HT Geothermal Well Materials

T. Pyatina

ARPA-E superhot geothermal workshop

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Summary

Materials used for well construction

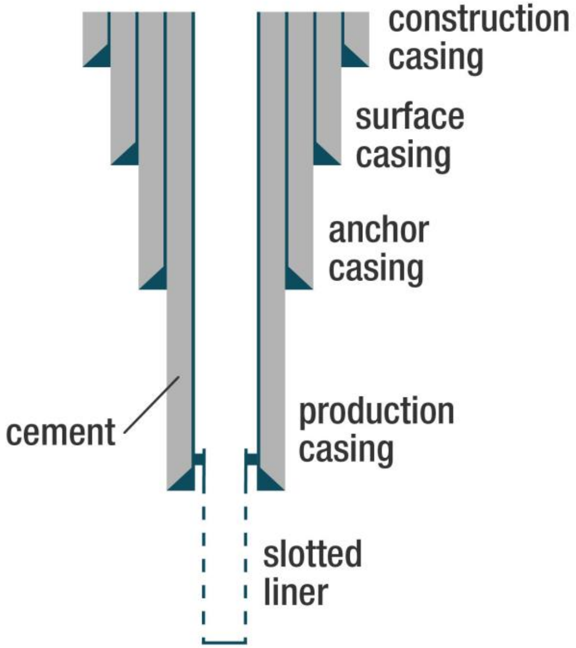
- **metals (**drill bits, well heads, **tubulars (casing/liner),** metal packers**),**
- lost-circulation materials (LCM),
- electronics,
- **elastomer seals,**
- **cementitious materials,**
- **various organic and inorganic additives to prepare lost-circulation, drilling, spacer fluids,** anti-scaling**, and cement slurries (temperature limit for the most resistant organic additives is ~200-250°C) – nonexistent for supercritical and subcritical conditions.**

Exposure Conditions

Expected service life

Current state of the art

Validation methods



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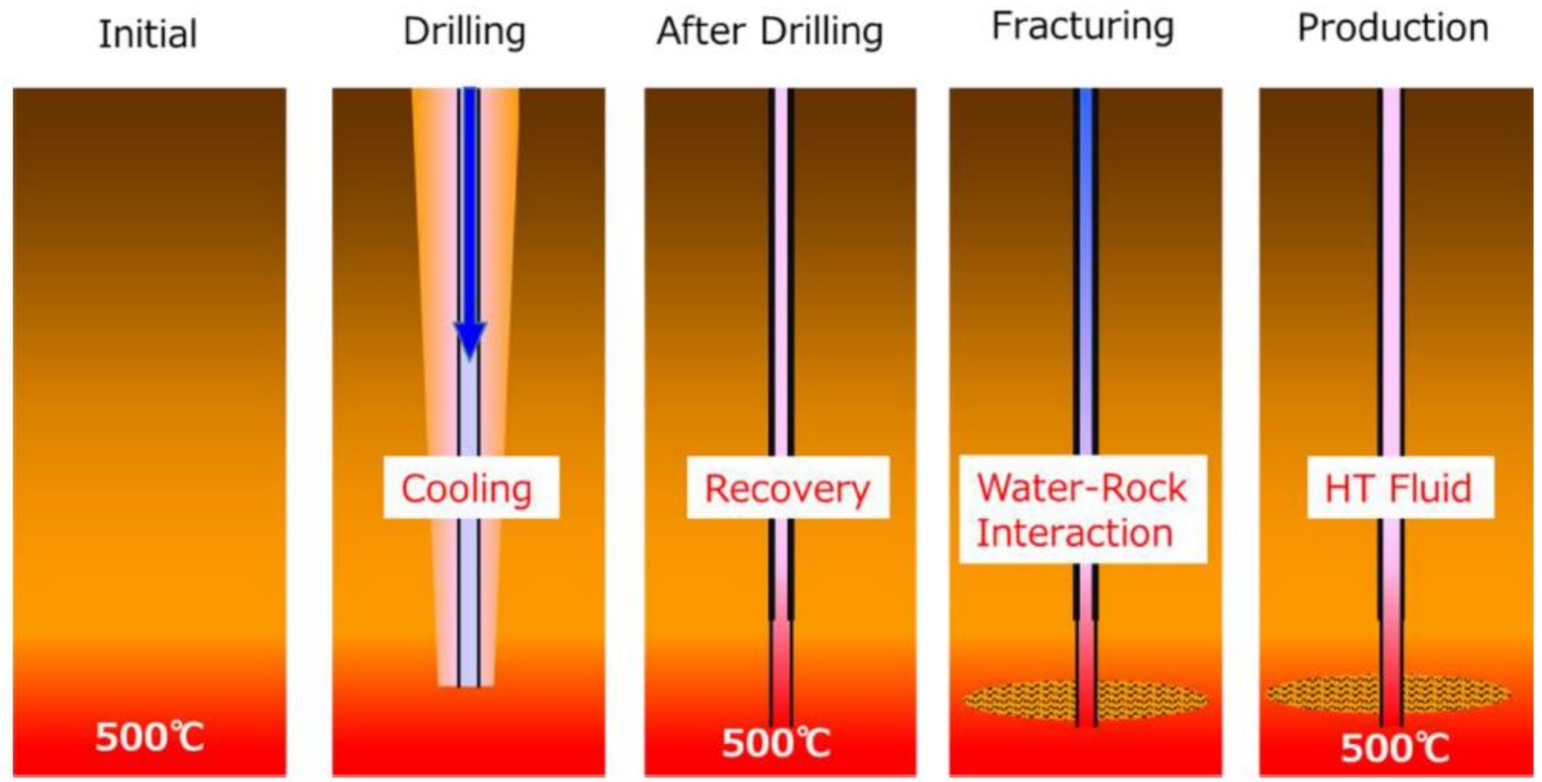
Exposure conditions (supercritical well example)



