EFFECTS OF EMBRITTLEMENT MECHANISMS ON MECHANICAL PERFORMANCE OF NODULAR CAST IRON

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History of geological spent nuclear fuel disposal in Scandinavia

- **In Sweden SKB AB was formed in 1973 and later in Finland Posiva Oy started in 1996.**
- **In 1983 the KBS-3 method was presented which led to continuous evaluation and development.**
- **In 1986 thorough evaluation of research, development and demonstration of KBS-3 project was started; FUD-reports published every 3 years.**
- **During 1990-1995 Äspö-laboratory was built in Oskarshamn, Sweden, for the development and demonstration of the KBS-3 method.**
- **Posiva selected Olkiluoto site, which was accepted by the Finnish government in 2001.**
- **In 2009 SKB selected Forsmark as the repository site and Oskarshamn is the site of the encapsulation plant.**

History of geological spent nuclear fuel disposal in Scandinavia

- In 2012 Posiva Oy submitted the application for the construction licence, which was granted by the Finnish government in 2015.
- The construction of the first spent fuel repository ”Onkalo” started in 2004 in Olkiluoto, Finland. The construction of the final repository and encapsulation plant takes place during 2015 - 2023.
- In Finland the operation licence application is planned to be submitted in 2021.
- Final disposal shall be started in the 2020’s and the repository is expected to be sealed in 2120’s.
- In Sweden SKB applied the construction licence for the repository of spent fuel in 2011, which resulted in both national and international evaluations.
- The Swedish Land and Environment Court began the hearing of the KBS-3 application on 5th September 2017.

History of geological spent nuclear fuel disposal in Scandinavia

The Swedish Land and Environment Court gave the conditional decision of the KBS-3 application on 23th January 2018. The operation is approved if:

1. SKB shows data which confirms the long-term safety of the site due to the uncertainties of copper canister corrosion performance affected by:

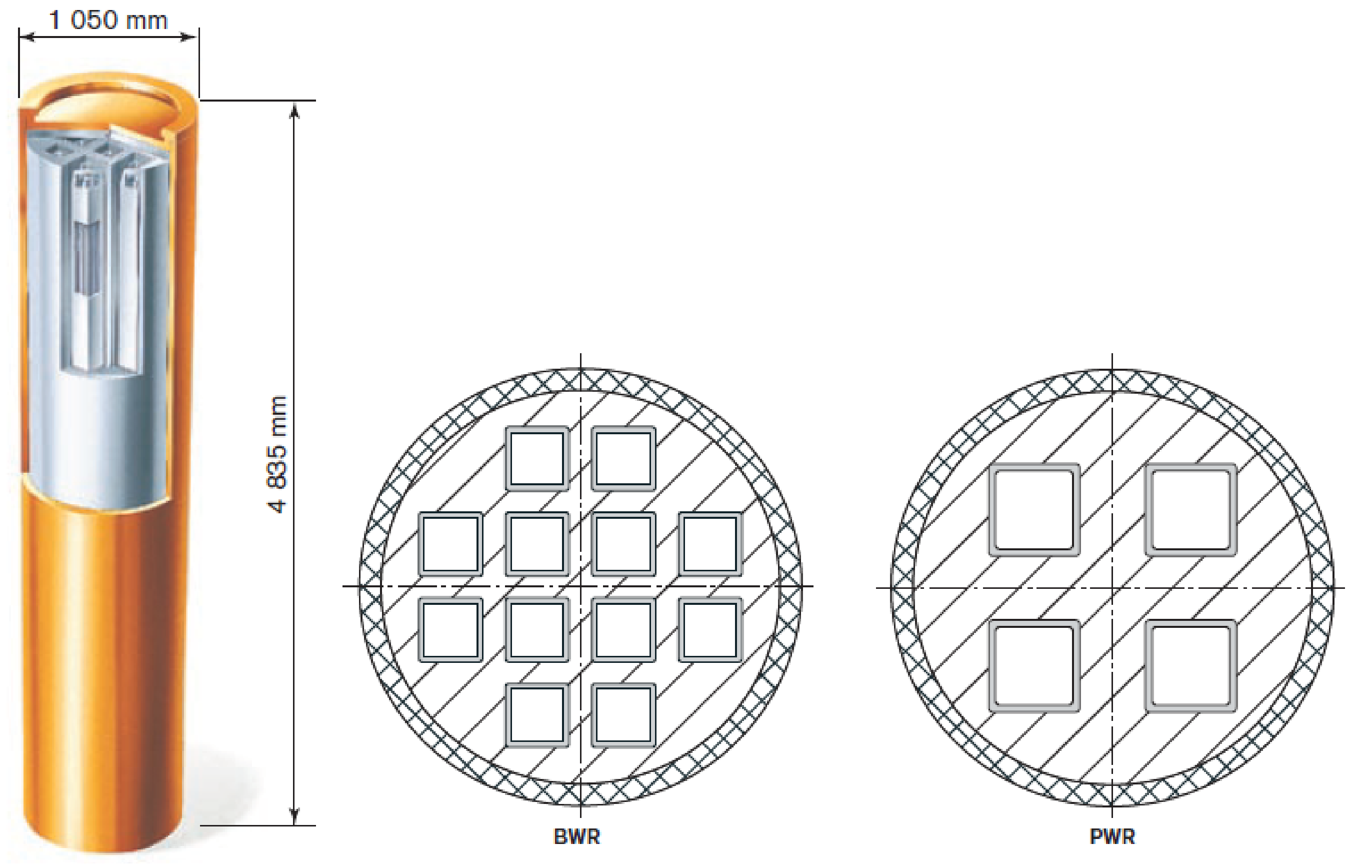
- **Corrosion in oxygen-free groundwater;**
- **Pitting corrosion in sulfide solutions, including so-called Sauna-effect;**
- **Stress corrosion cracking in sulfide solutions, including Sauna-effect;**
- **Hydrogen embrittlement;**
- **Effects of irradiation on pitting and stress corrosion as well as hydrogen embrittlement.**

2. SKB has to clarify who has according to the Swedish law the long-term responsibility on the geological spent nuclear fuel disposal site.

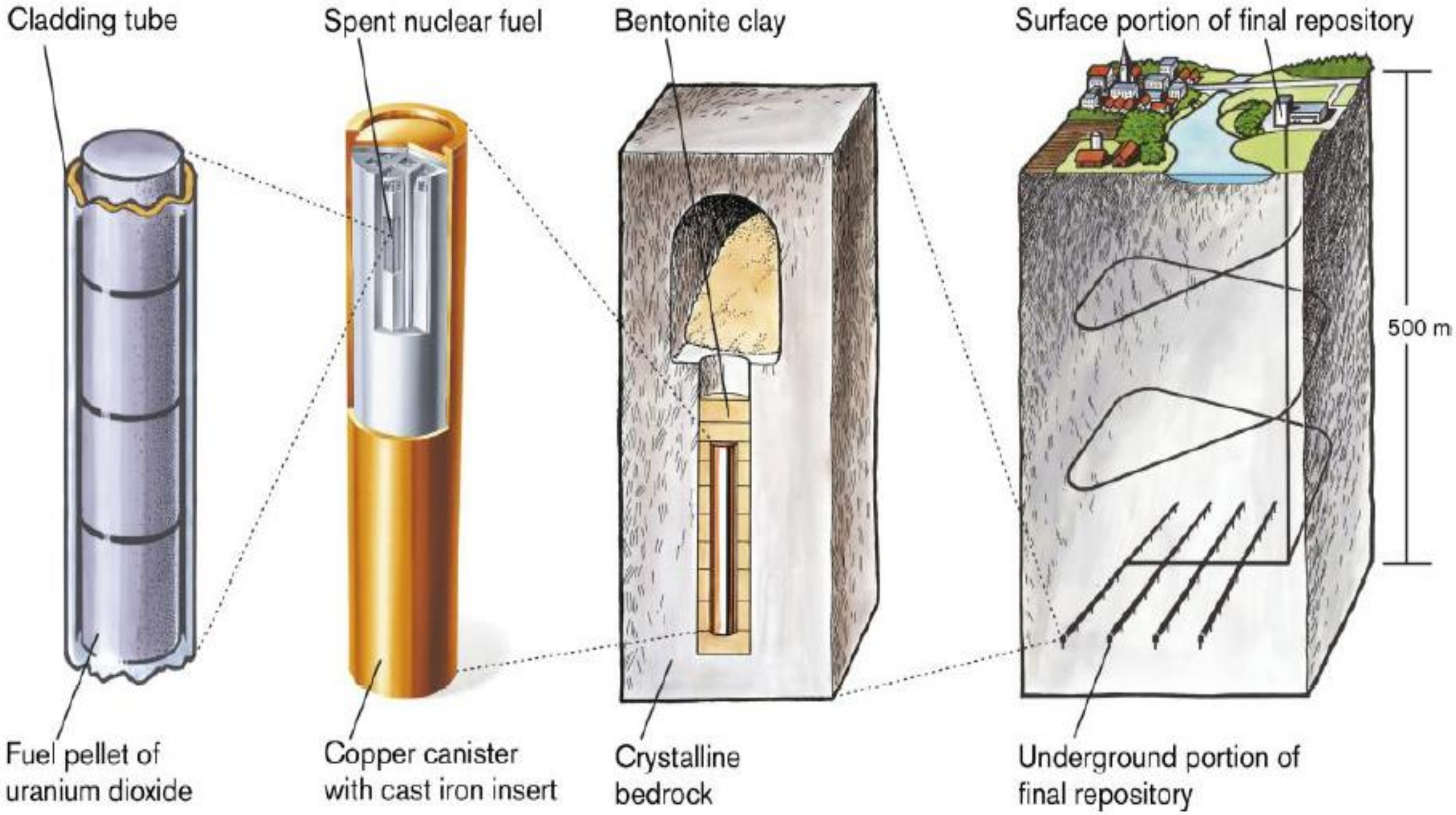
History of geological spent nuclear fuel disposal in Scandinavia

- SSM accepted the KBS-3 application according to the requirements of Nuclear energy law and saw that SKB has the qualification to fulfill the requirements related to the safe spent nuclear fuel geological disposal. The remaining uncertainties can be handled later – after the approval of the Swedish government – in the step-wise evaluation of SSM, e.g., before granting the operation license when the repository has been built.
- In June 2018 Swedish government sent the completion request to SKB with statement reports from SSM and Swedish Land and Environment Court.
- SKB submitted the completion statements in March 2019 which were examined and evaluated by SSM in September 2019.
- The Swedish government handles the application and sent the additional request to SSM and the Swedish Council of Nuclear Waste in September 2021 concerning remaining uncertainties related to copper corrosion and cast iron properties. Responses were submitted by 21.10.2021.

Design of the KBS-3 canisters with two different internal structures



Repository and canister for the spent nuclear fuel located at about 500 m depth



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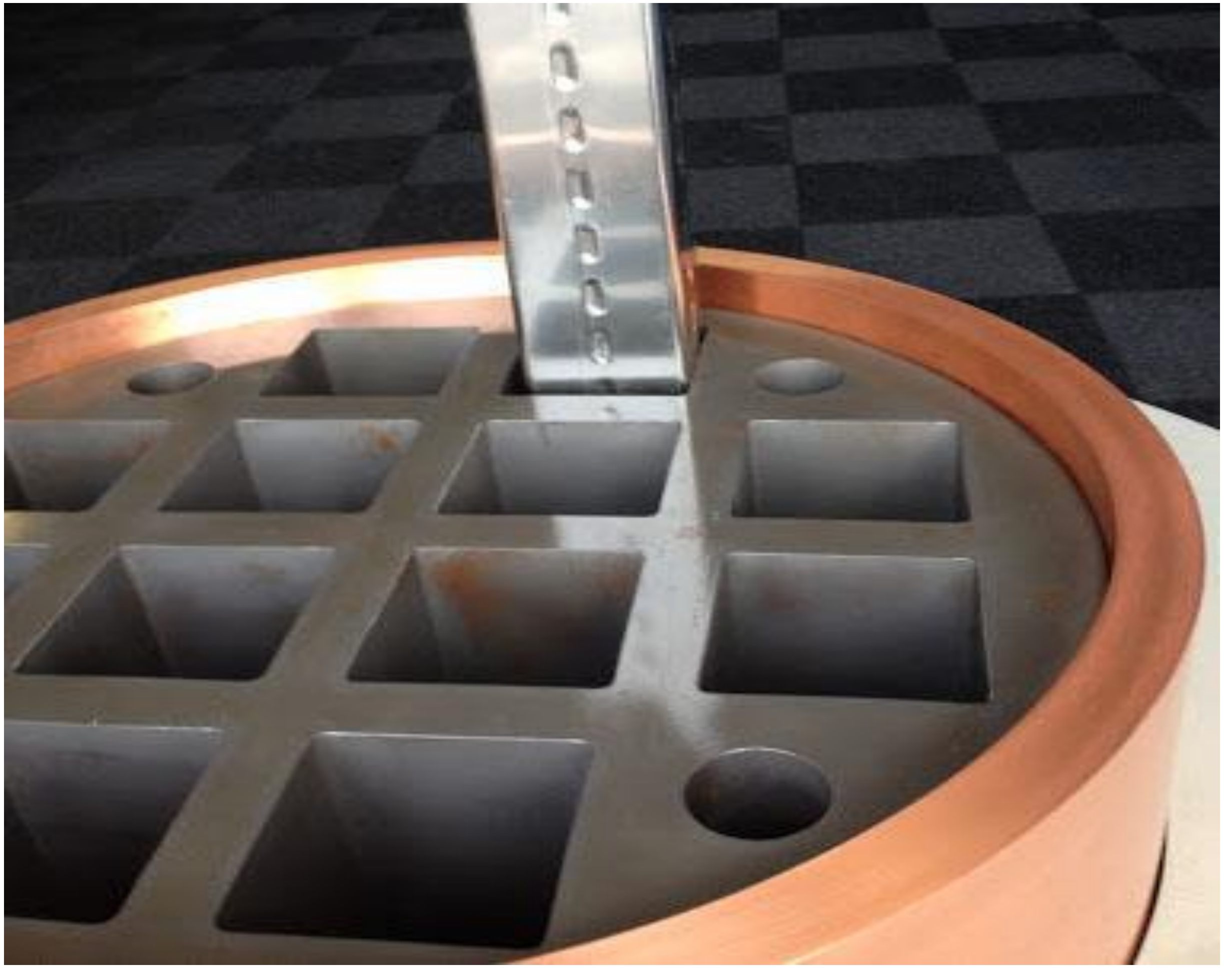
Design of the KBS-3 canister with BWR internal structure

