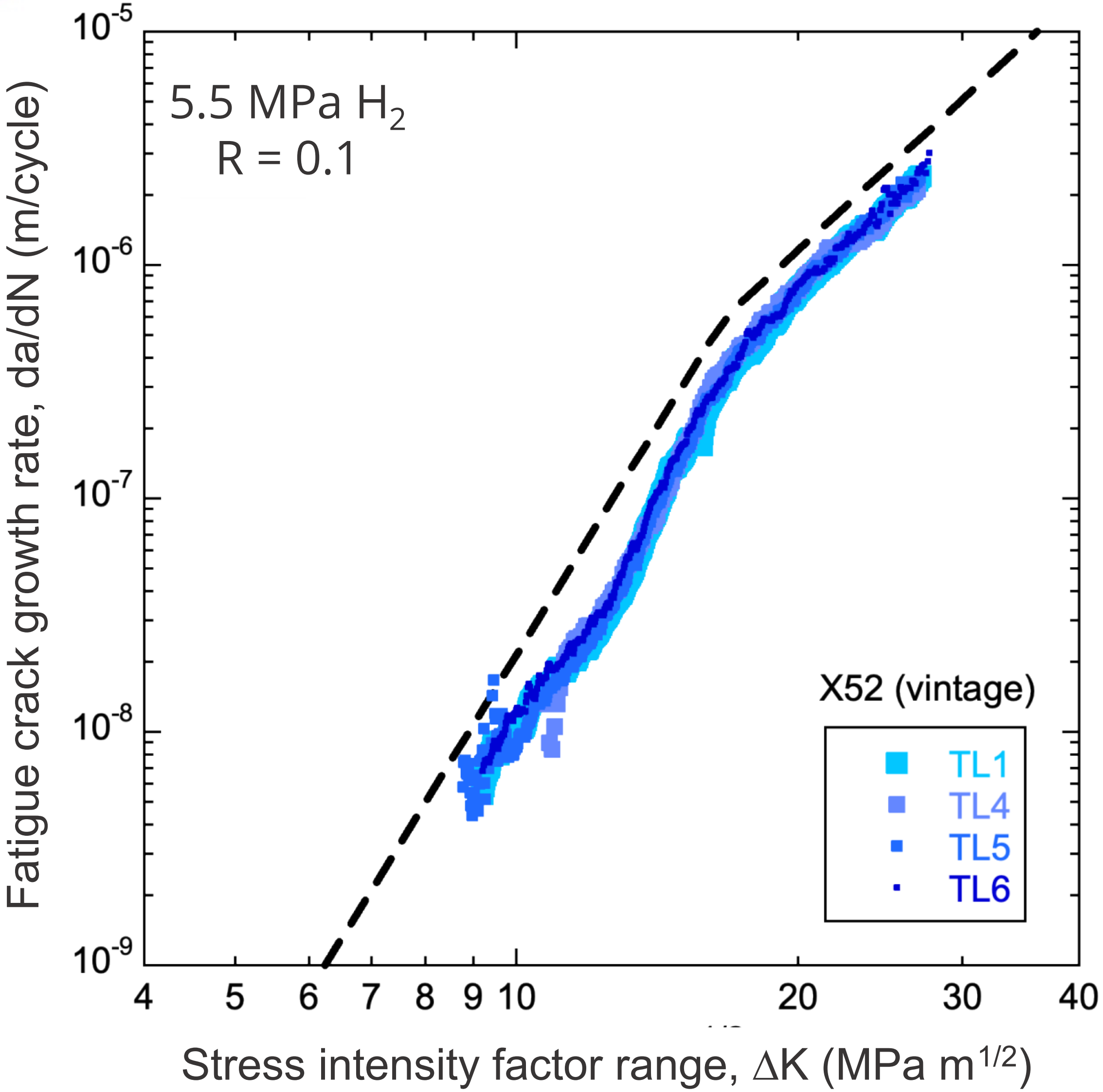


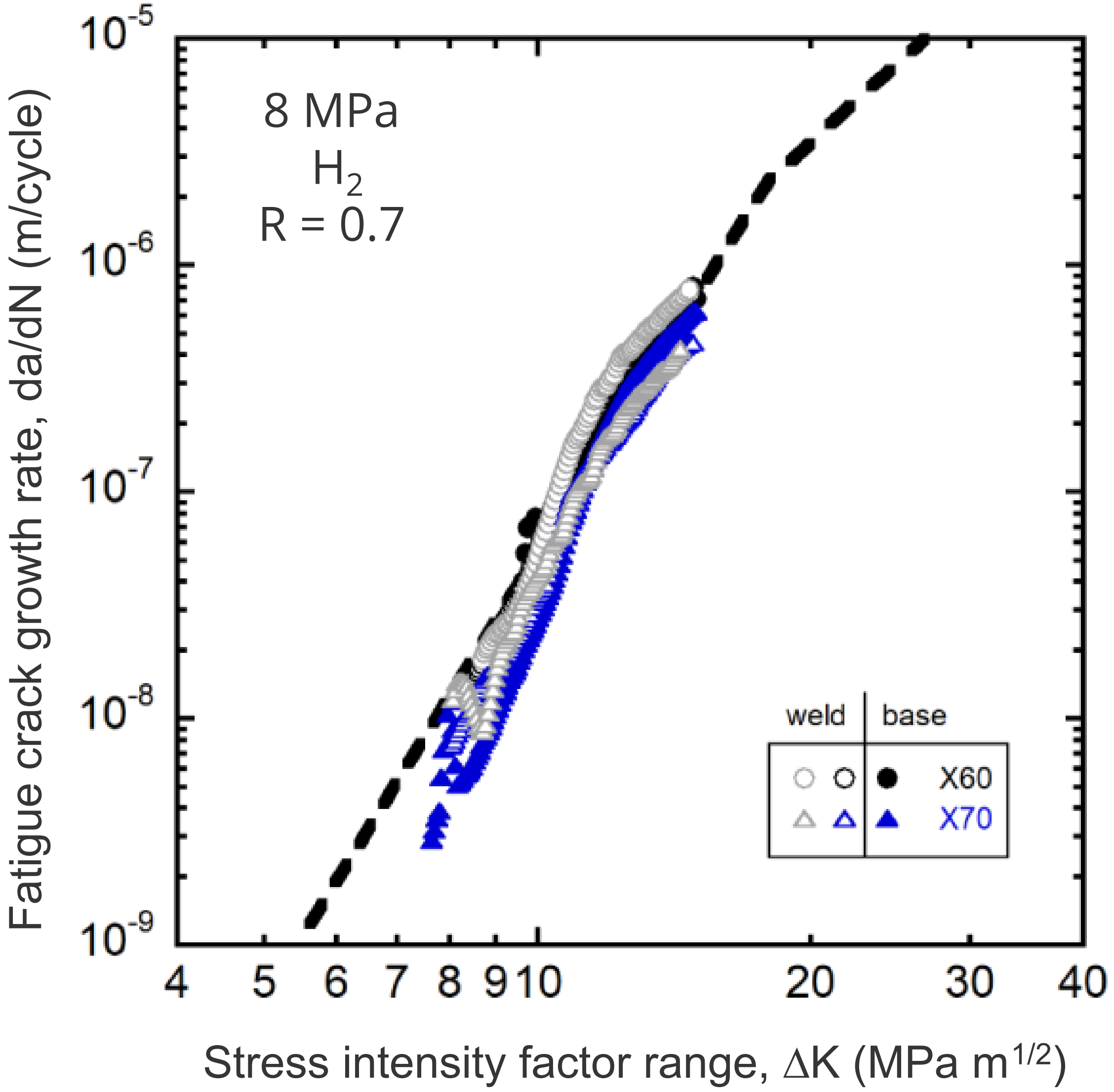


Ref.: San Marchi et