Model of the developmental process for (supercritical) geothermal resources

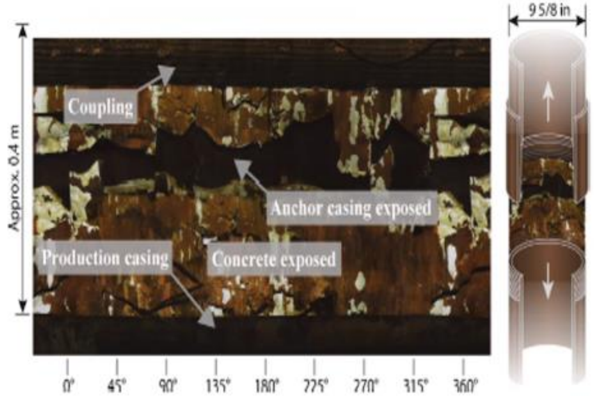
From: Yanagisama et al., 2021

There are repeated shocks (supercritical wells may require cooling for temperature and pressure control), aggressive environments with conditions changing over the life of a well (dissolution of carbonates will accelerate after stimulation operations in EGS, highly acidic conditions in volcanic areas).

Specifics of Geothermal Wells

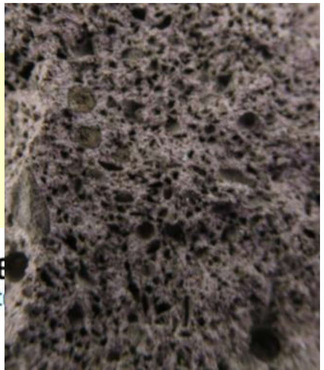
<u>Oil-field experience</u> have <u>limitations</u> in geothermal-well applications

- Significantly larger thermal-mechanical stresses than in oil-field; larger flow rates for economical wells; larger well diameters to avoid pressure drop – larger cement volumes
- Casing collapse with the Annual Pressure Buildup problem requires cementing the entire well. APB is time and location dependent.
- Fragile formations – common lost-circulation problems (formation damage, placement T is difficult to estimate)
- Durability under geothermal-well conditions (acidic, highly corrosive, high dissolved solids, frequent shocks, high temperatures)
- Expected service life and criteria of a successful well construction are very different
- Limited additives that can be used for modification of fluids' properties



Cement from Icelandic IDDP well

Increased class H/SiO_2 cement porosity after organic additives degradation at 300°C



Melted/degraded organic inclusions in the cement matrix at 300°C

Life expectancy for different materials

Metal (casings)/cement – years (both circulating and static conditions, high thermo-mechanical shocks)

Lost circulation materials /Elastomers – days/weeks (mostly circulating conditions, some static, repeated use)

Additives – hours (circulating conditions)

HT (subcritical and supercritical) well materials

"x" represents existence of issues, "no" represents no issues, and N/A represents no relevant information was found (compiled by Meng Meng, LANL)

Country	U.S.			Iceland			Italy	Japan	Kenya	New Zealand
Area	Salton Sea	Geyser	Puna, Hawaii	Krafla Field		--	--	--	--	--
Well number	State 2-14	Prati 31/32	KS-13	IDDP-1	IDDP-2	KJ-39	Venelle-2	WD-1A	MW-4	SC-1
Depth (m)	3220	3396	2528	2104	4650	2848	2900	3729	2500	2800
Temperature (°C)	355	400	1050	450 (wellhead)	427	386	>500	>500	~400	500
Pressure (MPa)	N/A	N/A	N/A	14 (wellhead)	34	23	45	N/A	14	26
Drill bit issue	x	x	N/A	x	**No**	N/A	x	x	N/A	N/A
Casing damage	x	x	x	x	x	x	x	x	x	x
Liner failure	x	x	x	x	x	x		x	N/A	N/A
Cement failure	N/A	N/A	N/A	x	x	N/A	x	x	N/A	N/A
Drilling fluid degradation	X	N/A	N/A	x	x	x	x	x	x	N/A
Lost circulation	X	x	X	x	x	N/A	x	x	X	N/A
Wellhead failure	N/A	x	N/A	x	x	x	N/A	N/A	N/A	N/A

