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A Review of Corrosion and Water Chemistry Aspects Concerning the Tokamak Cooling Water Systems of ITER

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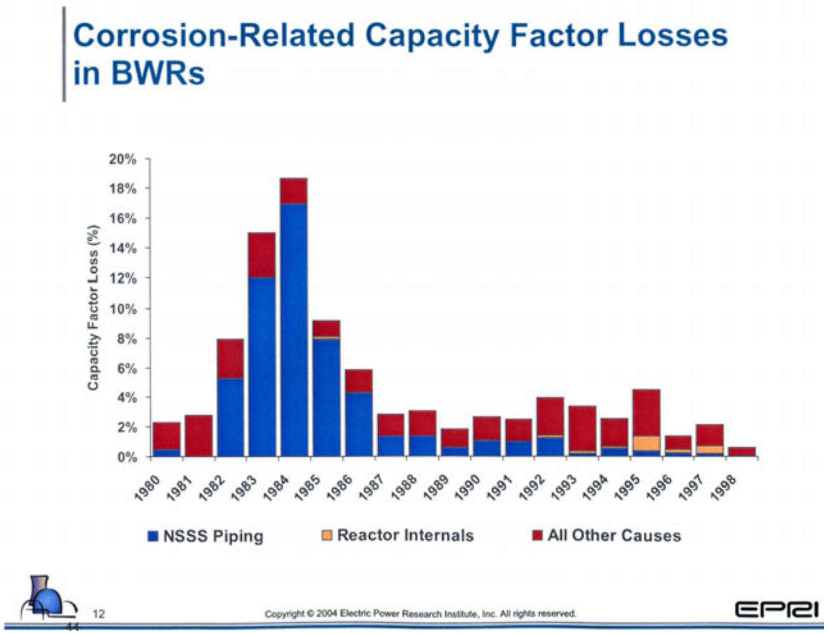
Introduction and outline– Review of corrosion and water chemistry of ITER performed

- Summary of the review of some aspects concerning
  – the materials behavior
  – water chemistry and
  – water side corrosion in ITER environment.
- Goals of the review
  – Identify critical corrosion aspects for ITER.
  – Summarize the system design from a corrosion engineering perspective.
  – Point our relevant corrosion mechanisms important for the systems.
  – Justify requirements concerning corrosion and water chemistry.
  – Point out any lacking knowledge and any need for additional work.
- Summary of key issues identified which need further considerations and investigations to assure the operational lifetime of ITER.

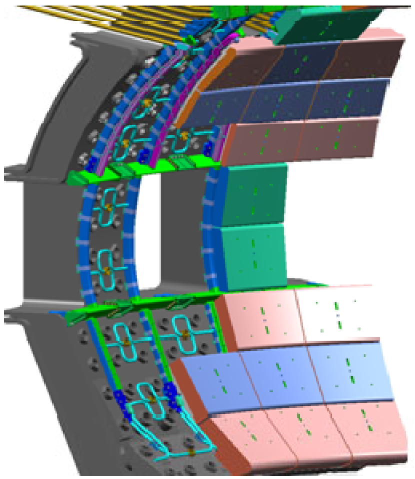
Proactive work – Experience from LWRs

Lessons learned from LWRs

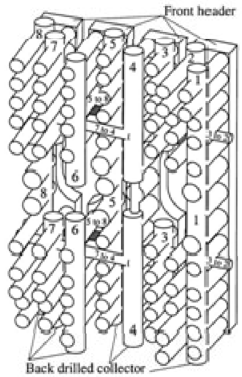
- Water quality
- Sensitized Type 304
- IASCC
- Crevices
- Condensers
- SCC of Type 316L

