

# Advanced Martensitic Stainless Steels for Carbon Capture and Storage



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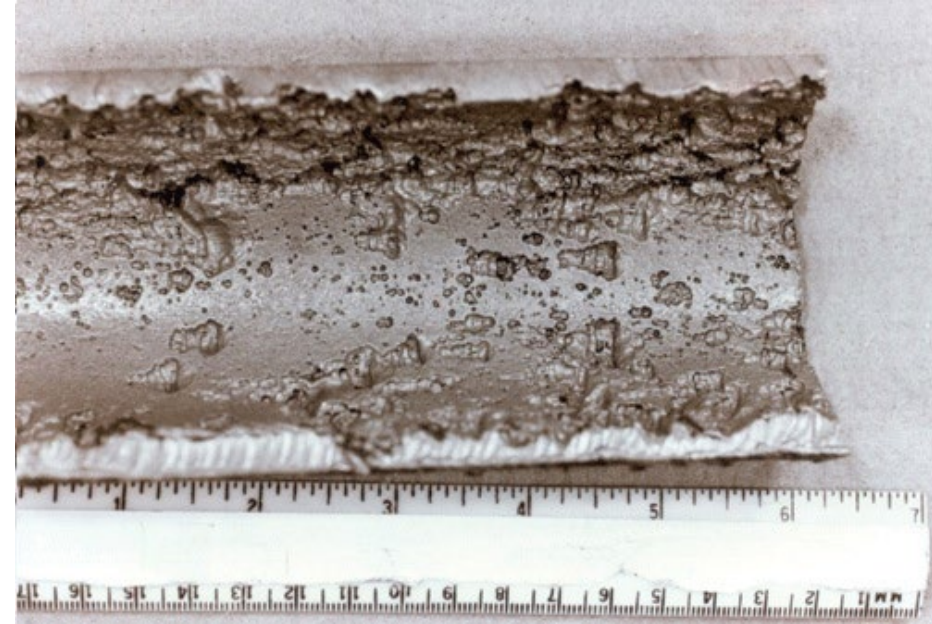




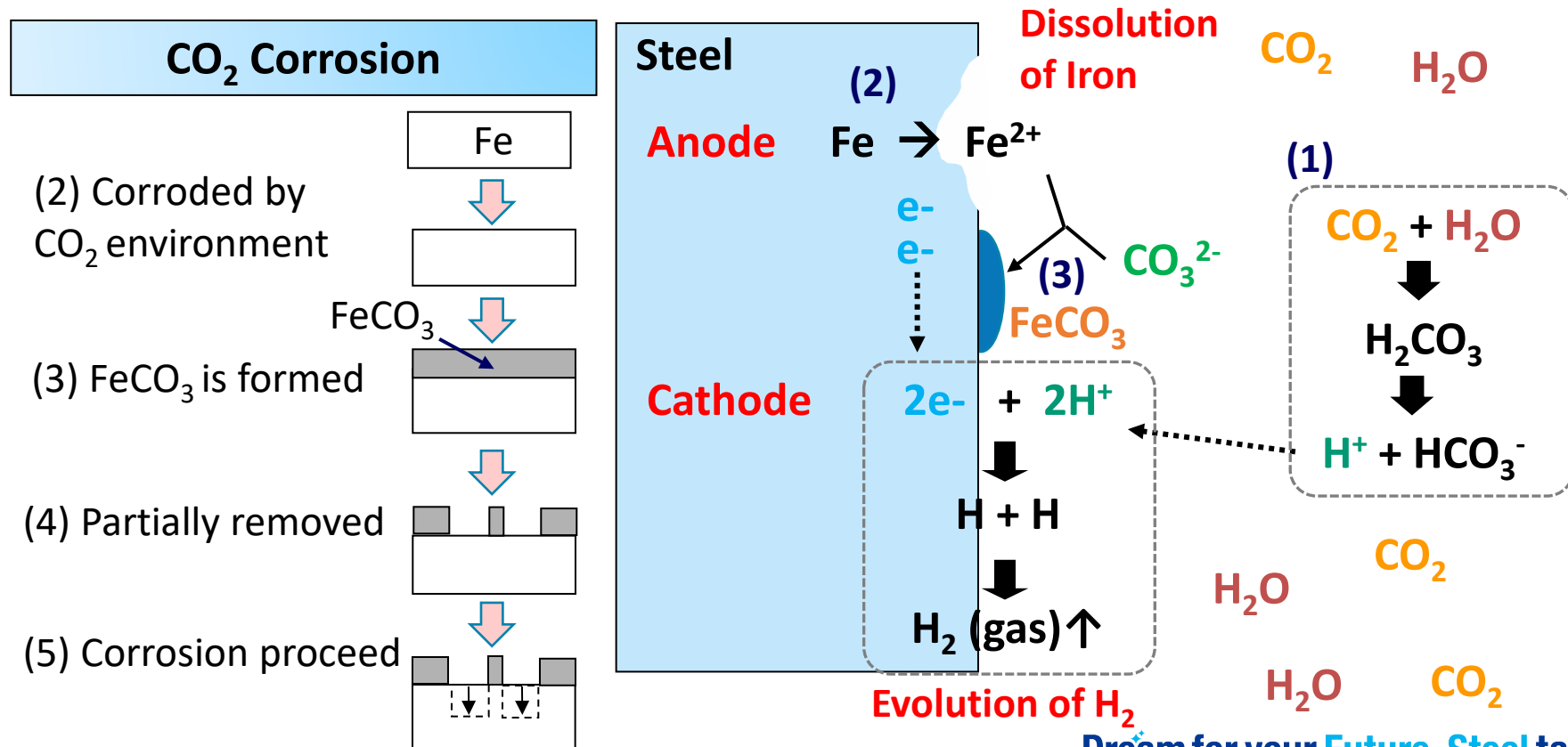
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# CO<sub>2</sub> Corrosion Resistance of 13+%Cr