Design of the KBS-3 canister with BWR internal structure



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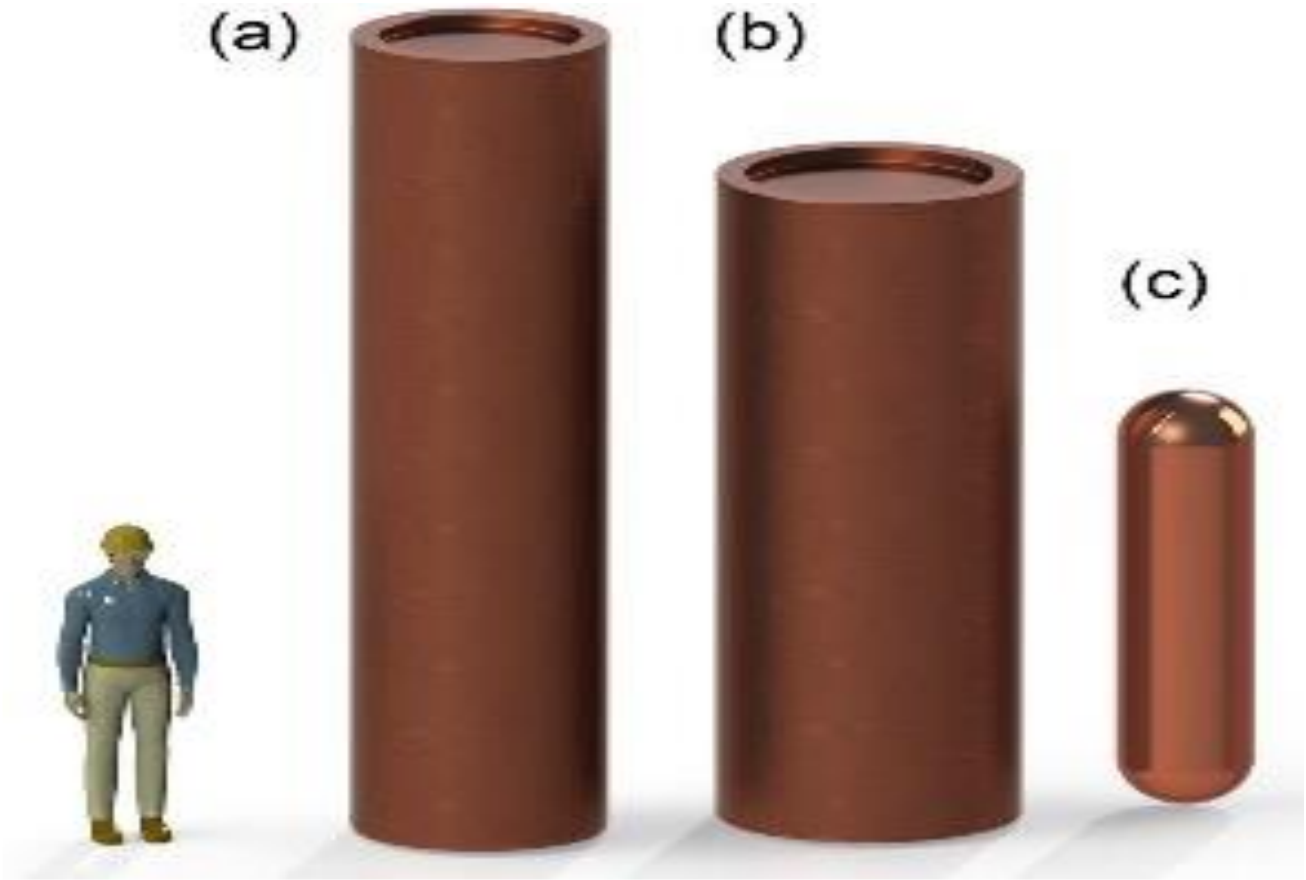
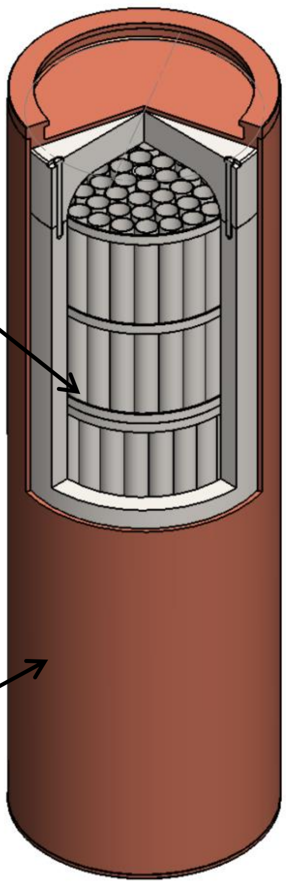
Comparison of the (a) KBS-3, (b) the original Canadian NWMO IV-25 (reference) and (c) current NWMO Mark II canister designs (Hall and Keech, 2017).



Used Fuel Container (UFC) Design Change

Original



Inner steel vessel
8 – 10 cm thick

Designed to withstand hydrostatic + clay swelling + glacial pressures.

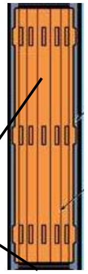
I mm gap

To facilitate assembly

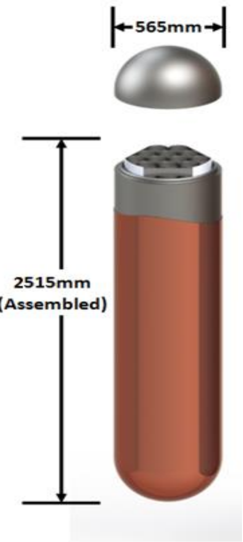
Outer Cu shell
2.5 cm thick

Fuel Design

CANDU



Mark II



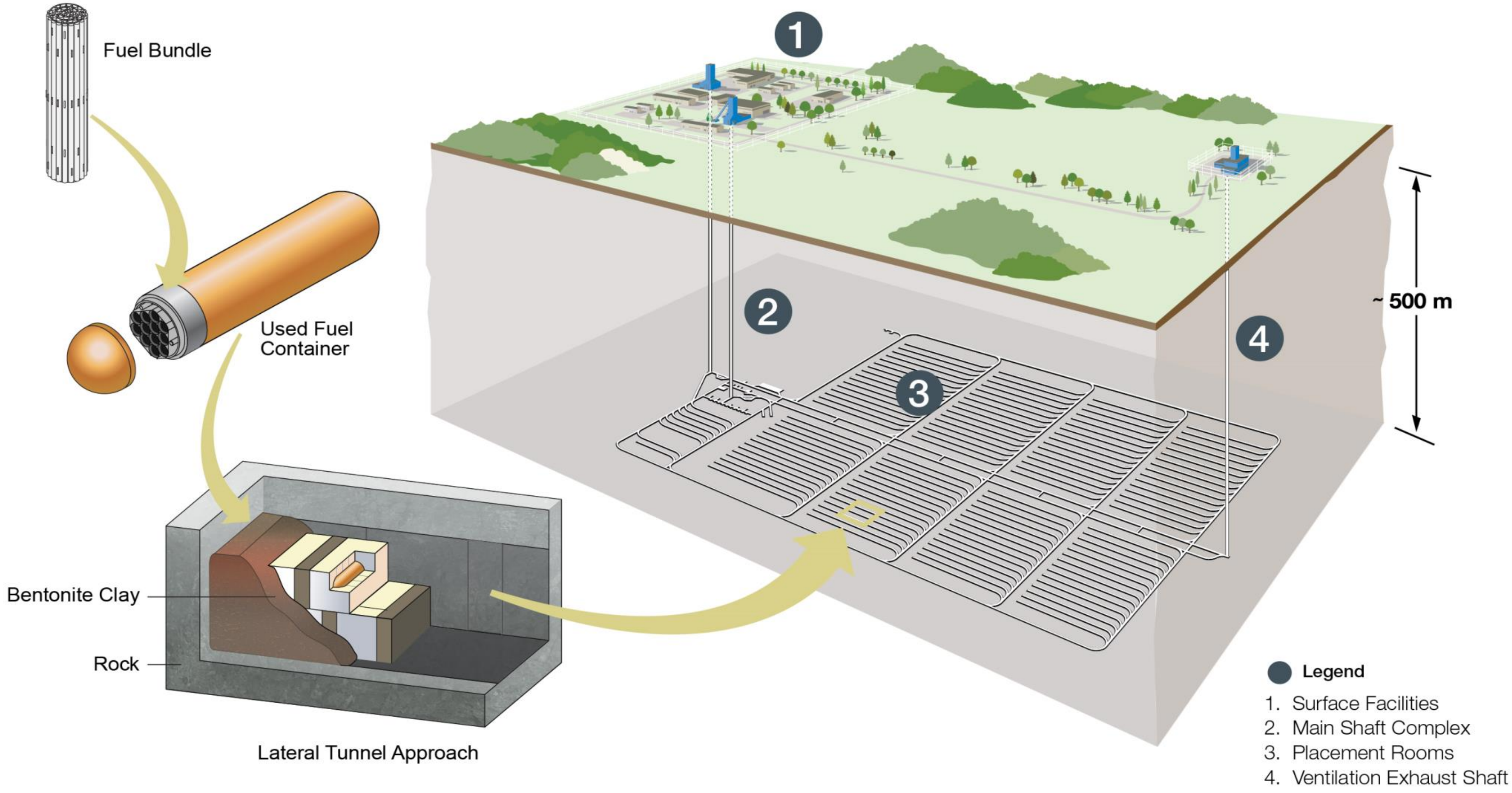
Inner steel vessel
4 cm thick

No gap

Outer Cu coating
0.3 – 0.4 cm thick

Conservative estimate for Cu corrosion rate (no radiation) = 1.27 mm per M years.

The multibarrier system of Canadian deep geological repository, showing the Mark II fuel container and bentonite buffer boxes.



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Design requirements of nuclear waste canisters

- The canister contains the spent fuel and prevents the release of radioactive substances into the surroundings. The canister shields also radiation and prevents criticality. The disposal canister will be subjected to varying loads in the repository conditions caused by **hydrostatic pressure, bentonite swelling, and shift of the bedrock.**
- The main aspects of the canister are the **copper shell thickness, corrosion resistance and creep strength/ductility**, as well as, the **strength and pressure-bearing capacity of the canister insert**.
- The **bentonite buffer** provides a self-healing medium when wet. This inhibits transportation of oxygen and sulphide ions to the canister surface, and the transport of released radionuclides from the canister if failed. The bentonite buffer accelerates the establishment of **anoxic conditions on the copper surface.** The bentonite buffer will **prevent the microbial activity** on the copper surface due to the high swelling pressure.
- Since all the **mechanical loads** on the canister are transferred through the **bentonite buffer**, the material properties of the bentonite clay define important conditions for the design analysis of the canister.
- The **initial state** of the canister is defined as the state when the canister is deposited in the repository. The **reference design** specifies, for example, that the maximum allowed surface temperature of the canister is 100ºC and maximum allowed surface dose rate is 1 Gy/h. The long-term performance of the copper canister is based on the **ideal conditions** prevailing for centuries.

History of KBS-3 geological spent nuclear fuel disposal in FUD-program

In FUD program during 2001…2007 the cast iron insert issues have been examined as follows:

- **In FUD 2001, 2004, and 2007 cast iron insert was evaluated based on the mechanical properties and reliability of material data for uncertainties such as glaciation and earthquakes.**
- **A probabilistic study of canister strength and structural integrity was made.**
- **Two pressure tests of canister mock-ups (full diameter, 95 cm long) were performed and collapse pressure was about 130 MPa.**
- **Nondestructive testing of cast iron was started for detecting defects in various parts of the cast iron insert.**
- **First calculations resulted in 19% plastic strain in cast iron insert with 20 cm rock shear (for 10 cm rock shear plastic strain was 1,6%)!**

History of KBS-3 geological spent nuclear fuel disposal in FUD-program

In FUD program during 2001…2007 the cast iron insert issues have been examined as follows:

- **Corrosion (including galvanic and stress corrosion) of cast iron was studied from canister tightness point of view in anoxic ground water. In FUD 2007 fuel drying was considered since residual water can cause long-term anoxic corrosion of cast iron resulting in the formation of hydrogen.**
- **In FUD 2007 long-term integrity of the canister insert for creep and other time-dependent phenomena was considered. Preliminary creep testing of cast iron was started, but since the total creep strain was small (less than 0.1%) creep has been omitted in later mechanical analyses.**
- **In FUD 2007 it was concluded that even though the calculations and modelling of the radiation dose to cast iron insert show small consequenses, the effects of irradiation on the cast iron insert must be studied further. The neutron fluence during 100000 years was estimated to be 4×10^{15} neutrons/cm^2 (E>1 MeV), while 10^{18} neutrons/cm^2 starts to cause detectable embrittlement in pressure vessel steel.**

History of KBS-3 geological spent nuclear fuel disposal in FUD-program

In FUD program during 2010…2019 the cast iron insert issues have been examined as follows:

- In FUD 2010 and 2013 requirements for manufacturing of cast iron insert and on the mechanical properties and acceptance criteria (design analysis) were presented.
- Canister must stand isostatic loading of 45 MPa (max. swelling pressure of bentonite and hydrostatic pressure). Max. acceptable rock shear (displacement-controlled load) is 5 cm, which results in local yielding and 1-2,5% plastic strain in the cast iron insert.
- Environment inside the canister contains > 90% Ar and fuel elements are dried so that the amount of water is max. 600 g (Ar-air-water vapor mixture). Radiation level outside canister is < 1 Gy/h.
- Nondestructive testing of cast iron insert was prioritized close to surface regions. Largest acceptable semi-elliptic surface cracks have critical depth of 4.5 mm.

History of KBS-3 geological spent nuclear fuel disposal in FUD-program

In FUD program during 2010…2019 the cast iron insert issues have been examined as follows:

- Initial state for canister was defined as properties when canister is placed in the deposition hole. Max. temperature is < 100ºC on the canister surface and 125ºC in the cast iron insert.
- Theoretical studies of irradiation on cast iron insert were continued taking into account Cu precipitation, P diffusion to grain boundaries and Late Blooming Phases (LBP) (Ni, P, Mn, Si, etc.).
- A preliminary study on charging, degassing and distribution of hydrogen in cast iron was made in 2015. It was proposed that modelling of hydrogen uptake in cast iron will be made and hydrogen effects on the strength properties of cast iron will be determined.
- In FUD 2016 and 2019 the design and defect analyses of cast iron insert are renewed and it was proposed that the requirements for mechanical properties (especially elongation to fracture) and acceptable defect sizes of cast iron as well as inspection volumes can be reduced.
- In FUD 2019 strain aging (blue brittleness) of cast iron was considered the first time and a test matrix for dynamic strain aging was proposed, but static strain aging was not thought to occur.

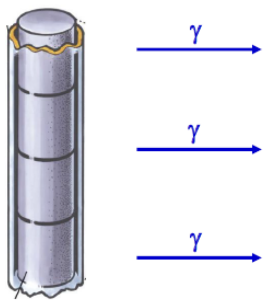
Embrittlement mechanisms of cast iron – definitions

- **Hydrogen embrittlement** of cast iron occurs because even small amounts of hydrogen can severely embrittle the ferrite matrix. Embrittlement occurs between -100 and +100ºC and is enhanced by slow strain rate. Fracture mode is brittle cleavage fracture of ferrite.
- **Irradiation** of cast iron results in hardening due to vacancies and precipitates and embrittles the metal. Radiation-induced segregation of different chemical species towards defect sinks (grain boundaries, dislocations, etc.) occurs also.
- **Strain aging** (dynamic and static) (blue brittleness) of cast iron is similar to that of carbon steels. Small preliminary plastic strain of iron and low temperature aging causes hardening due to free C and N atoms, i.e. very marked yield point, and brittleness of the material even at room temperature. Due to the pronounced high yield point the material rapidly reaches a high stress and failure occurs at a low elongation. Fracture mode is ductile dimpled fracture.
- **Creep** of cast iron is caused by plastic fow under constant stress under a long period of time. Some form of transient creep will occur at all temperatures, but creep rate is very temperature dependent.

Hydrogen absorption to copper and cast iron

- In sulphide-containing environments copper corrosion (2Cu + HS^- => Cu_2S + H^+ + e^-) is supported by the evolution of hydrogen. Some water remains trapped inside the fuel elements after the canister is closed and hydrogen is also formed inside the canister in corrosion reactions of cast iron.
- Hydrogen can be absorbed in copper canister both on outside and inside surfaces.
- A majority of the hydrogen atoms formed in corrosion combines to form hydrogen gas, but a fraction enters the copper and cast iron.
- Corrosion on copper surface is also controlled by the transport rate of gaseous H_2 away from the canister surface. Diffusion in compacted, water-saturated bentonite is, however, low.
- Ionizing radiation may enhance hydrogen absorption in copper and cast iron in a number of ways.

Radiation-induced corrosion of Cu nuclear waste canisters



The dominating nuclide in the fuel responsible for γ – radiation is Cs-137, with a half-life of 30 years

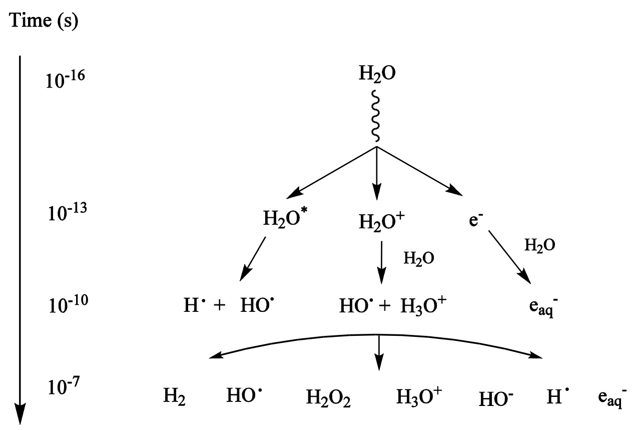
Radiation induced corrosion of copper is then mainly expected during the initial phase of deep repository

The outer copper canister surface will receive an estimated maximum total radiation dose of approximately 100 kGy (1Gy = 1 J /kg) during the first 100 years in deep repository.

