Bulk Storage of Gaseous Hydrogen Workshop
Surface Storage

Feb-11th-2022





Typical Hydrogen Refueling Station - HRS

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Typical Gaseous Hydrogen Installations

HRS

Industrial

HRS

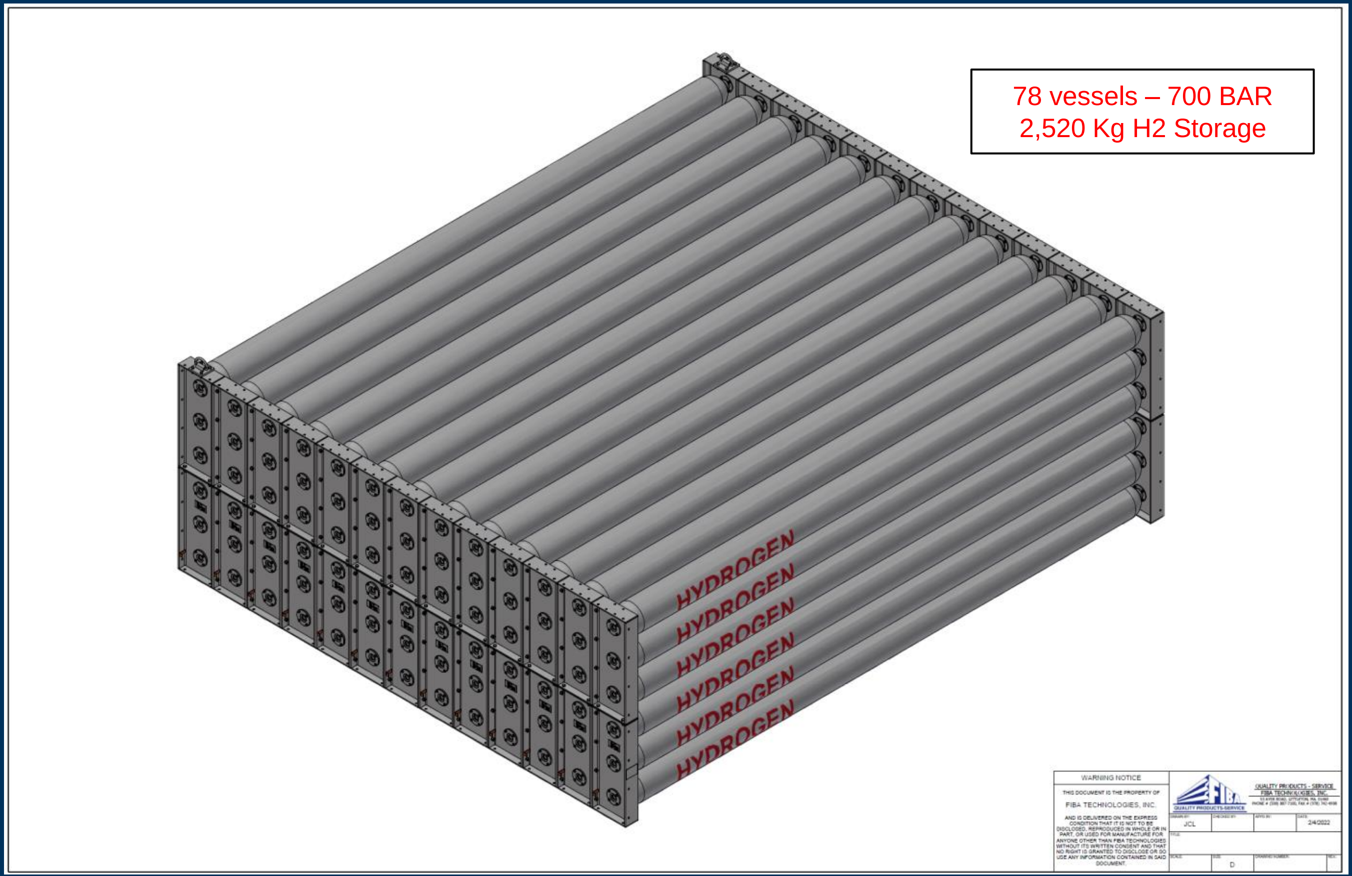
HRS

Typical Hydrogen Storage Pack Configurations

Designed to meet local Code e.g. seismic / wind loads etc

Vertical

Stackable Storage Possible



Pressure Vessels Classifications / Types

Pressure Vessel Types & Key Attributes

Vessel Type	Type I	Type II	Type III	Type IV
Vessel Photos				
Vessel Descriptions	Constructed entirely of metal, typically steel. Range from small cylinders up to jumbo tubes.	Mostly metallic, consisting of 2 layers, an inner layer made of metal and an outer partial wrapping of cable or fibrous material, usually glass fiber composite.	A vessel consisting of a metallic liner (usually aluminum) and a fully wrapped composite shell. The composite material bears the majority of the pressure load.	An all-composite constructed vessel, consisting of a polymeric liner (usually high density polyethylene) wrapped with a carbon fiber or carbon/glass fiber composite shell.
Typical Applications	Bulk transport and ground storage of industrial & specialty compressed gases and alternative fuels.	High pressure storage for compressed industrial gases and alternative fuels.	Special applications like medical, paint ball, fire fighting and aerospace along with storage for industrial gases and alternative fuels including on vehicle storage.	Special applications like medical, paint ball, fire fighting and aerospace along with storage for industrial gases and alternative fuels including on vehicle storage.

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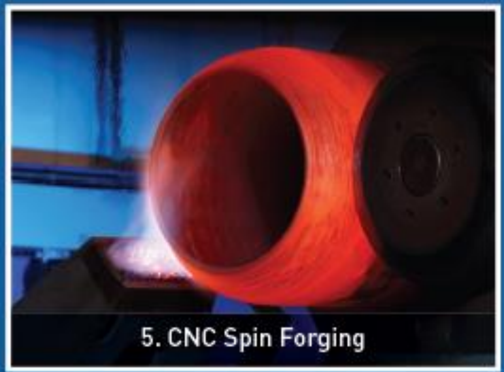
Type I - Manufacturing


