Corrosion Issues in Fusion Reactors

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Background

- Nuclear fusion is the process of fusing the light elements (primarily the isotopes of hydrogen, $^{1}H_{1}$, $^{2}D_{1}$, $^{3}T_{1}$.
- Fusion results in a loss of mass, which is converted into energy, $E = \Delta m.c^{2}$.
- Process that occurs in the sun and stars in nuclear synthesis. Minimum temperature for D + T is 10 keV = 300,000,000 ^{o}C equivalent.
- First demonstrated on earth in 1950s through thermonuclear weapons.
- Almost a limitless source of clean energy if it can be made to work.
- First controlled fusion demonstrated at JET in Oxford, UK, Q =0.75.
- First technology demonstration, ITER (‘the way”), being constructed at Cadarache, France. Q > 10.

Thermonuclear Reactions

Reaction	**Reaction Equation**	**Initial Mass (u)**	**Mass Change (u)**	**% Mass Change**
D-D	${}^{2}D_{1} + {}^{2}D_{1} \rightarrow {}^{3}He_{2} + {}^{1}n_{0}$	4.027106424	-2.44152×10^{-3}	0.06062
D-D	${}^{2}D_{1} + {}^{2}D_{1} \rightarrow {}^{3}H_{1} + {}^{1}p_{1}$	4.027106424	-3.780754×10^{-3}	0.09388
D-T	${}^{2}D_{1} + {}^{3}T_{1} \rightarrow {}^{4}He_{2} + {}^{1}n_{0}$	5.029602412	-0.019427508	0.3863
e^--p^+	$e^- + p^+ \rightarrow 2h\nu$	1.8219×10^{-31}	-1.8219×10^{-31}	100

Must overcome Coulombic repulsion of nuclei in the plasma

Preferred Reaction

- The easiest reaction to achieve is: $^2D_1 + {}^3T_1 \rightarrow {}^4He_2 + {}^1n_0$ because it has the lowest ignition temperature (10 keV).
- Deuterium occurs naturally (140 ppm of natural water) while tritium does not.
- Tritium must be "bred": $^6Li_3 + {}^1n_0 \rightarrow {}^3T_1 + {}^4He_2$
- Process can be run from just two elements: lithium and deuterium.
- Buy lithium futures for your grandkids!!!!

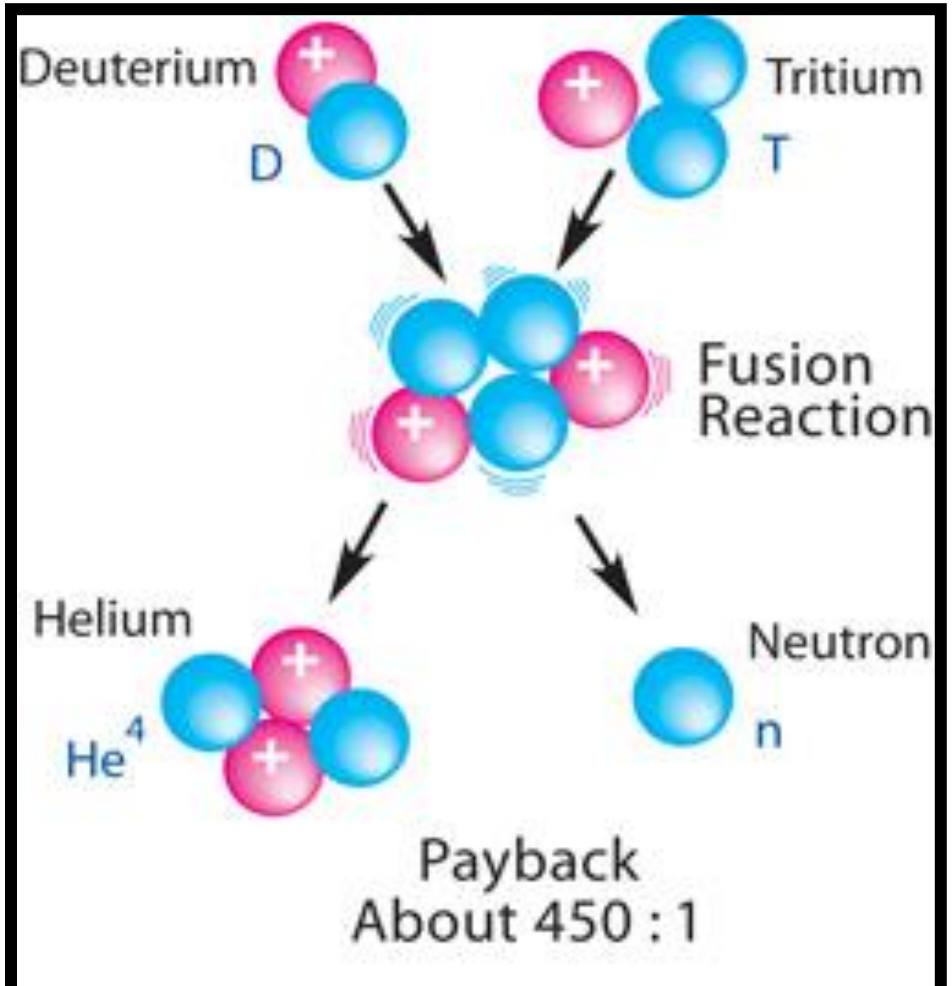
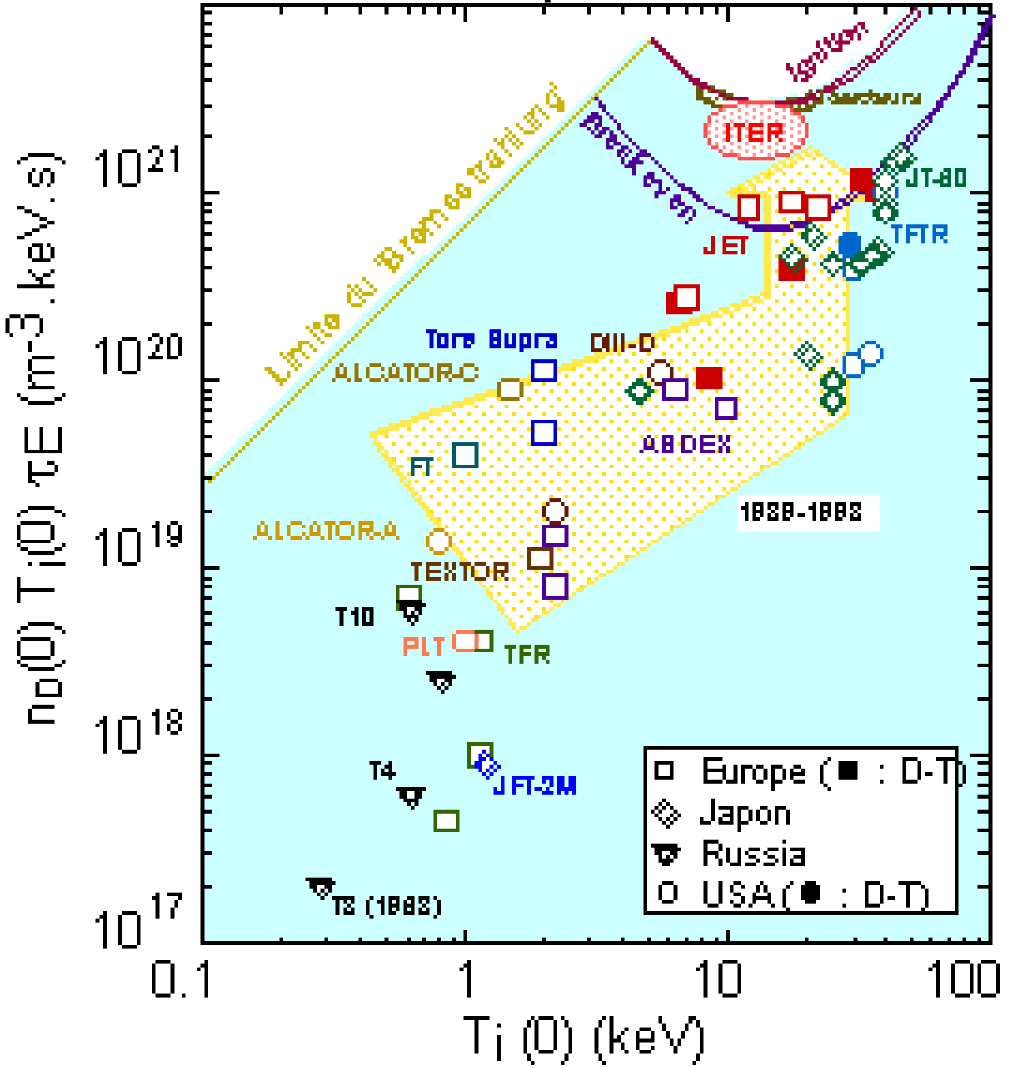