Radiolysis in the aqueous phase occurs upon absorption of γ-radiation. Produces short- and long-lived radiolytic products, two of which have higher standard reduction potentials than copper:

$H_2O_2/2H_2O$	1.77 V vs. SHE
$HO^{\cdot}/H_2O$	2.59
$Cu^{+}/Cu(s)$	0.52
$Cu^{2+}/Cu(s)$	0.34

Å. Björkbacka, S. Hosseinpour, M. Johnson, C. Leygraf and M. Jonsson, Radiation Physics and Chemistry, 92 (2013) 80



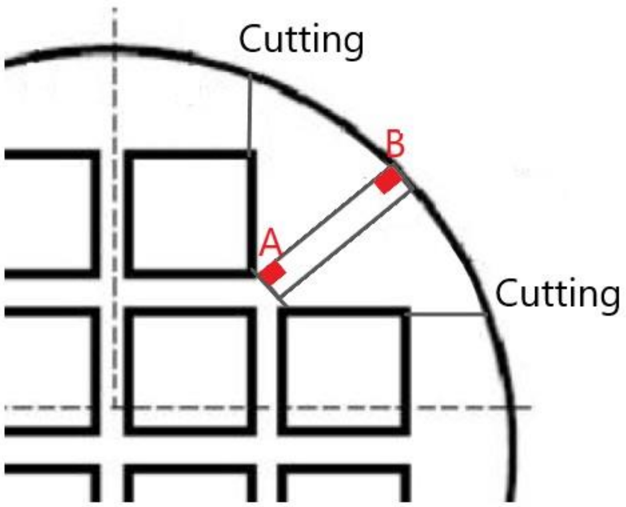
Motivation to study hydrogen effects on cast iron

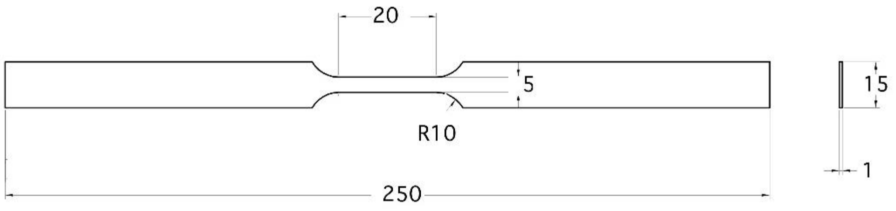
- There are both internal and external sources of hydrogen in the copper canister that can cause **hydrogen embrittlement**. In accordance with the design conditions for the canister, the amount of water left in each canister must be less than 600 g. It is plausible that oxygen-free iron corrosion can occur, causing hydrogen uptake and producing hydrogen gas.
- There are relatively few research reports on hydrogen embrittlement of ductile cast iron with a ferritic matrix.
- The hydrogen content of the cast iron (about 2 wt.-ppm) is much higher than that in carbon steel, for example, even with a high pearlite content.
- A systematic study was made on hydrogen effects on ductile cast iron used for the copper canister insert structure to understand the mechanisms of hydrogen embrittlement of cast iron better.
- At present there are no data on the effects of blue brittleness, radiation-induced embrittlement, hydrogen embrittlement and creep together. The future aim is to study these embrittlement mechanisms and their joint interaction with hydrogen embrittlement.

Experimental. Studied material and methods

Chemical composition of the nodular cast iron EN-GJS-400-15U used for the cast iron insert, wt. % .

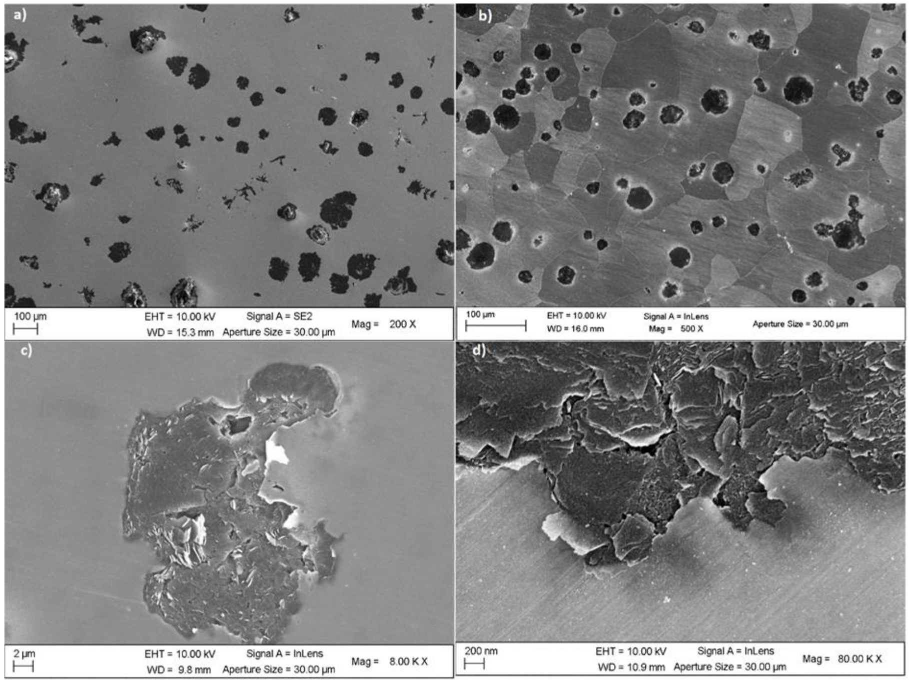
C	Si	Mn	S	P	Ni	Cu	Mg	Fe
3.48	2.48	0.22	0.004	0.01	0.04	0.02	0.04	bulk





Cutting of the test specimens and specimen type and size.

Material



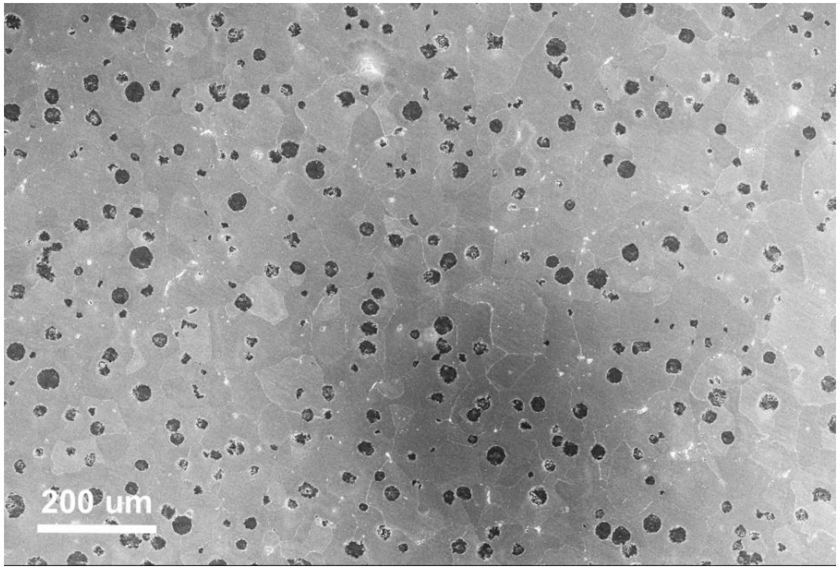
- Cut from Posiva insert I73

C	Si	Mn	S	P	Ni	Cu	Mg	Fe
3.48	2.48	0.22	0.004	0.01	0.04	0.02	0.04	Bulk

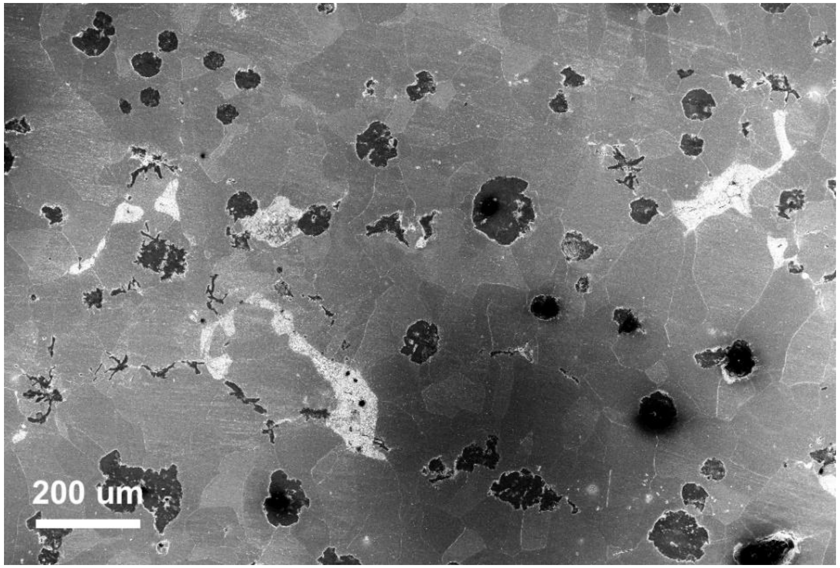
- Ferritic matrix with graphite nodules

Experimental. Studied material and methods

Type A



Type B



- *Cast iron of the outer surface of the insert manifests a markedly coarser microstructure.*
- *Volume fractions of the graphite nodules are 0.059 and 0.056 in A- and B-type of the cast iron, respectively.*
- *Average nodule size in the A-type cast iron is 20.4 μm, while in the B-type it is 44.5 μm.*
- *Graphite nodule densities are 6.96×10^{12} m^{-3} and 6.31×10^{12} m^{-3}, respectively.*
- *Nodularity (type V and VI) is close to 100 % and pearlite content is less than 5 %.*

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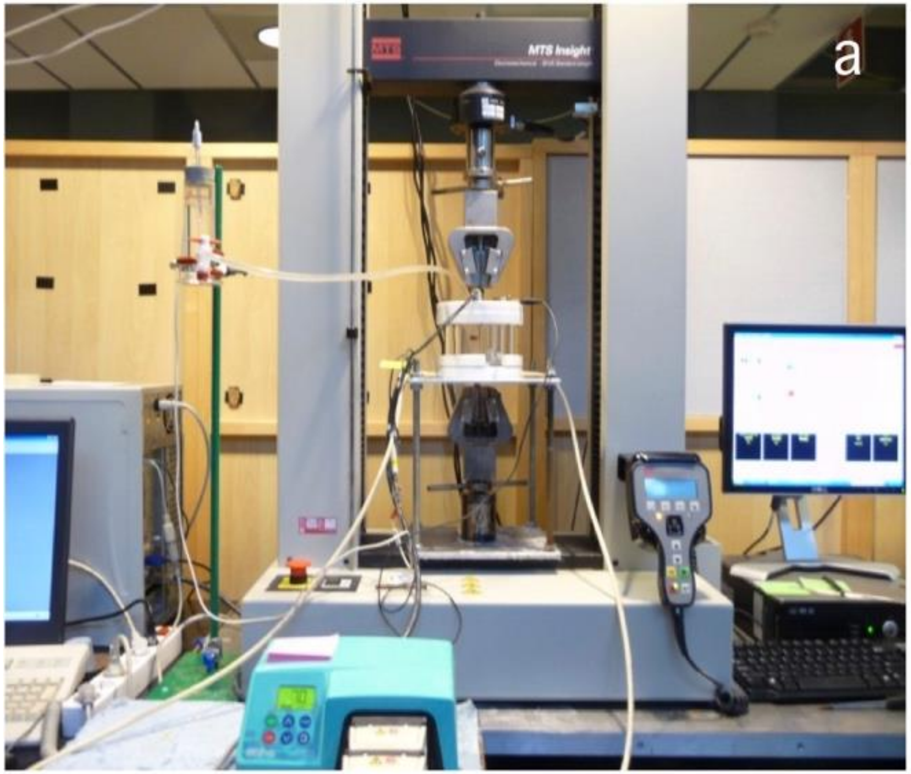
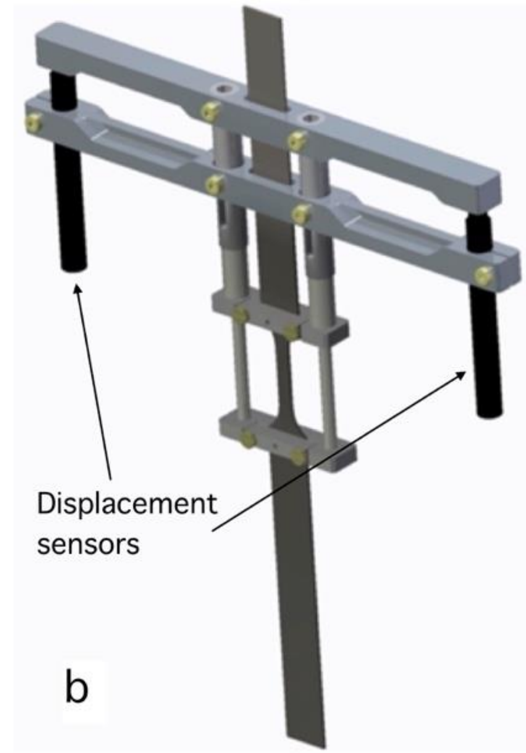
Experimental. Studied material and methods





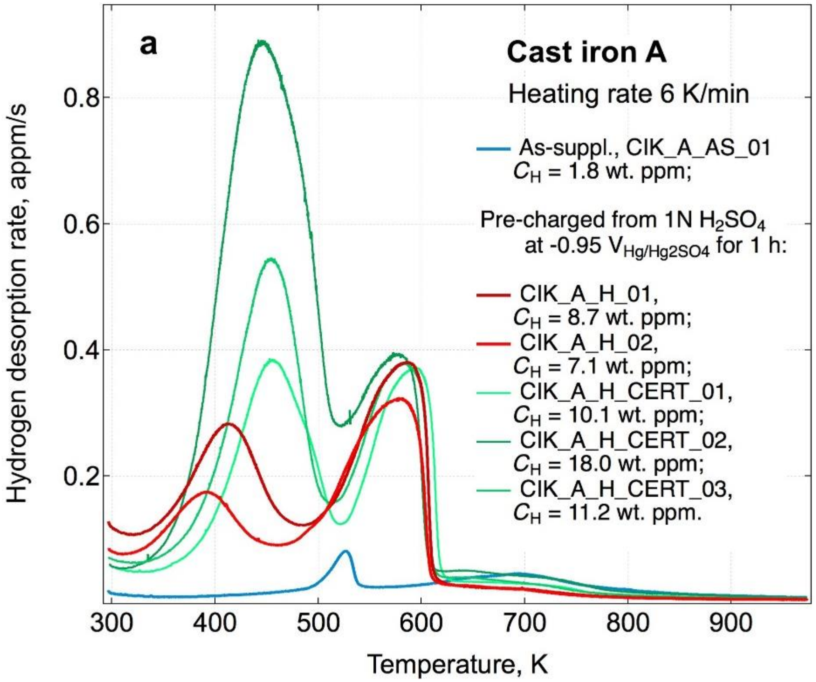
The testing system consisting of 35 kN MTS desktop machine equipped with electrochemical cell and Gamry potentiostat to control the applied electrochemical potential a) and extensometer device for displacement measurement in CLT b).