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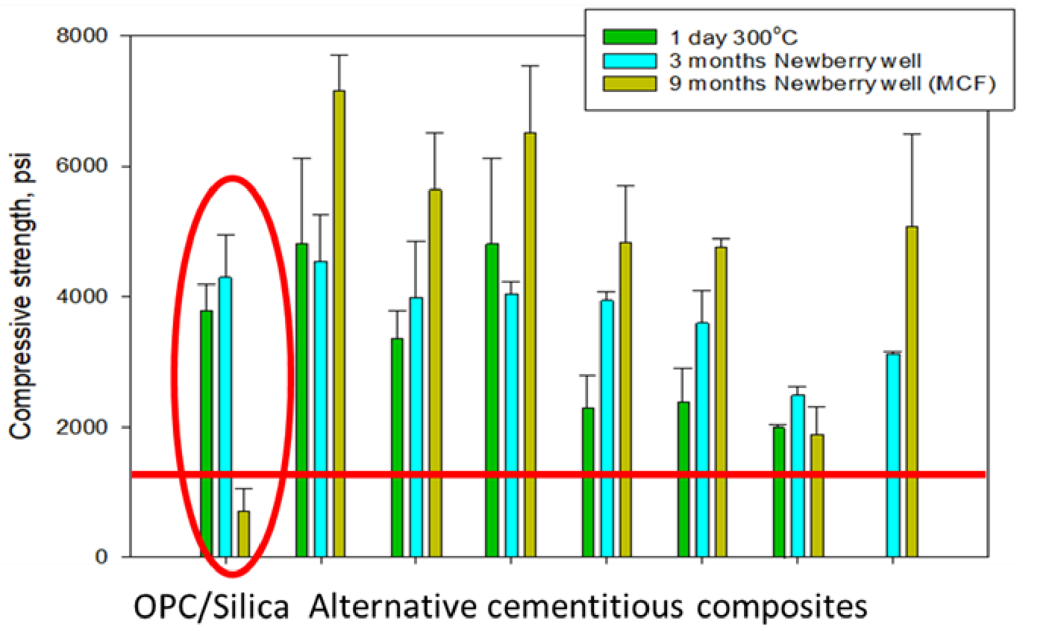
For all supercritical wells there were problems with materials or information was not available

Performance of different cements in HT geothermal well



Newberry well exposure tests results

Exposure depth 1.7 km

Temperature ~350°C

Pressure 2000 psi (~140 bar)

Exposure time 3 and 9 months; initial curing 1-day 300°C

Currently used Portland cement could not survive HT geothermal conditions (~350°C Newberry well)

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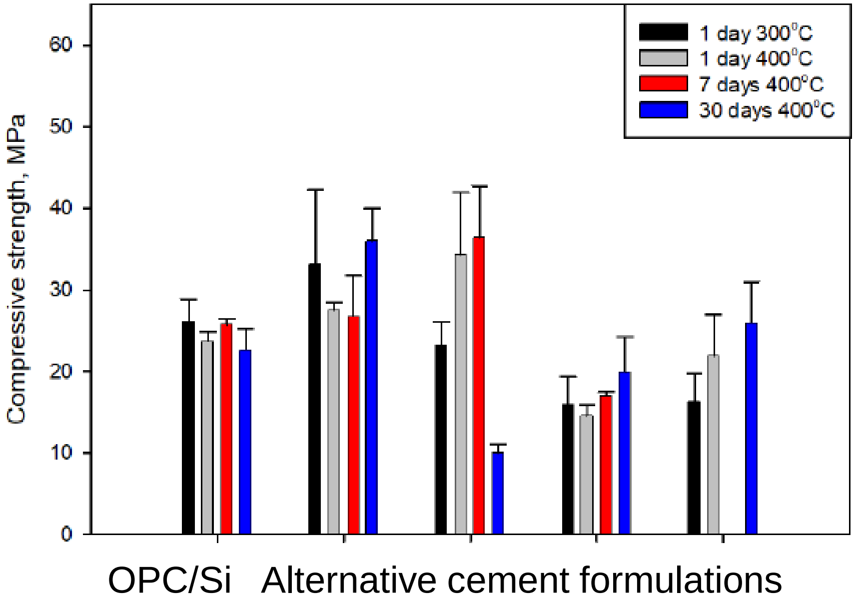
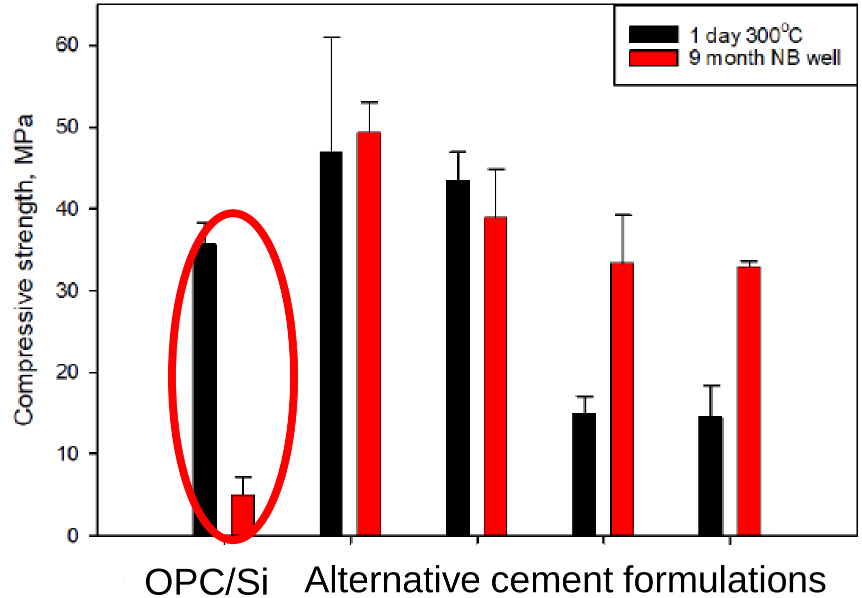
Degradation is highly environment dependent