Diagram of deuterium-tritium reaction.

PRINCETON PLASMA PHYSICS LABORATORY.
<www.pppl.gov>.

Lawson Energy Balance

Yields the conditions necessary for the generation of power from a confined plasma.



nT τ_E **> 10^{21} keV.m^{-3}.s**

***n* = plasma density (m^{-3}).**

***T* = plasma temperature (keV)**

τ_E **= confinement time (s)**

- **Low density, long confinement time – Tokamak**
- **High density, short confinement time – Laser fusion**
- **Q = *nT*τ_E/Input power > 10 for practical reactor (ITER).**

Containment Methods

- Fusion must be controlled to be useful, because of the very high temperatures of the plasma (300,000,000 ^{o}C).
- Three major containment categories:
  - Gravitational –Sun & stars.
  - Magnetic – Tokamaks. Closest to fruition, JET, EAST, ITER.
  - Inertial – Laser. Under development at LBNL, Princeton University, and elsewhere. Simulates miniature thermonuclear weapons blasts by adiabatic compression/heating. Has not yet “broken even”.

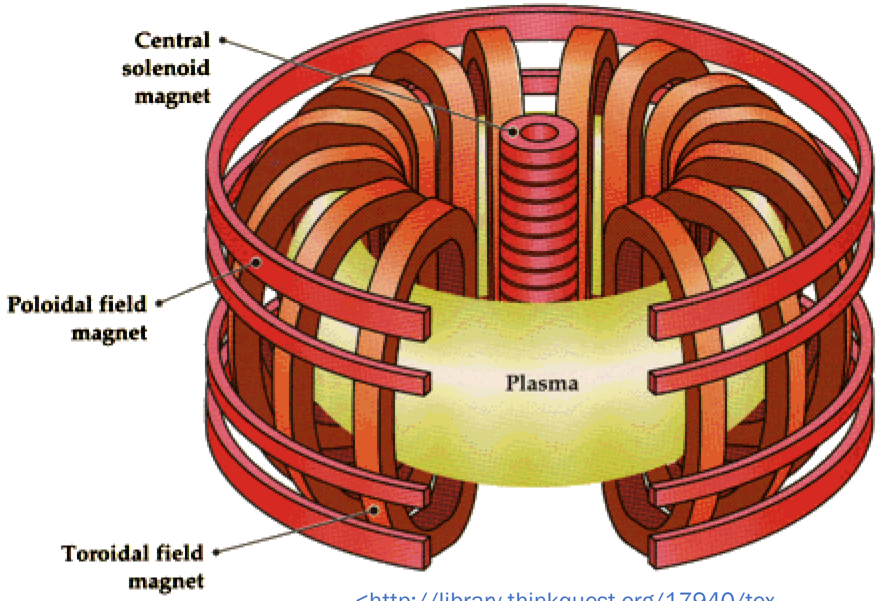
Experimental Reactors

- **Joint European Torus (JET)**
  Uses Deuterium and Tritium.
  Has produced 16.1 MW of fusion power for an input of 24 MW, Q = 0.75.
- **Experimental Advanced Superconducting Tokamak (EAST).**
  D-shaped containment
  Superconducting electromagnets
- **ITER ("The Way" in Latin), designed do achieve Q > 10.**
  Tokamak ("Doughnut" in Russian).
  Superconducting electromagnets.
  Under construction in Cadarache, France.
  Funded by international consortium of EU, US, UK, Russia, China, Japan, and others.
  Scheduled to begin operation in 2024.