1. Raw Steel Pipe Inspection


2. Ultrasonic Examination


3. Interior Grinding and Cleaning


4. Saw Cutting


5. CNC Spin Forging


6. Heat Treating


7. Liquid Quenching


8. NDE and Mechanical Testing


9. CNC Tube Threading

Type I - Manufacturing


10. Hydrostatic Testing


11. Internal Steam Cleaning

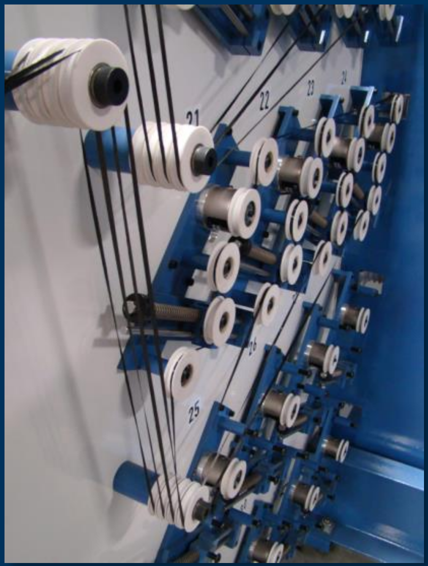

12. Internal Blasting and Cleaning


13. External Shotblasting and Cleaning


14. Robotic Stamp Marking


15. Coating and Finishing

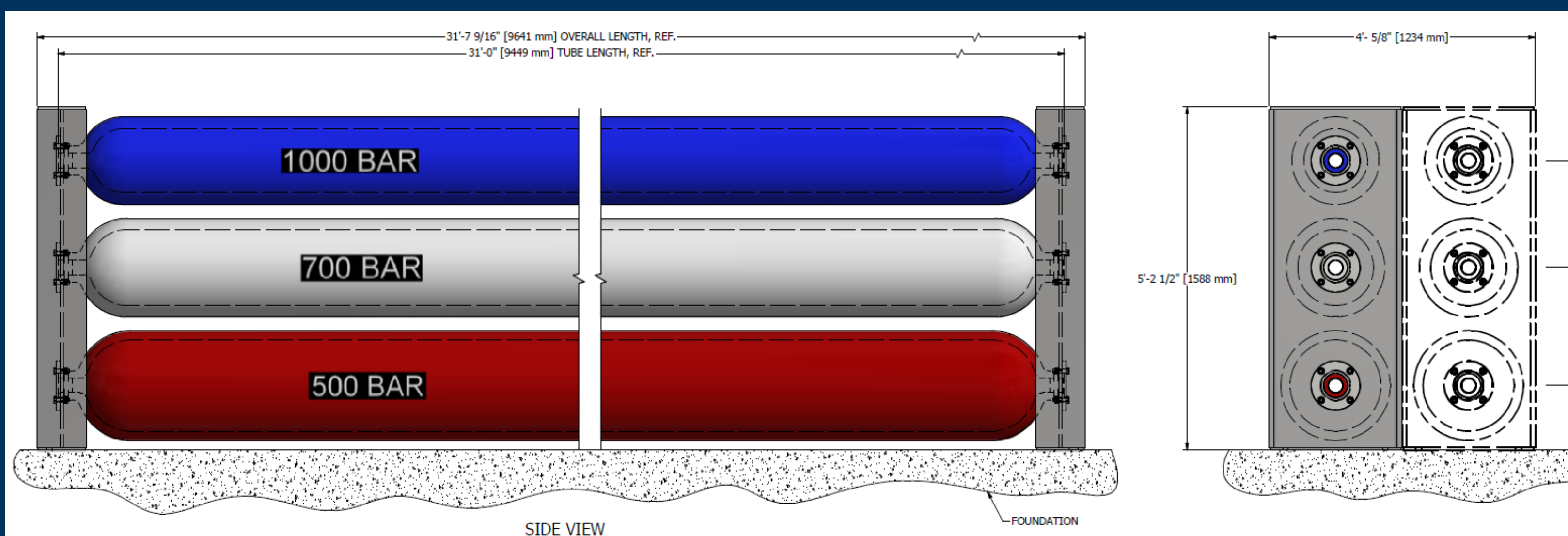
Type II - Manufacturing



Typical H_2 Vessels Sizes and Capacities

ASME Type I – H_2 Refueling Stations with 3-Zone Cascade Module
500 , 700 and 1,034 BAR

Pressure		Length		Water Volume		H2 Weight		H2 Payload	
Psi	Bar	Feet	Meters	Cubic Feet	Liters	Pounds	Kilograms	Cubic Feet	Cubic Meters
7,252	500	31	9.4	41.9	1,189	83	37.7	15,938	451
10,153	700	31	9.4	28.3	803	71.1	32.3	13,663	387
15,000	1,034	31	9.4	19.5	553	62.8	28.5	12,063	342



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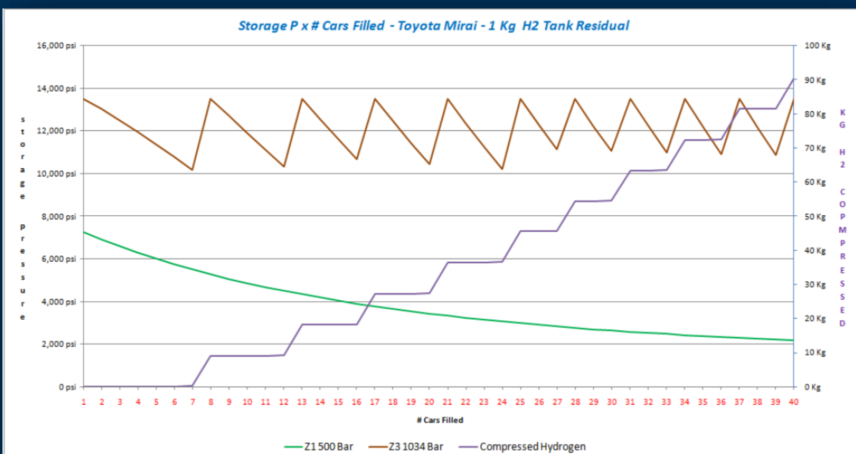
Demonstrated Benefit of Intermediate Zone With Cascading

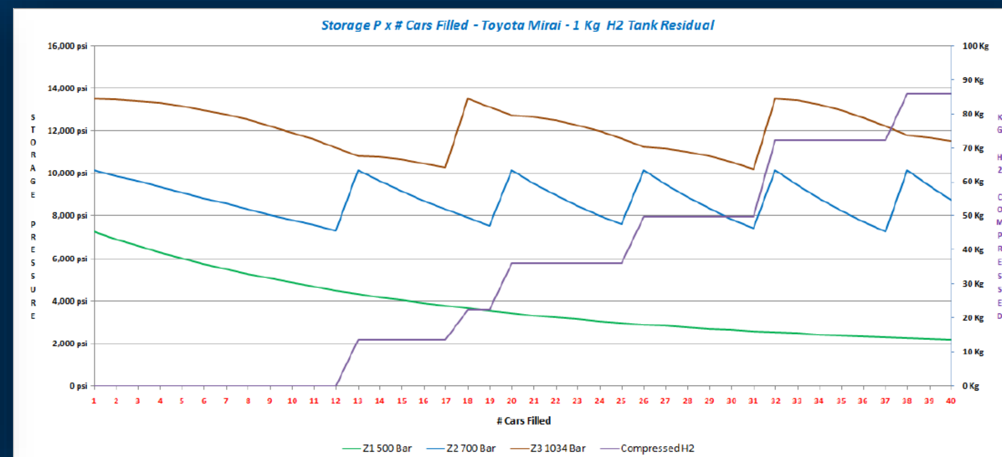
Addition of a 700 BAR middle zone between 500 BAR and 1,034 BAR zones introduces system improvements:

- Allows cascading of more vehicles before compressor starts.
- Reduces min-max pressure range (stress intensity) within a cycle, increasing fatigue life of the pressure vessel.