Supercritical conditions (400ºC, ~14 MPa)



Newberry well tests

OPC/silica survived 30 days of supercritical exposures with persistent mechanical properties but not 350ºC in a well!

(1) Exposure conditions are important.

(2) Subcritical temperatures may be more difficult for materials to survive than supercritical

Metal corrosion at HTHP

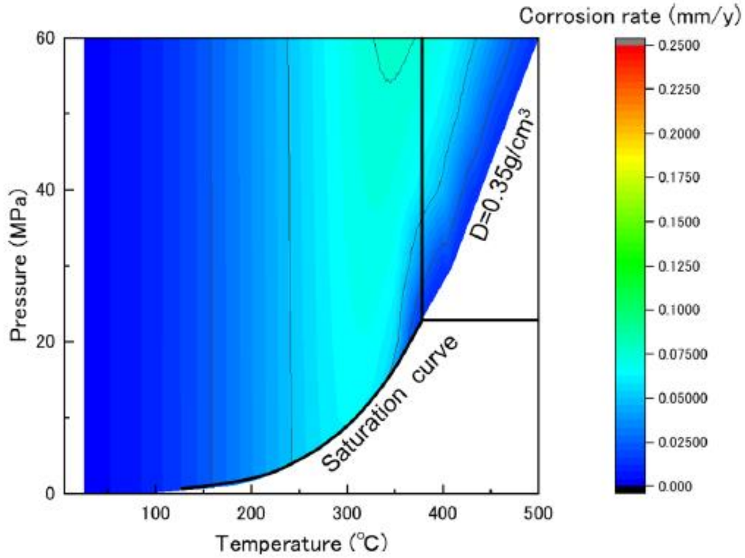


Fig. 7. Corrosion rates for Hastelloy C-276 in higher pressure regions than the saturation and 0.35 g/cm^3 lines for the Kakkonda WD-1a well model.

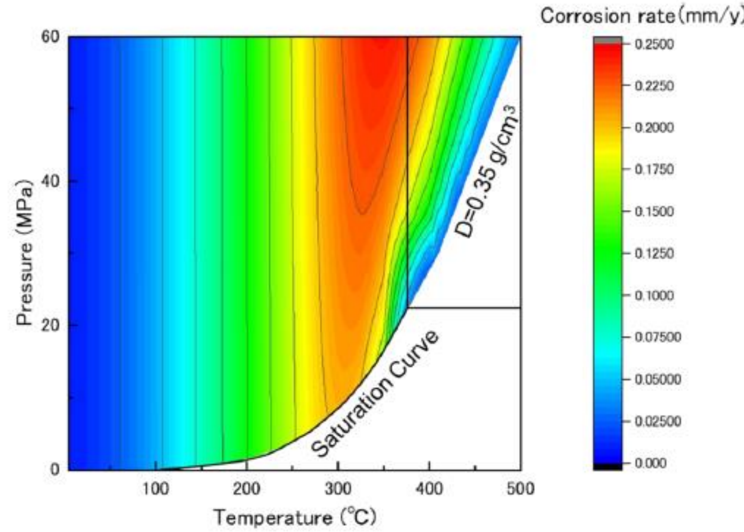


Fig. 9. Corrosion rates for the Hastelloy C-276 distribution in higher pressure regions than the saturation and 0.35 g/cm^3 lines for the IDDP-1 well model.

From: Yanagisama et al., 2021

Corrosion rates for low-alloy steel in higher pressure regions for the Kakkonda WD-1a well model and IDDP-1 well model

Metal corrosion depends on well conditions (location) and may be more rapid at subcritical temperatures than at supercritical temperatures!