# Typical CO<sub>2</sub> Corrosion

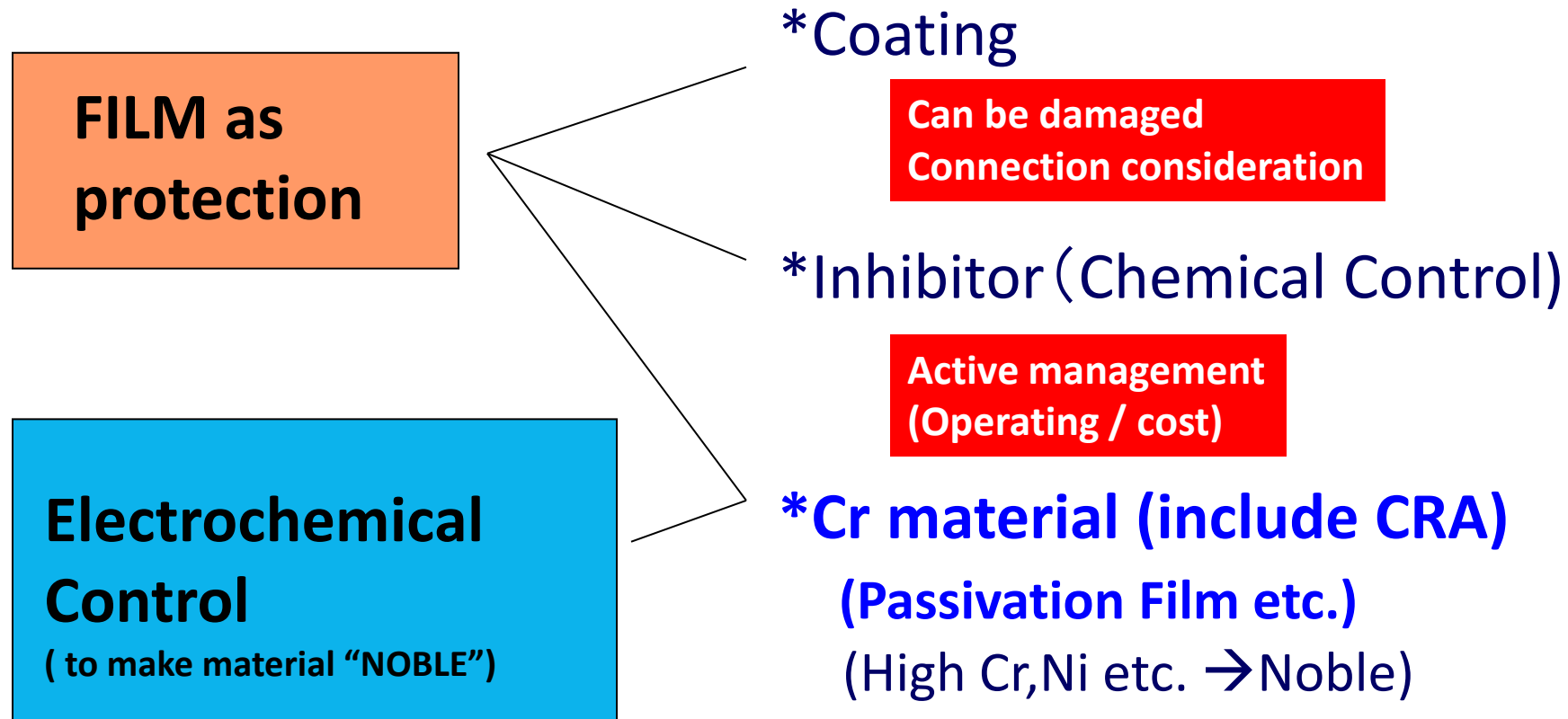


- CO<sub>2</sub> corrosion phenomenon is defined as Anodic Reaction.
- (1) CO<sub>2</sub> gas makes low pH in solution.
- (2) Fe is corroded into Fe<sup>2+</sup> at low pH.
- (3) FeCO<sub>3</sub> is formed on surface
- (4) FeCO<sub>3</sub> is partially removed by flowing production fluid.
- (5) Corrosion proceeds only on peeled-off area.

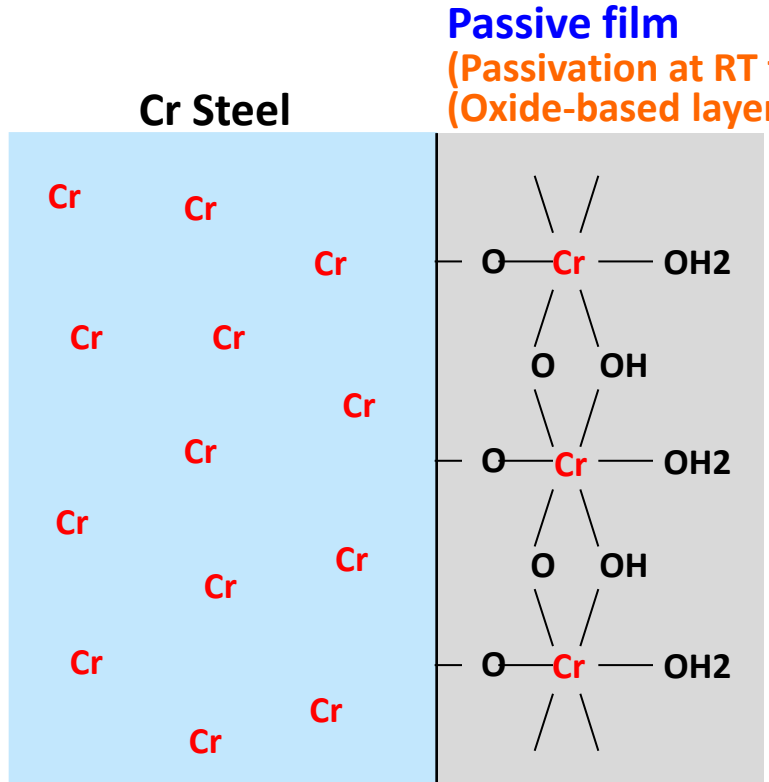


# Method to have Corrosion Resistance

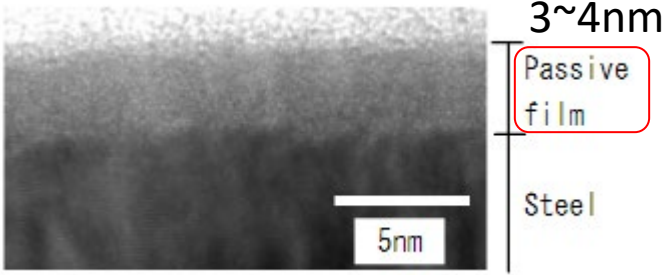
- There are several way to prevent from corrosion.
- Cr material is the one of method to have Corrosion resistance.



**Cr in steel makes Cr-Oxide/Hydroxide on surface. (Passive film)**



direct observation of **passive film** of stainless steel



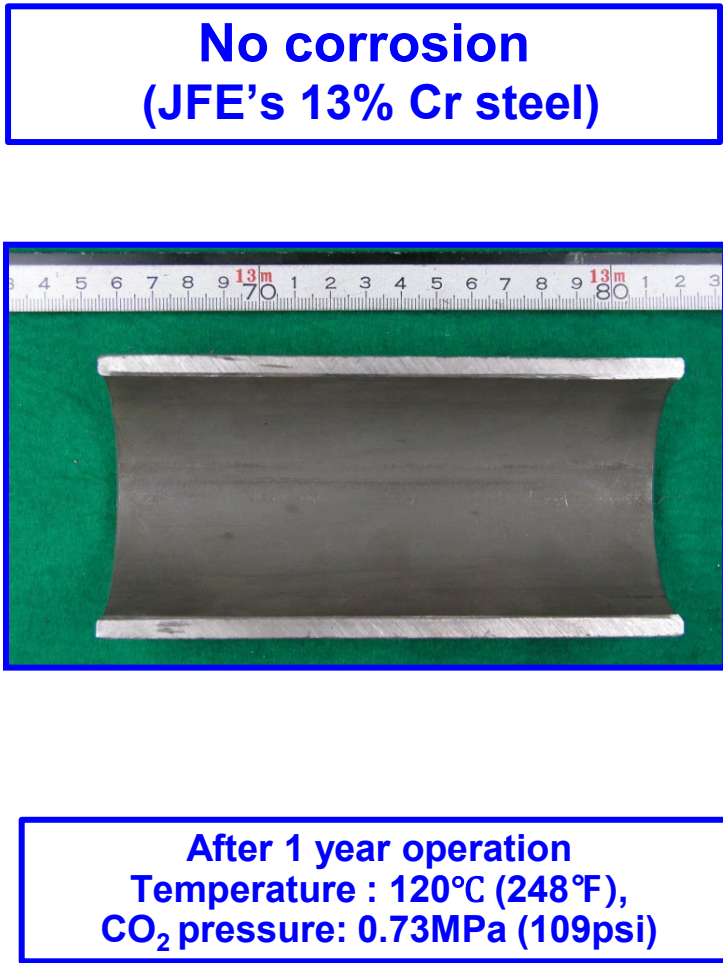
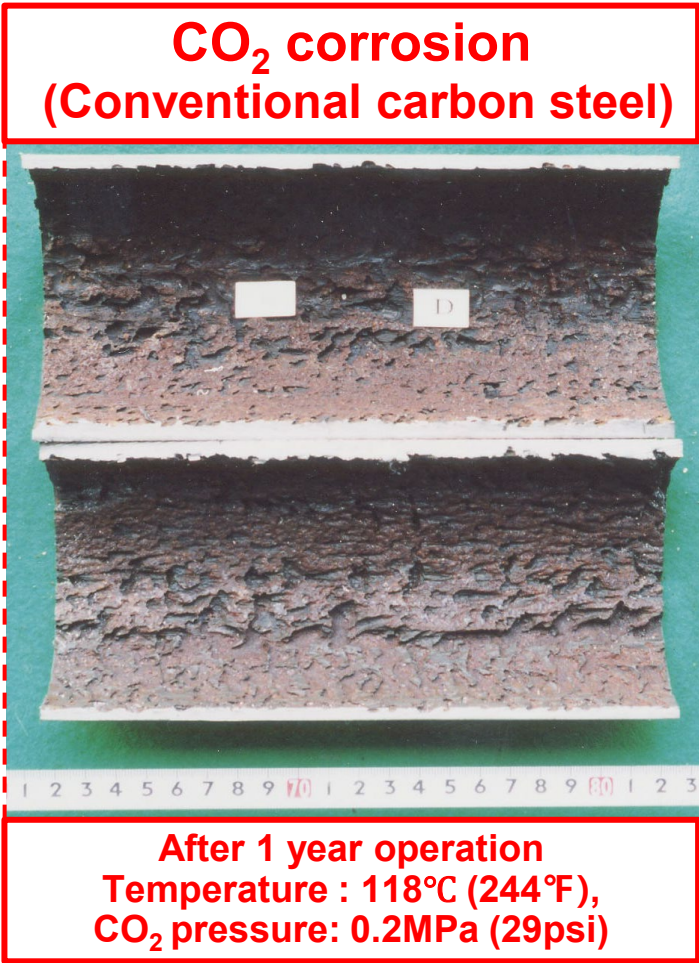
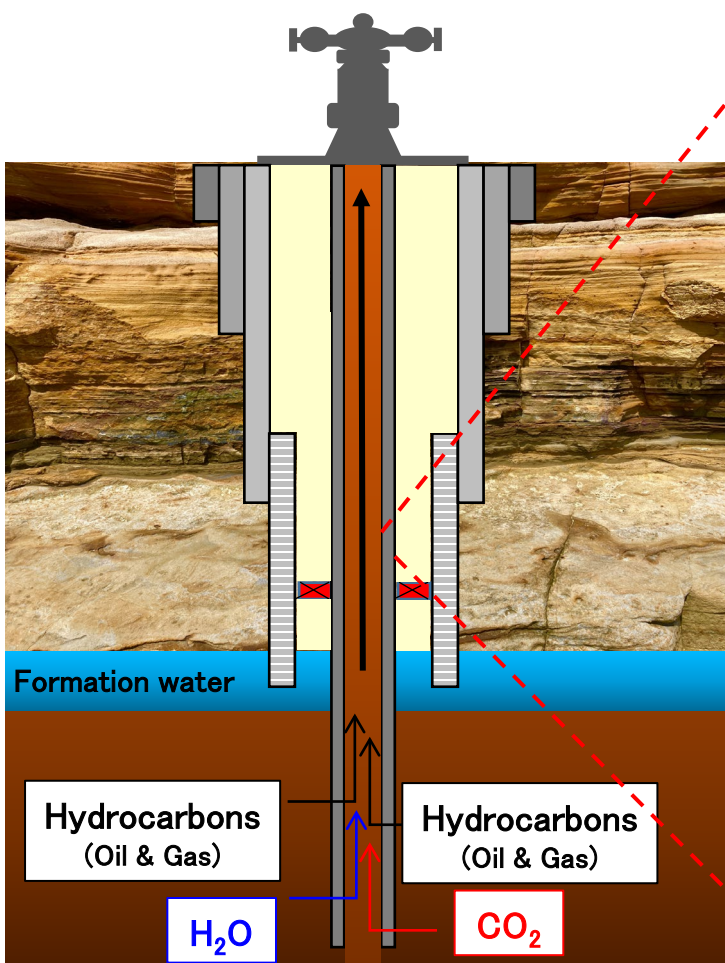
SUS304