al., ASME PVP2019-93907

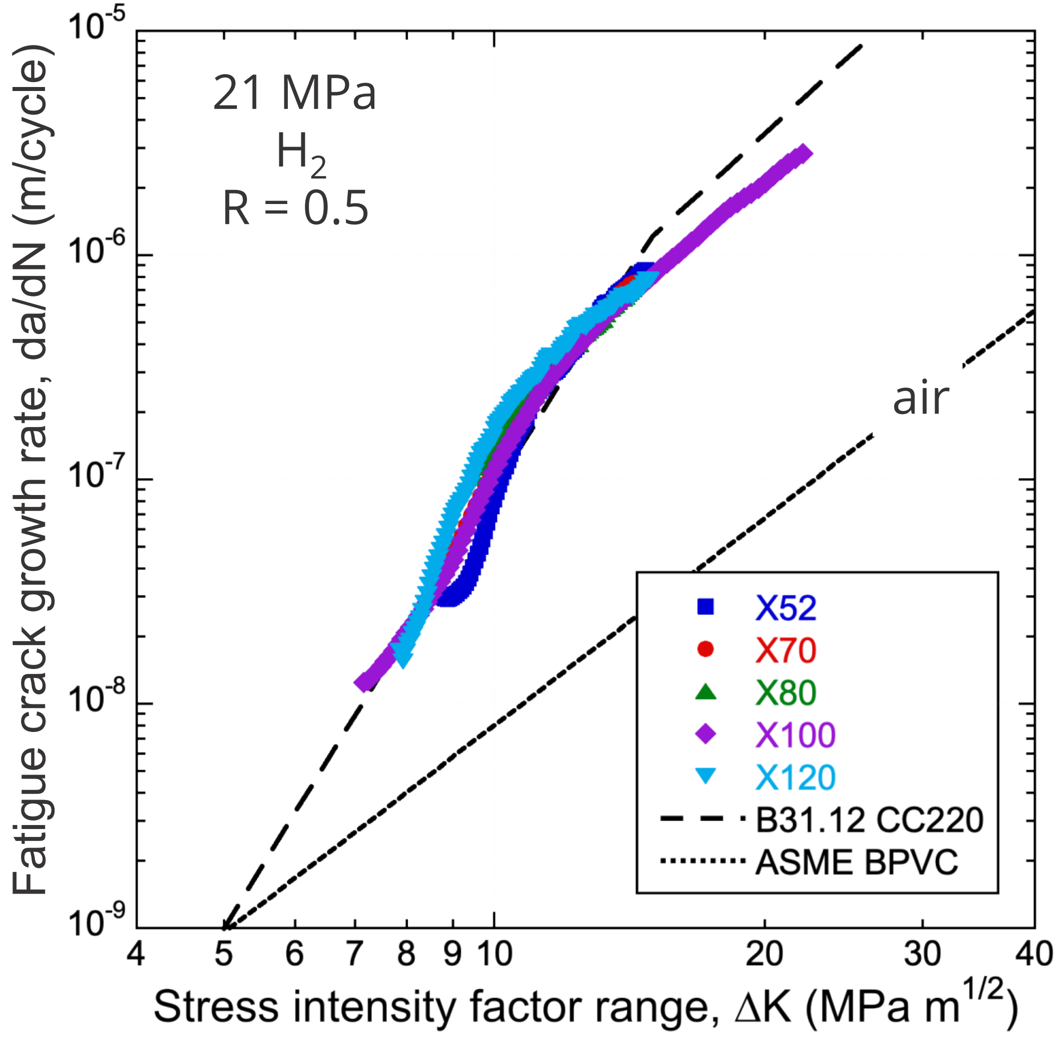
Ref.: Bortot et al., ASME PVP2023-106417