Cycles without 700 BAR Vessel (1,034 Bar – brown line)



Cycles with 700 BAR Vessel (blue line)



Typical H_2 Vessels Sizes and Capacities

ASME Type I – other H_2 applications

Pressure		Length		Water Volume		H2 Weight		H2 Payload	
Psi	Bar	Feet	Meters	Cubic Feet	Liters	Pounds	Kilograms	Cubic Feet	Cubic Meters
2,800	193	38	11.5	97.6	2,765	88.6	40.2	17,022	482
4,000	275	38	11.5	90.9	2,574	112.2	50.9	21,540	610
5,500	379	38	11.5	57.8	1,638	92.5	42	17,771	503
8,000	551	38	11.5	31.8	902	67.7	30.7	12,995	368

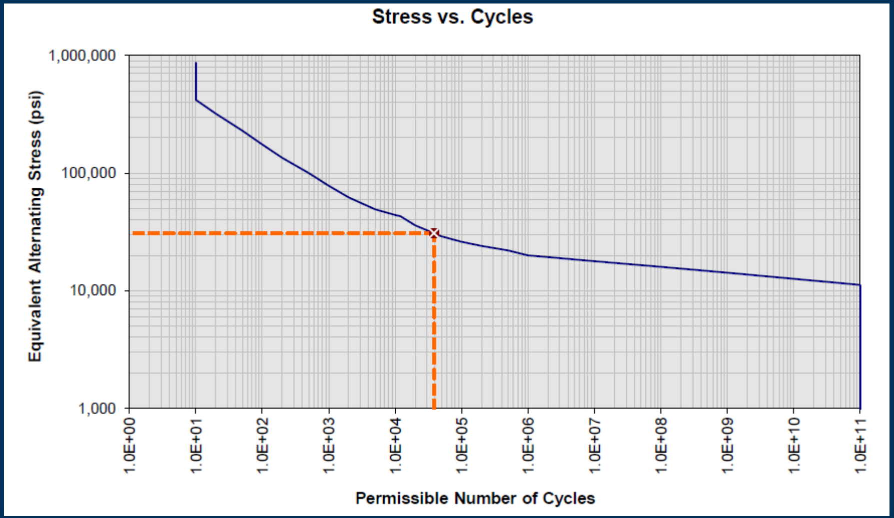
ASME Type II / Composite

Pressure		Length		Water Volume		H2 Weight		H2 Payload	
Psi	Bar	Feet	Meters	Cubic Feet	Liters	Pounds	Kilograms	Cubic Feet	Cubic Meters
15,000	1,034	7	2.1	4.9	140	15.9	7.2	3,055	87
		9.5	2.9	7.1	202	22.9	10.4	4,395	124
		14.5	4.4	11.4	325	36.8	16.7	7,074	200
		18.5	5.6	14.9	423	48	21.8	9,216	261

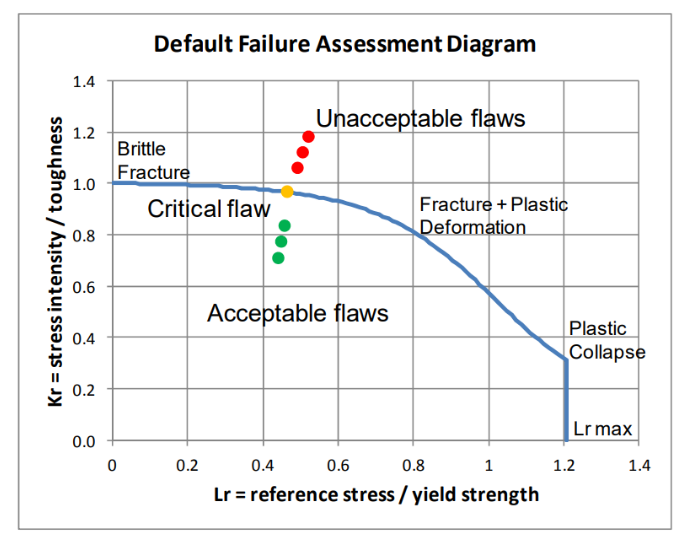
Are Design Codes prepared for the H2-based economy?

ASME Code	Wall Thickness Design Rule	Safety Factor	Specific Rules for H_2?	Fatigue Rules?	Mandatory material test in H_2?
Division 1	Formula	3 App. 22(thicker)	No	No	No
Division 2	Formula	2.4	No	S-N Curves - Air	No
Division 3	Formula or Elastic-Plastic	Diameter ratio / thick shell theory	Yes - KD-10	Fracture Mechanics - FAD	Yes

Div.2 S-N Curve



Div.3 FAD

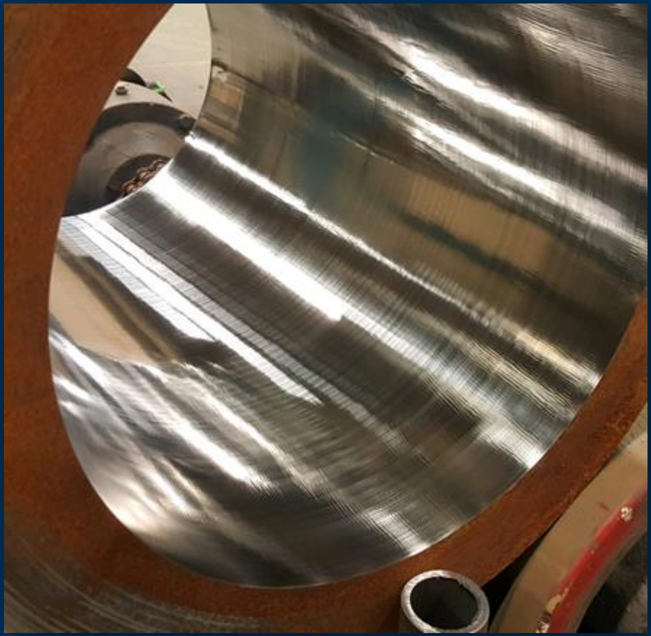


Are Design Codes prepared for the H2-based economy?
USA, Canada, Europe, Japan, ISO

Standard and code	country	Design Rule	Service life (Number of cycle)	Special requirements for H_2 gas
AD 2000-Merkblatt	Germany	Prescriptive formula for minimum wall thickness	S-N approach	Considered through a safety factor of 10 on the number of cycles
EN 13445	EC	Prescriptive formula for minimum wall thickness	S-N approach	H_2 isn't considered
ASME Section VIII, Div. 1/2	USA	Prescriptive formula for minimum wall thickness	S-N approach	H_2 isn't considered
CODAP	France	Prescriptive formula for minimum wall thickness	S-N approach	Recommendations : max UTS ≤ 950 MPa (Low alloyed Steels)
ASME Section VIII, Div.3	USA	Prescriptive formula for minimum wall thickness or elastic-plastic analysis (according to KD-2)	Yes, depending on fracture mechanics calculations (according to KD-10)	Yes, through KD-10 article Crack propagation
KHK S 0220	Japan	Follows the approach of ASME section VIII, Divs. 1, 2, 3	Design life based on fatigue analysis based on S-N curves and crack growth analysis similar to KD-10	H_2 isn't considered
ISO11114-4	International	Not for design.	-	Selection of materials for Hydrogen use (3 methods)
CSA-CHMC1	Canada	Not for design.		Selection of materials for Hydrogen use (fatigue tests)

H_2 Storage Vessel - ASME Div.3
Type I - 15,000 psi Monobloc Design

- *First in the world. Product innovation achieved through NDE and surface finish techniques + material processing*
- *Life is not limited to 20 years. Life extension possible*
- *Demonstrated ability to detect small initial flaw sizes = longer life*
- *Fully meets the unique requirements of ASME Section VIII Division 3 and Article KD 10 for H_2 storage*

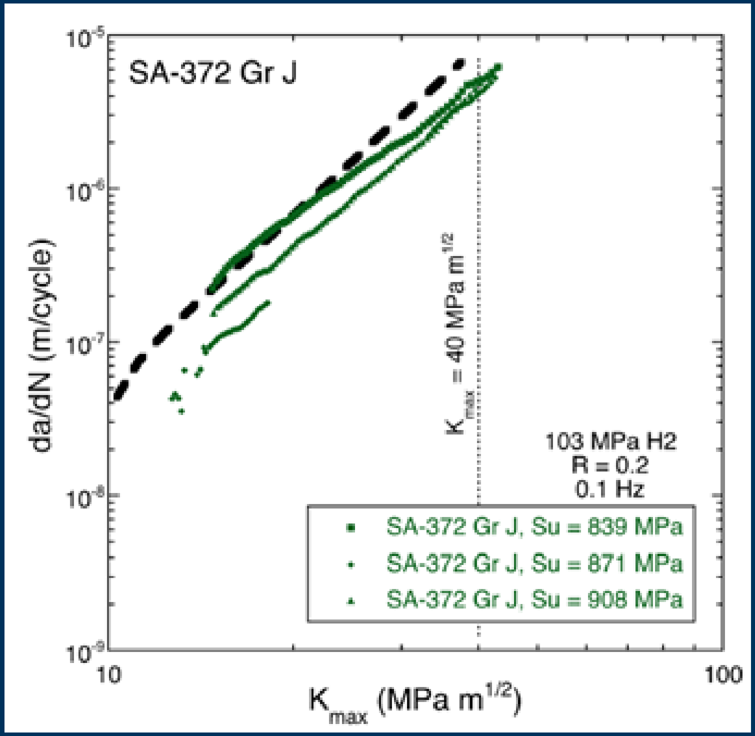


Inside surface condition is critical to achieve detection of smaller notches / longer life.