Experimental. Studied material and methods

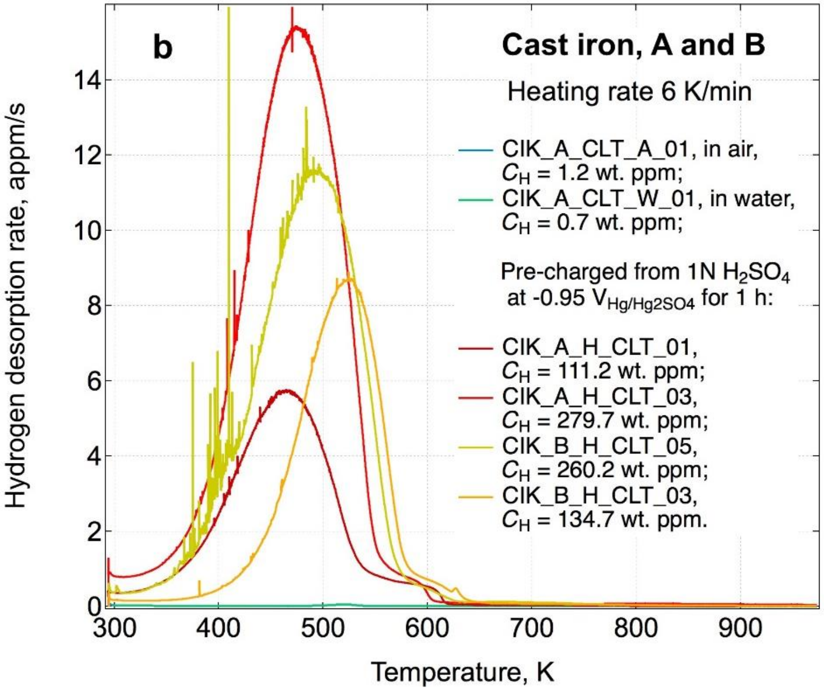
- *TDS apparatus designed and assembled at Aalto University School of Engineering;*
- *Vacuum in the UHV chamber better than 5 $\times$ 10^{-9} mbar;*
- *The apparatus allows to measure a small quantity of hydrogen in metals up to 0.1 at. ppm;*
- *The temperature of the TDS measurements ranges from RT to 1200 ^{o}C;*
- *The heating rates of the specimen are in the range of 1 to 10 K/min.*

Hydrogen uptake and trapping in cast iron

CERT



CLT



TDS curves show few characteristic peaks of hydrogen desorption rate.

a) CERT results in a dramatic increase of the 400 K peak, while the 500 K peak increases only slightly.

b) TDS after CLT shows a dramatic increase of the 400 K peak and corresponding hydrogen uptake.

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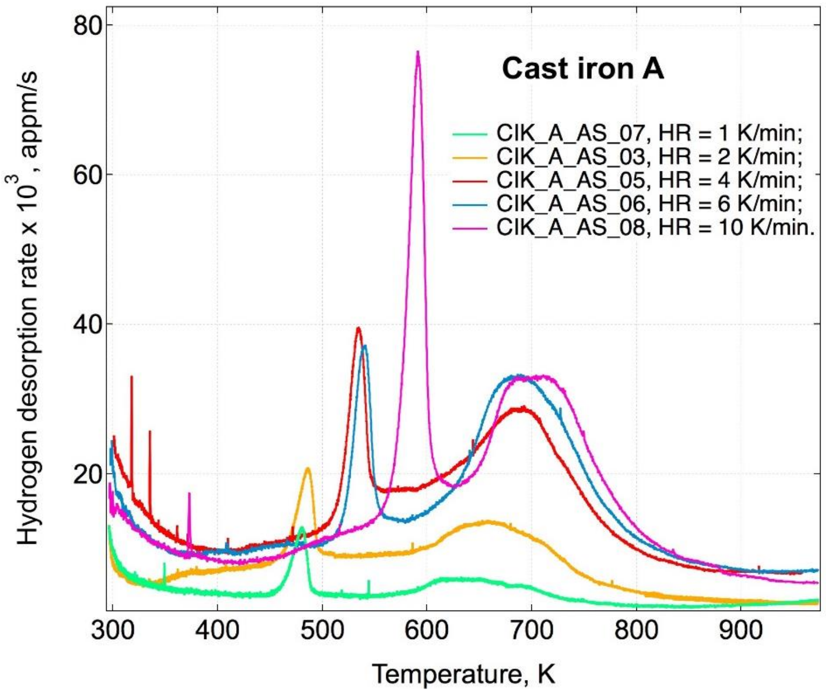
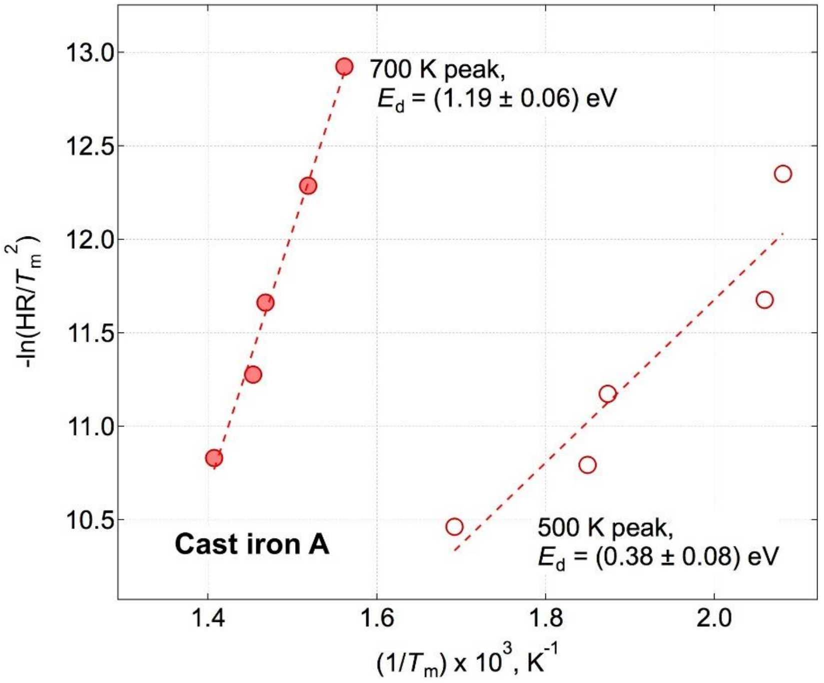
Activation analysis of hydrogen TDS peaks of cast iron



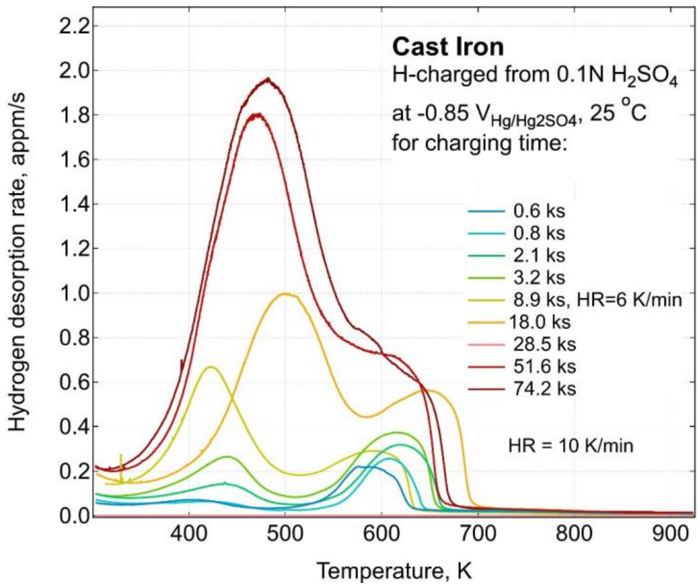


a) Shift of the temperature position of 500 K and 700 K TDS peaks with heating rate.

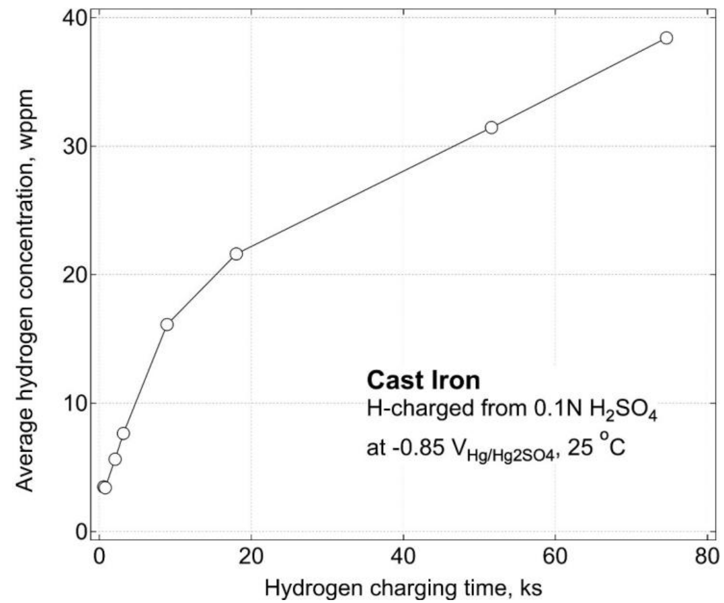
b) The activation energies of hydrogen desorption from trapping sites are 0.38 ± 0.08 eV and 1.19 ± 0.06 eV for 500 K and 700 K peak, respectively.

Hydrogen uptake in cast iron under electrochemical hydrogen charging

TDS curves vs. temperature after electrochemical H-charging for different times



Hydrogen content vs. H-charging time



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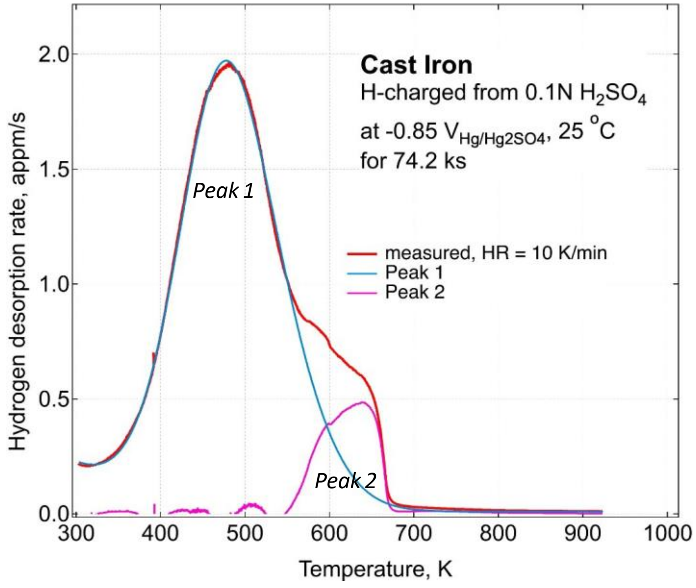
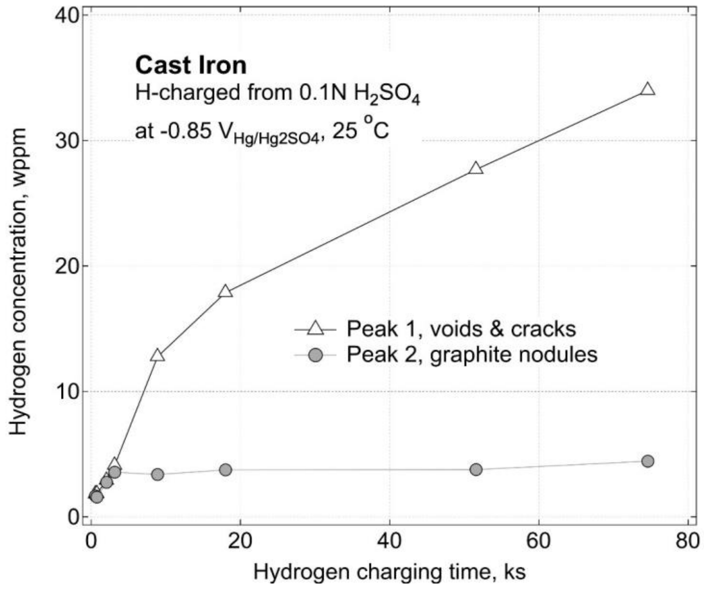
The two components of hydrogen TDS curves of nodular cast iron

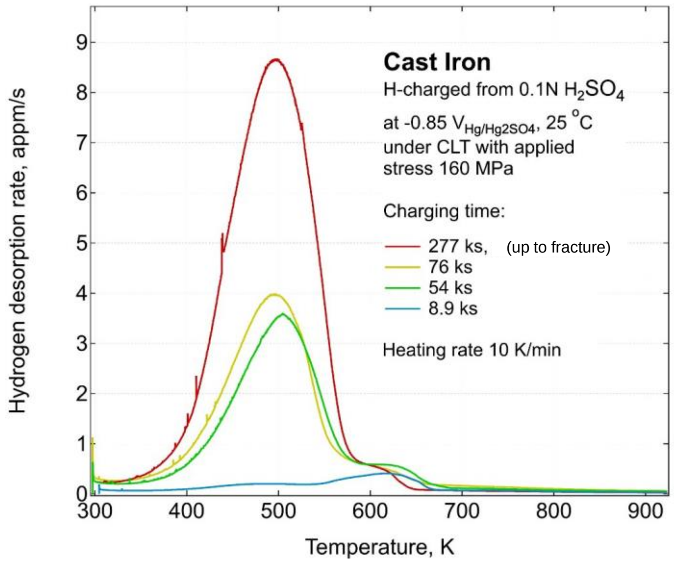
The TDS peak of nodular cast iron consists of two main components; The first component (Peak 1) originates, probably, from hydrogen gas collected in voids formed around the graphite nodules and short cracks caused by internal hydrogen pressure. The second one (Peak 2) corresponds, probably, to hydrogen trapped in the graphite nodules. The hydrogen content in the two peaks may be separately calculated.

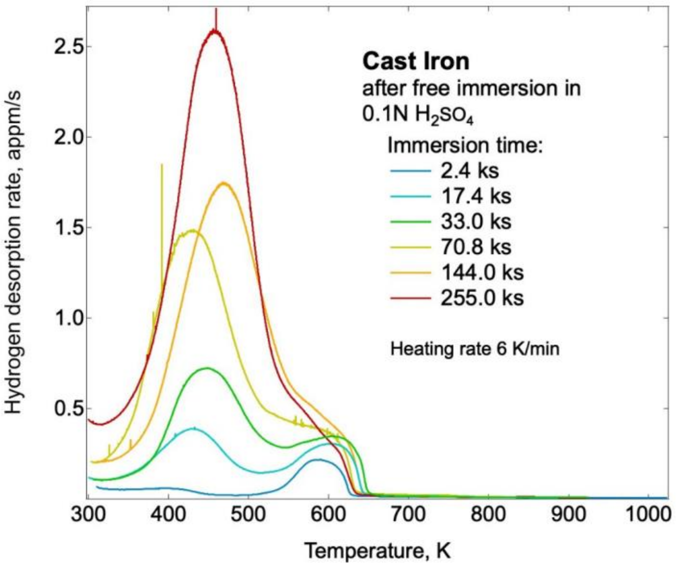




Hydrogen uptake in cast iron under continuous H-charging and constant load testing, and in free immersion in weak sulfuric acid

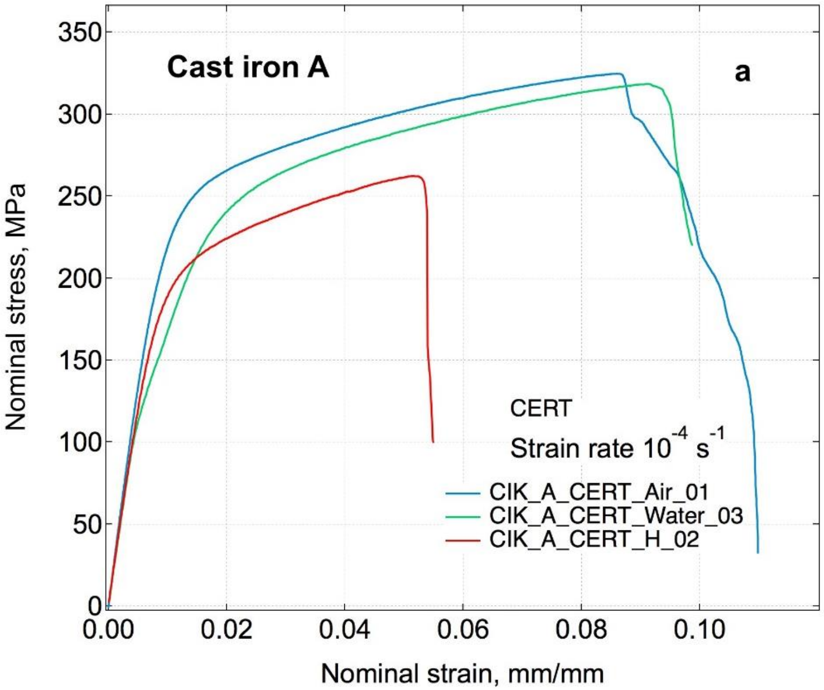
Tensile loading of cast iron under continuous H-charging results in a remarkable increase of hydrogen uptake and consequent early fracture. Hydrogen uptake in cast iron takes place even in free immersion in 0.1N sulfuric acid solution. This may be relevant, for example, if the canister inserts are stored outside.