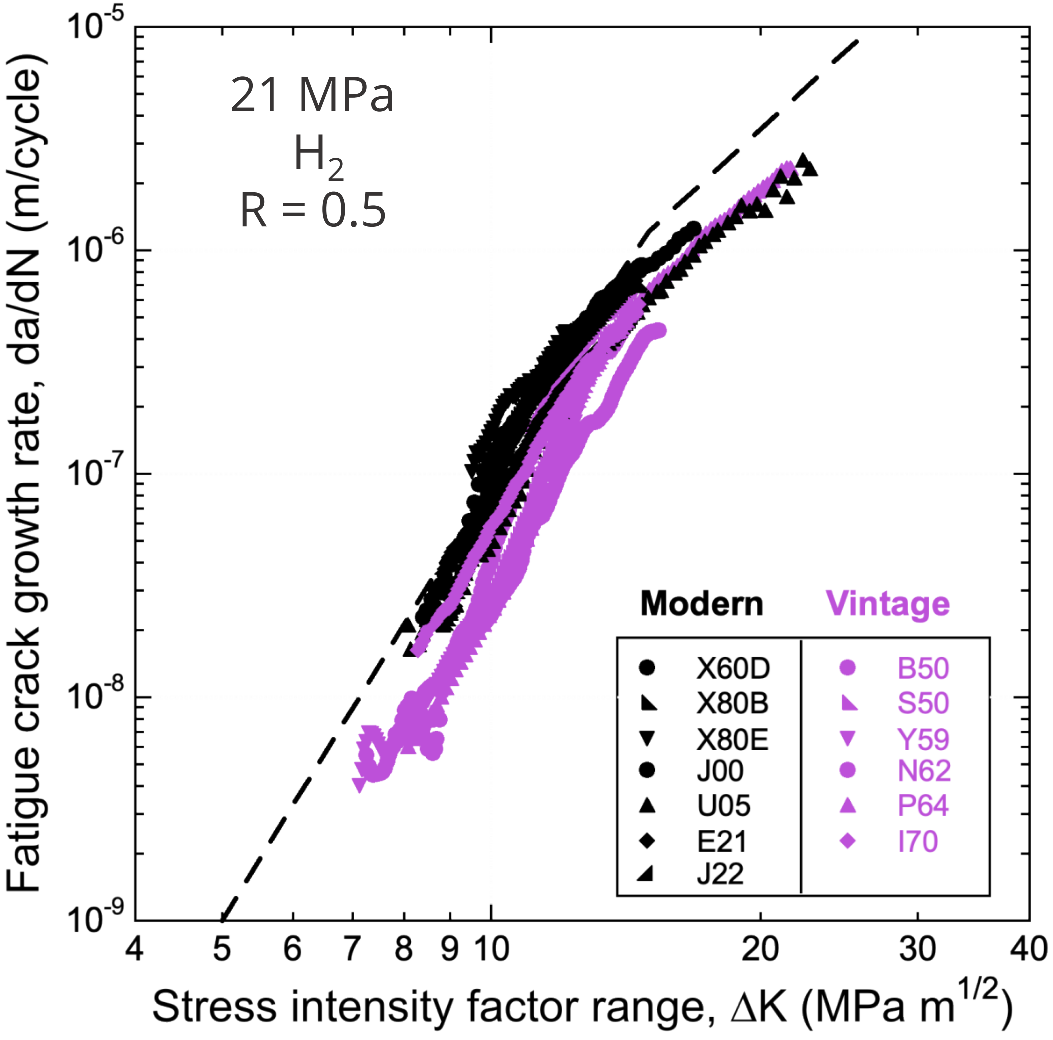
Fatigue crack growth of line pipe steels: low pressure



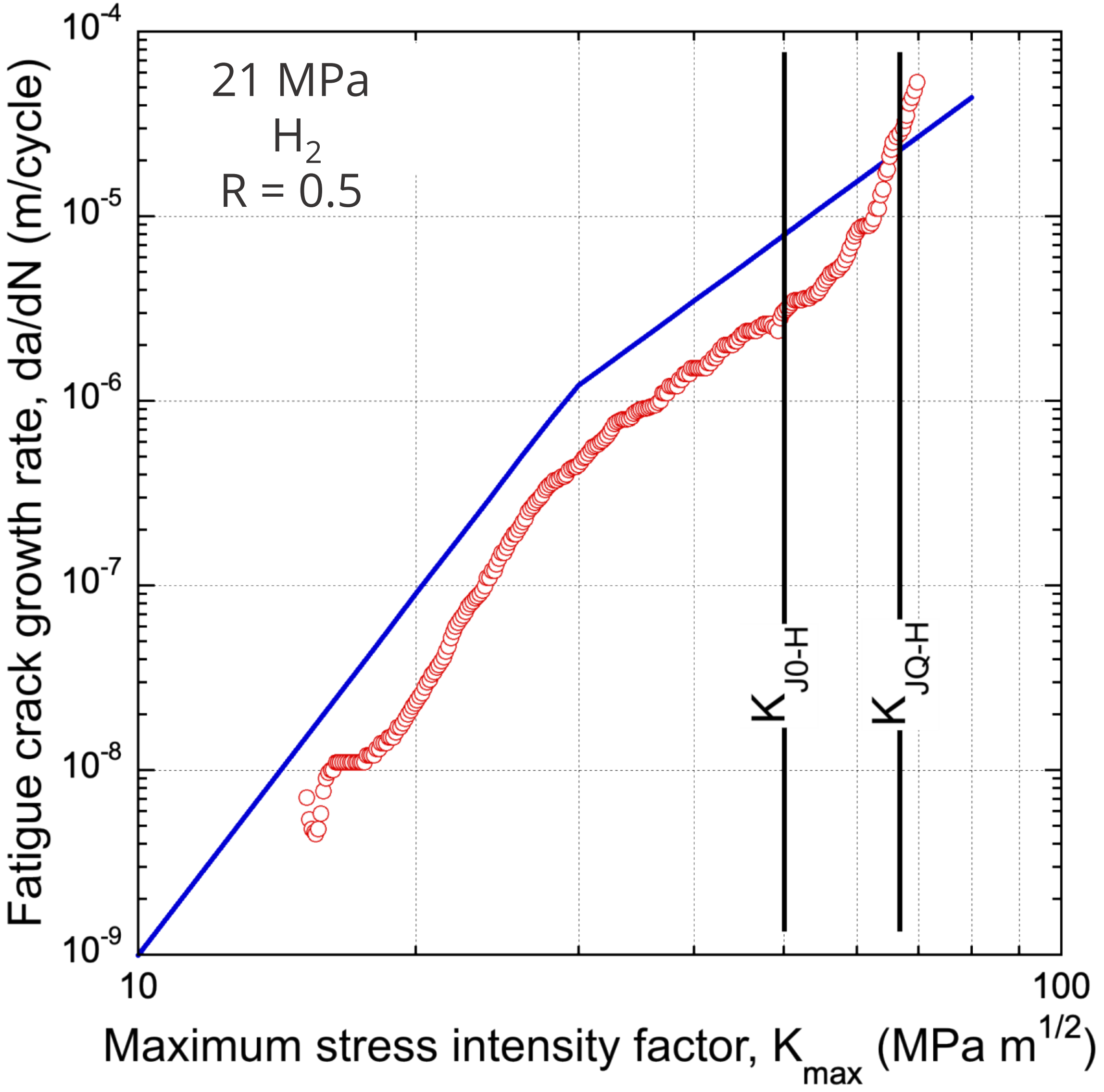


Both vintage and modern linepipe steels are bounded by proposed fatigue design curves, regardless of strength