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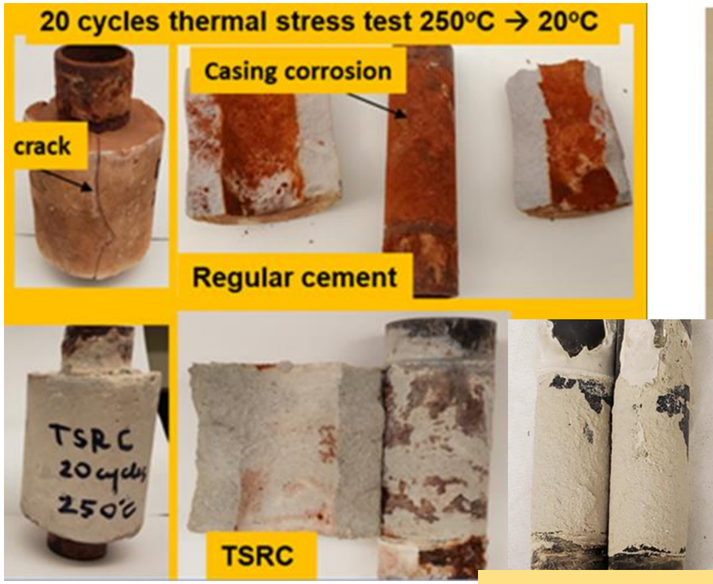
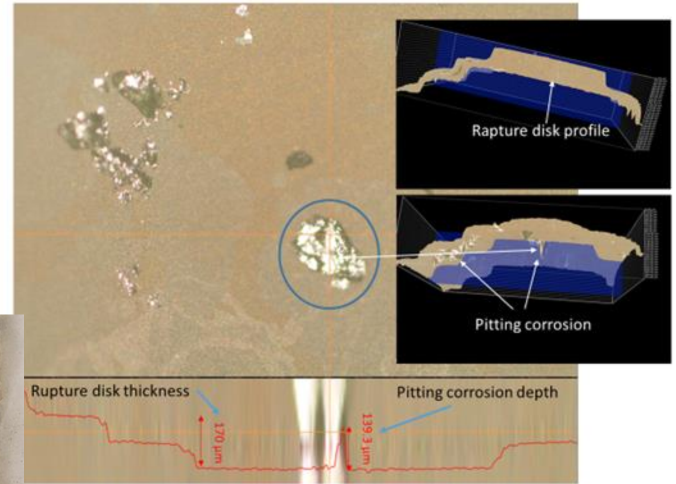
Thermal shock and subcritical conditions

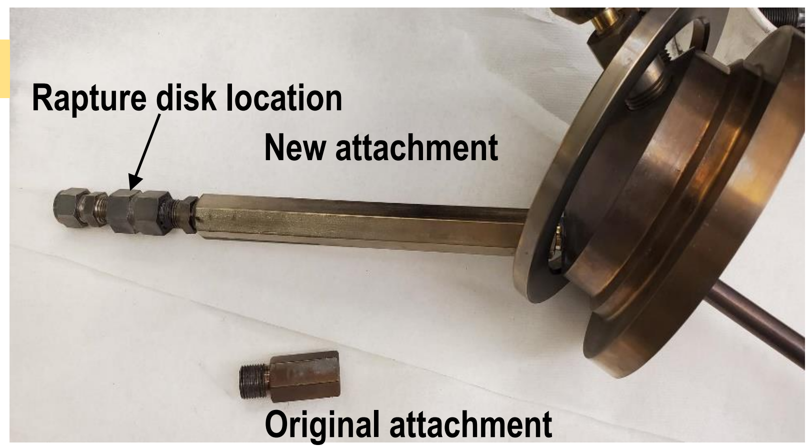


Advanced design



Hastelloy rapture disk corrosion after 7 days under subcritical temperatures

Thermal shock effect on cement integrity and casing corrosion **at subcritical temperatures <u>in water</u>**



Fast metal corrosion under hydrothermal conditions

Alloys can provide better corrosion resistance but are costly. Ni alloys also experience strong expansion under geothermal T, Ti are very costly and difficult to thread. Cladding and coatings are considered.

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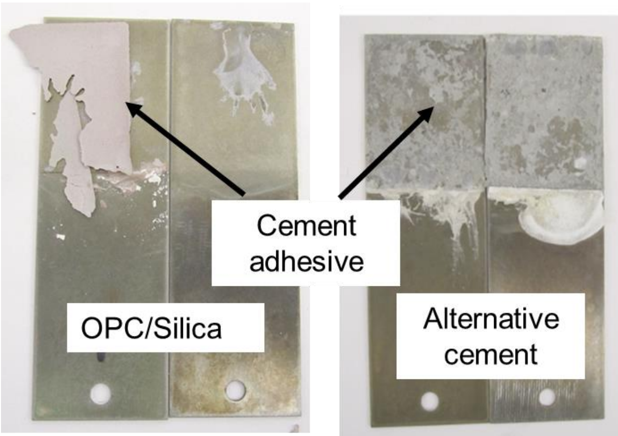
Metal-cement bonding

Lap-shear bond tests, 7 days 400^oC, Ni-alloy



- ***Currently used cement (OPC/Silica) cannot provide metal protection;***
- ***Cement must be multifunctional***