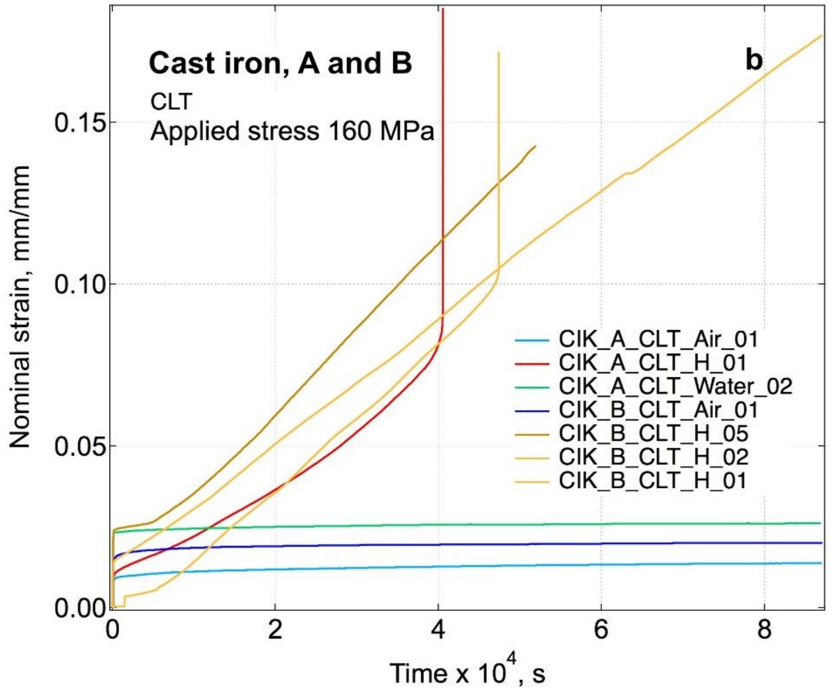


Hydrogen effects in tensile testing of cast iron

CERT



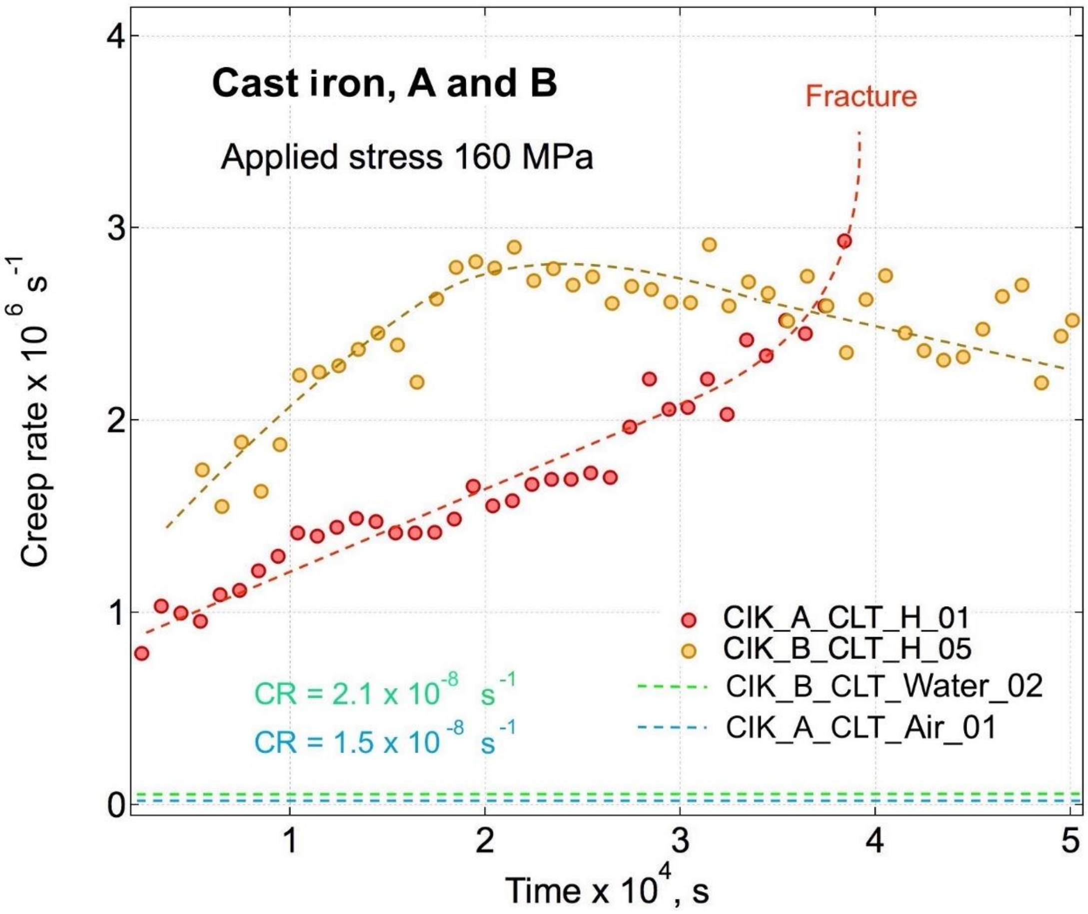
CLT



a). CERT of A-type specimens in air, distilled water, and under continuous hydrogen charging.

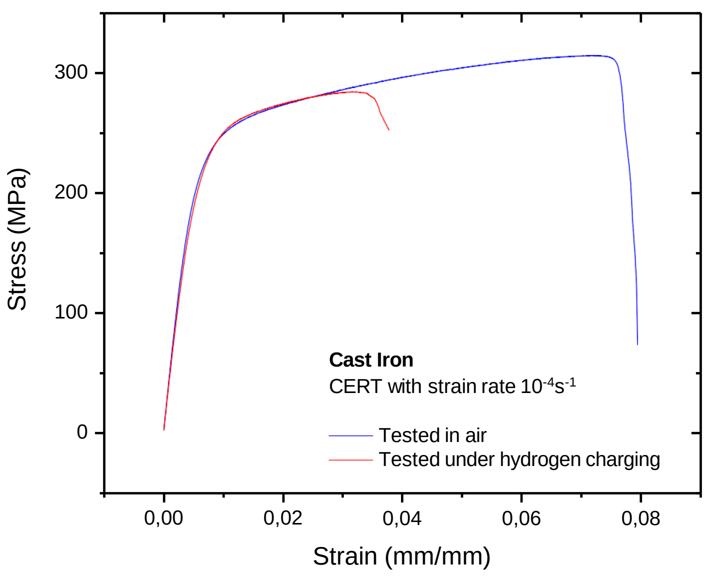
b). CLT at applied stress of 160 MPa in air and distilled water, as well as under continuous hydrogen charging. A remarkable increase of strain and strain rate in CLT under continuous hydrogen charging is observed.

Creep rate of cast iron under continuous H-charging

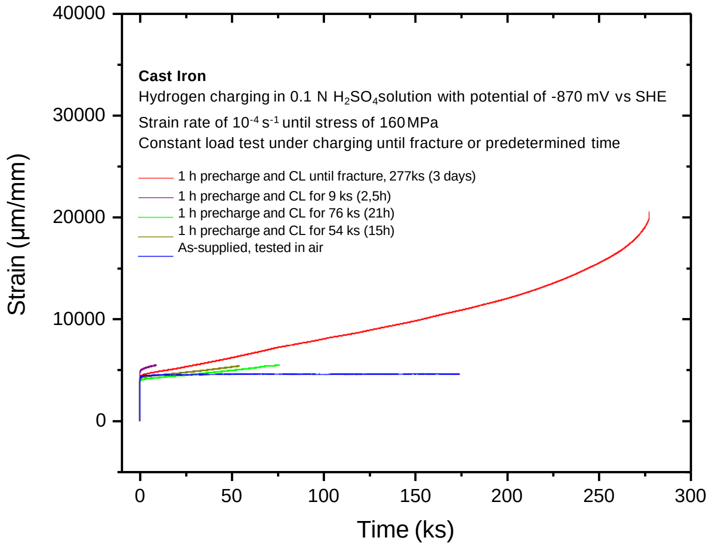


- *Under continuous hydrogen charging the creep rate of both types of cast iron specimens, A and B, is about two orders of magnitude higher than that for the specimens tested in air or distilled water.*
- *Creep rate of the B-type cast iron specimens is about two times faster than that of A-type specimens.*

Tensile tests under hydrogen charging



Several interrupted constant load tests were performed.



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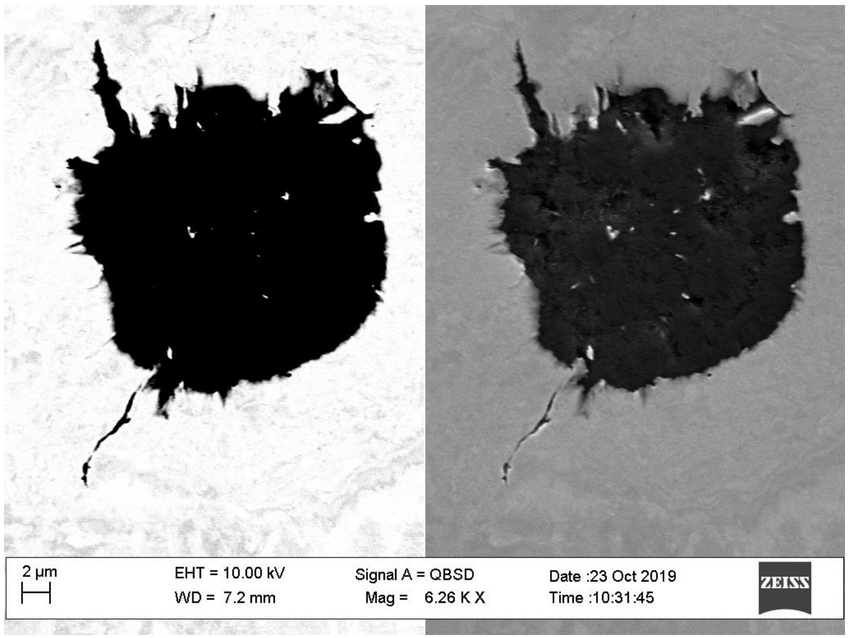
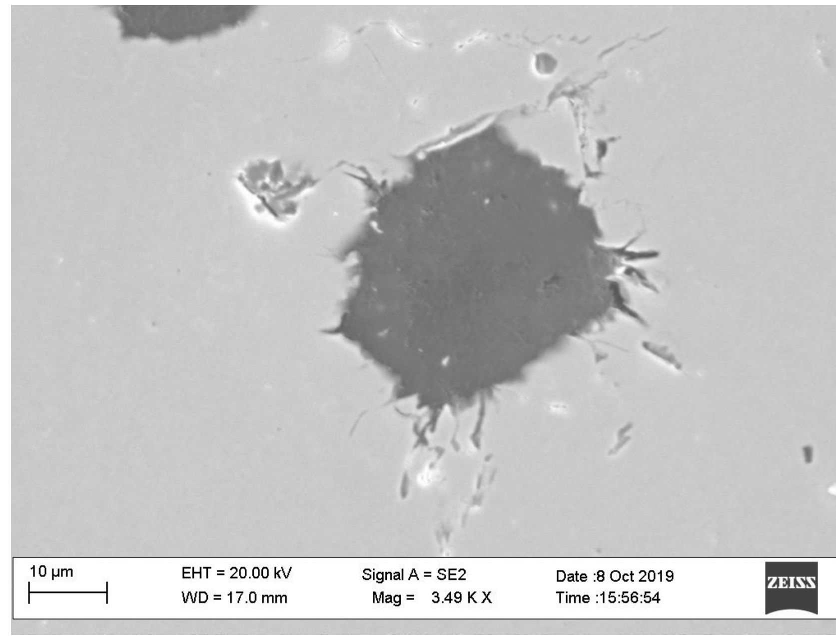
Graphite morphology of different states: as-supplied and free immersed

As-supplied: some defects from manufacturing

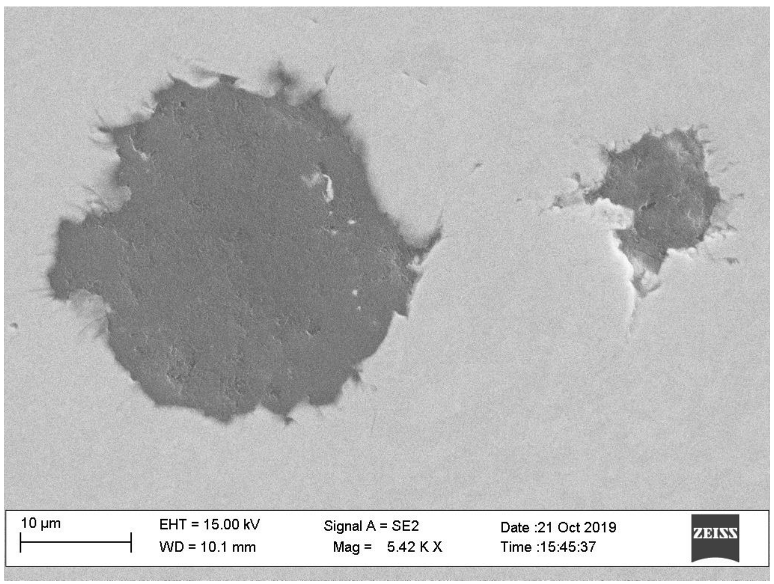


Free immersion in 0.1N H_2SO_4 for 48 hours: small defects may be found around the graphite nodules

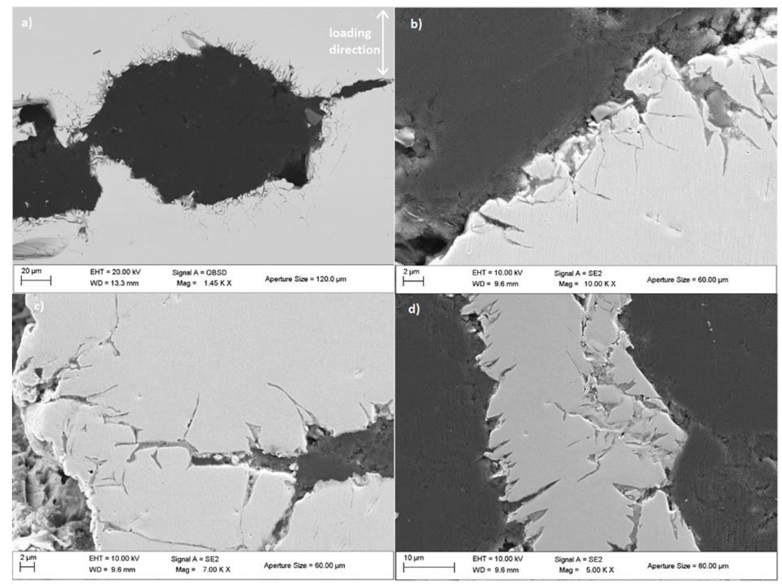


Graphite morphology of different states: electrochemical H-charging and constant load testing in H-charging

Electrochemical charging for 14 h may result in some nodules having small cracks around them and some linking in between.