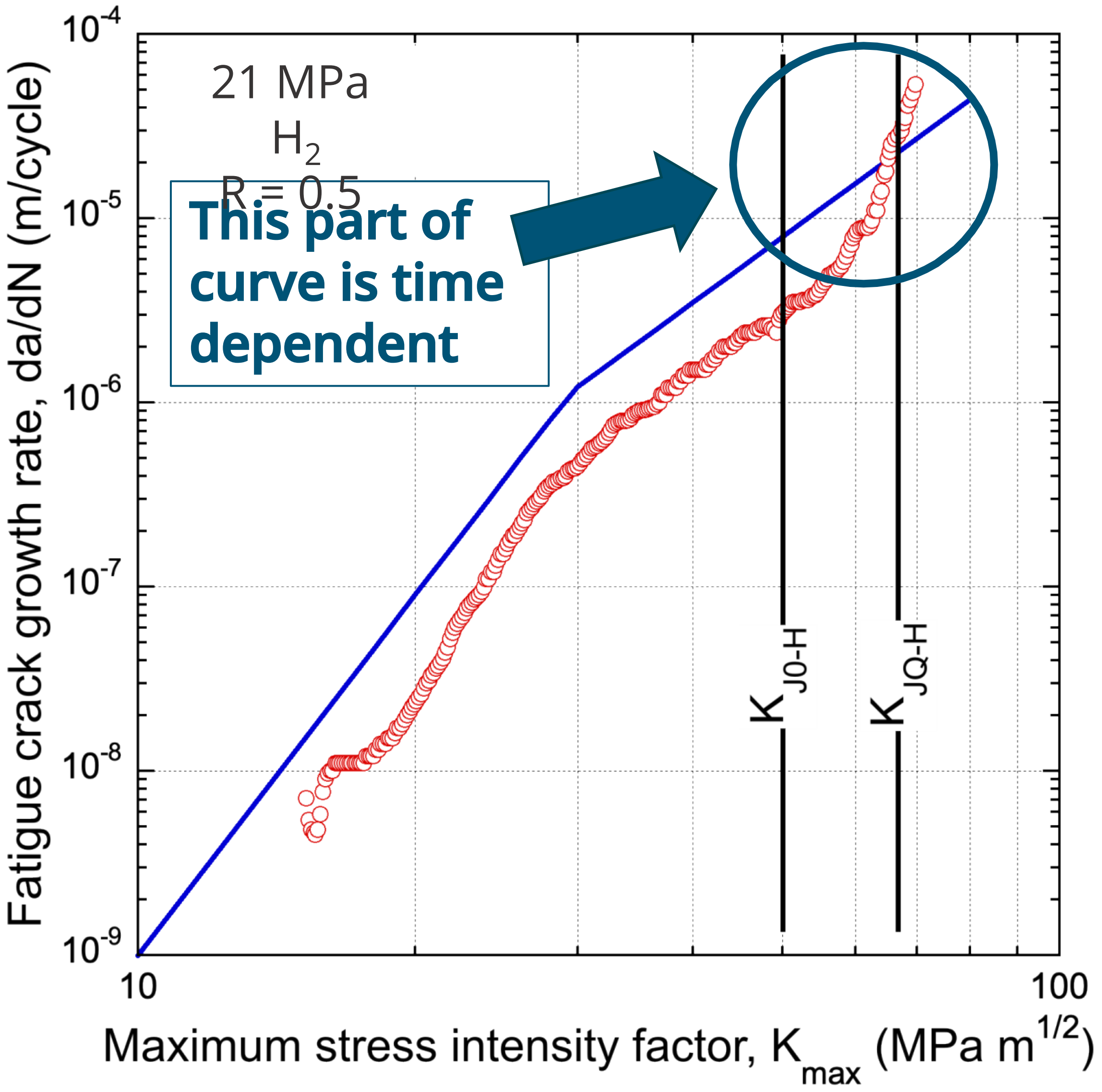


Application of fatigue curves is limited by fracture resistance



- **Fatigue crack growth curves cannot be extrapolated to any stress intensity factor (K)**
- **Practical application of fatigue curves is limited to 40 MPa $m^{1/2}$, perhaps lower in some cases**

Application of fatigue curves is limited by fracture resistance



This part of curve is time dependent

- **Fatigue crack growth curves cannot be extrapolated to any stress intensity factor (K)**
- **Practical application of fatigue curves is limited to 40 MPa $m^{1/2}$, perhaps lower in some cases**
- **Also important to recognize that $K_{max} > K_{J0-H}$ is time dependent**
  - **Meaning this portion of the curve is frequency dependent**

Pressure dependence based on thermodynamics

- Consider the hydrogen effect as proportional to the equilibrium hydrogen concentration

$$\frac{da}{dN} \propto [\mathrm{H}]$$

- Concentration is proportional to square root of fugacity

$$\overline{H}(\mathrm{metal}) \leftrightarrow \frac{1}{2} H_2 \xrightarrow{\text{Sieverts' Law}} [H] = K(P_H)^{1/2} \xrightarrow{\text{Non-ideal gas}} [H] = K f^{1/2}$$

- Use high-pressure condition (106 MPa) as reference pressure (fugacity)

$$\frac{da}{dN}^{low} = \underbrace{C\left[\frac{1+C_H R}{1-R}\right]\Delta K^m}_{\textit{Specifically for } f_{ref}} \underbrace{\left(\frac{f}{f_{ref}}\right)^{1/2}}_{= g(P)}$$