Tokamak

- Ohmic – initial heating
- Neutral beam injection
- Radio waves
- Magnetic compression

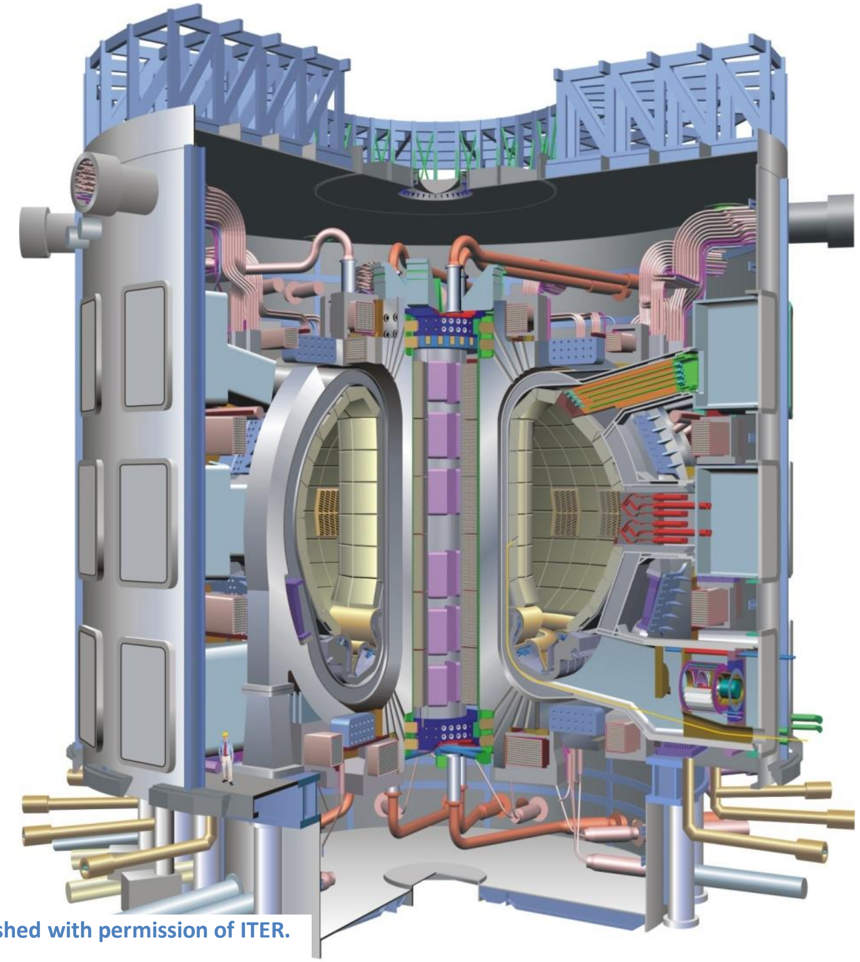
- Uses poloidal and toroidal magnets to control the shape and density of the plasma



<http://library.thinkquest.org/17940/texts/magnetic_confinement/magnetic_confinement.html>

ITER

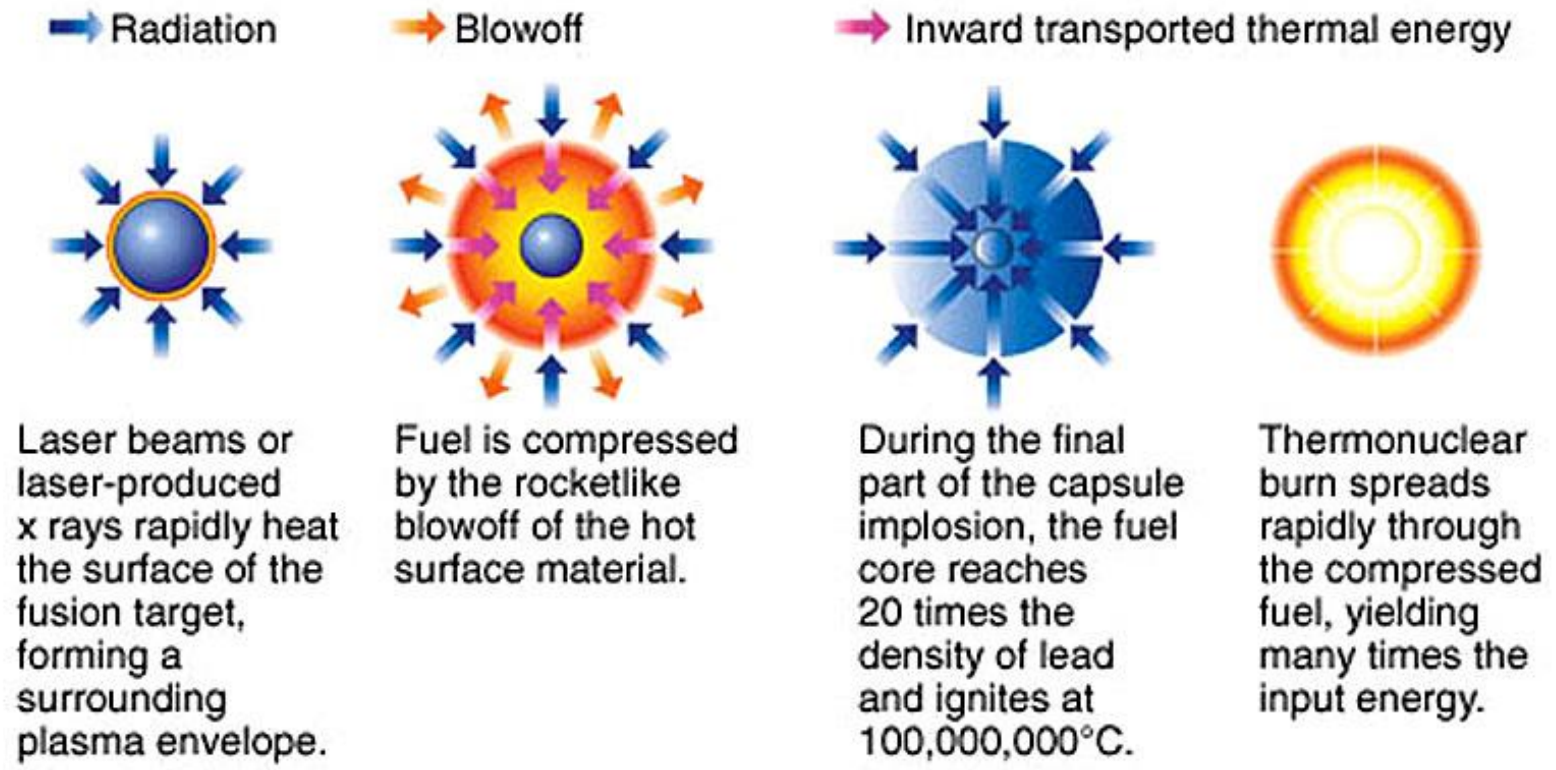
- Being funded by the international community
- Full scale device
  - Produce 500MW of power.
  - 500 second burn length.
- Goal is to prove that fusion power is attainable.
- Under construction at Cadarache, France.
- Scheduled to begin operation in 2024.