Observation condition:  
 - FIB sample preparation  
 - Cs-corrected TEM  
 E. Hamada et al. @JFE: Corrosion Sci, 52 (2010) pp3851-3854.

- **Thin Layer (Passivation : nm @ ambient)**
- **Strong & Tight protective layer**
- **Even if it's removed, Cr in the steel naturally re-makes protective layer, provided that the protective layer is stable in the condition.**



- CO<sub>2</sub> corrosion of the tubing in hydrocarbon and CO<sub>2</sub> injection wells could happen.
- 13+% Cr steel have better CO<sub>2</sub> corrosion resistance compared to carbon steel.





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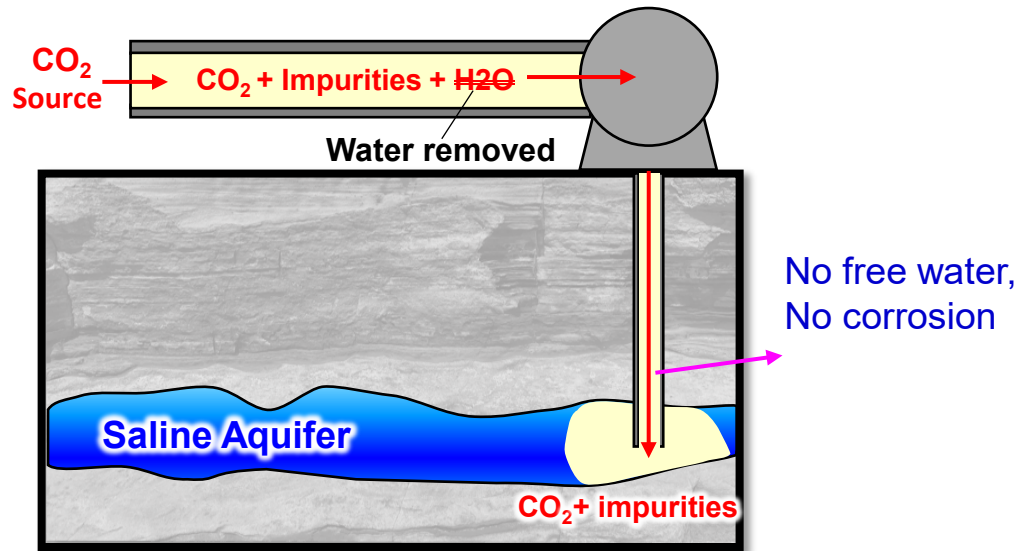
# Corrosion in CCS environment



# CO<sub>2</sub> injection tubing risks contact with formation water during shut-in Autoclave simulates shut-in conditions for corrosion testing

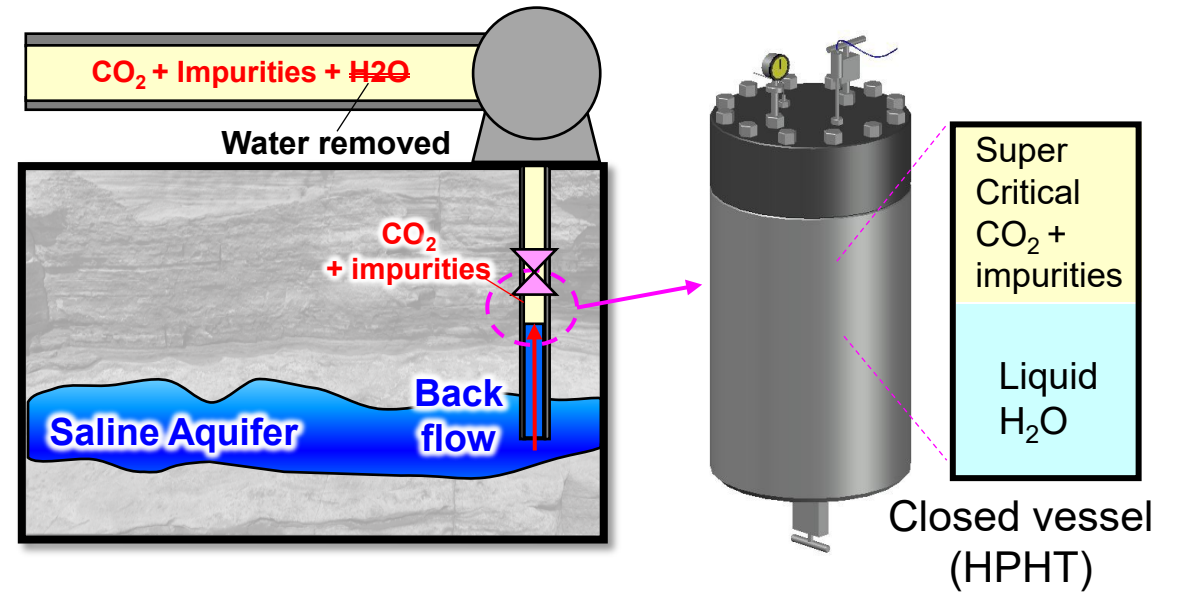
## [During Injection]