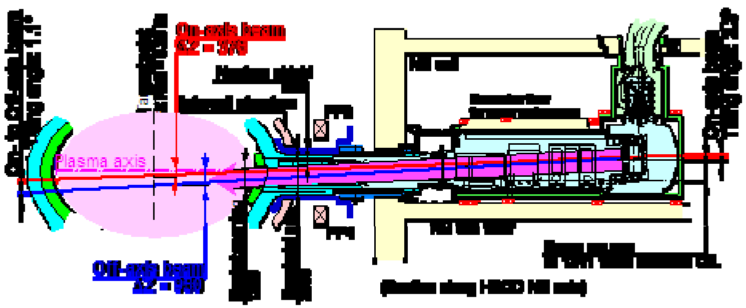


The Tokamak Cooling Water Systems of ITER

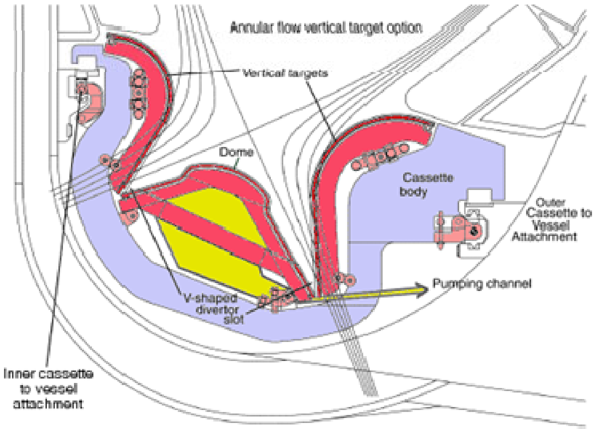


First wall and blanket

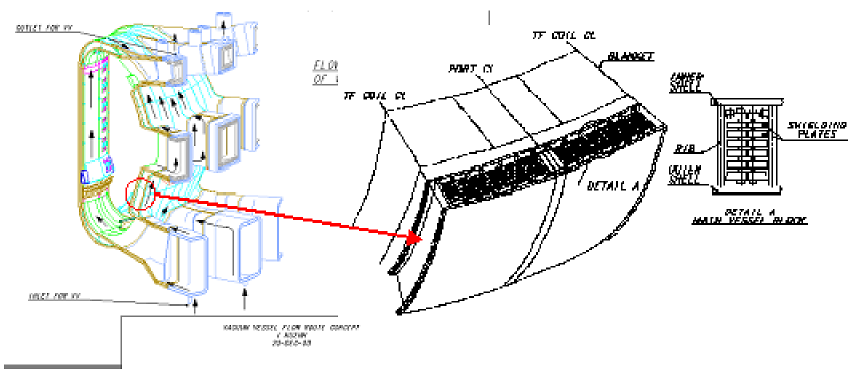




Neutral beam injector



Diverter and limiter



Vaccum vessel

Environment

- Pure water at temp lower than BWRs
- Temperature close to ambient →100-150°C →240°C
- Irradiation: Radiolysis and hydrogen addition.
  - Hydrogen is planned to be added to ITER systems (except VV) to achieve reducing conditions
  - But ITER conditions less favorable for radiolysis suppression than for LWRs.

Radiolysis aspects

- Hydrogen decreases the radiolytic oxidant concentrations significantly but only down to a plateau level

  The residual oxidant amount is enough to create high corrosion potentials

  Radiolysis suppression as in LWRs is not possible to obtain in ITER PHTS according to **EU studies**.

  → Oxidizing conditions will prevail

  → Corrosion potential will be high

  Hydrogen is still recommended to decrease the oxidant formation.

- According to a **Russian study** reducing conditions are possible to obtain.