Performance of alternative cements after 7 and 30 days under sc conditions

400^oC_7 days 400^oC_30 days

TSRC

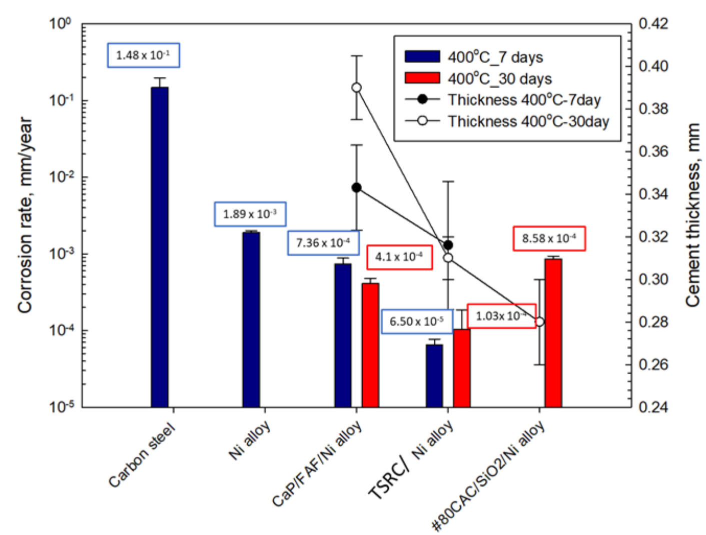
Adhesive failure

400^oC_7 days 400^oC_30 days

CaP#71/FAF

400^oC_7 days 400^oC_30 days

#80CAC/Silica



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Elastomers' performance under different conditions

300^{o}C

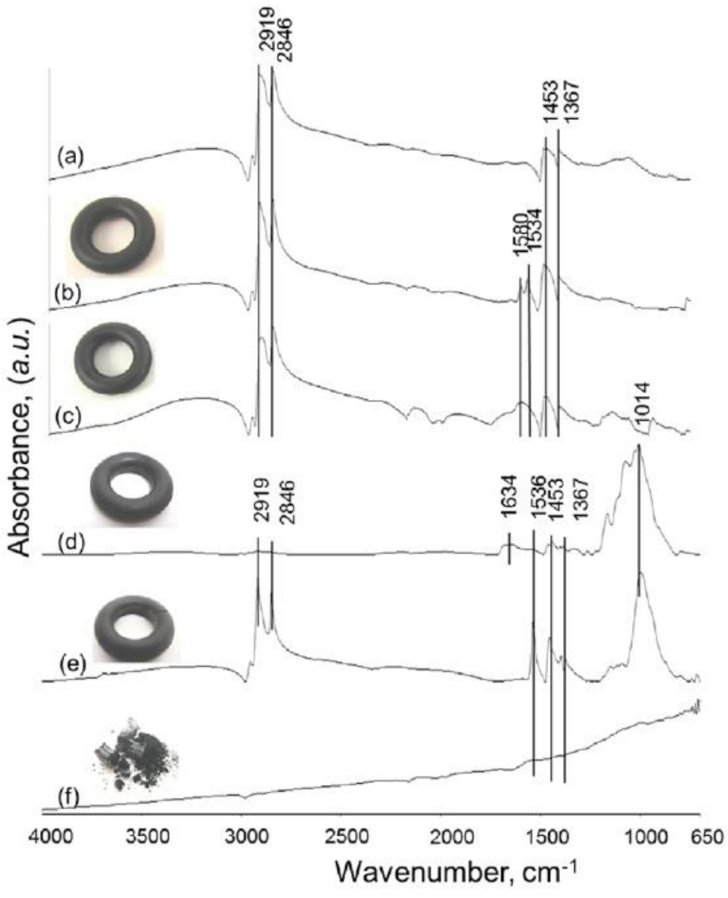


Fig. 2. ATR-FTIR absorption spectra and appearance of EPDM O-rings before (a) control, and after: (b) No. 1 non-aerated (N_2), (c) No. 2 aerated steam/cooling cycles, (d) No. 3 drilling fluid, (e) No. 4 geo-brine fluid, (f) No. 5 thermal shock tests.