- ✓ CO<sub>2</sub> flow and supply
  - ✓ No water
- ⇒ No corrosion

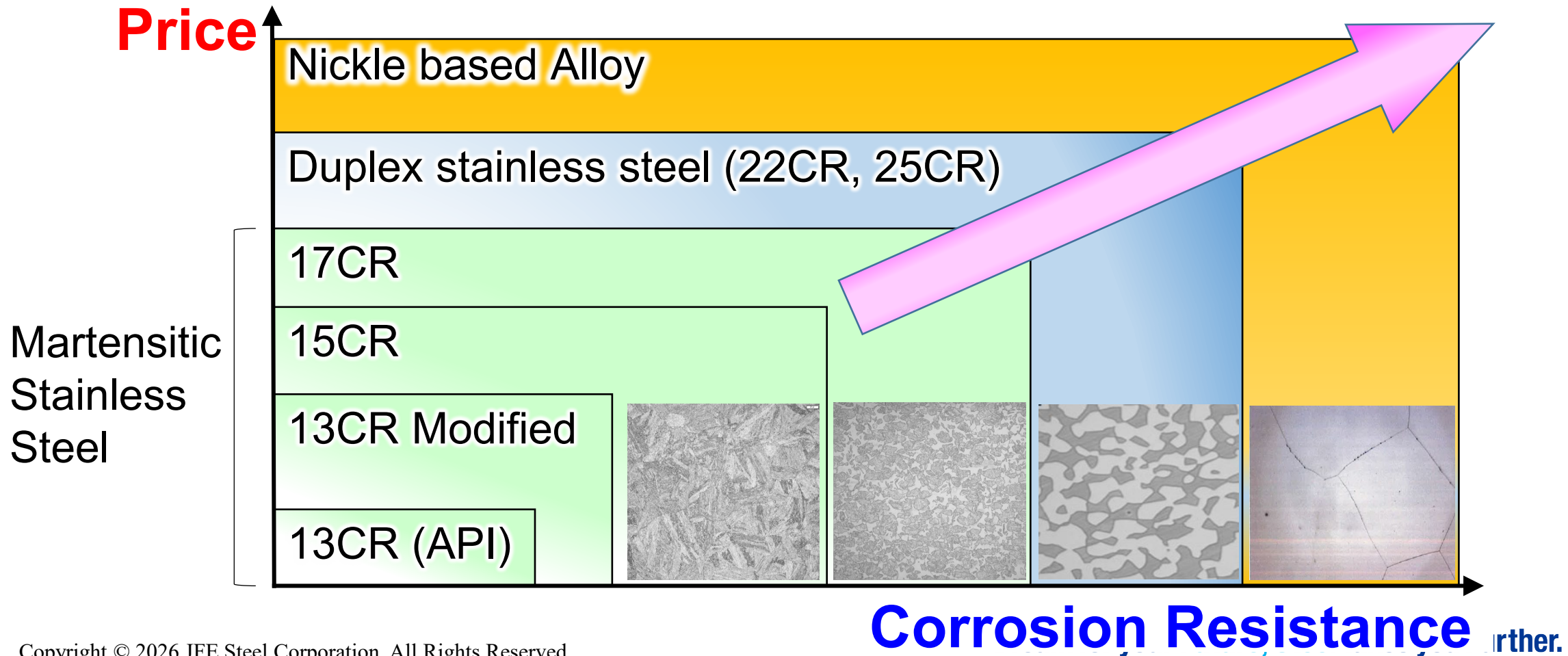


## [During shut-in]

- ✓ No CO<sub>2</sub> flow nor supply
  - ✓ Formation water
- ⇒ Corrosion risk shall be evaluated using autoclave

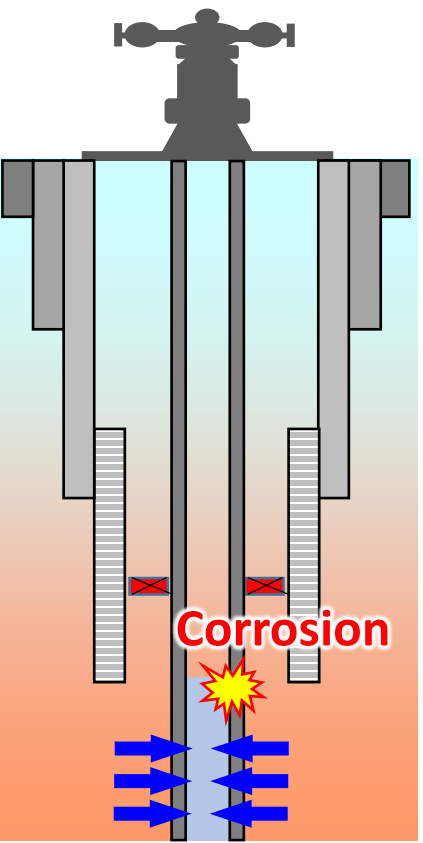


**Important to select appropriate material to reduce the initial cost.**





- **Several impurities** might be included in CO<sub>2</sub> depends on its source.
- **Appropriate evaluations are needed** for each risk.



Element	Effect	evaluation / Criteria	Test method	CO <sub>2</sub> Source					
				Oil & Gas production	Power plant	DAC, Biomass, Ethanol	Cement	Blue H <sub>2</sub>	Hub & Cluster
SO <sub>2</sub>	<b>General Corrosion</b>	Mass loss / Corr. Rate $\leq 0.127\text{mm/y}$	Crevice Corrosion Test		✓		✓		✓
NO <sub>2</sub>					✓		✓		✓
O <sub>2</sub>	<b>Pitting Risk</b>	Crevice depth / 25 $\mu\text{m}$ as per ASTM G48		✓	✓			✓	
H <sub>2</sub>	<b>Hydrogen Embrittlement</b>	Crack / No crack	Four-Point Bend					✓	✓
H <sub>2</sub> S				✓					✓

## 1. Corrosion Test

- Materials, Test Method and conditions
- Results (Corrosion rate, Crevice corrosion, SCC susceptibility)

## 2. Domain Maps

- How to make?
- 17Cr domain map examples

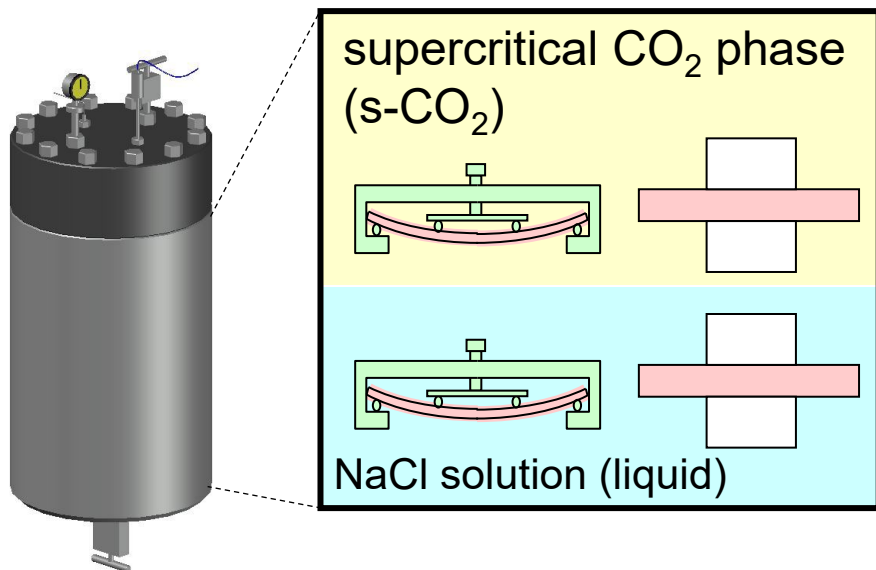


## Materials used for corrosion tests

Sample ID	UNS No.	C	Cr	Ni	Mo	Others	PREN	SMYS(ksi)
13CR	S42000	0.20	13.0	0.22	-	-	13.0	80
Mod. 13CR	S41426	0.01	12.5	6.0	2.2	0.09Ti	19.8	95
15CR	S42625	0.03	14.7	6.3	2.0	1Cu added	21.7	125
17CR	S42825	0.03	16.7	3.9	2.5	1Cu and 1W added	27.2	110
S25CR	S32760	0.02	25.3	7.2	3.7	0.54Cu-0.54W-0.25N	42.3	80