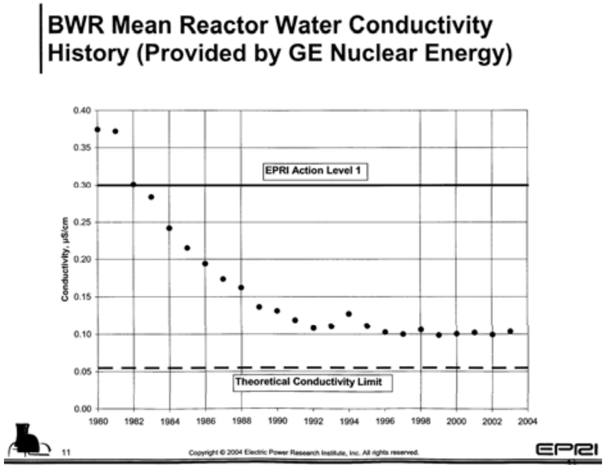
Water chemistry specification

- The ITER specification was set in the 90ies from BWR guidelines at that time

Required Operational Parameter[2]	Feedwater	Upper limits for action
Conductivity (at 20°C), µS/cm	<0.1	<0.3
Oxygen, µg/kg	<100	<10[1]
Chloride and/or Fluoride, µg/kg	<0.5	<5
Sulphate, µg/kg	<20	<5
Copper, µg/kg	<0.5	<5
Iron, µg/kg	<1	<5
Hardness (Ca, Mg, etc), µg/kg	<5	<5
Oil products, organic, µg/kg	<100	<100
pH at RT	neutral	-
Hydrogen added to suppress radiolysis (cm3/kg @ STP)	25	-

(1) The oxygen content for the vacuum vessel cooling system will be limited <100 µg/kg.

(2) A plasma pulse will not be initiated if any of the above limits is foreseen to be exceeded during the course of the pulse itself.



- Revised target values and action levels were tentatively suggested for each PHTS.
- Situation for VV: Hydrogen addition and CVCS system should be considered.

Importance of keeping high purity water

- Low levels of impurities affect several types of corrosion
  - Stress corrosion cracking of stainless steels
  - Crevice corrosion of stainless steels
- Low levels of impurities affect can accumulate in narrow crevices causing
  - Aggressive local solutions in crevices/low flow regions
  - Increased local corrosion rates
  - Corrosion during drying
  - Increased stresses through the formation of corrosion products
  - Stress corrosion cracking

Water purity

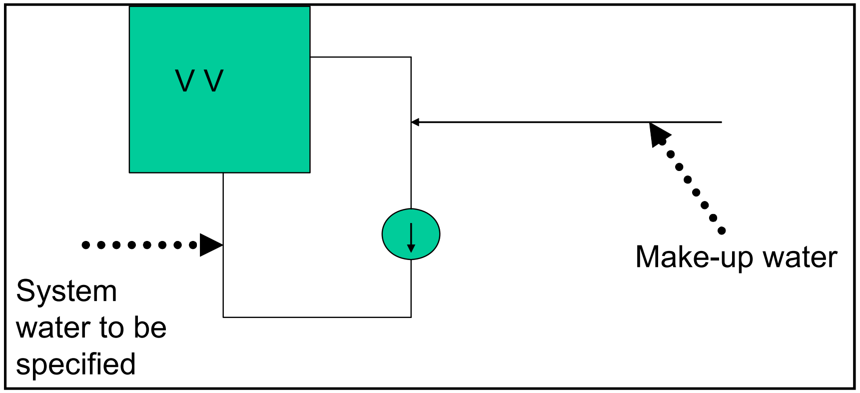
Tentative system water target values

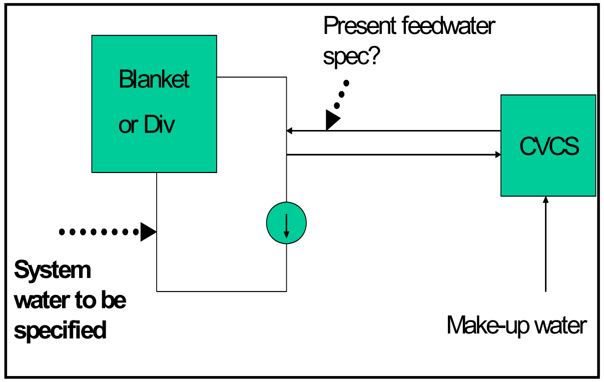
Parameter/PHTS	PFW/BLK	DIV/LIM	NBI	VV
Conductivity, μS/cm	<0.1	<0.1	<0.1	<0.1
Sulfate, ppb	<5	<5	<5	<5
Chloride, ppb	<5	<5	<5	<5
Copper, ppb	<0.5	<2	<0.5	<0.5
Hydrogen, Ncm^3/kg	25	25	25	- -?
Oxygen, ppb	-	-	-	<100?