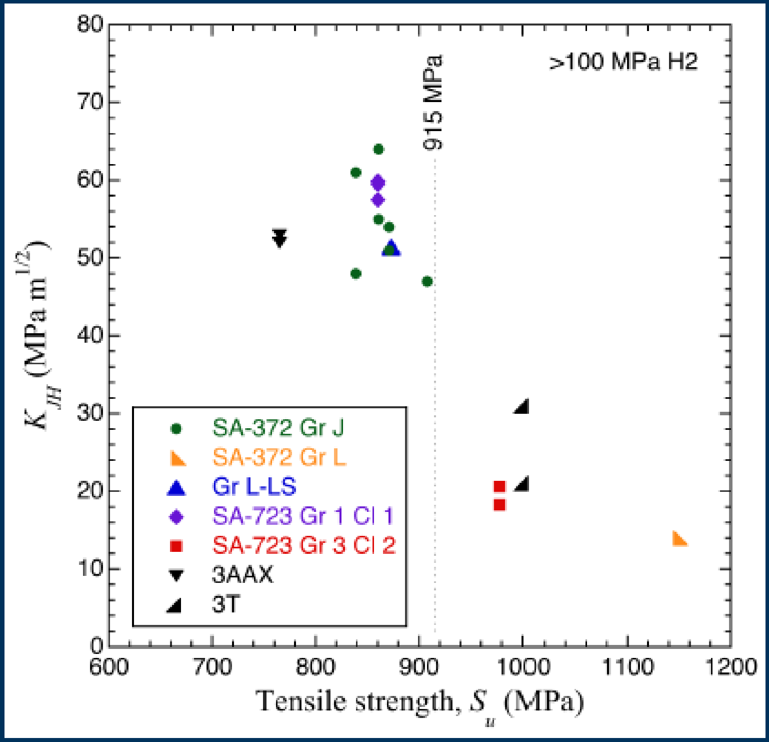
Code Material Requirements
(Test material in H_2 environment at high pressure)

No evidence of transition to stage III for K_{max} up to 40 MPa $m^{1/2}$ in SA-372 Gr J steels

Measured K_{JH} values for SA 372 J in 103 MPa H_2 is > 40 MPa $m^{1/2}$ requirement



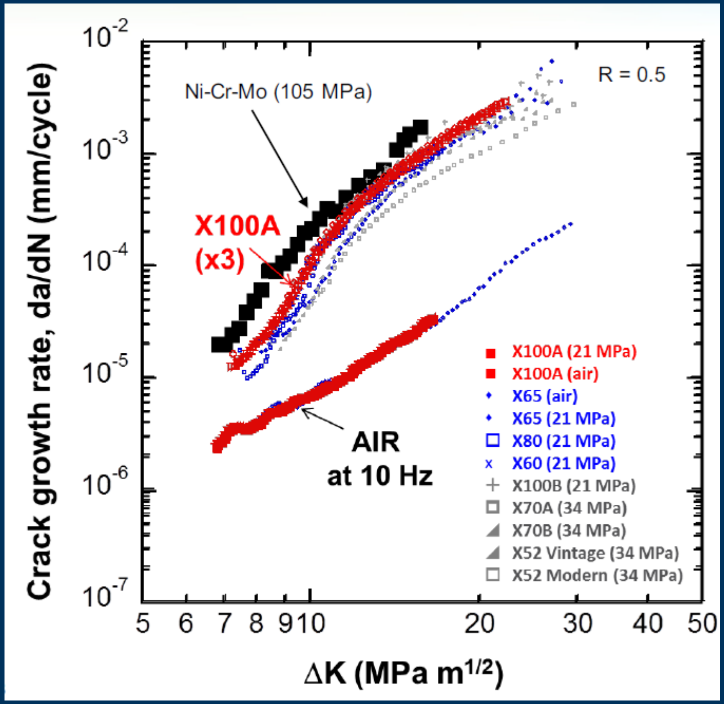
Fatigue crack growth rate of SA-372 Gr. J steel in gaseous hydrogen 103 MPa
SANDIA2018_8867PE



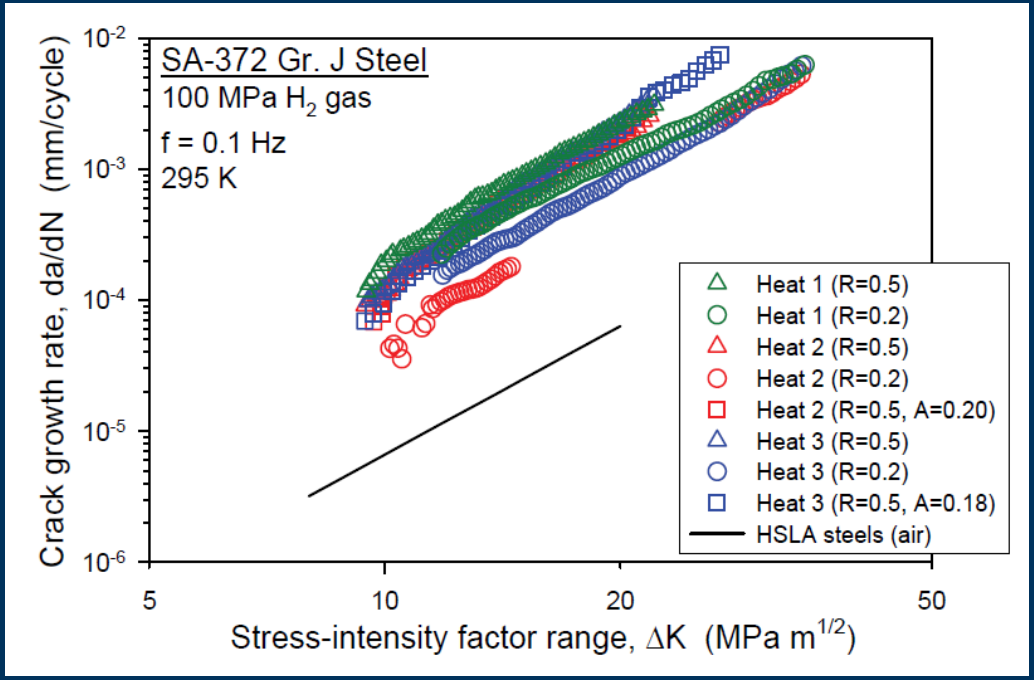
Fracture Resistance (K_{JH}) as a function of tensile strength (S_u) for different pressure vessel steels
PVP2019-93907

Fatigue Crack Growth Rate Hydrogen x Air

Hydrogen accelerates fatigue crack growth rates by 1.5 to 2 orders of magnitude relative to crack growth rates in air environment.