For comparison

$$PREN = Cr + 3.3 \times (Mo + 0.5W) + 16N$$



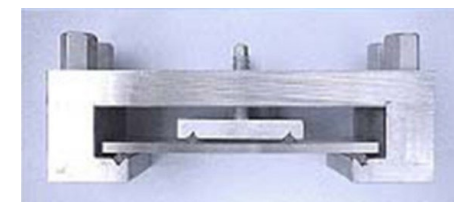
### [Test Method]

#### 1. Four-Point Bend Test

**Specimens: L115 x W15 x T5 mm**  
**STD: NACE TM0316-2016 AYS100%**  
**Number of Tests: 2 for each material**

#### 2. Crevice Corrosion Test

**Specimens: L50 x W20 x T3 mm**  
**STD: ASTM G48**  
**Load: 3.0 N/mm<sup>2</sup>**  
**Number of Tests: 2 for each material**



Four-Point Bend specimen



Crevice fixtures (PTFE)



# Testing condition

JFE

No.	CO <sub>2</sub> specs or expected CO <sub>2</sub> source	Temp. (°C/°F)	Pressure (MPa/psi)	Amount of impurities					Cl <sup>-</sup> (mg/L)
				SO <sub>2</sub>	NO <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub>	
				(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	
1	AMPP Guide 21532 (2023)	90 / 194	20 / 2900	10	10	20	10	10000	121,200
2-1		90 / 194	20 / 2900	10	10	20	10	10000	180,000
2-2		24 / 75							
3		120 / 248	40 / 5800	10	10	20	10	10000	65,000
4	ISO 27913 (2016) (modified)	120 / 248	40 / 5800	50	50	50	20 (modified)	7,500	65,000
5	Oil & Gas	120 / 248	40 / 5800	0	0	0	25	0	65,000
6-1 6-2 (90 days)	Oil & Gas with oxygen	90 / 194	20 / 2900	0	0	68	244	0	19,600
7-1	Blue hydrogen	120 / 248	40 / 5800	0	0	0	200	20,000	65,000
7-2		24 / 75							
8	O <sub>2</sub> (50 ppm)	120 / 248	40 / 5800	0	0	50	0	0	65,000
9	SO <sub>2</sub> , NO <sub>2</sub> (50 ppm each)	120 / 248	40 / 5800	50	50	0	0	0	65,000



- Higher Cr concentration gives lower corrosion rate.
- Mod.13Cr or higher grades have enough general corrosion resistance.

No.	CO <sub>2</sub> specs or expected CO <sub>2</sub> source	Corrosion rate (mm/y)									
		13Cr		Mod. 13Cr		15Cr		17Cr		S25Cr	
		s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid
1	AMPP Guide 21532 (2023)	-	-	0.0014	0.1023	0.0020	0.0048	0.0007	0.0021	0.0005	0.0003
2		-	-	0.0016	0.0233	0.0023	0.0056	0.0010	0.0026	-	-
3		-	-	0.0054	0.0090	0.0025	0.0059	0.0009	0.0014	-	-
4	ISO 27913 (2016) (modified)	-	-	0.0023	0.0314	0.0021	0.0037	0.0005	0.0008	0.0010	0.0003
5	Oil & Gas	-	-	0.0007	0.0038	0.0002	0.0028	0.0002	0.0013	-	-
6-1	Oil & Gas with oxygen	-	-	-	0.007	-	0.006	-	0.002	-	-
6-2		-	-	-	0.0013	-	0.0010	-	0.0003	-	-
7	Blue hydrogen	-	-	0.0003	0.0096	0.0002	0.0055	0.0	0.0021	-	-
8	O <sub>2</sub> (50 ppm)	0.109	0.266	0.015	0.002	0.007	0.003	0.003	0.001	-	-
9	SO <sub>2</sub> , NO <sub>2</sub> (50 ppm each)	0.012	0.214	0.004	0.010	0.003	0.002	0.002	0.002	-	-

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: Lower than 0.127 mm/y (5 mils/y)

: Larger than 0.127 mm/y (5 mils/y)





- **Crevice corrosion occurred on most of the specimens (even S25Cr)**
- **17Cr steel was acceptable in all conditions when judged as per ASTM G48.**

No.	CO <sub>2</sub> specs or expected CO <sub>2</sub> source	Maximum depth of corroded part (µm)									
		13Cr-80		Mod. 13Cr-95		15Cr-125		17Cr-110		S25Cr-80	
		s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid
1	AMPP Guide 21532 (2023)	-	-	35	34	36	21	12	18	7	9
2		-	-	53	40	39	18	23	12	-	-
3		-	-	57	110	11	110	13	No depth	-	-
4	ISO 27913 (2016) (modified)	-	-	36	38	34	24	No localized corrosion	3	11	9
5	Oil & Gas	-	-	35	12	13	No localized corrosion	No localized corrosion	No localized corrosion	-	-
6-1	Oil & Gas with oxygen	-	-	-	26	-	45	-	20	-	-
6-2		-	-	-	21	-	16	-	8	-	-
7	Blue hydrogen	-	-	27	No localized corrosion	No localized corrosion	No localized corrosion	No localized corrosion	No localized corrosion	-	-
8	O <sub>2</sub> (50 ppm)	99	284	78	No localized corrosion	29	No localized corrosion	No localized corrosion	No localized corrosion	-	-
9	SO <sub>2</sub> , NO <sub>2</sub> (50 ppm each)	No localized corrosion	62	No localized corrosion	105	30	No localized corrosion	No localized corrosion	No localized corrosion	-	-

No localized corrosion: No localized corrosion was observed.

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No depth: Localized corrosion was observed, but depth of the part was not detected by optical microscope.

: No localized corrosion or No depth     : Depth larger than 25 µm (1 mil)

: Depth lower than 25 µm (1 mil)



• **Maximum depth of crevice corrosion did not increase by test duration.**  
 ⇒ **Shallow crevice-corrosion (depth < 25 μm) would be stable and harmless.**

No.	CO <sub>2</sub> specs or expected CO <sub>2</sub> source	Test duration (days)	Maximum depth of corroded part (μm)	
			17Cr	
			s-CO <sub>2</sub>	liquid
6-1	Oil & Gas with oxygen	30	-	20
6-2		90	-	8