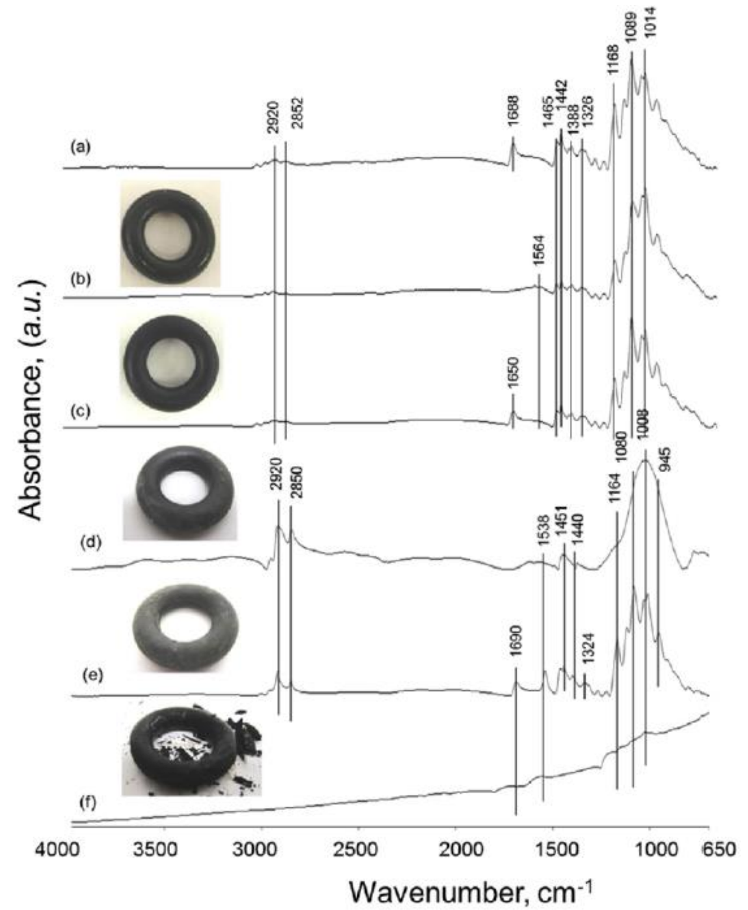


Fig. 3. ATR-FTIR absorption spectra and appearance of FEPM O-rings before (a) control, and after: (b) No. 1 non-aerated (N_2), (c) No. 2 aerated steam/cooling cycles, (d) No. 3 drilling fluid, (e) No. 4 geo-brine fluid, (f) No. 5 thermal shock tests.

From: Sugama et al., 2015

Degradation strongly depends on the environment for the same elastomer chemistry

Elastomers' performance under different conditions

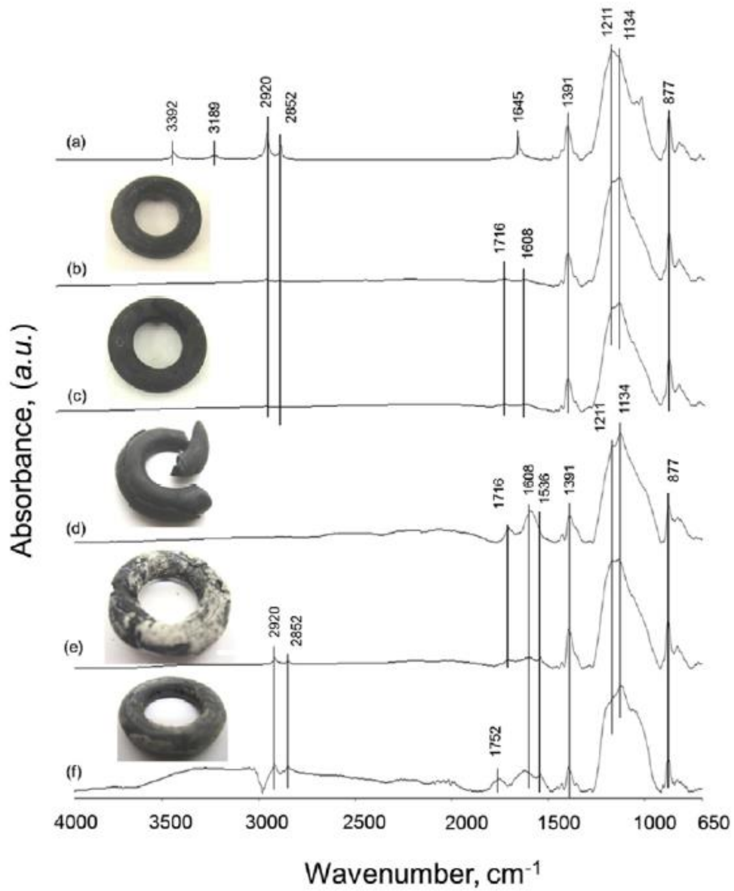


Fig. 7. ATR-FTIR absorption spectra and appearance for Type I FKM O-rings before (a) control, and after: (b) No. 1 non-aerated (N_2), (c) No. 2 aerated steam/cooling cycles, (d) No. 3 drilling fluid, (e) No. 4 geo-brine fluid, (f) No. 5 thermal shock tests.