Use thermodynamics to determine pressure relationship: $g(P)$

Abel-Noble EOS
Pure gas

$$\frac{f}{P_H} = exp\left(\frac{P_H b}{RT}\right)$$

Regular solution model
Mixed gas

$$\frac{f}{P_H} = exp\left(\frac{P_t b}{RT}\right)$$

Reference pressure

$$\frac{f_{ref}}{P^*} = exp\left(\frac{P^* b}{RT}\right)$$

$$g(P) = \left(\frac{f}{f_{ref}}\right)^{1/2}$$

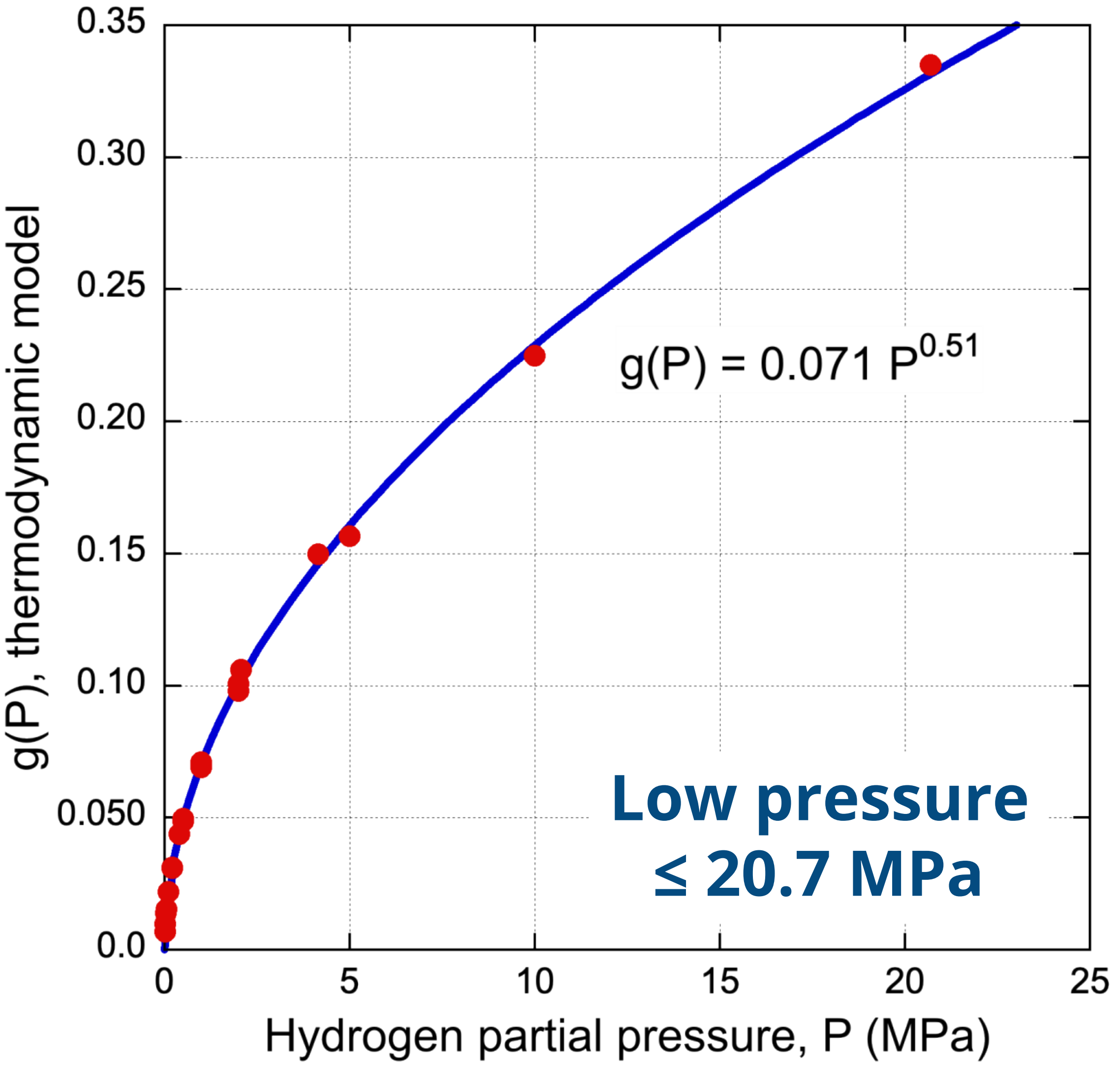
Combining on Abel-Noble EOS and regular solution model

$$g(P) = \left[\left(\frac{P_H}{P^*}\right)\exp\left(\frac{b}{RT}(P_t - P^*)\right)\right]^{1/2}$$

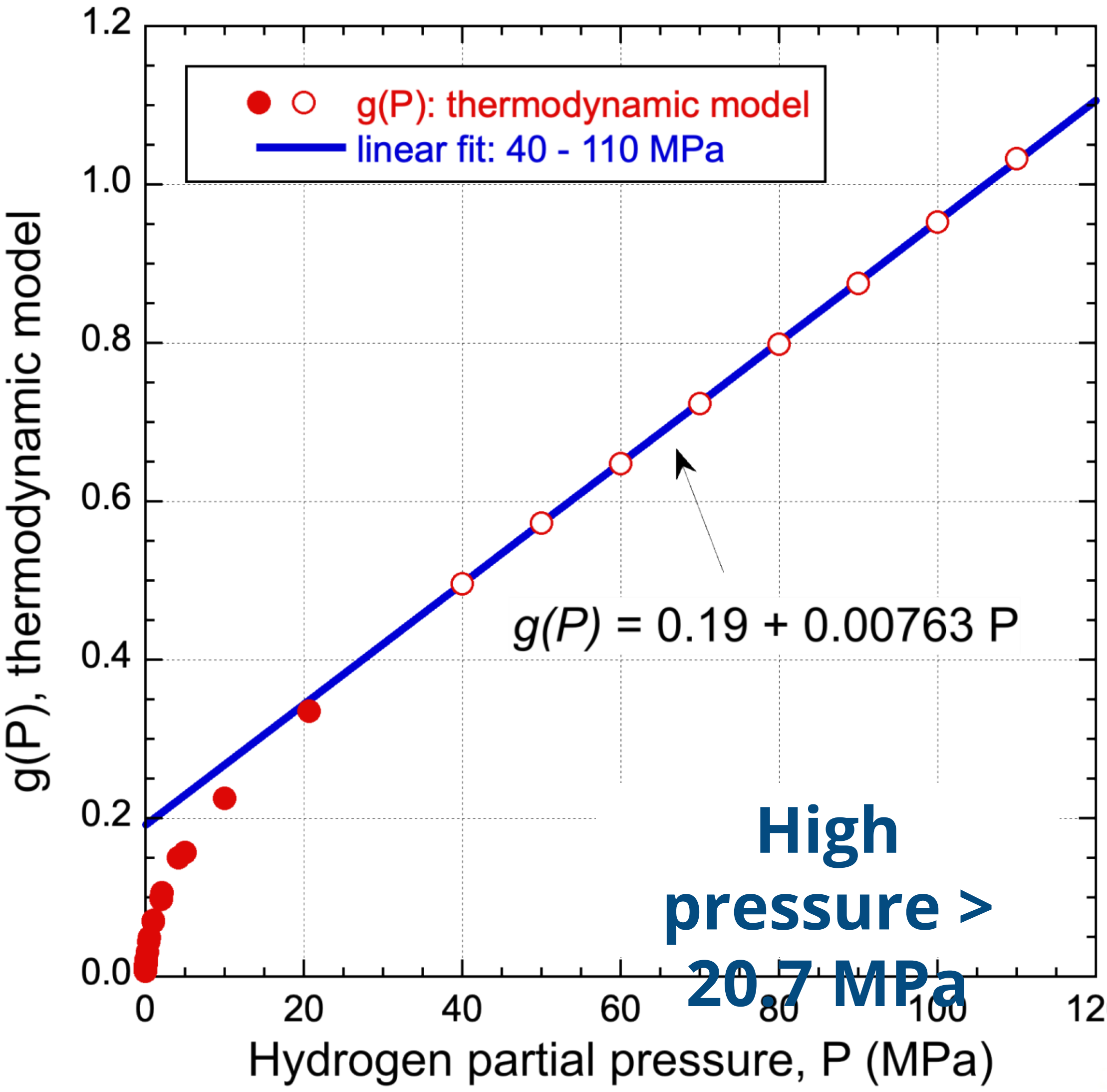
P^*	Reference pressure: = 106 MPa (15,374 psi)
P_t	Total pressure
P_H	Hydrogen partial pressure