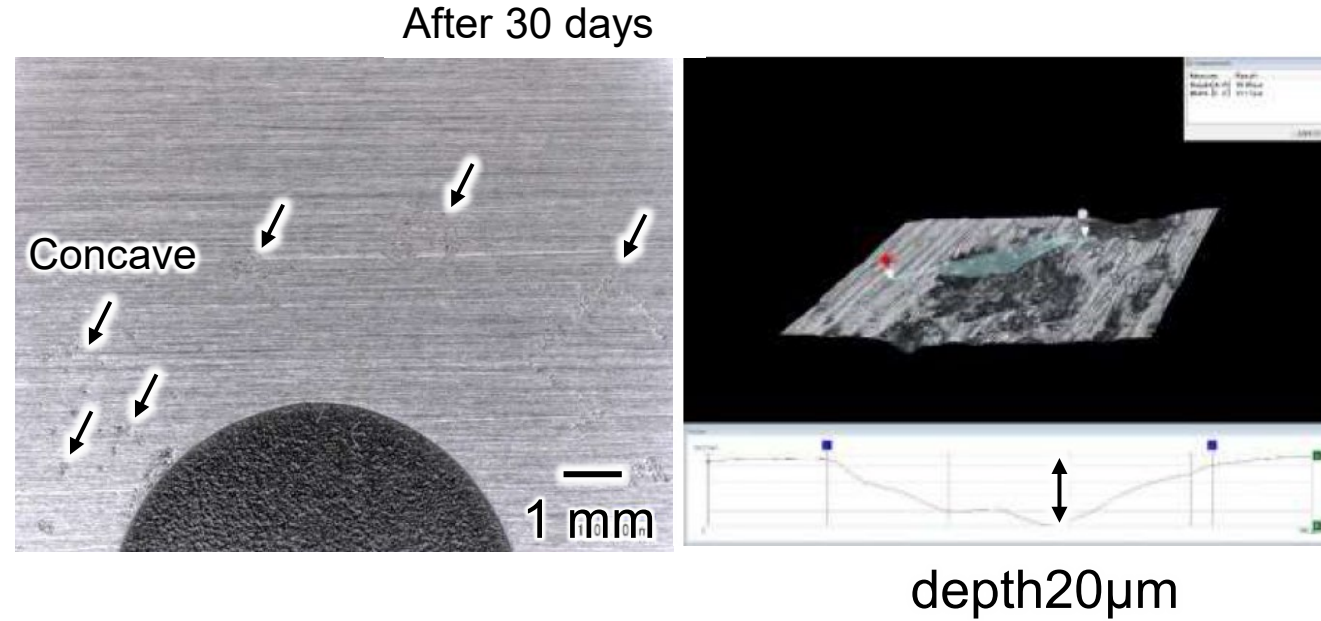
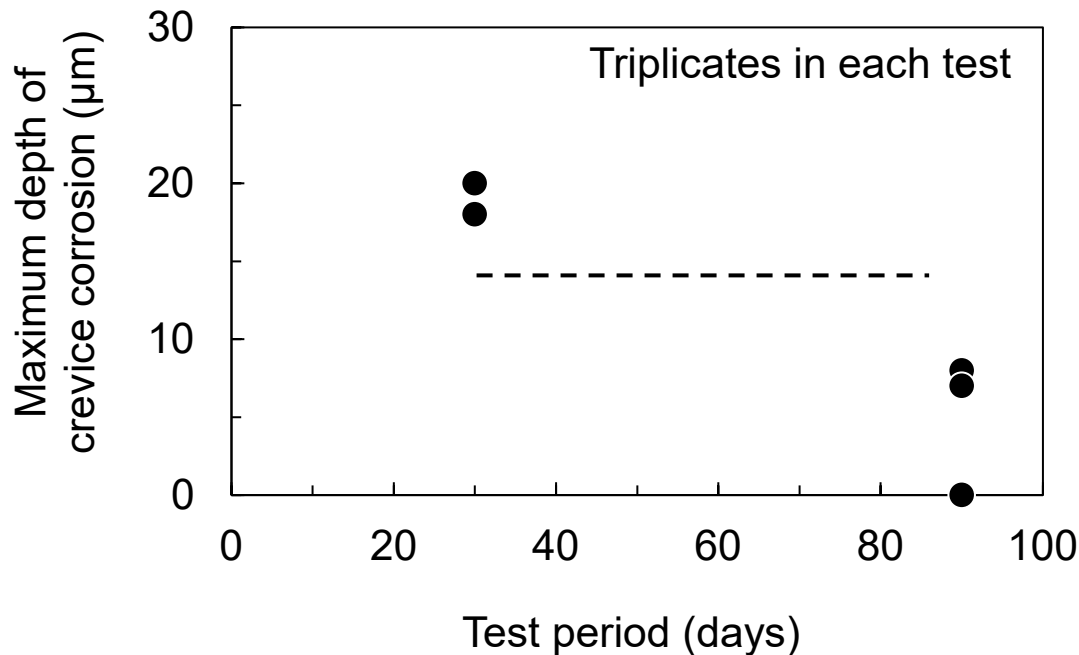


Fig. Microscope images of the crevice corrosion after 30 days test.



• **17Cr steel passed all conditions.**

No.	CO <sub>2</sub> specs or expected CO <sub>2</sub> source	Occurrence of cracking on FPB specimens									
		13Cr		Mod. 13Cr		15Cr		17Cr		S25Cr	
		s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid	s-CO <sub>2</sub>	liquid
1	AMPP Guide 21532 (2023)	-	-	No crack	Cracking	Cracking	Cracking	No crack	No crack	No crack	No crack
2		-	-	Cracking	No crack	Cracking	Cracking	No crack	No crack	-	-
3		-	-	No crack	No crack	No crack	No crack	No crack	No crack	-	-
4	ISO 27913 (2016) (modified)	-	-	Cracking	Cracking	Cracking	Cracking	No crack	No crack	No crack	No crack
5	Oil & Gas	-	-	Cracking	No crack	No crack	No crack	No crack	No crack	-	-
6-1	Oil & Gas with oxygen	-	-	-	No crack	-	No crack	-	No crack	-	-
6-2		-	-	-	No crack	-	Cracking	-	No crack	-	-
7	Blue hydrogen	-	-	No crack	Cracking	No crack	Cracking	No crack	No crack	-	-
8	O <sub>2</sub> (50 ppm)	No crack	No crack	No crack	No crack	Cracking	No crack	No crack	No crack	-	-
9	SO <sub>2</sub> , NO <sub>2</sub> (50 ppm each)	No crack	No crack	No crack	No crack	No crack	No crack	No crack	No crack	-	-

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## • 17Cr steel passed 4PB tests at 24°C

No.	CO <sub>2</sub> specs or expected CO <sub>2</sub> source	Applied stress	Occurrence of cracking on FPB specimens	
			s-CO <sub>2</sub>	liquid
2-2	AMPP Guide 21532 (2023)	441 MPa (64 ksi)* at 24°C	No crack	No crack
7-2	Blue hydrogen	441 MPa (64 ksi)* at 24°C	No crack	No crack

\* 80% of 80ksi, fit for purpose test

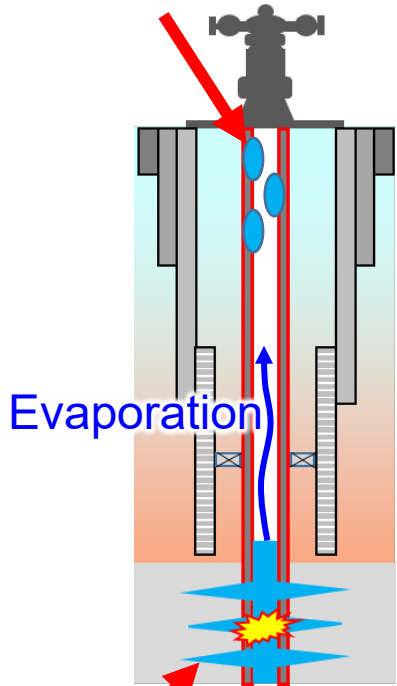


# Making domain maps based on corrosion test results

Table: Test results of 17Cr at **high temp.**

No.	CO <sub>2</sub> specs	Temp. (°C)	Pressure (MPa)	Cl <sup>-</sup>	Results of 17Cr		
				(mg/L)	corrosion rate	crevice corrosion	4PB test
1	AMPP Guide 21532 (2023)	90	20	121,200	<b>Pass</b>	<b>Pass</b>	<b>Pass</b>
2-1		90	20	180,000	<b>Pass</b>	<b>Pass</b>	<b>Pass</b>
3		120	40	65,000	<b>Pass</b>	<b>Pass</b>	<b>Pass</b>