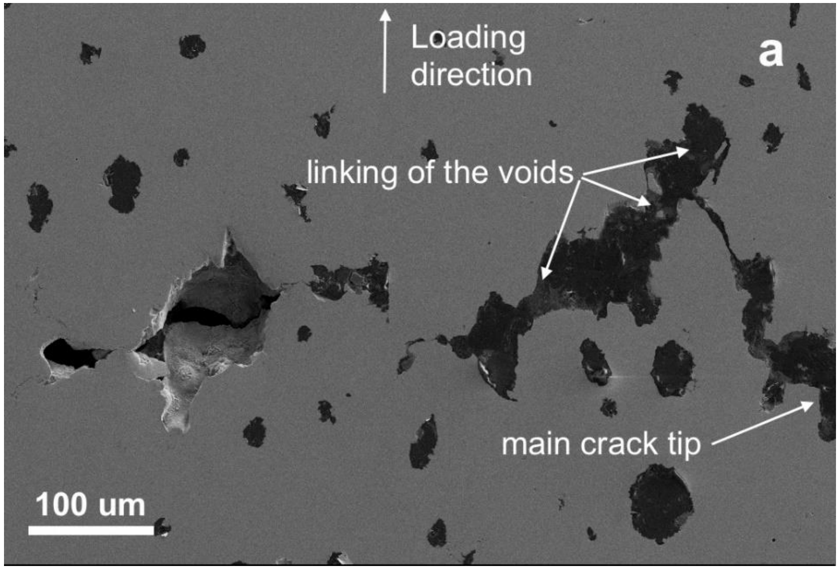


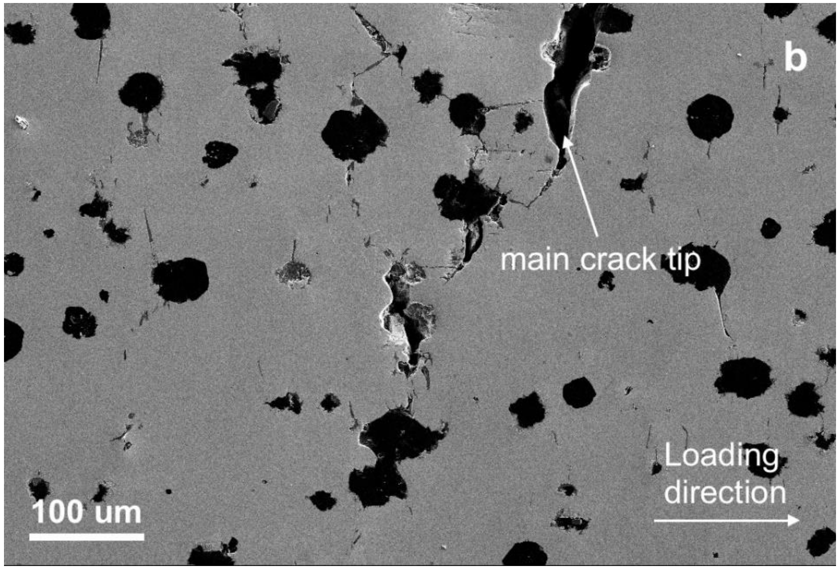
H-charging + constant loading results in the nodules having small cracks around them and cracking in the ferrite matrix linking nodules.



Hydrogen effect on crack advance in cast iron

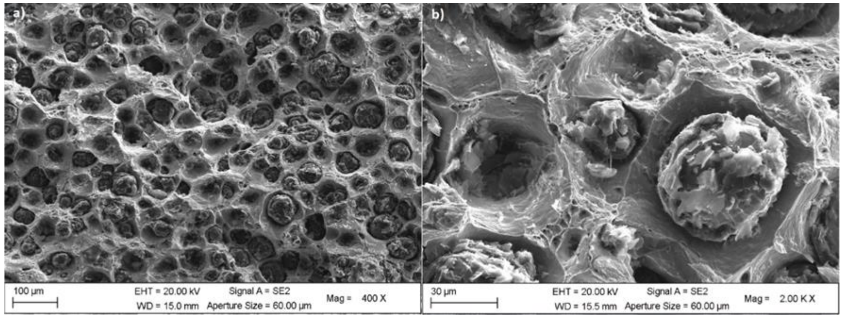
H-free **H-charged**

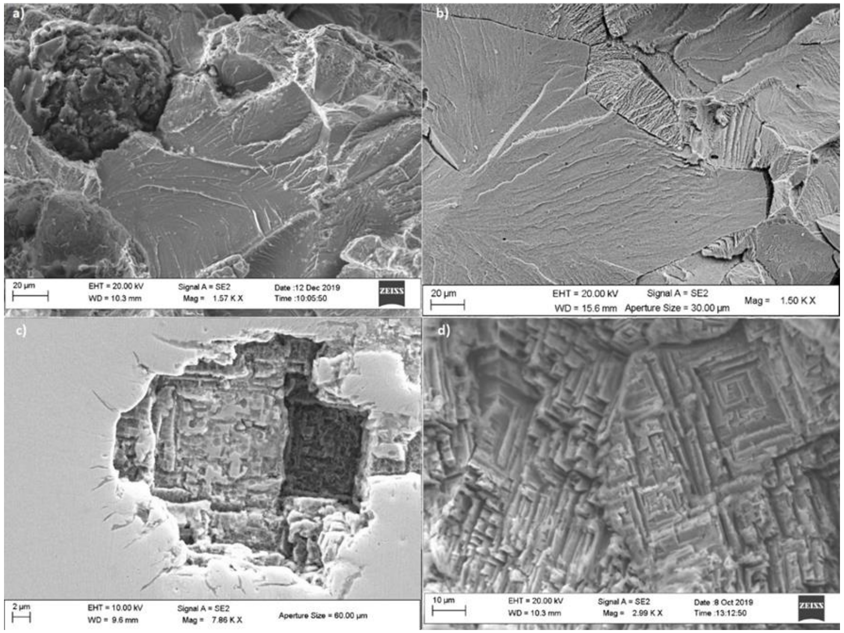




Side-view of the polished specimen surface ahead of the crack tip after interrupted CLT in distilled water a) and under continuous H-charging b). The ligaments between the large voids crack by shear and development of microvoids in distilled water a) and by cleavage fracture in the presence of hydrogen b).

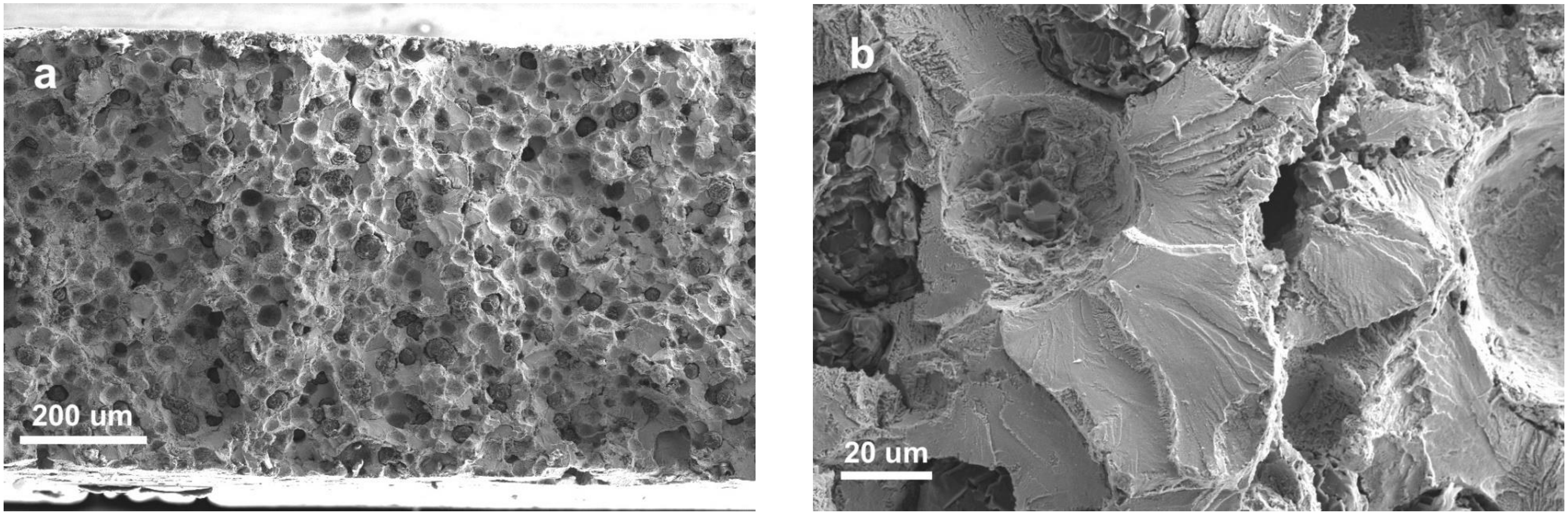
Fracture surface examination





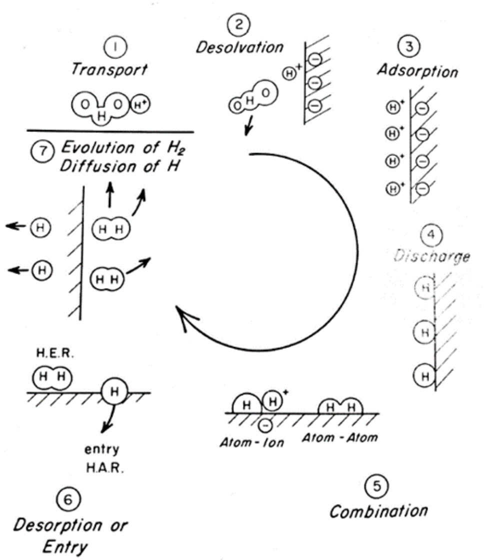
- Above: the fracture surface of uncharged CERT sample
- Right: hydrogen charged CLT specimen

Hydrogen-induced fracture of cast iron

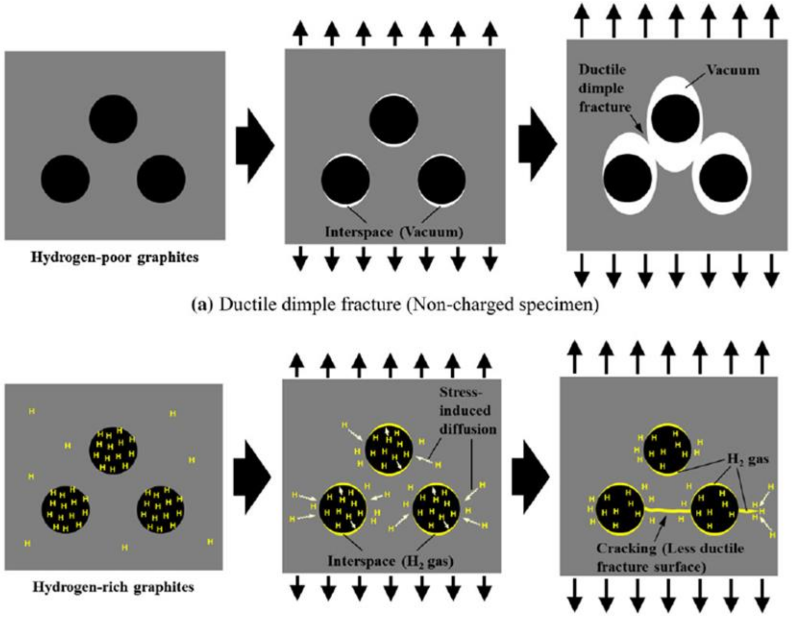


Fracture surface of A-type cast iron after CLT under continuous H-charging a) and fractography of a large dimple around the graphite nodule showing the initiation of the brittle cleavage facets from the graphite nodule interface b).

Hydrogen in DCI

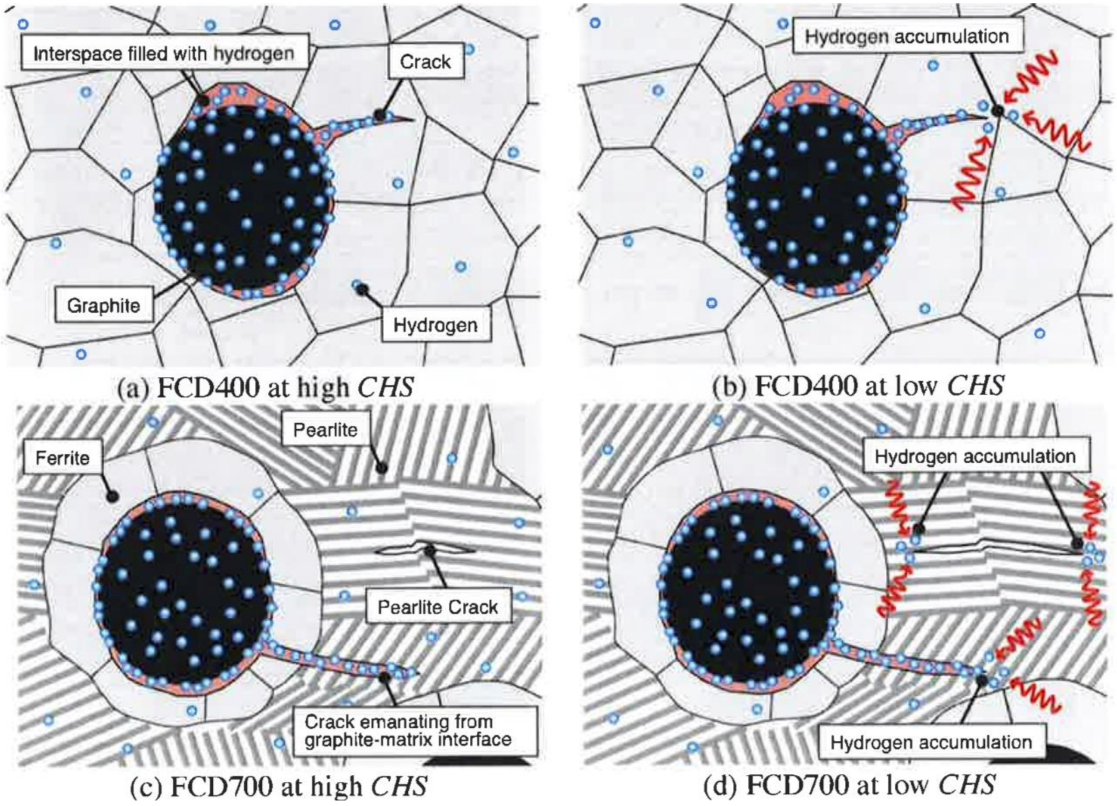


The hydrogen evolution and absorption reactions. (McCright 1973)



Ductile a) and hydrogen-induced b) fracture mechanisms of DCI. (Matsunaga, Usuda et al. 2014)

Mechanism of hydrogen-induced cracking of cast iron



By T. Matsuo, 2017, Journal of Physics: Conf. Series, 843, 012012.

Schematic illustration of crack growth of hydrogen-charged ductile cast iron.

Summary of hydrogen effects on ductile cast iron

- Hydrogen TDS from the cast iron manifests three distinct peaks with maxima located close to 400 K, close to 500 K, and at 700 K at TDS heating rate of 6 K/min. The 400 K peak and corresponding hydrogen concentration increase markedly, up to two orders of magnitude after CLT under continuous hydrogen charging as compared to the unloaded pre-charged specimen.
- CLTs of cast iron under continuous hydrogen charging result in a remarkable increase of the creep strain and strain rate up to 10^{-6} s^{-1} as compared to the CLTs in air and distilled water, where the creep strain rate was about 10^{-8} s^{-1}.
- Fractography of the cast iron specimens after CERT and CLT under continuous hydrogen charging manifests large dimples forming around the graphite nodules. Ligaments between the dimples consist of brittle cleavage fracture facets in the presence of hydrogen, while these ligaments show a characteristic ductile appearance of shear and microdimples in air and distilled water.
- Micrographs of the crack advance in hydrogen-free cast iron show large void formation at the graphite nodules ahead of the main crack growing under applied load by linking of the voids by shear and sheet of microdimples.
- Continuous hydrogen charging under applied load results in a number of brittle cleavage cracks initiating from the graphite nodules and their coalescence ahead of the main crack causes the crack advance.

Summary of hydrogen effects on cast iron insert

- The damage tolerance analyses of the cast iron insert are based on the allowed defect sizes and actual mechanical properties without properly taking into account, e.g., hydrogen embrittlement, blue brittleness, irradiation embrittlement and creep.
- The mechanical degradation mechanisms for cast iron inserts in deposition conditions include only ductile collapse (buckling). Brittle cleavage fracture is excluded and cast iron is considered to be ductile material in all expected conditions in the repository. However, ductile cast iron has a ductile-to-brittle transition temperature in low temperatures and at increased strain rates.
- The ductility of ductile cast iron is affected drastically by hydrogen and brittle cleavage fracture occurs around the graphite nodules. The separation of graphite from the matrix takes place before the initiation of cracks, and the susceptibility to brittle cracking increases if the strain rate decreases.
- There is no data summarizing effects of hydrogen embrittlement, blue brittleness, irradiation embrittlement, hydrogen embrittlement and creep together on performance of ductile cast iron which is prone to all these embrittlement mechanisms.