<u>References of EOS and mixed gas</u>:
(1) San Marchi et al, IJHE 32 (2007)
(2) ASME PVP2021-62045

Fit $g(P)$ in low pressure and high pressure regime separately



Low pressure ≤ 20.7 MPa



High pressure > 20.7 MPa

Formulation of Fatigue Design Curves (FDCs) for steels in hydrogen service

	da/dN_{low}	da/dN_{high}
C (m/cycle)	3.5 x10^{-14}	1.5 x10^{-11}
C_H	0.4286	2.00
m	6.5	3.66
$f(P \leq 20.7 \text{ MPa})$	$0.071\ P^{0.51}$	1
$f(P > 20.7 \text{ MPa})$	$0.19 + 0.00763\ P$	

Low ΔK:
pressure dependent

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

High ΔK:
pressure independent

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

Formulation of Fatigue Design Curves (FDCs) for steels in hydrogen service

	da/dN_{low}	da/dN_{high}
C (m/cycle)	$3.5 \text{ x}10^{-14}$	$1.5 \text{ x}10^{-11}$
C_H	0.4286	2.00
m	6.5	3.66
$f(P \leq 20.7 \text{ MPa})$	$0.071\,P^{0.51}$	1
$f(P > 20.7 \text{ MPa})$	$0.19 + 0.00763\,P$	

$$= g(P) = \left[\left(\frac{P_H}{P^*}\right)\exp\left(\frac{b}{RT}\left(P_t - P^*\right)\right)\right]^{1/2}$$

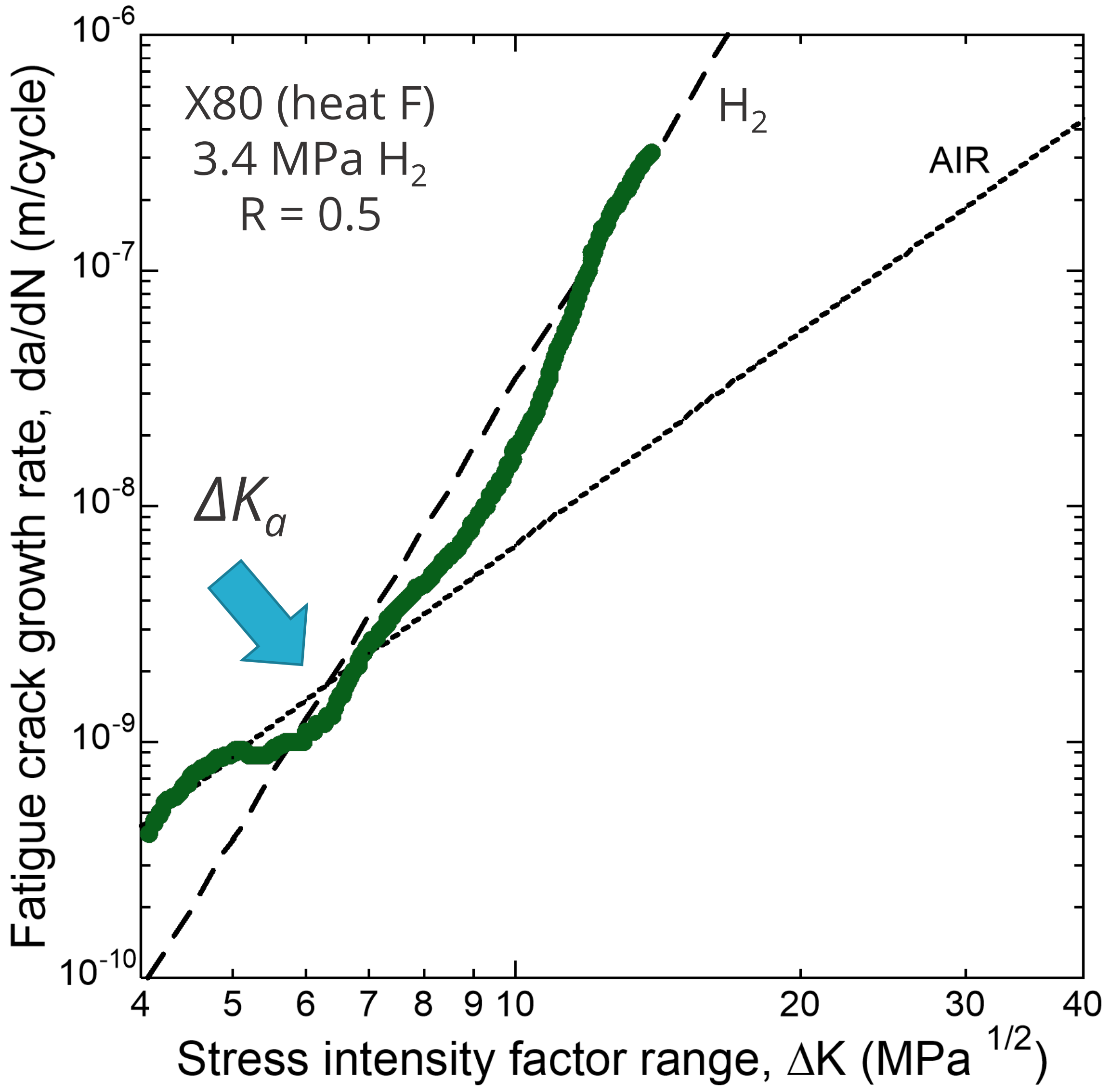
Low ΔK:
pressure dependent

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

High ΔK:
pressure independent

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

One more thing…



- At low stress intensity (and low pressure) fatigue design curves extrapolate to crack growth rates less than air
- However, experimental observations show that material response can transition to the behavior in air

Fatigue design curves should not be extrapolated below the air curve

Three regimes of fatigue crack growth must be considered for hydrogen service

$\Delta K < \Delta K_a$

$$da/dN = da/dN_{air} \qquad da/dN_{air} = 3.8\,x10^{-12}\left(\frac{2.88}{2.88 - R_k}\right)^{3.07} \Delta K^{3.07}$$

steels
$S_y \leq 620$ MPa

$\Delta K_a < \Delta K < \Delta K_c$

$$da/dN = da/dN_{low} \qquad da/dN_{low} = 3.5\,x10^{-14}\left(\frac{1 + 0.43R_k}{1 - R_k}\right)\Delta K^{6.5}\left[\underbrace{0.071P^{0.51}}_{g(P \leq 20.7\text{MPa})}\right]$$

g(P ≤ 20.7MPa)