**EAC Risk Highest by H<sub>2</sub>/H<sub>2</sub>S**



**General corrosion  
Crevice corrosion  
by CO<sub>2</sub> etc**

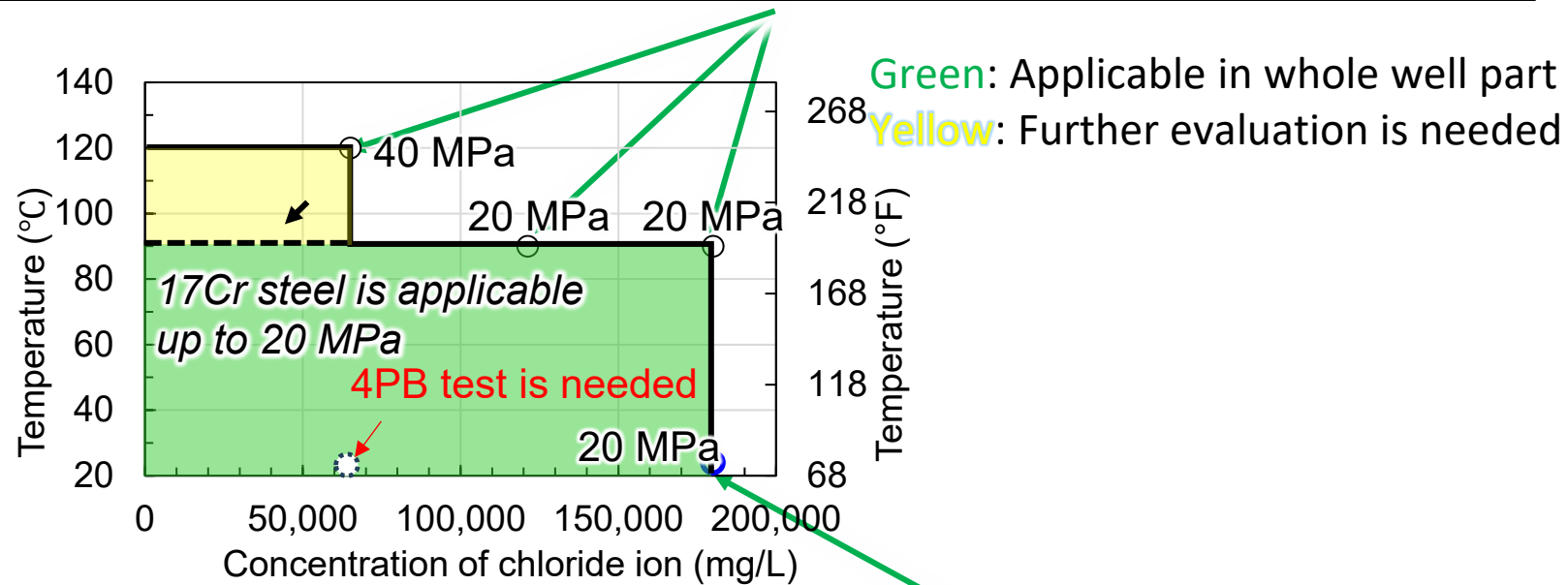






Table: Test results of 17Cr at **24 °C**

No.	CO <sub>2</sub> specs	Applied stress	Results of 4PB specimens	
			s-CO <sub>2</sub>	liquid
2-2	AMPP Guide 21532 (2023)	441 MPa (64 ksi) at 24°C	No crack	No crack



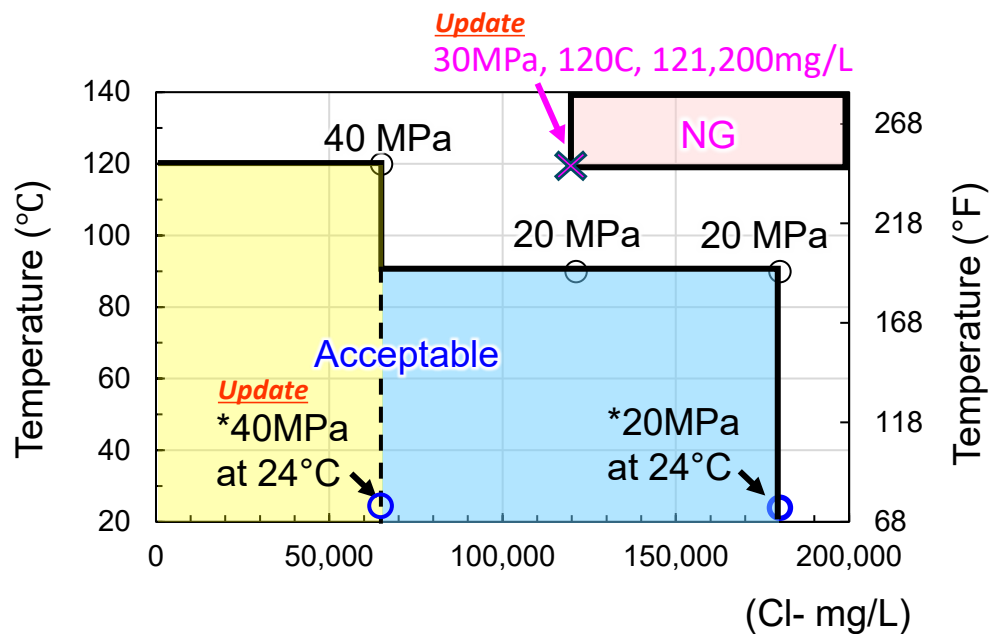
# 17Cr Domain maps for Mixed CO<sub>2</sub>

JFE

	:Acceptable up to 40MPa		:Acceptable up to 20MPa		:NG		:Not tested
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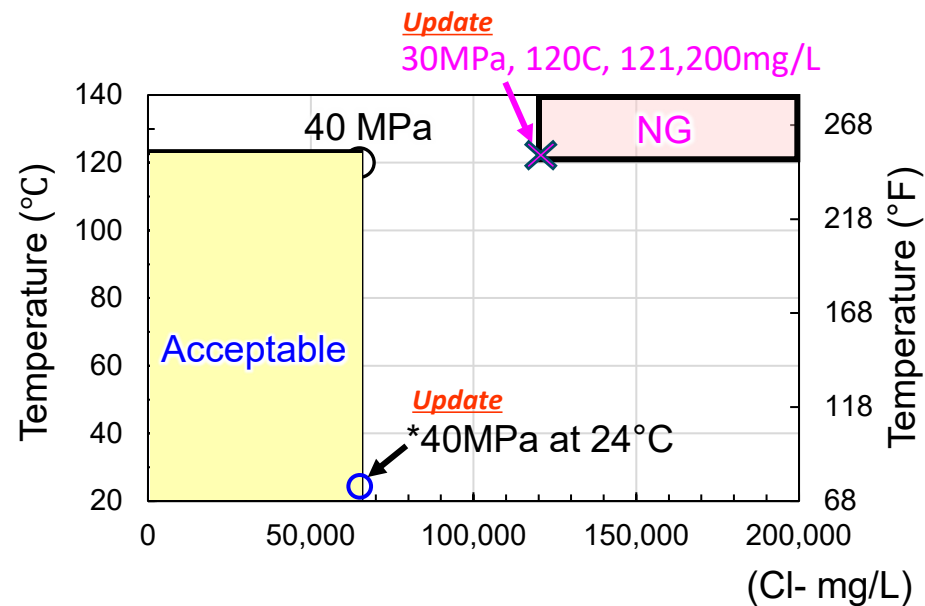
(a) Mixed contaminant (AMPP Guide)

CO <sub>2</sub> spec	Amount of impurities				
	SO <sub>2</sub>	NO <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub>
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
AMPP Guide 21532 (2023)	10	10	20	10	10000* <sup>1</sup>







(b) Mixed contaminant (ISO27913:2016-modified)

CO <sub>2</sub> spec	Amount of impurities				
	SO <sub>2</sub>	NO <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub>
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
ISO 27913 mod. (2016)	50	50	50* <sup>2</sup>	20* <sup>3</sup>	7,500