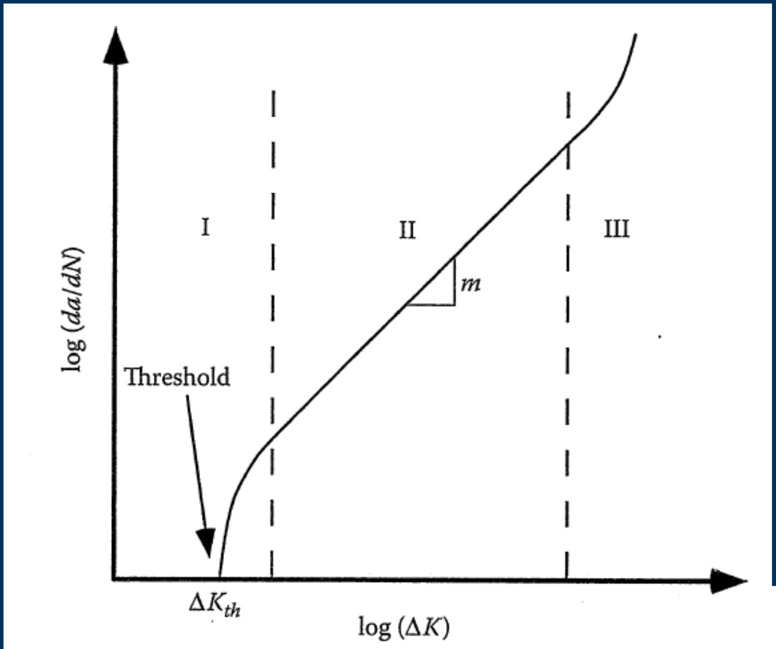


Fatigue Crack Growth Rate for low Strength Pipeline Steels
Sandia SAND2017-8212 PE

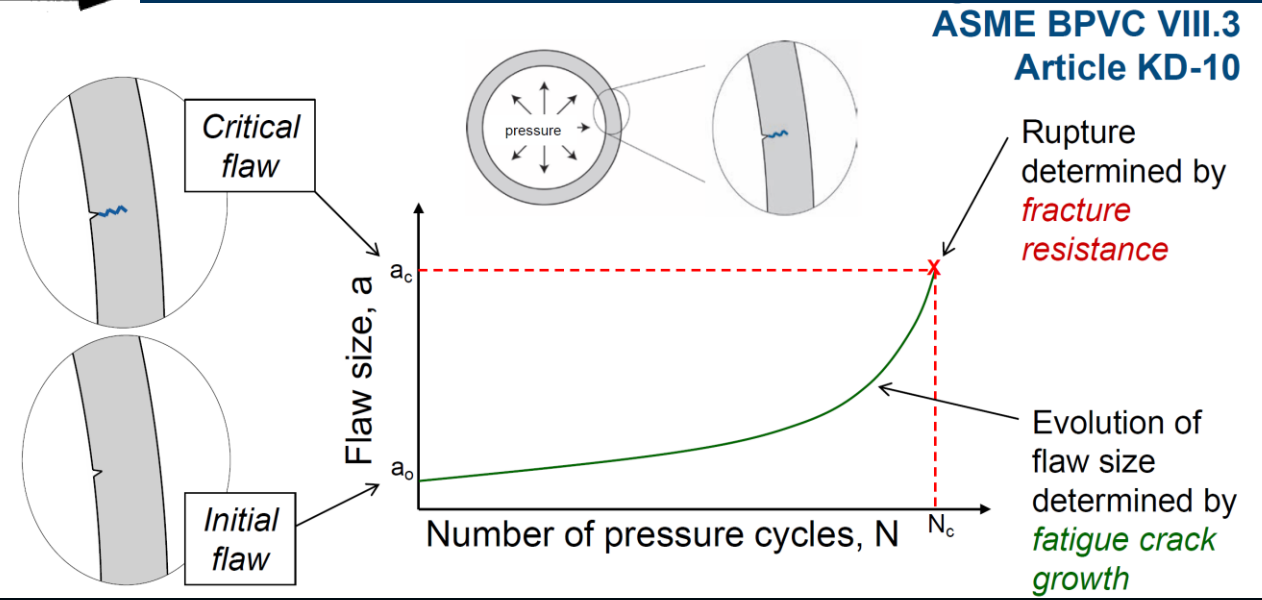


Fatigue crack growth rate relationships for SA-372 GR. J steel in 100 MPa hydrogen gas
PVP2013-97455

Fracture Mechanics
Stages of Fatigue Crack Growth

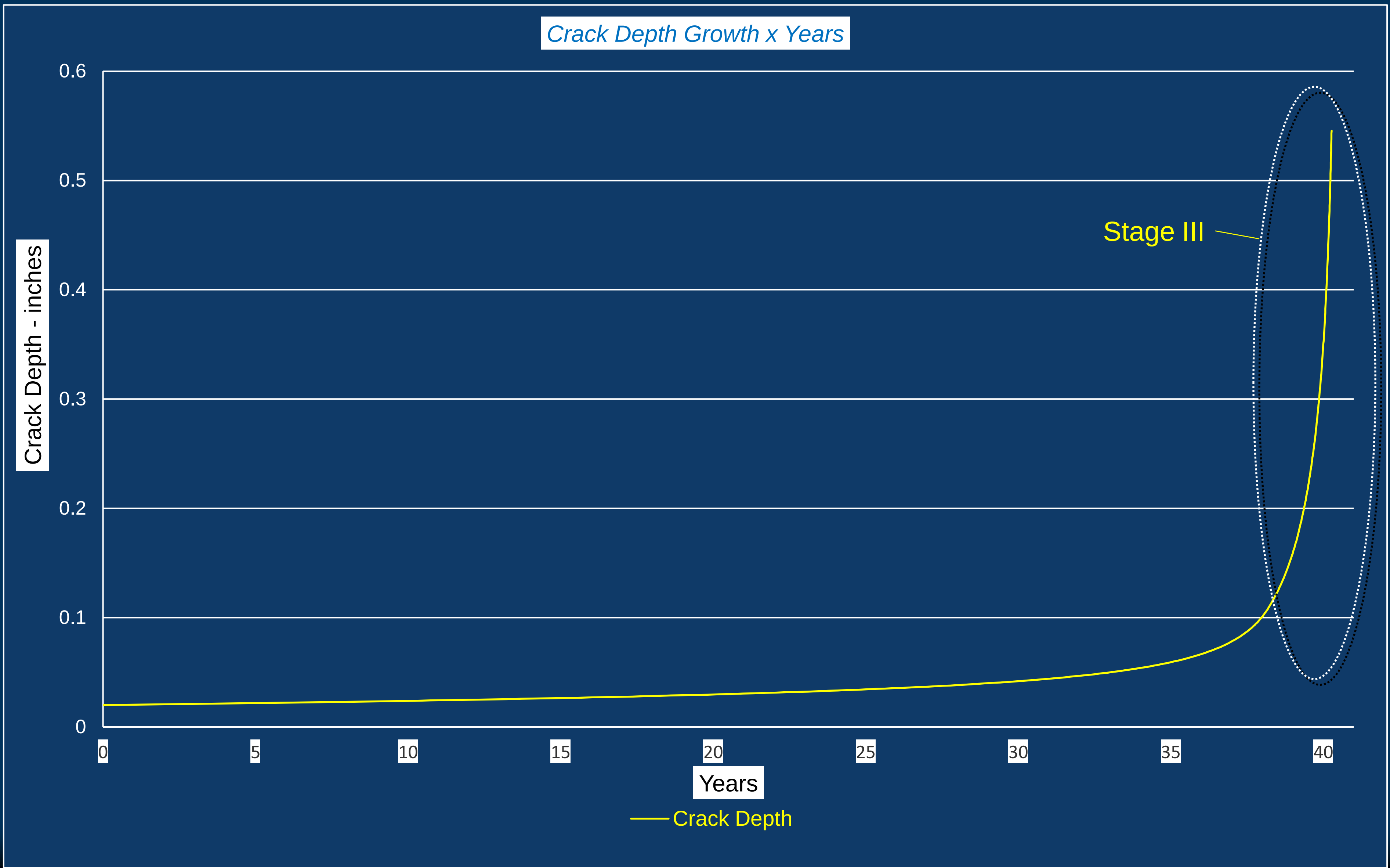


Typical fatigue crack growth behavior in metals:
Sigmoidal or “S”-shaped curve contains three distinct regions with low, intermediate and high ΔK levels
T.L. Anderson 4th Ed.