The effects of static strain aging on mechanical performance of nodular cast iron

MSc. thesis of Ville Björklund

Motivation and aims of the study

Motivation:

- The nuclear decay of the spent fuel causes the temperature inside the canister insert to increase up to 125 ℃.
- The canister may be subject to bending and yielding due to a rock shear movement crossing the deposition hole.

→ The cast iron insert may be subject to static strain aging (SSA):

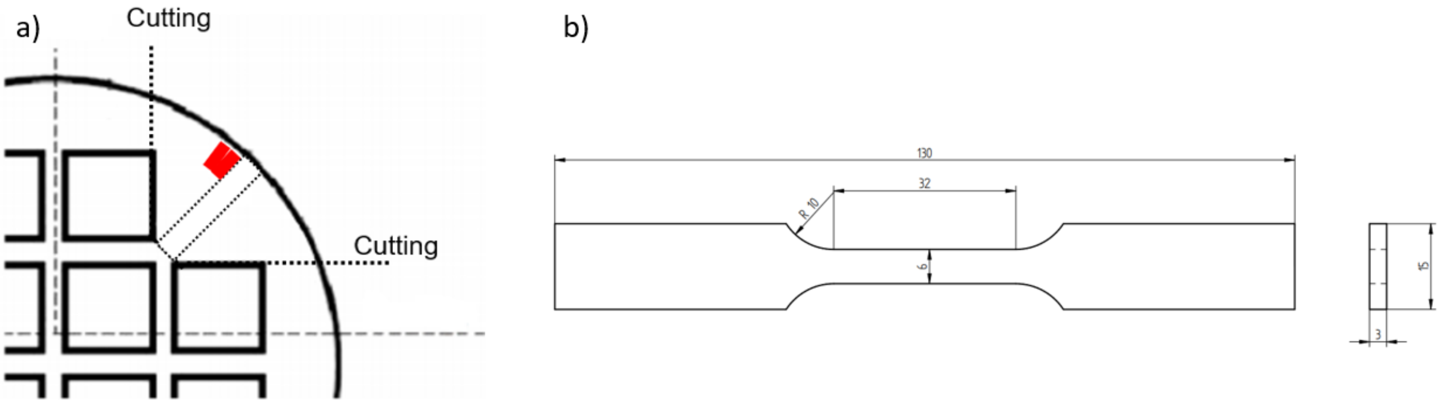
  - SSA is a known phenomenon of ferritic steels even at low temperatures
  - SSA of ductile cast iron has not been studied, yet

Aims of the study:

- To study if SSA can occur in the cast iron insert in the repository conditions
- How SSA affects the mechanical properties of the cast iron insert

Material and specimen geometry

- Tensile specimens were manufactured from casting I73 provided by Posiva

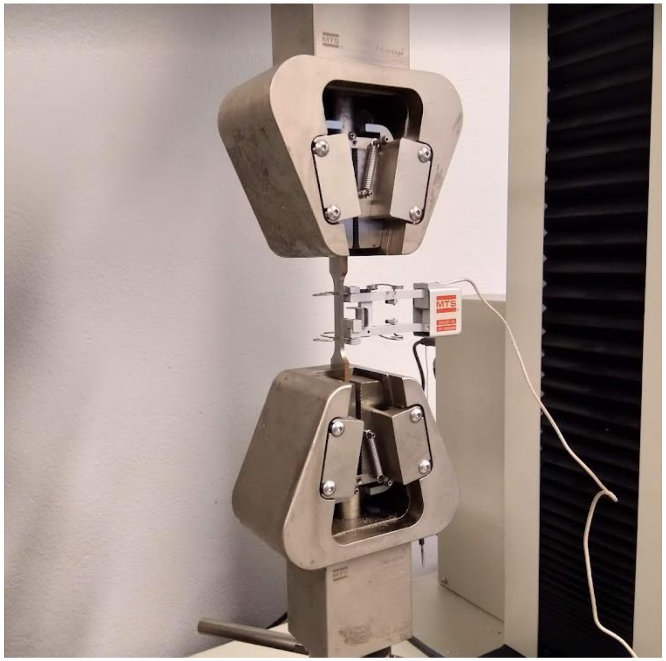


C	Si	Mn	S	P	Ni	Cu	Mg	Fe
3.48	2.48	0.22	0.004	0.01	0.04	0.02	0.04	Bulk

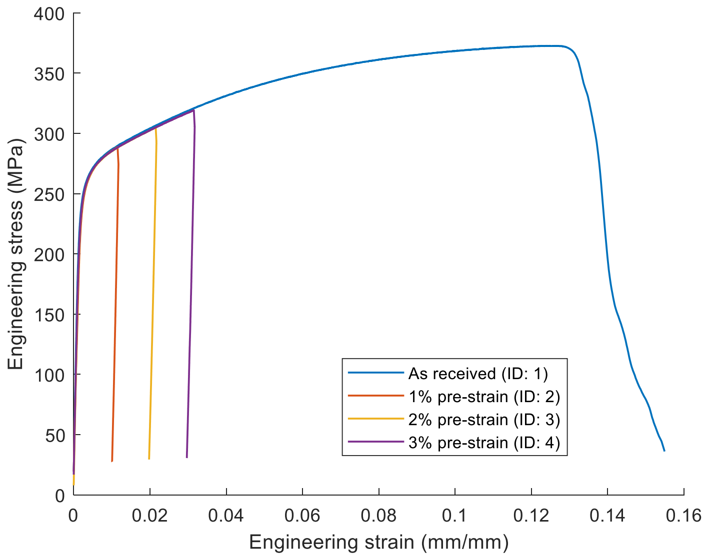
Chemical composition of the nodular cast iron EN-GJS-400-15U used for the cast iron insert, wt.%

Experimental methods

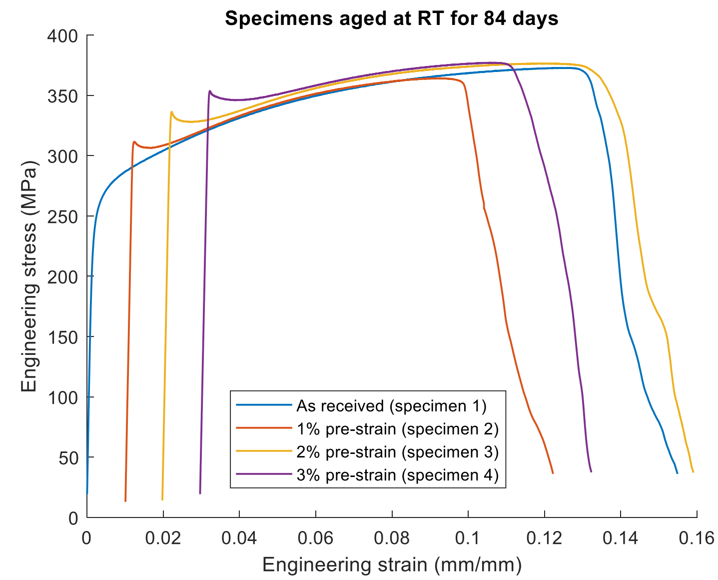
- Specimens were pre-strained to 1%, 2% or 3% plastic strain with constant cross-head speed of 0.016 mm/s.
- Specimens were aged at RT, 100℃, 200℃, 300℃ and 400℃ for varying times.
  - Additionally non-strained specimens were aged at 100℃ and 200℃ in order to rule out thermal aging (no effect was found).
- Tensile tests were performed for aged specimens with the same constant cross-head speed.
- 4 specimens were patterned with spray paint and pre-straining and tensile tests were performed using digital image correlation (DIC).



Results



Aging



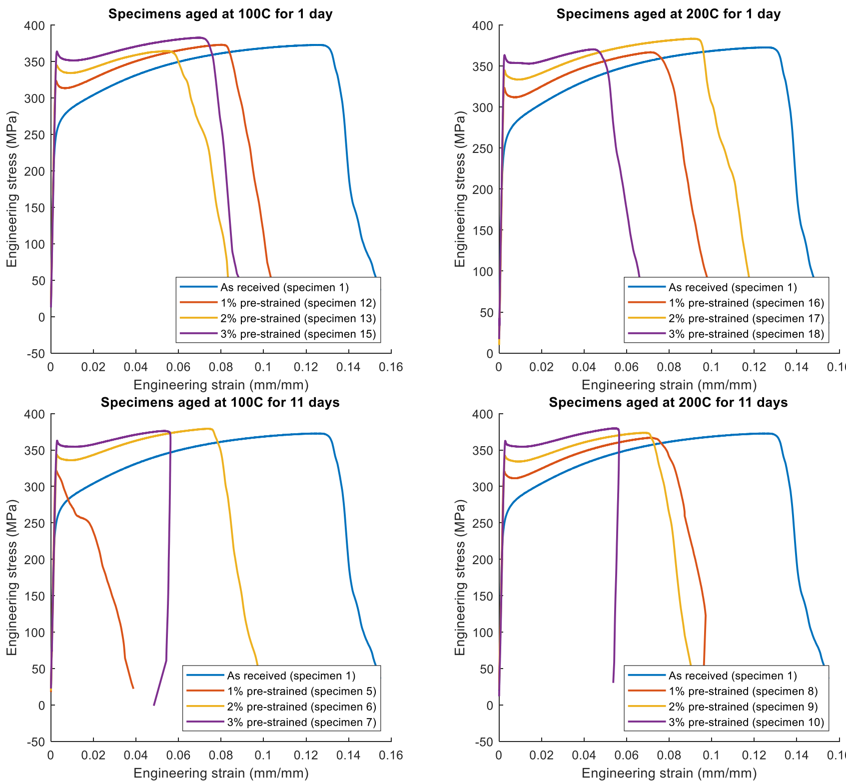
Pre-straining

Tensile test

Aalto University

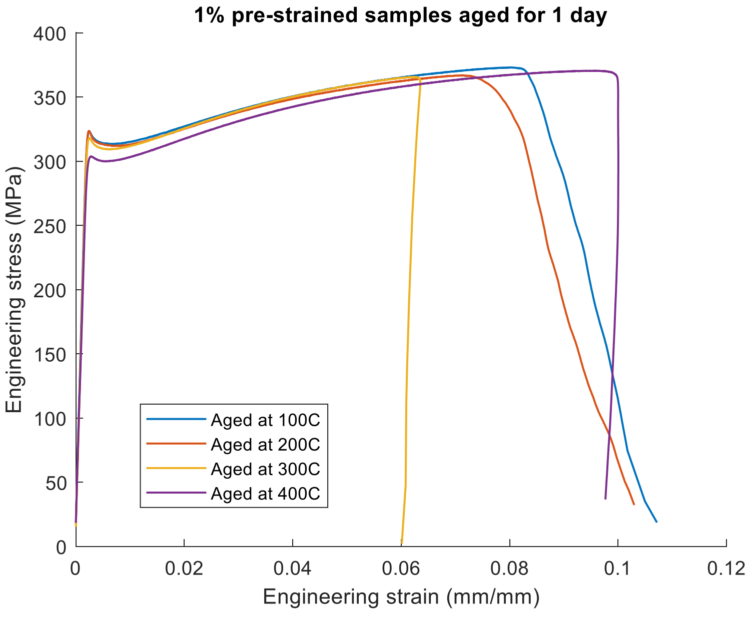
Results

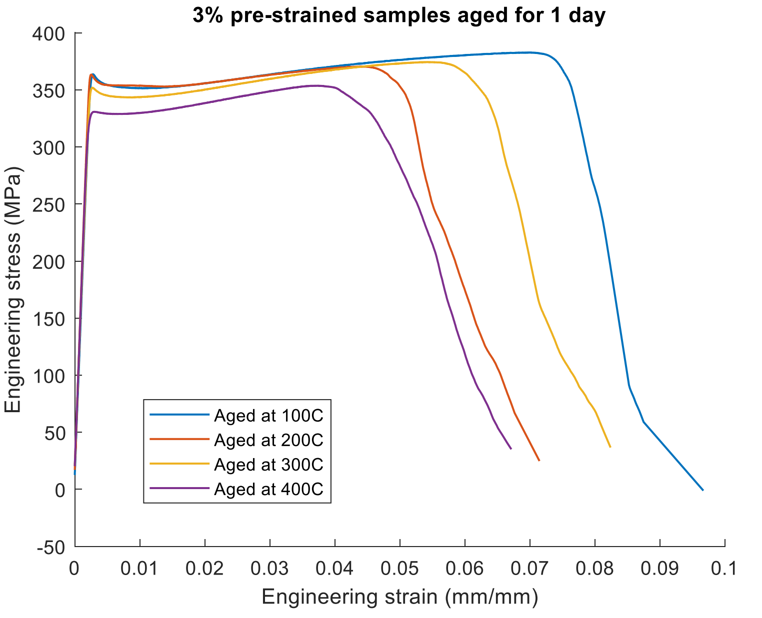
- Aging saturates already after 1 day aging at 100℃:
  - No further yield stress increase at higher temperatures.
  - No marked difference in yield stress between 1 day and 11 days aging at 100℃ and 200℃.
  - The scatter in the elongation to fracture is caused by casting defects and natural scatter in the microstructure.



Results

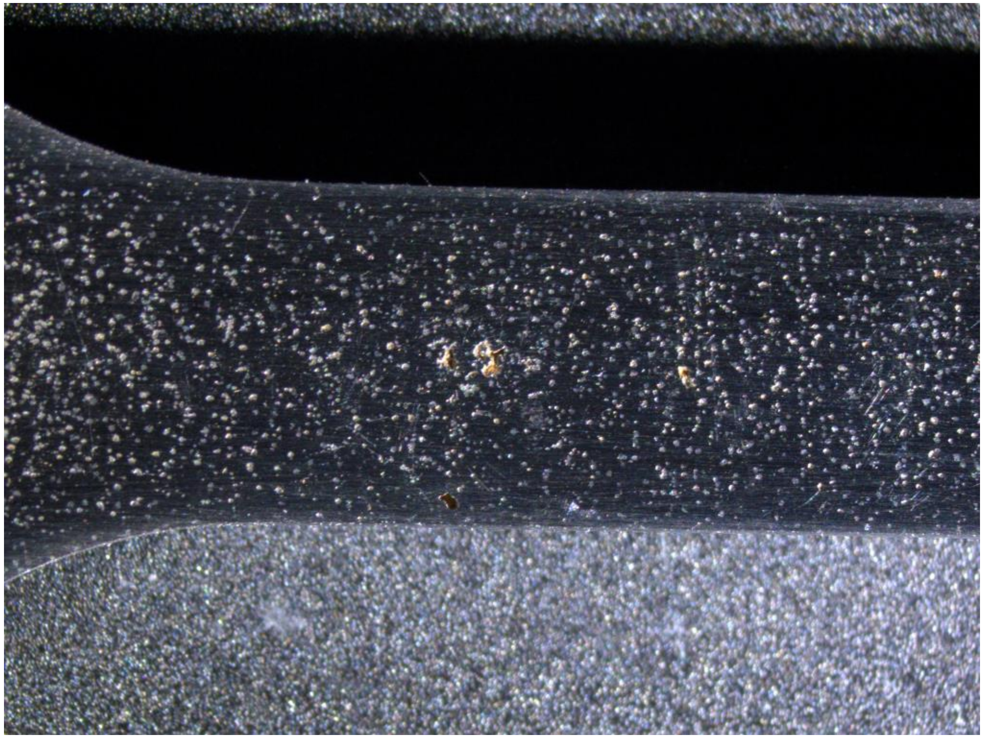
- At higher temperatures of 300℃ and 400℃ yield stress increases less than at lower temperatures and the yield point becomes less pronounced.
- Whether or not similar overaging occurs at lower temperatures in longer time scale is not known.