Inertial Confinement

- Uses lasers to heat and compress fuel pellets of deuterium and tritium
- Energy levels become so high they can overcome natural repelling forces and the nuclei collide and fuse.
- These collisions create energy and causes the ignition of the rest of the fuel.

LLNL version uses 192 laser beams designed to deliver 1.8 million joules of ultraviolet laser energy and 500 terawatts of power to millimeter-sized targets. <http://www.llnl.gov/nif/project/nif_works.html>



<http://en.wikipedia.org/wiki/ICF>

Nuclear vs. Other forms of Energy

- If an average size, 1000 MWe plant is run at 90 % capacity for one year, 7.9 billion KWh are produced.
- Enough to supply electricity to about 740,000 homes.
- To equal this with other forms of energy, you would need the following amounts of fuel.

Oil – 13.7 million barrels	1 barrel yields 576 KWh
Coal – 3.4 million short tons	1 ton yields 2,297 KWh
Natural Gas – 65.8 billion cubic feet	100 cubic feet yields 12 KWh
(based on average conversion rates from the Energy Information Administration	

Coal versus Fusion Energy

Fuel/emissions per day

1000 MWe Power Plant

	COAL	D-T FUSION
FUEL	9000 T. Coal	1.0 lb. D_2 3.0 lb. Li^6 (1.5 lb. T_2)
WASTE	30,000 T. CO_2 600 T. SO_2 80 T. NO_2 (23.4 lb. U) (57.6 lb. Th)	4.0 lb. He^4

- If coal plants were held to the same standards as fission nuclear plants for radioactive emissions, they would all be shut down.

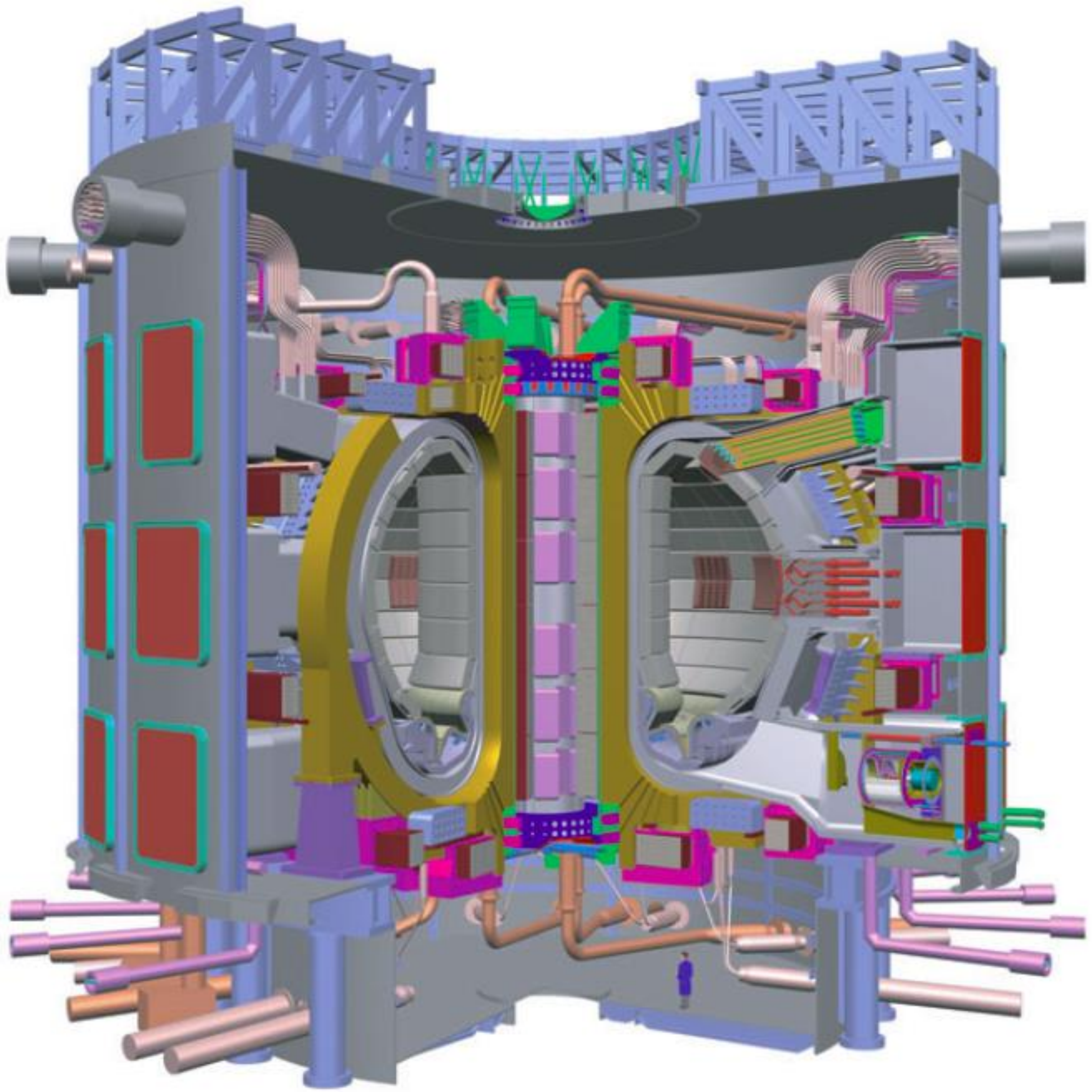


Figure 4. Cutaway view of the ITER fusion reactor (from Aymar, Barabaschi, and Shimomura [3]).