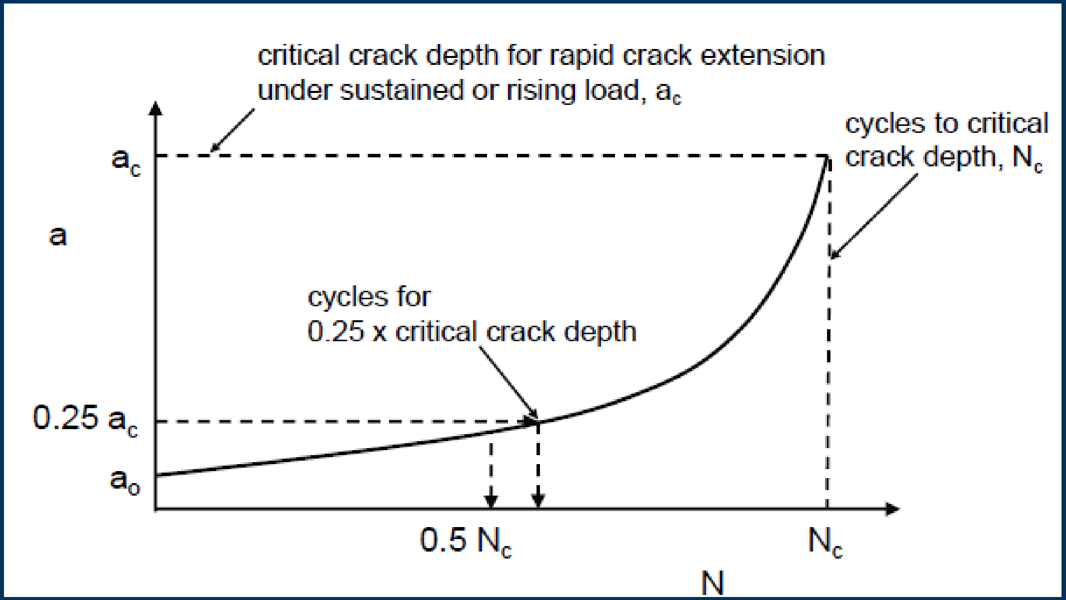


Sandia SCS005

Fracture Mechanics
Stages of Fatigue Crack Growth



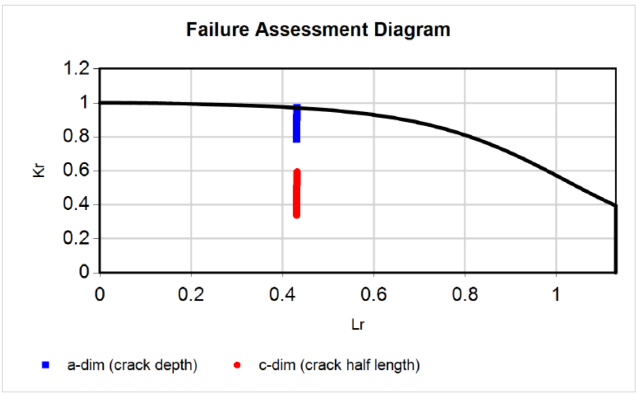
Fracture Mechanics
ASME Div.3 approach to establish cycle life