$\Delta K > \Delta K_c$

$$da/dN = da/dN_{high} \qquad da/dN_{high} = 1.5\,x10^{-11}\left(\frac{1 + 2R_k}{1 - R_k}\right)\Delta K^{3.66}$$

← ***f(P) = 1***

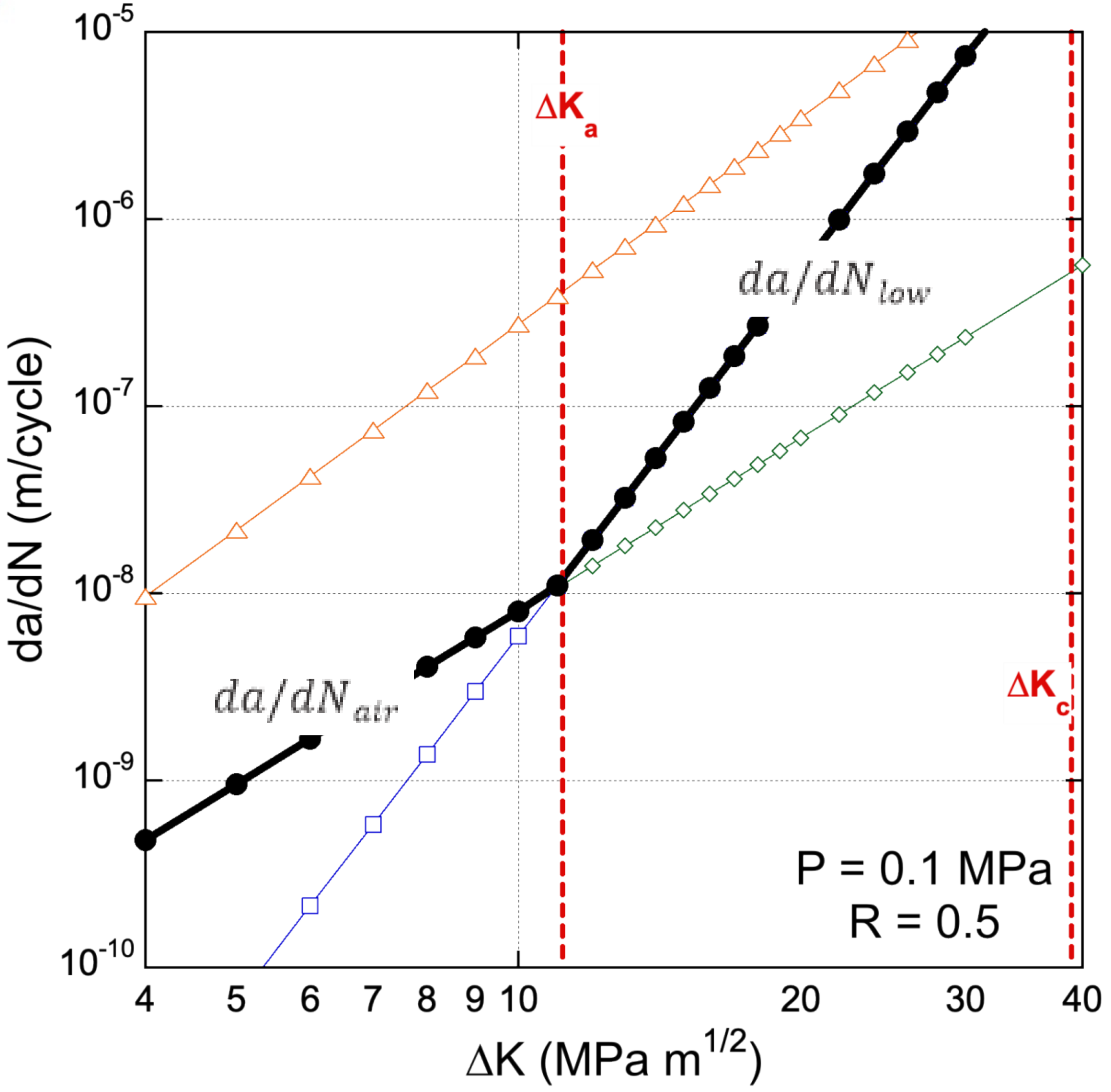
$$\Delta K_a \rightarrow da/dN_{air} = da/dN_{low}$$

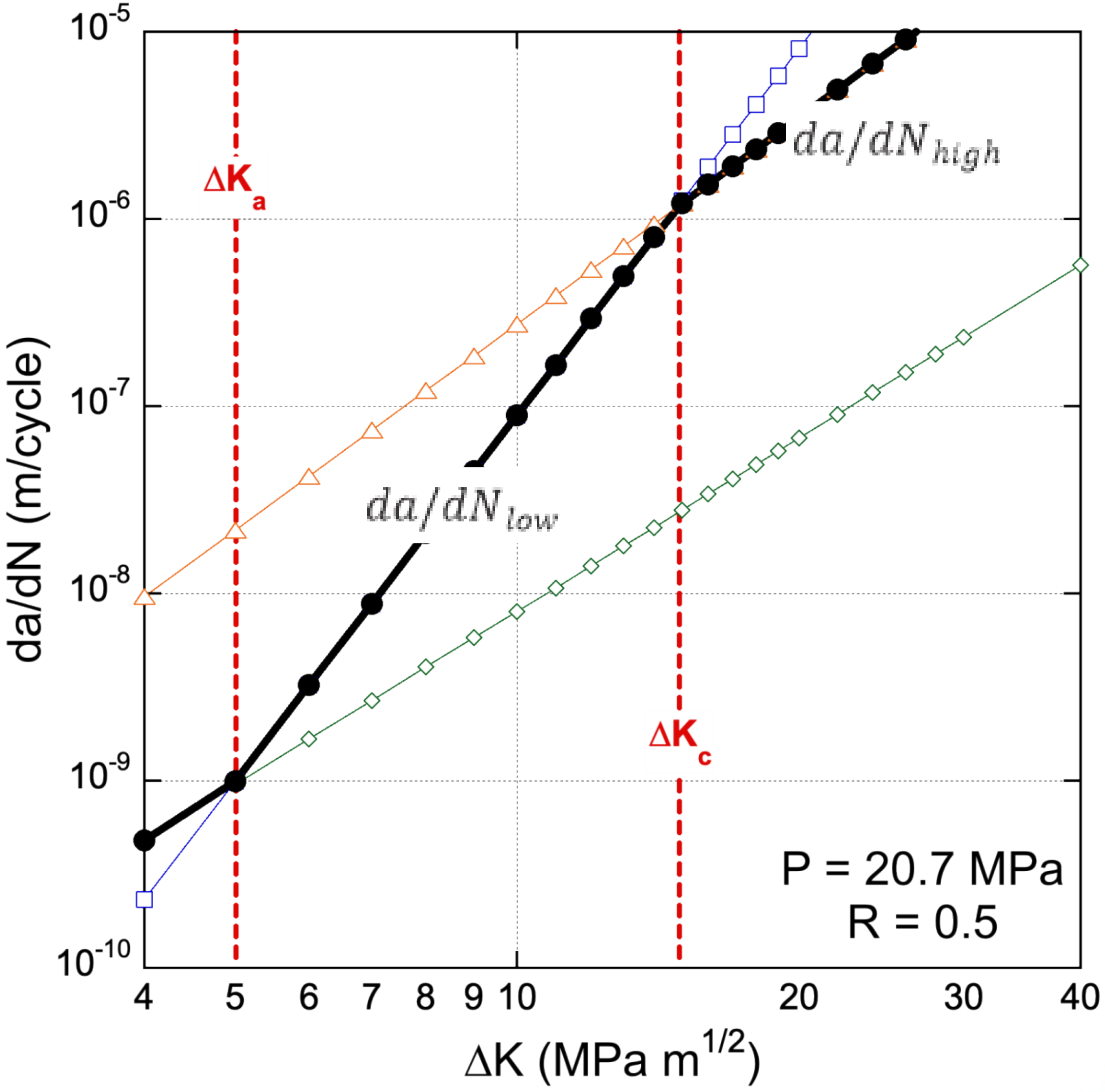
$$\Delta K_c \rightarrow da/dN_{low} = da/dN_{high}$$