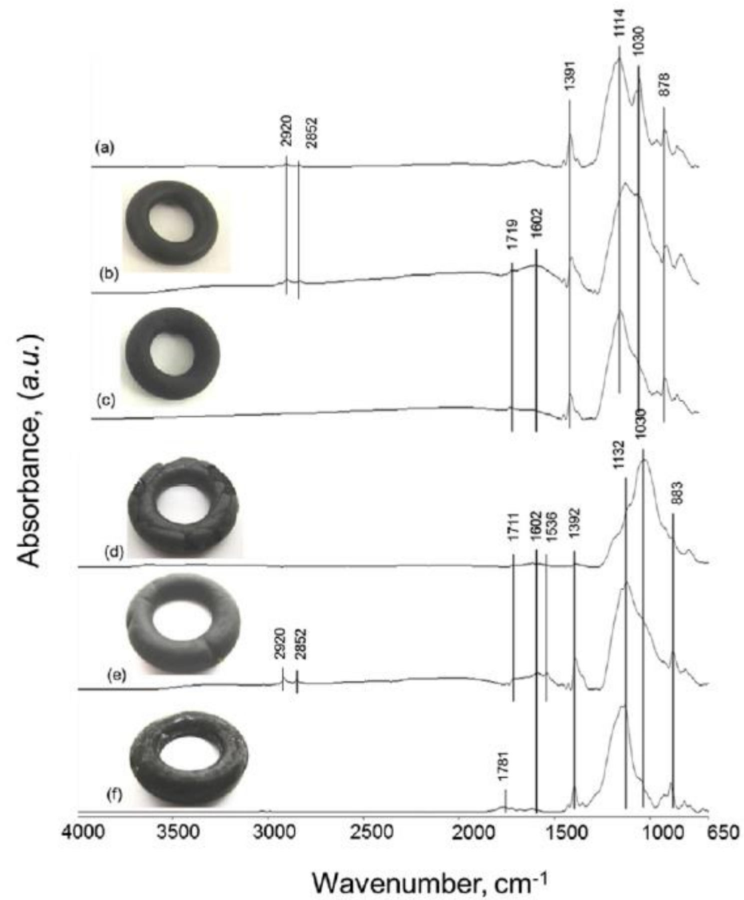


Fig. 8. ATR-FTIR absorption spectra and appearance for Type II FKM O-rings before (a) control, and after: (b) No. 1 non-aerated (N_2), (c) No. 2 aerated steam/cooling cycles, (d) No. 3 drilling fluid, (e) No. 4 geo-brine fluid, (f) No. 5 thermal shock tests.

From: Sugama et al., 2015

None of tested elastomers survives under all possible geothermal conditions

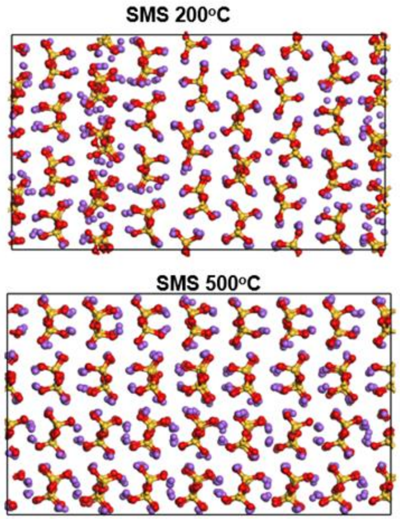
Fluorocarbon polymers degrade with the release of very aggressive HF.

Materials validation methods

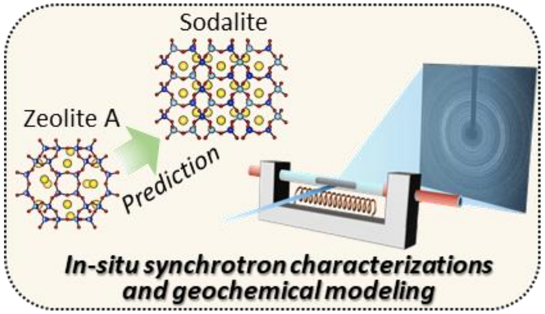
Testing and validating these materials under relevant conditions

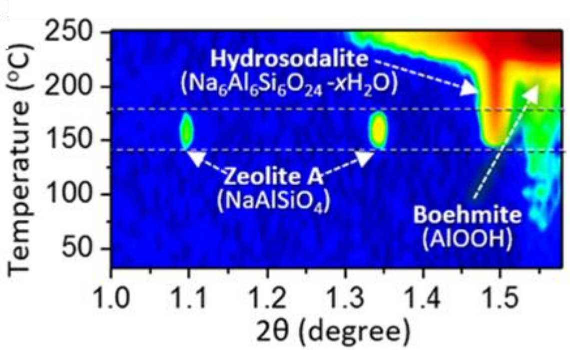
- HTHP for in-situ measurements,
- long-term exposures with a possibilities of periodic measurements under HTHP conditions,
- measurements in aggressive environments,
- measurements under stress conditions (e.g., thermal shock)

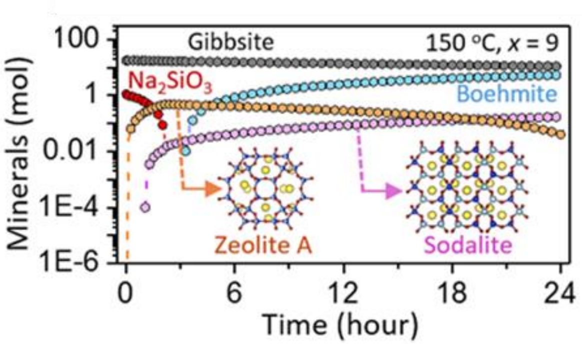
Testing and validating these materials for years of service life (accelerated aging? Long term tests combined with modeling (there is no materials' properties database in the format that can be used by ML)?)



Example of Molecular dynamic modeling of reactant's structural changes at different temperatures.







Example of thermodynamic modeling verified with in-situ synchrotron experiments.

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Way forward – a few thoughts

1. Advanced materials (cement, coatings, elastomers) can be considered for supercritical and subcritical conditions – need to be evaluated under relevant environments and optimized as needed, their applicability envelops defined.

2. Alternative well construction techniques may be considered that do not involve cementing parts of the well.

3. Development of auxiliary materials, such as additives and coatings, will depend on the selected materials solutions for well construction.

4. Costs and environmental impact of materials may limit solutions