Based on present BWR mean values and guidelines.

Additional recommendations

- Specifications should clearly refer to the system water.
- Defining CVCS outlet water (feedwater) or make-up water for VV not enough.
- Define monitoring points and methods.





Summary of water chemistry concerns

To resolve the radiolysis situation is a key issue for predicting ITER corrosion conditions.

To design for high water purity is essential to avoid corrosion attacks.

Hydrogen addition and CVCS system for the VV should be considered.

Define monitoring points and methods.

Corrosion properties of ITER materials

Type 304

- IGSCC of sensitized stainless steel
- The most common and most familiar corrosion phenomena in BWRs
- Caused early significant power losses and repair costs
- Now well understood and mitigation methods are available

Corrosion properties of ITER materials

Type 316L(N)-IG

- Through the introduction of L-grade materials in BWRs it was believed that the probability for future cracking incidents would be very low. However IGSCC reported from several countries
- In most cases cracking seems promoted by a cold deformed/hardened surface layer caused by grinding or other type of machining. Mechanical factors important like the residual strain close to the weld fusion line and high local tensile stresses at the bottom end of the weld which usually is in contact with reactor water
- For ITER cold working and post weld treatments are considered as an important remaining issue.
- Non-sensitized stainless steel in annealed conditions should not show SCC in pure reasonably oxidizing water as in ITER

Corrosion properties of ITER materials

XM-19 stainless steel (22Cr-13Ni-5Mn-2Mo-0.3N)

- XM-19 XM-19 was developed as a high strength corrosion resistant alloy
- Good experience in BWRs
- Stress corrosion properties have been found excellent for XM-19, but tests also show that SCC can occur, especially for high stresses in oxygenated conditions. Crevices enhance the attacks as for Type 316L materials.
- In summary, the corrosion properties in general should be better for XM-19 than for Type 316L and the dependence on different parameters such as temperature, crevice conditions and irradiation should resemble those of Type 316L.

Corrosion properties of ITER materials

Borated stainless steels

- Most literature indicate slightly worse corrosion behavior than for Type 304 in non sensitized condition and slightly better behavior in sensitized condition.
- Pitting and crevice corrosion resistance seems slightly worse than for Type 304.
- The general corrosion rate should be similar or marginally higher than for Type 304.
- Irradiation effects have not been covered as the neutron flux is low inside the vacuum vessel.
- Crevice corrosion concerns, see below.

Corrosion properties of ITER materials

Ferritic steel Type 430

- Literature search gave only limited relevant data.
- Type 430 should withstand the nominal environment of the VV.
- Type 430 is considered to have the lowest corrosion resistance of the ITER steels but still good enough for pure water at 100°C if not sensitized.
- From experiments as a TSP material for PWRs Type 430 showed as good behavior as Type 347 in the bulk environment. In crevice environment the behavior was worse.
- Crevice corrosion concern, see below