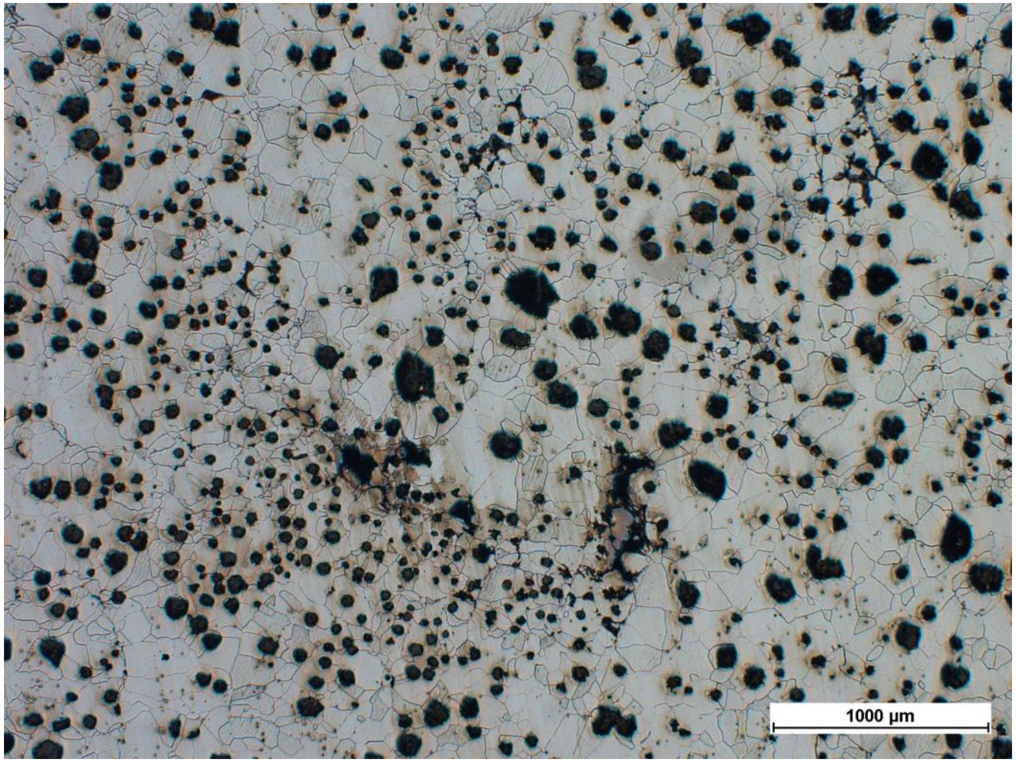
Casting defects

- Visible pores on tensile specimen surface in macroscale.

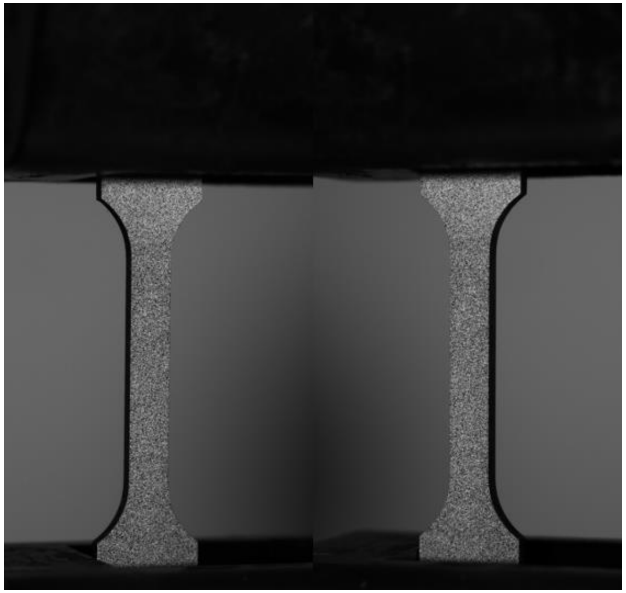


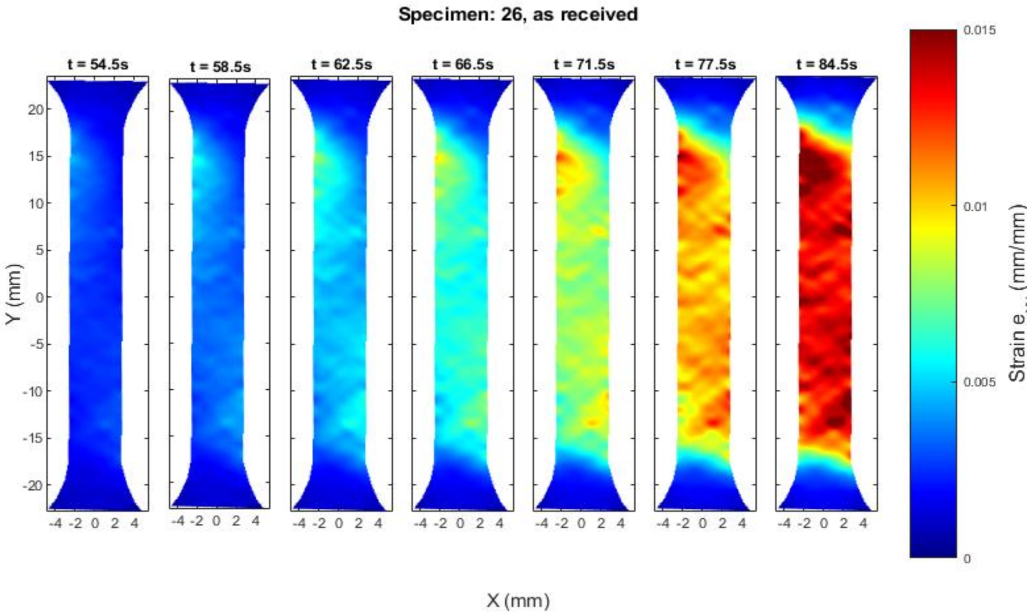
Scatter in the microstructure

- Size of the graphite nodules varies markedly even locally.
- Some casting defects can be seen in the micrograph.



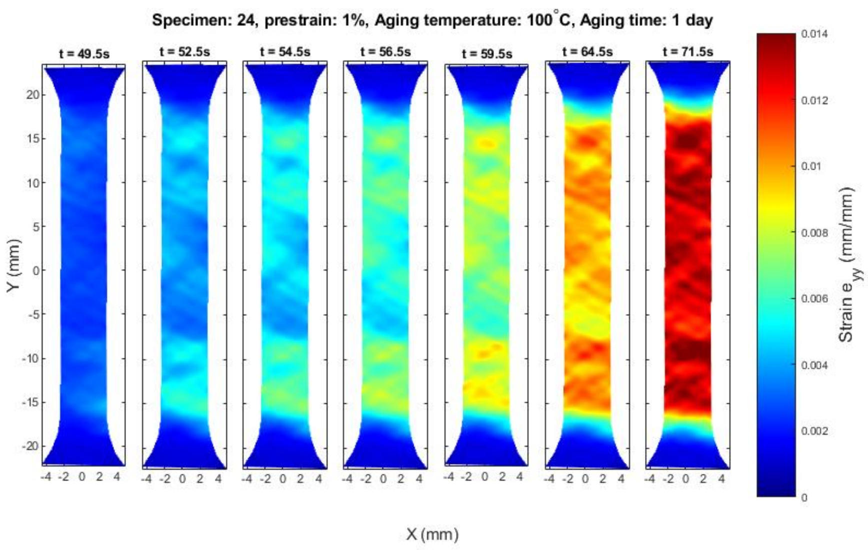
DIC results: reference material



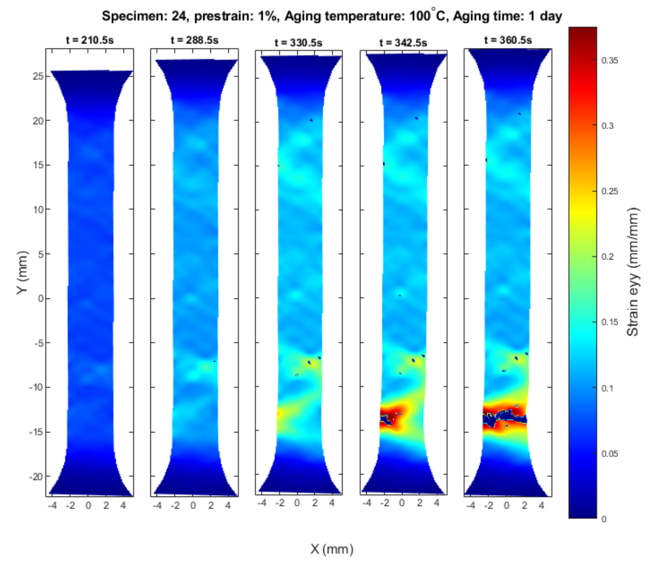


Strain localization after yield point

DIC results: pre-strained 1% and aged at 100 ℃ for 1 day

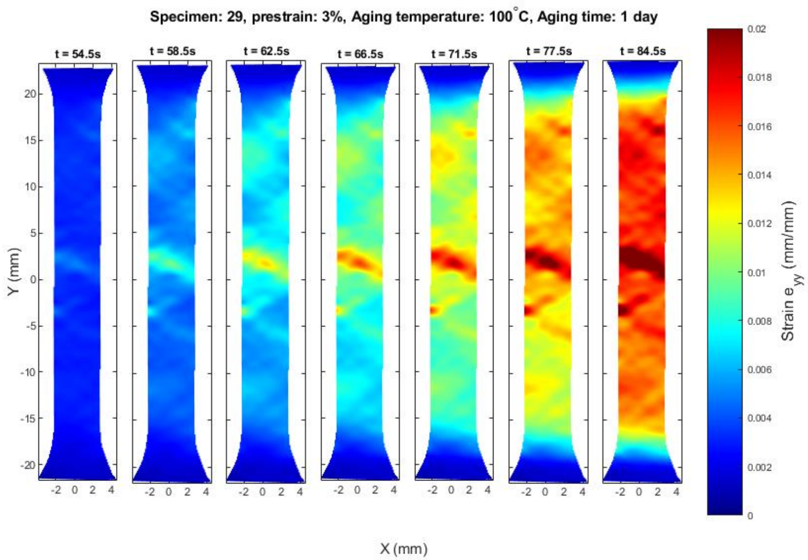


Strain localization after yield point

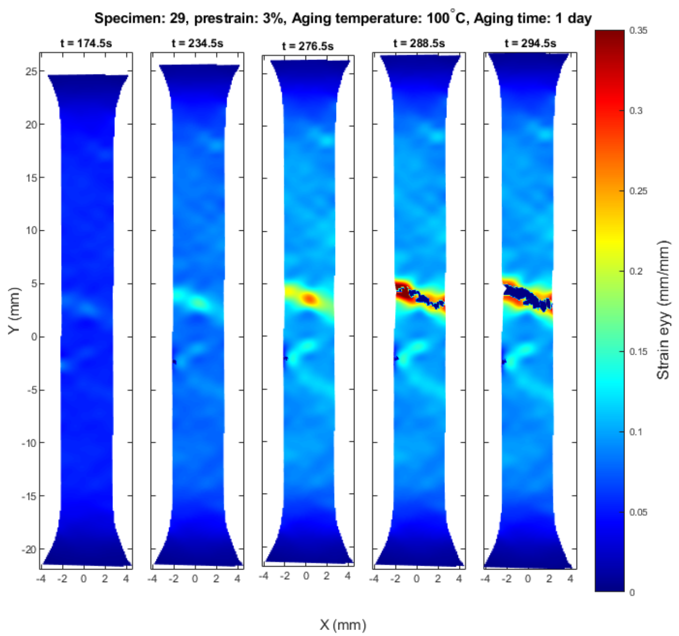


Final fracture

DIC results: pre-strained 3% and aged at 100 ℃ for 1 day



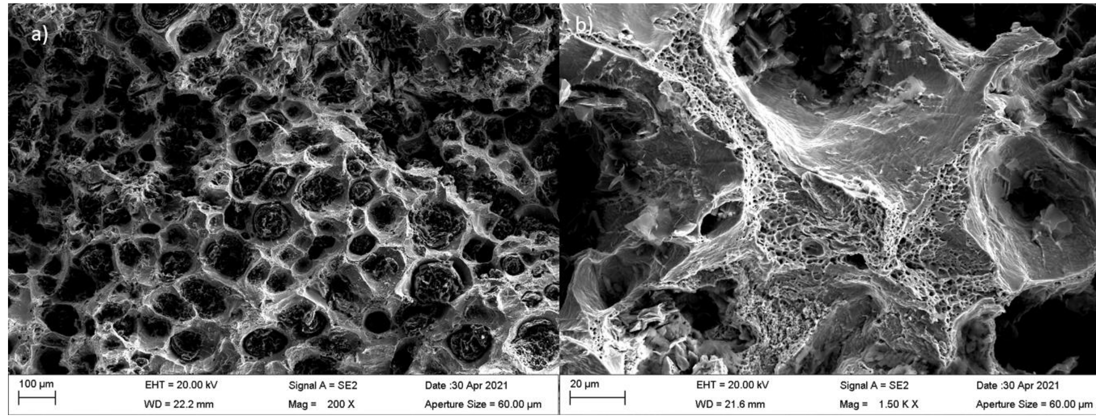
Strain localization after yield point



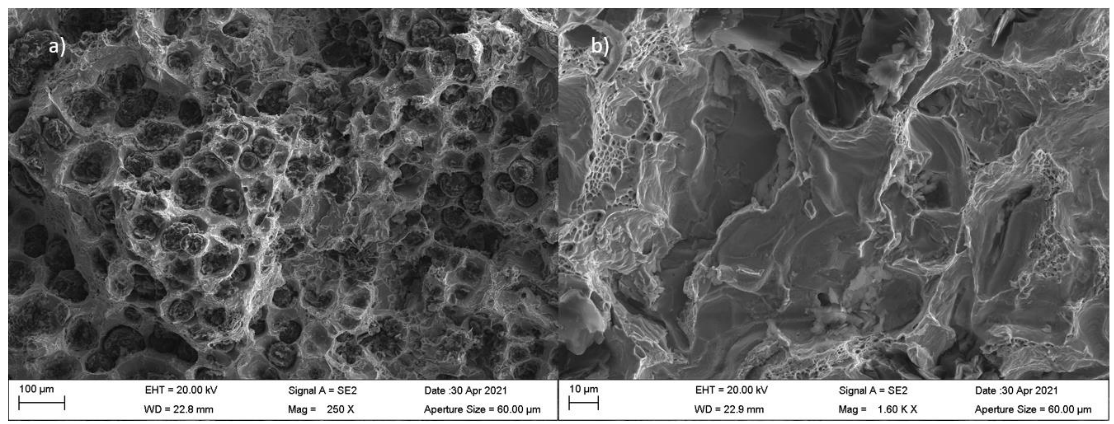
Final fracture

Fractography

- Reference material



- Pre-strained to 1% and aged at 100 °C for 11 days



Aalto University

Conclusions

- SSA occurs in all conditions through the whole test matrix.
- SSA results in an elevated pronounced yield point of the material and reduces markedly the elongation to fracture.
- SSA saturates already after aging at 100℃ for 1 day.
- SSA at higher temperatures of 300 ℃ and 400 ℃ increases the yield stress less and the yield point becomes less pronounced.
- SSA increases strongly the localization of plastic strain.
- Despite the casting defects and the scatter in the material properties, the cast iron behaves predictably up to certain point before and after SSA.
- Fracture mode does not change due to SSA and it stays as ductile dimpled fracture.
- For SSA to have impact on the canister safety there needs to be two separate loading events in the same canister.

Embrittlement mechanisms of cast iron – general conclusion

- **Hydrogen embrittlement, irradiation embrittlement, strain aging (dynamic and static) (blue brittleness) and creep of cast iron insert are the important embrittlement mechanisms which occur in all repository conditions during the whole deposition period.**
- **The embrittlement processes have been examined only a little as separate phenomena, even though they occur simultaneously. Therefore, their additive and synergistic effects have to be examined and the safety analysis must be based on the real material properties of the cast iron instead of those of the initial state.**
- **Possibility of canister failure due to hydrostatic pressure or rock shear is considered low. The probability of a large earthquake in the vicinity of the repository site is low, but may become significant due to the long time scale involved. Only a small fraction of deposition holes, that will be intersected by fractures capable for significant rock shear movements, are affected.**
- **Excessive shear loading of the canister can be avoided by locating deposition holes outside the major fracture zones and avoiding high rock stresses. Probability that the shear movement will occur more than once on the same canister is considered low.**