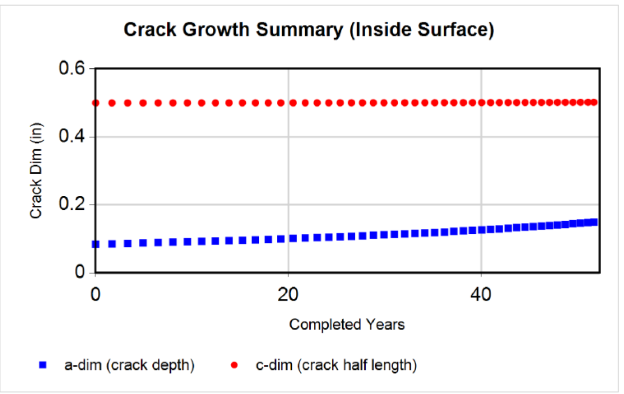


ASME DIV.3 Life Estimation

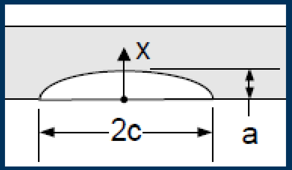
PVP2013-97455

Sample calculation – Inside surface crack



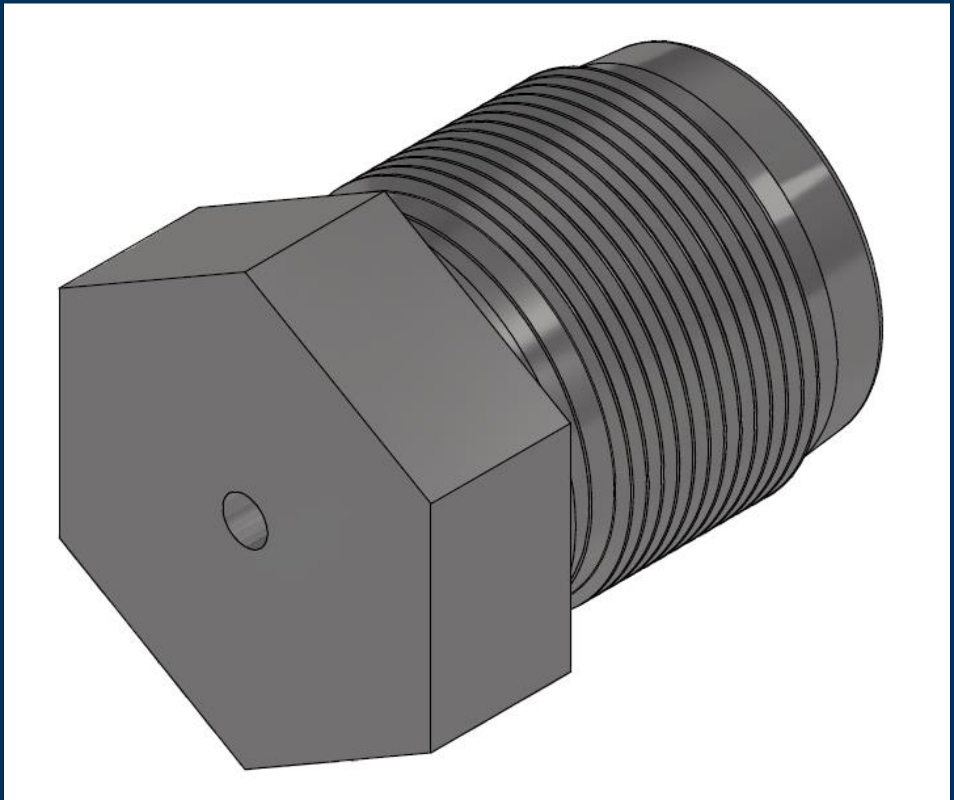


Inside surface crack

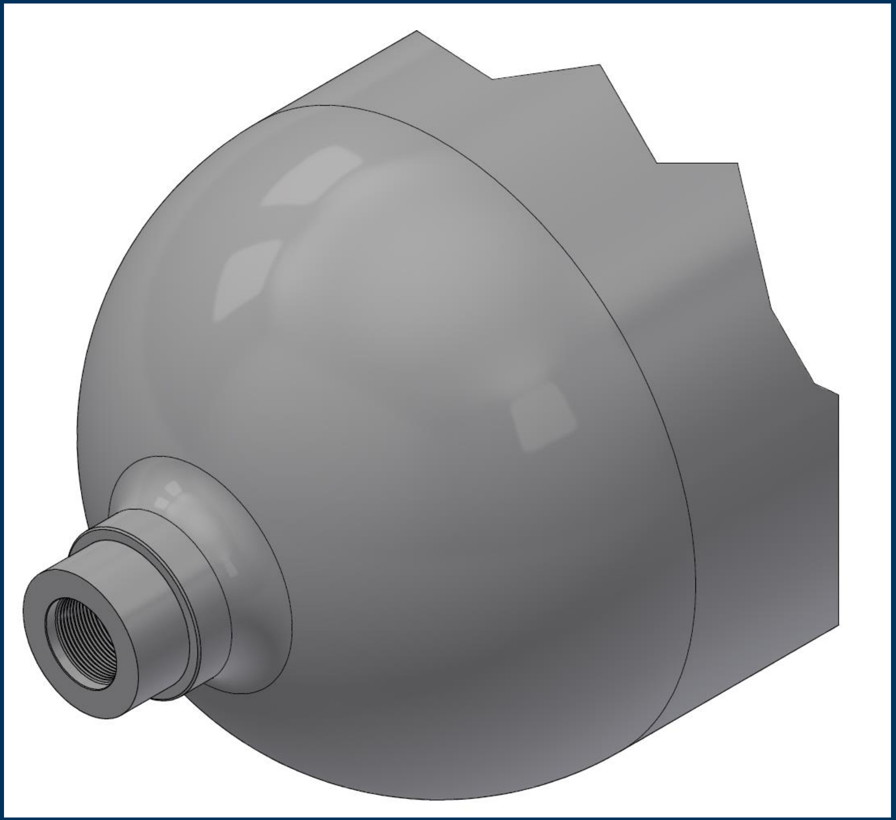


Finite Element Analysis - Model

Plug

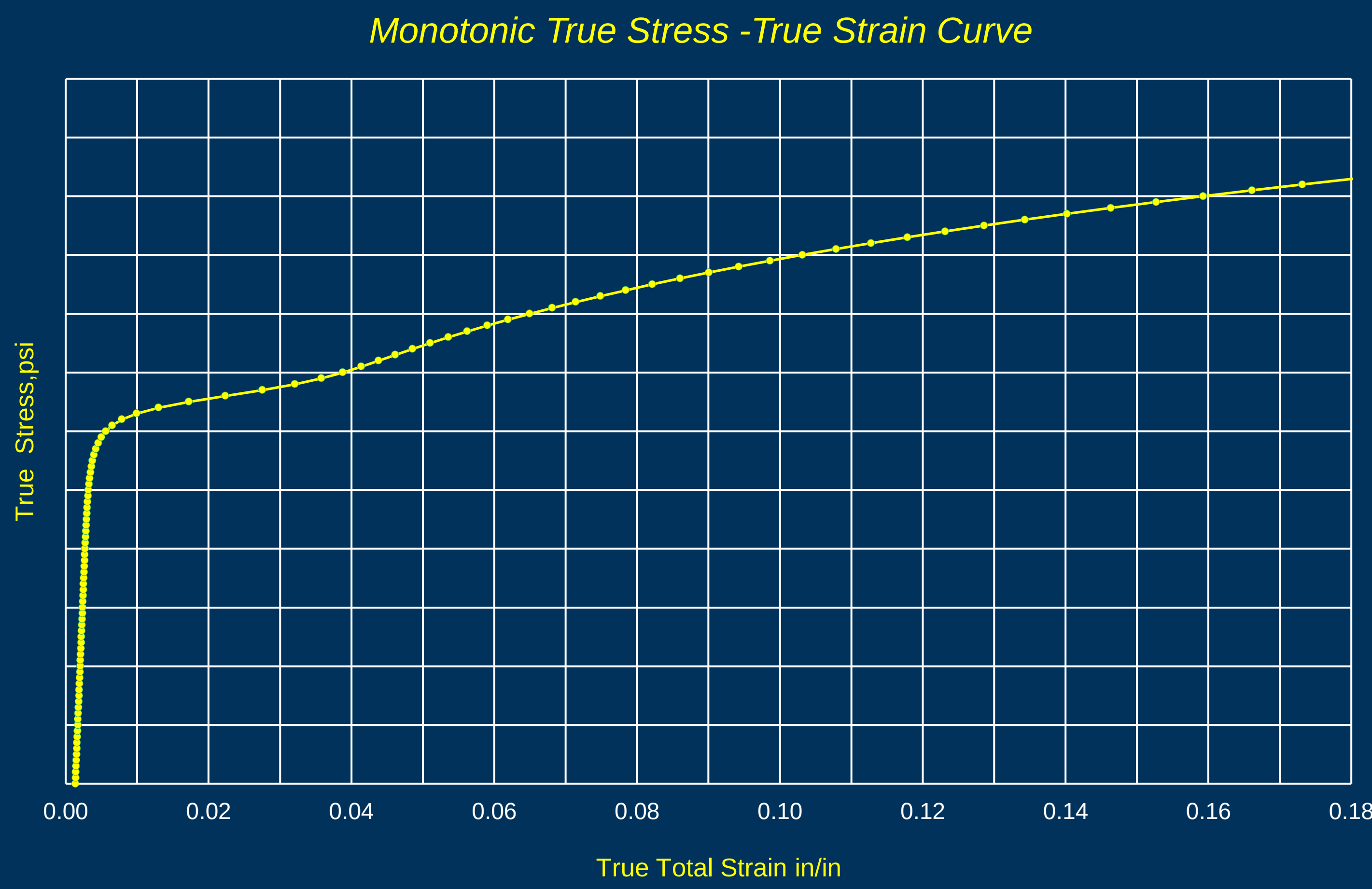


Vessel



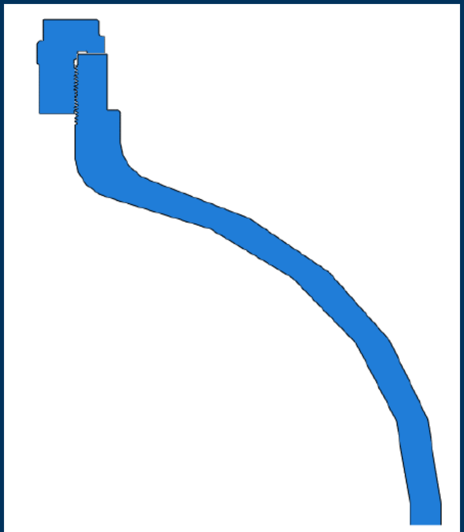
Cyclic Curve Generation

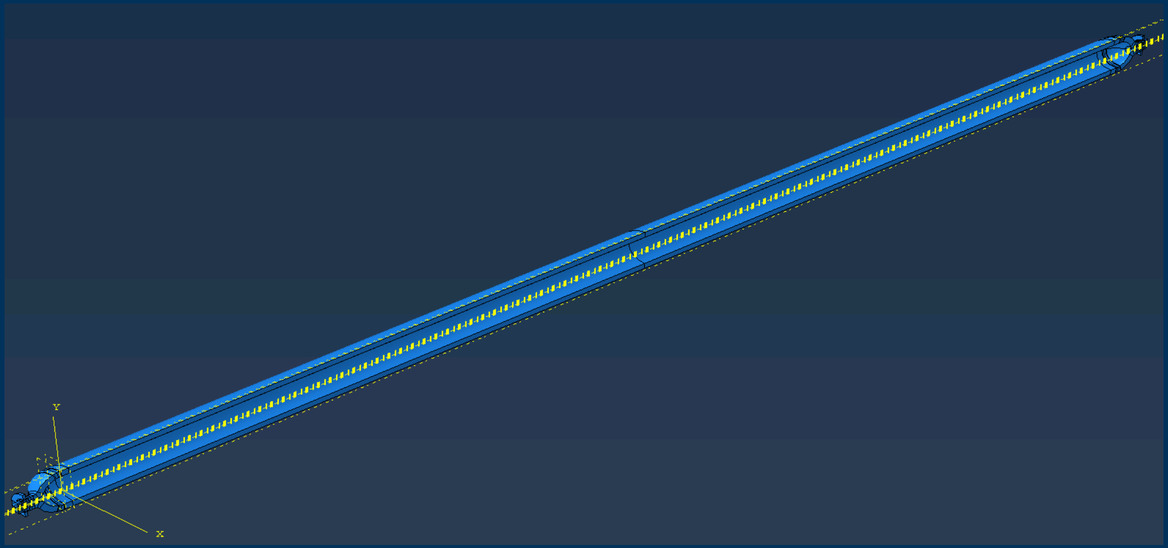
True Stress / True strain curve generated for material modeling in cyclic service, considering strain hardening and large displacement theory

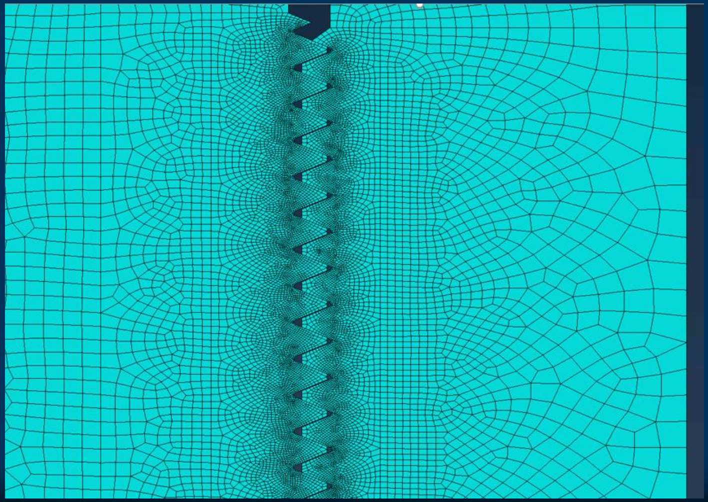


Finite Element Analysis - Model

Model Type = Axisymmetric or 3D depending on the analysis type