Corrosion properties of ITER materials

Copper alloys

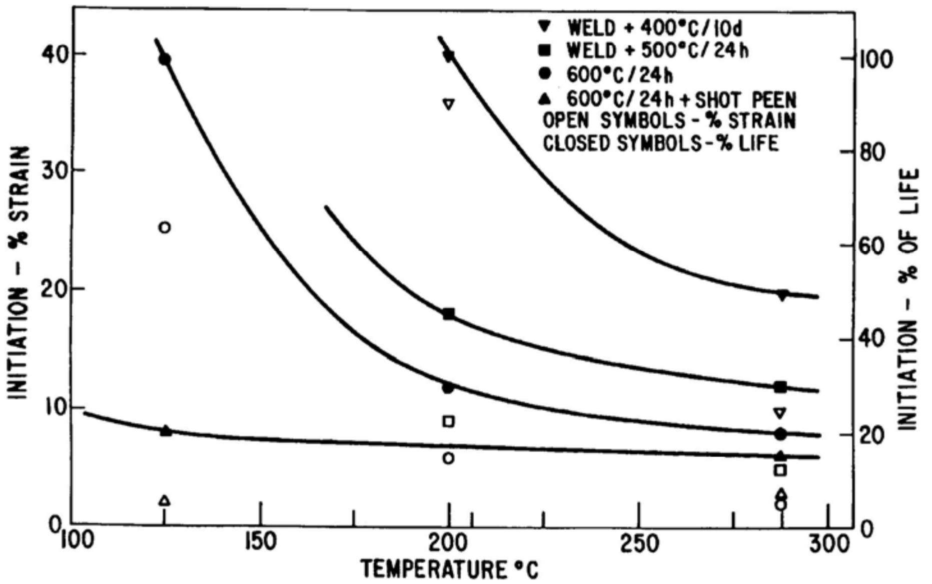
- Reducing conditions are said to be needed to protect Cu from corrosion
- Radiolysis work indicates that reducing conditions cannot be established in irradiated system parts
- High corrosion rates >10 µm/year will be obtained according to tests during such conditions
- Low risk for galvanic corrosion in pure oxidant-free solution but possible in oxidizing environment
- From a corrosion point of view Cu behavior seems as a serious concern

Some important corrosion issues with focus on stainless steels

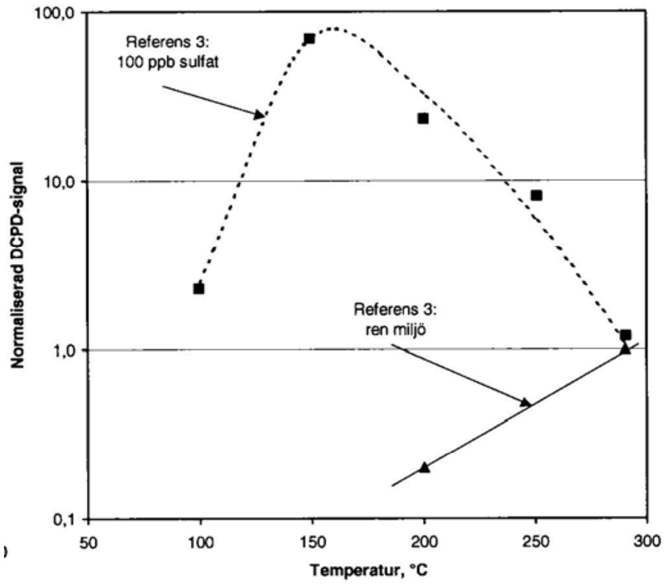
- Effect of temperature
- Crevice corrosion
- Effect of impurities
- Effect of Cu on SS corrosion
- IASCC

Temperature dependence - BWR data

Initiation slower at lower temperatures



High CGR in un-pure water at about ITER temperature



Effect of temperature on SCC

- Few data and some contradictory data makes it difficult to use the data for ITER predictions
- But initiation retarded with decreasing temperature
- Some propagation data shows a max at about ITER-temp, other data show a monotonic decrease with temp.
- Initiation is promoted and propagation increases with conductivity (poor water chemistry), increasing ECP and presence of cold work.

Advice to BWR plants

Poor water chemistry at any temperature will cause significant SCC. A plant should do everything possible to identify and fix problems before they occur.

Should also apply for ITER…

Crevice corrosion and crevice enhanced IGSCC

- Crevices are known to accelerate crack initiation both in sensitized and non-sensitized material
- In plant failures in BWRs have occurred
- In crevices different species can be concentrated with factors of hundreds or thousands
- In the crevice dissolution of metals to positive ions will draw negative ions into the crevice
- Thus, a more aggressive usually acidic crevice environment will form and keep the crevice attack going