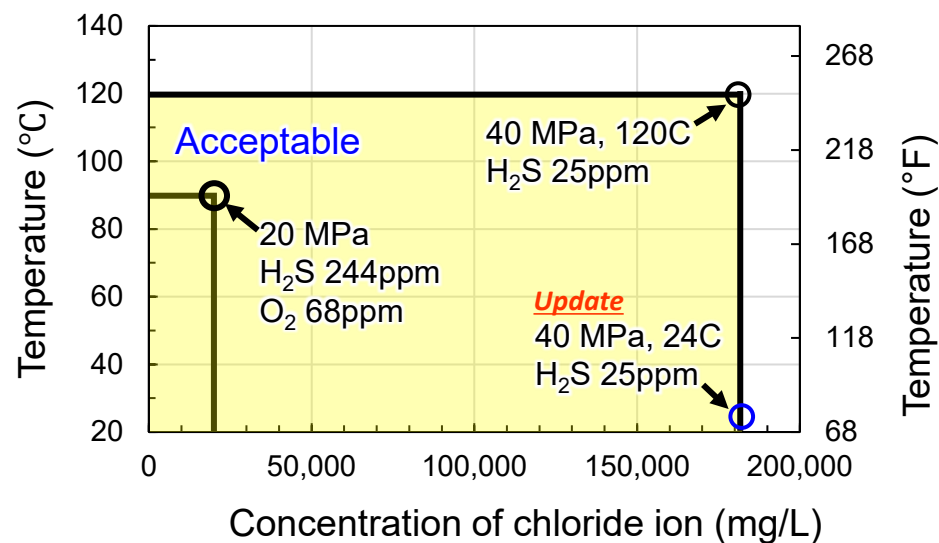


# 17Cr Domain maps for CO<sub>2</sub>, H<sub>2</sub>S, H<sub>2</sub>

	:Acceptable up to 40MPa		:Acceptable up to 20MPa		:NG		:Not tested
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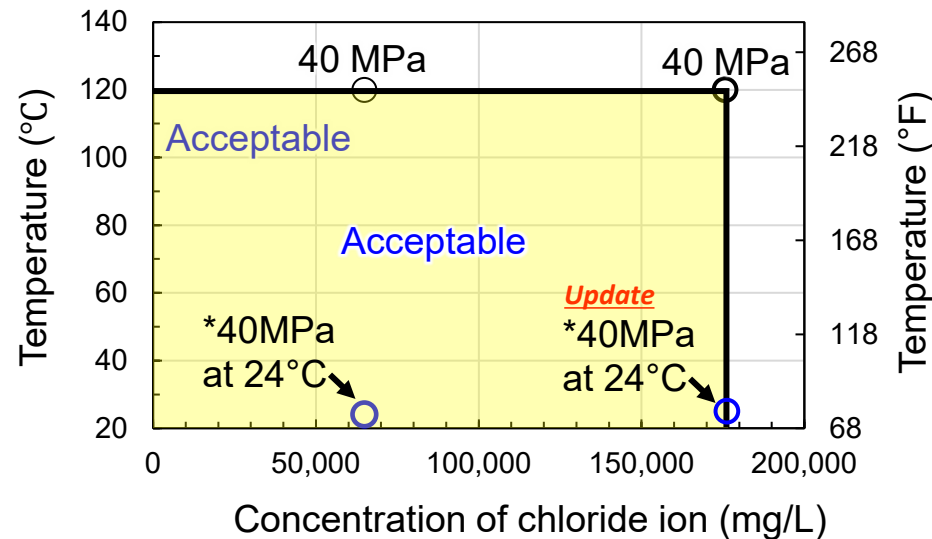
### (c) CO<sub>2</sub> +H<sub>2</sub>S from oil and gas production

CO <sub>2</sub> specs	Amount of impurities				
	SO <sub>2</sub>	NO <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub>
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Oil & Gas	0	0	0	25	0
Oil & Gas with Oxygen	0	0	68	244	0



### (d) CO<sub>2</sub> from "Blue-Hydrogen" production

CO <sub>2</sub> specs	Amount of impurities				
	SO <sub>2</sub>	NO <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub>
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
Blue hydrogen	0	0	0	0	20,000



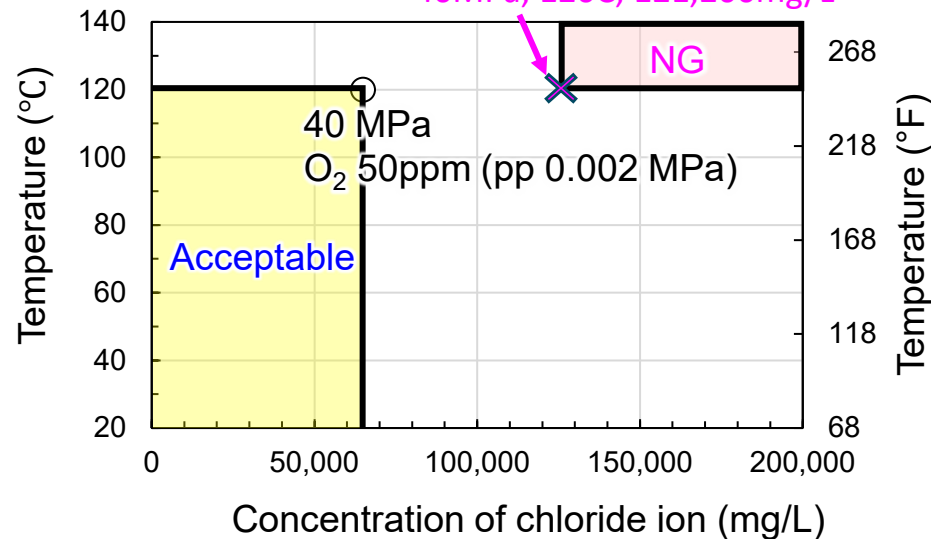
**H<sub>2</sub>, H<sub>2</sub>S are not included, and all 4PB specimens were free from cracking.  
⇒ 17Cr steel is applicable down to RT.**

:Acceptable up to 40MPa    
  :Acceptable up to 20MPa    
  :NG    
  :Not tested

(e) O<sub>2</sub>

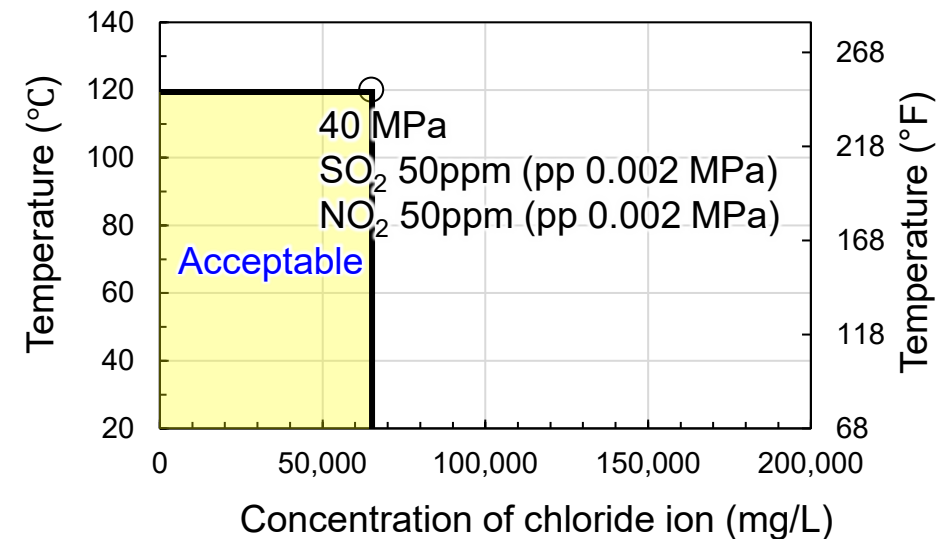
CO <sub>2</sub> spec	Amount of impurities				
	SO <sub>2</sub>	NO <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub>
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
DAC	0	0	50	0	0

Update  
40MPa, 120C, 121,200mg/L



(f) SO<sub>2</sub> and NO<sub>2</sub>

CO <sub>2</sub> specs	Amount of impurities				
	SO <sub>2</sub>	NO <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub> S	H <sub>2</sub>
	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
SO <sub>2</sub> , NO <sub>2</sub>	50	50	0	0	0





Corrosion behavior of martensite-based stainless steels in NaCl solutions saturated with CO<sub>2</sub> containing various impurities was studied.

- ✓ **General corrosion rates** for the martensite-based stainless steels **Mod.13Cr or higher grades were below 0.127 mm/y.** →to be candidates for CO<sub>2</sub> injection tubing
- ✓ Most specimens experienced crevice corrosion. **17Cr and S25Cr showed shallow crevice corrosion with depths under 25 μm.**  
→17Cr is suitable for all tested conditions.
- ✓ **17Cr showed no cracking under any tested conditions.**
- ✓ Based on the results, **17Cr applicability range in CCS was illustrated in Domain Map.**  
**We are trying to expand the range** by adding future testing results.



# Thank you



JFE Steel Corporation

**Dream for your Future,  
Steel takes you Further.**