Mesh is refined to capture local plastic strain that may occur in areas of high stress concentration such as thread roots

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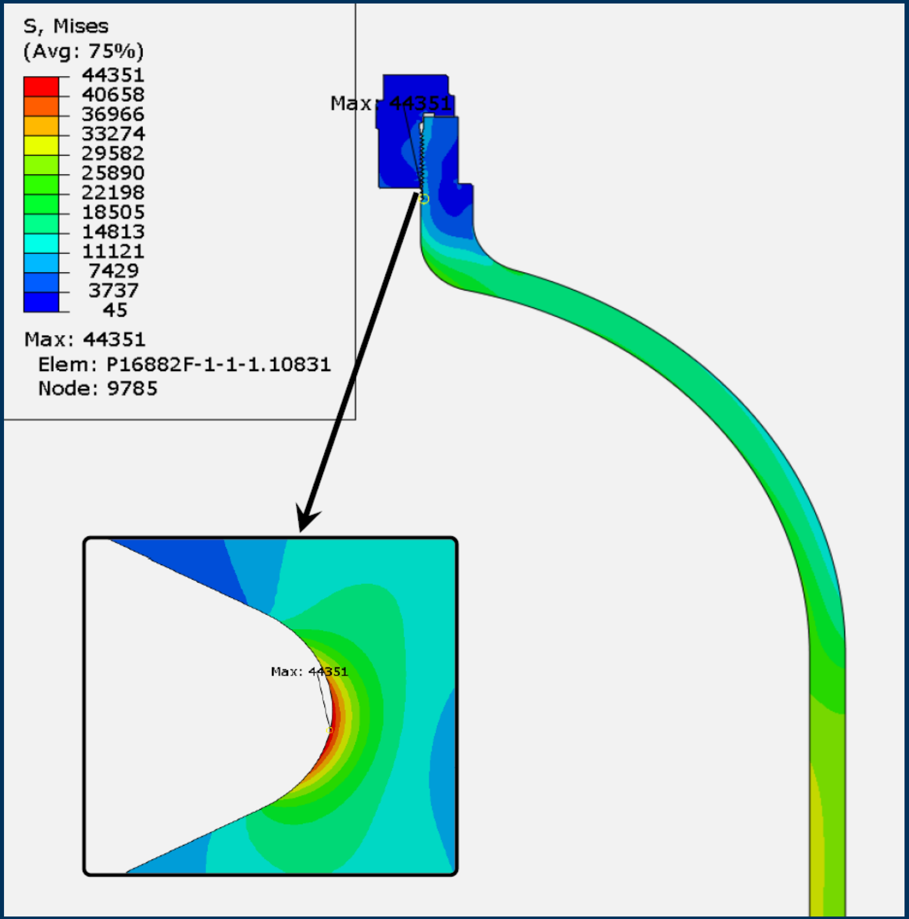
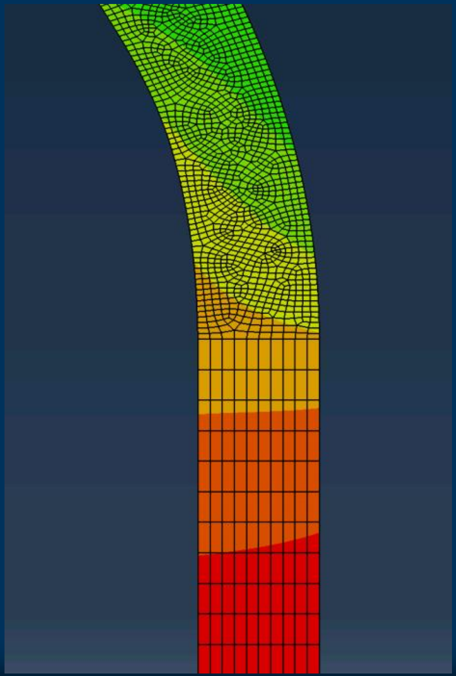
Finite Element Analysis - Results



Output from FEA used for:

- Elastic-Plastic Analysis
- Demonstrate protection against local failure (limit strain damage)
- Ratcheting evaluation (progressive incremental inelastic deformation or strain)
- Cyclic stress / Fracture mechanics
- Global loading (to check for external loads / events such as seismic, wind etc)



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Thank You

Questions?

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