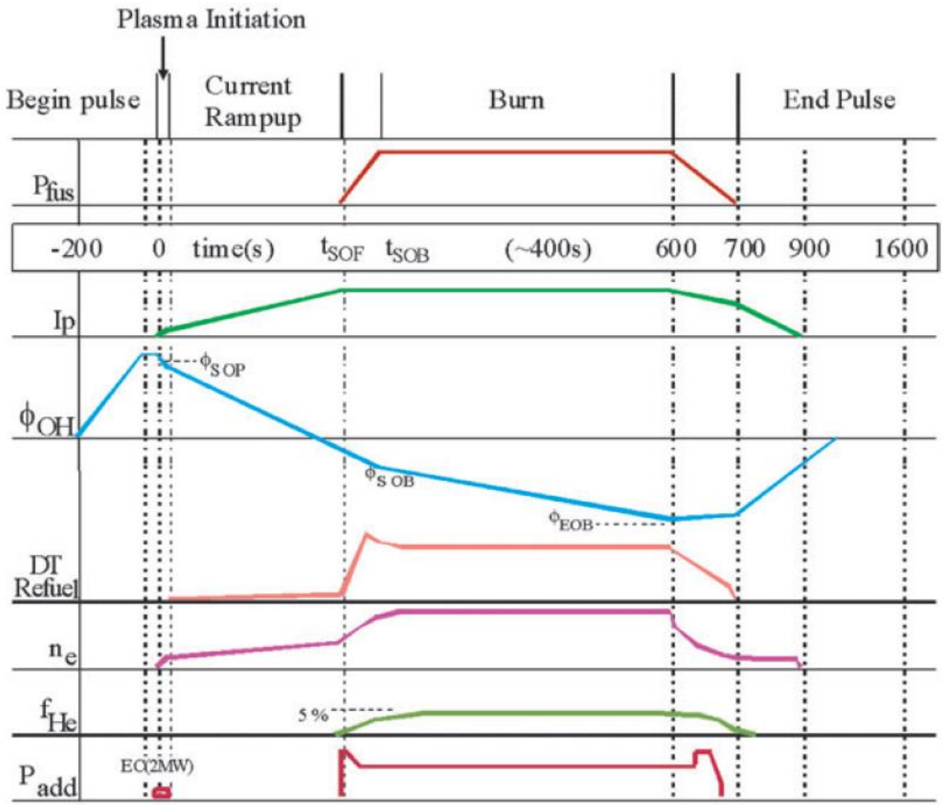


Figure 12. Standard plasma burn operation. P_{fus} = Fusion Power, P_{add} = Added power to initiate fusion, n_e = Electron density in the plasma, f_{He} = He density in the plasma, and I_p = Plasma current (after Aymar, Barabaschi, and Shimomura [3]).

Radiation Environment

- Intense neutron and γ-photon emissions leads to the substantial energy deposition rates in cooling water, Q. For each of n-and γ-photon fluxes Q has the order of 0.1-10 W/cm^3.
- Intense radiolysis of cooling water to produce

e_{aq}^-, H, OH, H_2O_2, HO_2, HO_2^-,O_2, O_2^-, O_2^{2-},O^-, O, H_2, OH^-, H^+, and possibly others

- Only H_2, O_2, and H_2O_2 are is sufficient concentration to effect the ECP.

Radiolysis of the coolant circuit modelled by D. D. Macdonald and G. R. Engelhardt, "Review and Assessment of Radiolysis in the TCWS IBED PHTS", Report to US ITER, ORNL, Oak Ridge, TN (2017).