UNITS:

UNITS:	**ΔK**	**(MPa $m^{1/2}$)**
	da/dN	**(m/cycle)**
	P	**(MPa)**

Example Fatigue Design Curves: unique for each combination of P and R





Summary of fatigue design curves

For carbon steels and low alloy steels, $S_y \leq 915$ MPa

$$\Delta K < \Delta K_a$$

$$da/dN = da/dN_{air}$$

Material	$\boldsymbol{da/dN_{air}}$ [m/cycle]†	R_k
Carbon and low alloy steels $S_y \leq 620$ MPa	$3.8\,x10^{-12}\left(\frac{2.88}{2.88-R_k}\right)^{3.07}\Delta K^{3.07}$	$0 \leq R_k < 1$
High strength low alloys steels Sy > 620 MPa	$3.64\,x10^{-12}(1+3.53R_k)\Delta K^{3.26}$	$R_k \geq 0$

† relationships from the ASME BPVC

Summary of fatigue design curves

For carbon steels and low alloy steels, $S_y \leq 915$ MPa

$$\Delta K_a < \Delta K < \Delta K_c$$

$$da/dN = da/dN_{low}\ [\mathrm{m/cycle}] = 3.5\ x10^{-14}\left(\frac{1+0.43R_k}{1-R_k}\right)\Delta K^{6.5}[g(P)]$$

P range [MPa]	$g(P)$ [MPa]	Material	ΔK_a [MPa m$^{1/2}$]
0.1 to 20.7	$0.071\ P^{0.51}$	Carbon and low alloy steels, $S_y \leq 620$ MPa	$(8.6 - 3.0R_k + 7.9{R_k}^2 - 9.4{R_k}^3)\ P^{-0.15}$
		High strength low alloys steels, Sy > 620 MPa	$(9.6 + 2.7R_k + 0{R_k}^2 - 7.8{R_k}^3)\ P^{-0.16}$
20.7 to 110 †	$0.19 + 0.00763\ P$	Carbon and low alloy steels, $S_y \leq 620$ MPa	$(10.6 - 3.7R_k + 9.8{R_k}^2 - 11.7{R_k}^3)\ P^{-0.21}$
		High strength low alloys steels, Sy > 620 MPa	$(11.9 + 3.4R_k + 0{R_k}^2 - 9.6{R_k}^3)\ P^{-0.22}$

† relationships fit to pressure range of 40 to 110 MPa

Summary of fatigue design curves

For carbon steels and low alloy steels, $S_y \leq 915$ MPa

Note: da/dN pressure independent

$$\Delta K > \Delta K_c$$

$$da/dN = da/dN_{high}\ [\mathrm{m/cycle}] = 1.5\,x10^{-11}\left(\frac{1+2R_k}{1-R_k}\right)\Delta K^{3.66}$$

P range [MPa]	ΔK_c [MPa m$^{1/2}$]
0.1 to 20.7	$(21.66 + 10R_k - 3.7{R_k}^2)\ P^{-0.18}$
20.7 to 110 †	$(27.4 + 12.7R_k - 4.8{R_k}^2)\ P^{-0.25}$

† relationships fit to pressure range of 40 to 110 MPa

Transition is pressure dependent because da/dN_{low} depends on pressure

ΔK_c is defined by $da/dN_{low} = da/dN_{high}$

Summary

- **Measured fatigue crack growth of steels in gaseous hydrogen can be bounded by a two-part ‘Paris Law’ (simple power law)**
    - **And consideration for fatigue in air**
- **Fatigue Design Curves (FDCs) have a wide range of applicability for pressure vessel steels and line pipe steels in gaseous hydrogen service**
    - **FDCs are *<u>pressure</u>* dependent**
        - **0.1 MPa to 110 MPa**
    - **FDCs account for dependence on *<u>stress ratio</u>* R**
        - **0.1 to 0.7 (potentially 0.9 and higher)**
    - **FDCs are relatively simple Paris Law (power law) relationships**

Thank You for your attention

Chris San Marchi
cwsanma@sandia.gov

Joe Ronevich
jaronev@sandia.gov

Paolo Bortot, Matteo Ortolani – Tenaris (Italy)
Kang Xu – Linde
Mahendra Rana – ASME Fellow

Acknowledgement:
This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Hydrogen and Fuel Cell Technologies Office (HFTO) Safety Codes and Standards sub- program, under the direction of Laura Hill.

H-Mat Hydrogen Materials Compatibility Consortium SM

HyBlend U.S. DEPARTMENT OF ENERGY

Additional resources:

https://h-mat.org/

https://www.sandia.gov/matlsTechRef/

https://granta-mi.sandia.gov/

Hydrogen Effects on Materials Laboratory (HEML) team

Ben Schroeder
James McNair
Brendan Davis
Keri McArthur
Tanner McDonnell
Rob Wheeler
Fernando Leon-Cazares
Milan Agnani