Conditions in the VV

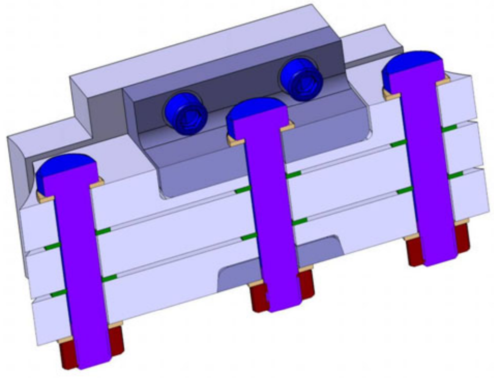
- As the flow conditions in the VV are rather slow, corrosion products and impurities can accumulate in creviced close to stagnant areas.
- During such conditions more a aggressive environment can be formed as the metal ions attract negative ions like chlorides.
- If so Type 430 is susceptible to local corrosion like crevice corrosion and pitting.

Shielding blocks in VV

High number of crevices in low flow environment

Limited corrosion data base for the given materials

Testing suggested



Crevice attacks promoted by drying/wetting

- During drying impurities are trapped in low flow areas and crevices
- More aggressive solutions formed
- During refilling deposits dissolve and again an aggressive solution can be formed
- Repeated drying/wetting can cause corrosion, in particular crevice corrosion
- Tests performed show attacks even on Type 316L(N)-IG
- Difficult to define a realistic concentration factor but from literature factors of hundreds and thousands are well-known

Corrosion experiments during simulated drying conditions

- Shutko, Belous and Akimkin found severe corrosion during testing in 1M NaCl + 1 M Na_2SO_4 at 120°C already after 65 hours.
- Lorenzetto, Helie and Molander found also severe cracking at temp >300°C. The concentration factors were 100 to 1000.
- Tähtinen also found SCC and severe corrosion on CuCrZr in an aggressive solution.
- In all cases the environments might have been too corrosive but the results indicate the importance of the drying procedure not only for shielding plates.

Crevice Corrosion - Summary

- Crevice corrosion in shielding block material is considered to be a potential risk for the VV-system
- Corrosion tests for VV are suggested:
  - to establish an acceptable concentration factor
  - to estimate possible concentration factors that can be obtained
- Other locations in all other systems should be identified and considered
- A realistic, not over conservative, test method is needed.
- Conditions during drying should be taken into account.

Influence of impurities on IGSCC

- Ingress of sulfate and chloride are well know to increase the SCC CGR rate of Type 304 and to decrease the initiation time
- Transients and increased conductivity can have a tremendous impact on the estimated total crack growth rate during a reactor year
- Should in general be true also for Type 316L(N)-IG
- At 5 ppb no major detrimental effect has been detected from either sulfate or chloride in lab tests
- At 30 ppb an obvious acceleration is obtained
- After an impurity ingress an increased CGR can remain for an extended period
- Water chemistry extremely important during all phases of operation

Effect of Cu on SS corrosion

- Presence of Cu is known to have certain detrimental effects in LWRs
  - BWR fuel cladding
  - PWR steam generator corrosion
- Rather high Cu contents needed to influence SCC behavior in Type 304.
- Some BWRs are running with copper contents up to ppb level without any evident effects compared to non-copper BWRs.
- Same concentrations of Cu as in BWRs (copper plants) are specified for ITER.
- If such low concentrations are possible to maintain in the divertor system is however uncertain
- Running the divertor system with high oxidant contents will produce unfavorable conditions for SS with a risk for localized corrosion as a consequence.

IASCC concerns

- The maximum dose of ITER components
  - is above the threshold for IASCC in oxidizing LWR environments
  - is in the same range as the threshold for IASCC in reducing LWR environments
- The time after obtaining the critical dose is limited
- ITER temperature is lower than for LWR which should delay initiation but the influence of temperature on IASCC as well as SCC is unclear.
- The time and the temperature are regarded as beneficial factors but knowledge of the redox conditions and the ECP considered essential to better estimate the IASCC risk.

Summary of concerns

- Radiolysis
- Cu- alloys behavior in all aspects in slightly oxidizing environments
- Crevice corrosion
    - Shielding blocks
    - All other system during **drying**/wetting conditions
- Welds and cold work in Type 316L(N)-IG
- IASCC – Redox conditions?
- Water purity – Monitoring – Cu-contents

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