Materials in the ITER

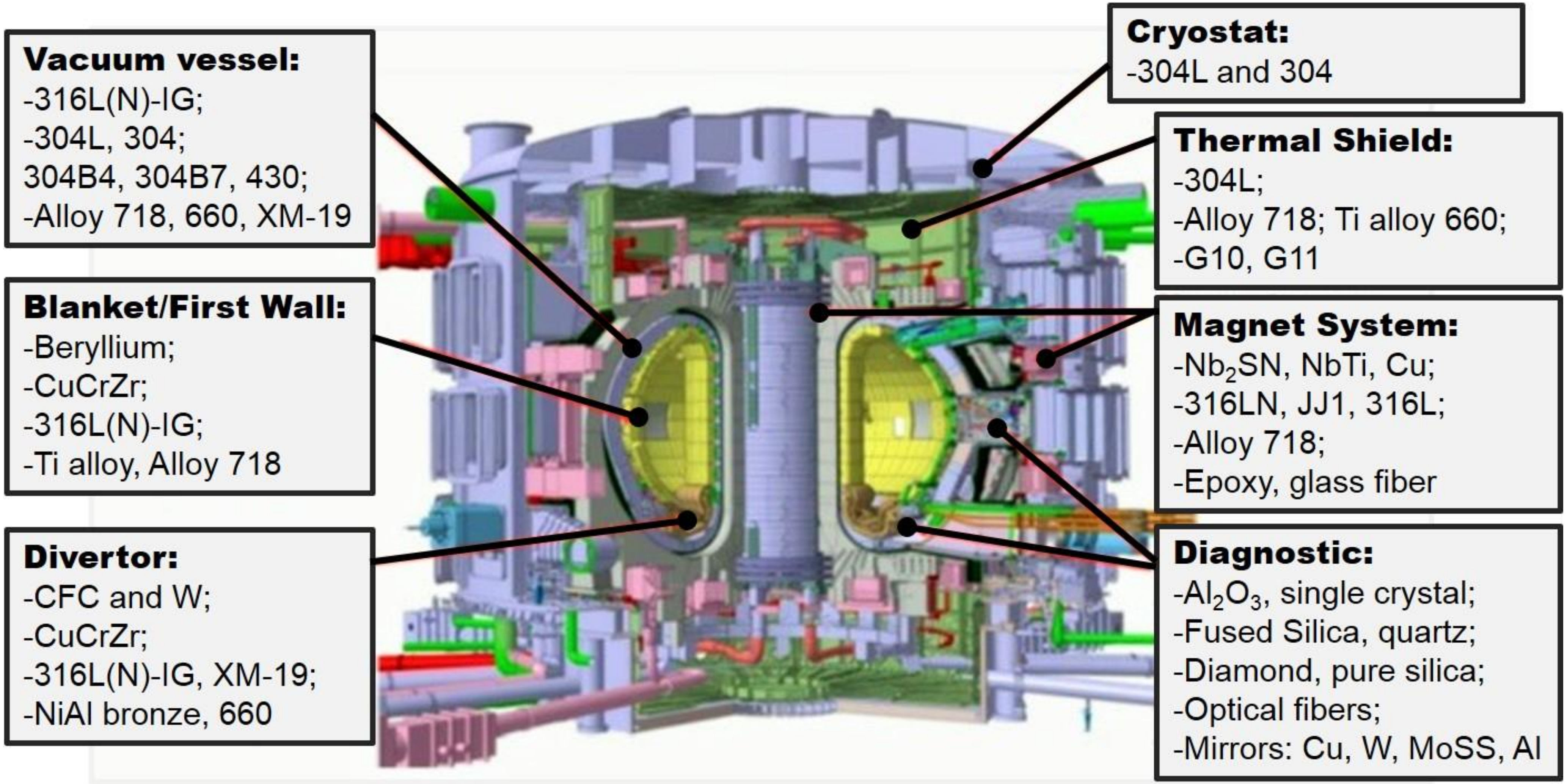


Figure 14. Summary of materials tentatively selected for ITER tokamak [14].

ITER Coolant Chemistry Specifications

- Similar to a BWR.
- Water, no pH control.
- HWC has been explored.
- Response to HWC similar to that of BWRs.

Table 24. Water chemistry parameters for the ITER PHTS coolant [26]

Parameters of water reactor during operation	Feedwater	Values to start plasma ignition	Upper limits for action
Conductivity (at 25 °C), uS/cm	<0.1	<0.1	<0.3
Hydrogen (cm^3/kg at STP)		~25	
(wppm)		~2	
Electrochemical Corrosion Potential (mV SHE)		TBD	<TBD
Oxygen (wppb)	<20	<1	<10
Chloride and Fluoride (wppb)	<0.5	<1	<5
Sulfate (wppb)	<20	<2	<5
Copper (wppb)	<0.5*	<5*	<5*
Iron (wppb)	<1		<5*
Hardness (Ca. Mo, etc.) (wppb)	<5		<5*
Oil products, organic (wppb)	<100		<100*

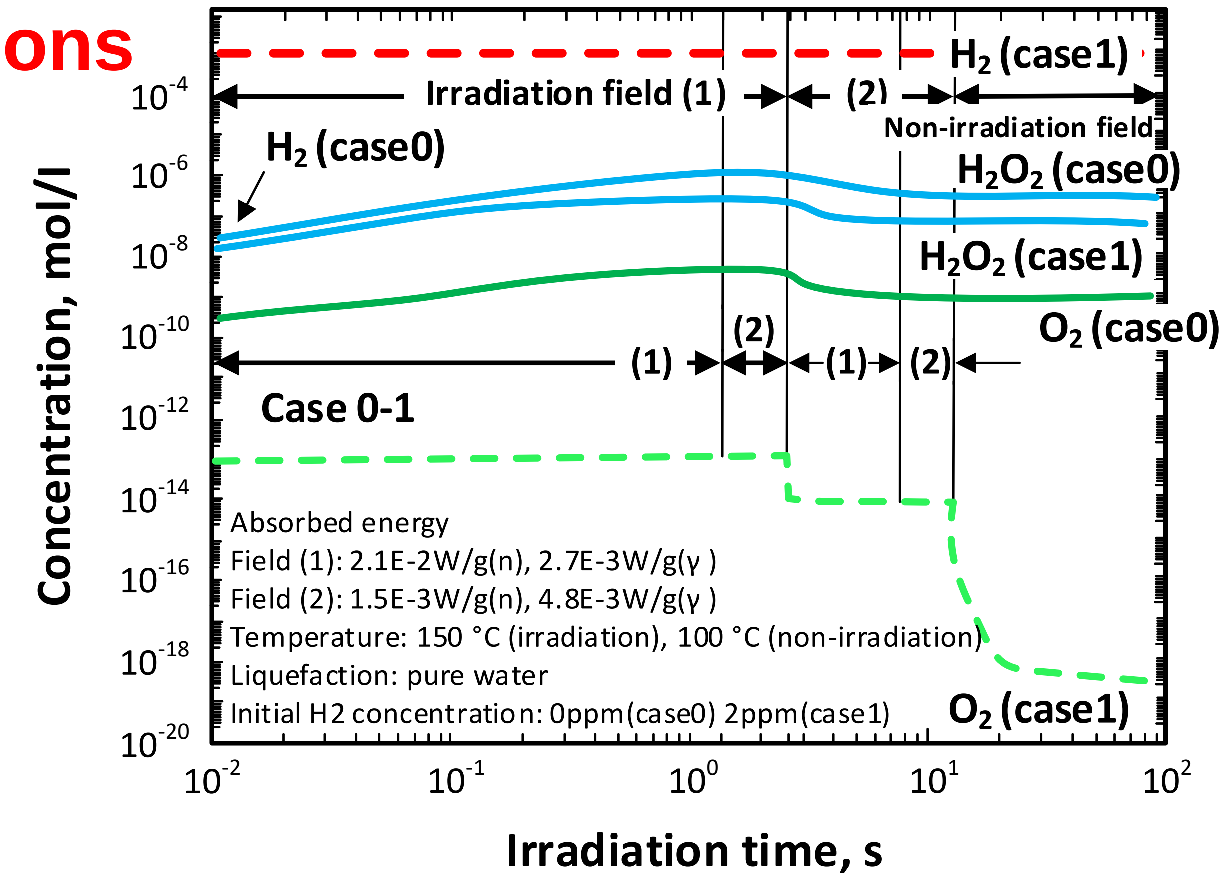


Figure 31. Predicted concentrations of radiolytic species in the ITER blanket PHTS cooling water without (Case 0) and with (Case 1) the addition of 2 ppm (1×10^{-3} m) hydrogen (after Sato et al. [24]).

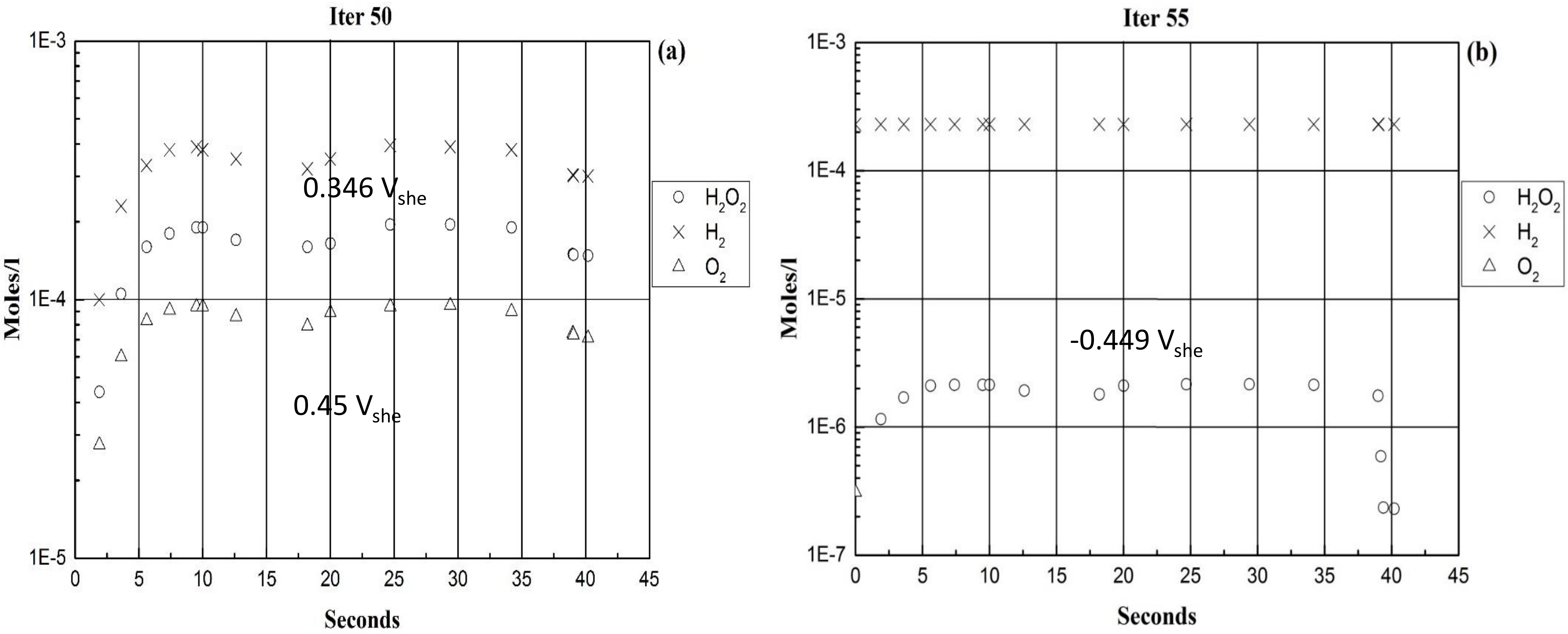


Figure 37. Radiolysis of water in the Studsvik INCA loop at 50 ^oC, with (a) no added hydrogen and (b) 5 cm^3(STP)/kg H_2O (after Christensen et al. [27]). T = 100 ^oC, V_f = 1 m/s, channel diameter = 0.1 m.

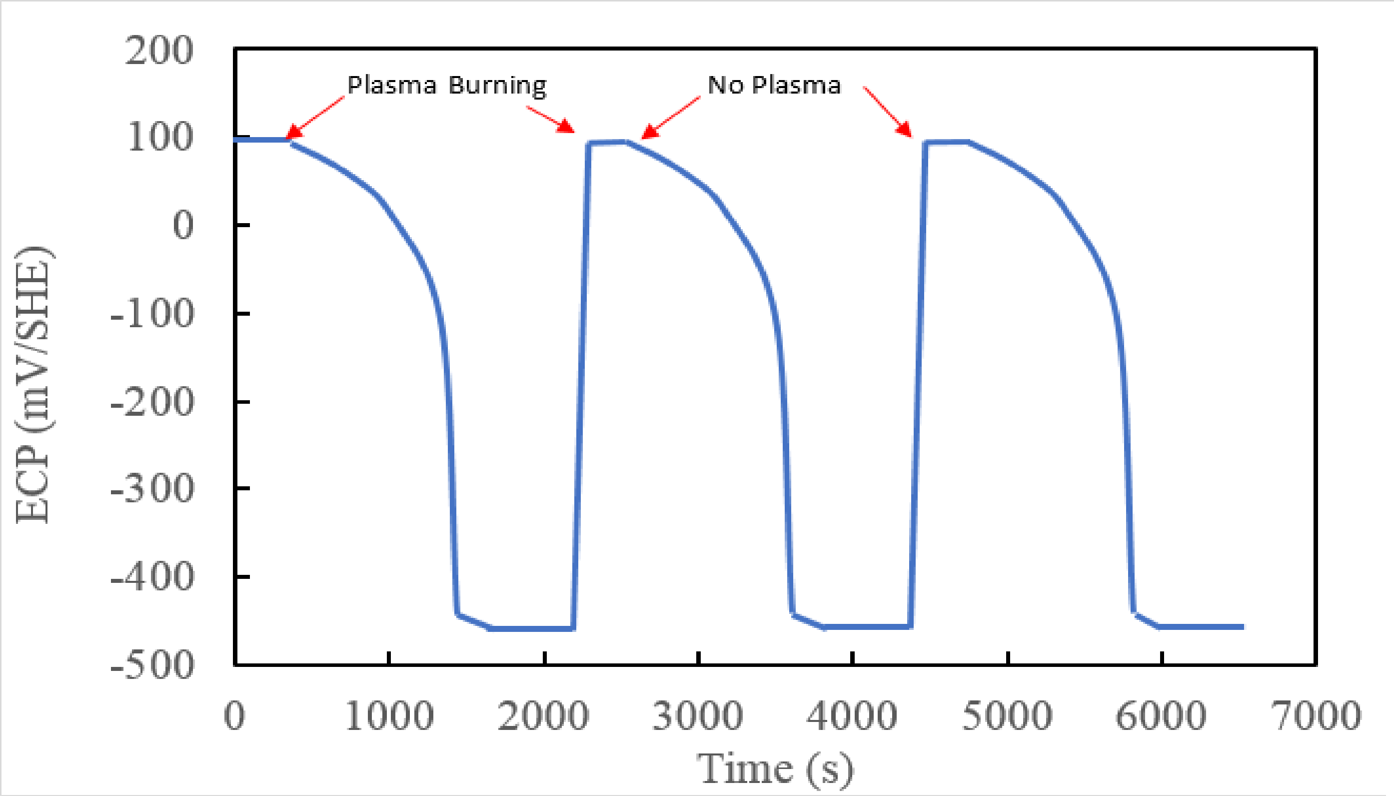


Figure 55. Variation of ECP of stainless steel in the ITER PHTS as a function of periodic plasma burning of 400 s (after Wikman et.al. [18]).

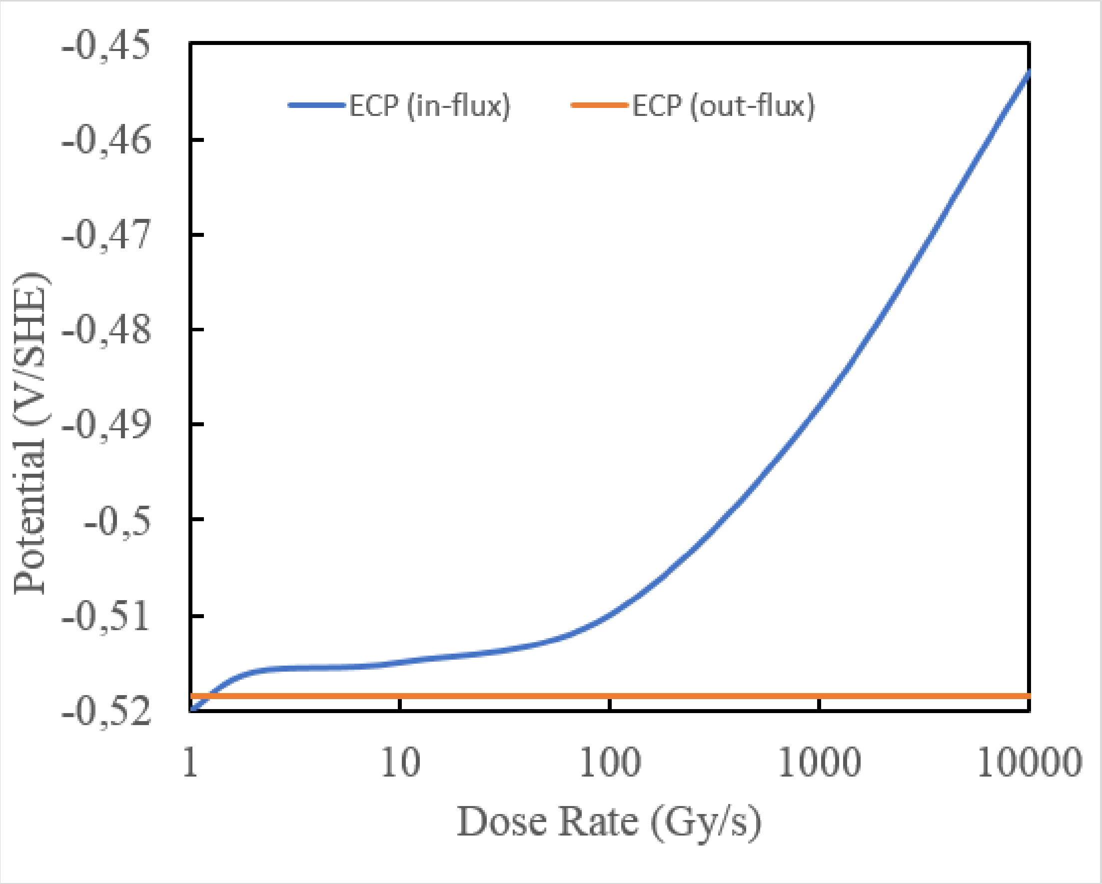
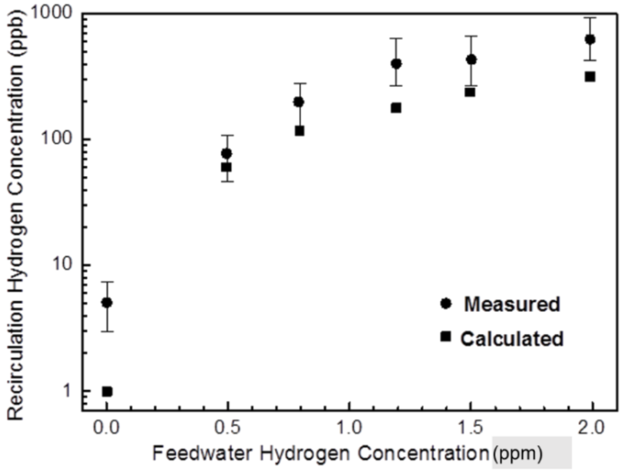


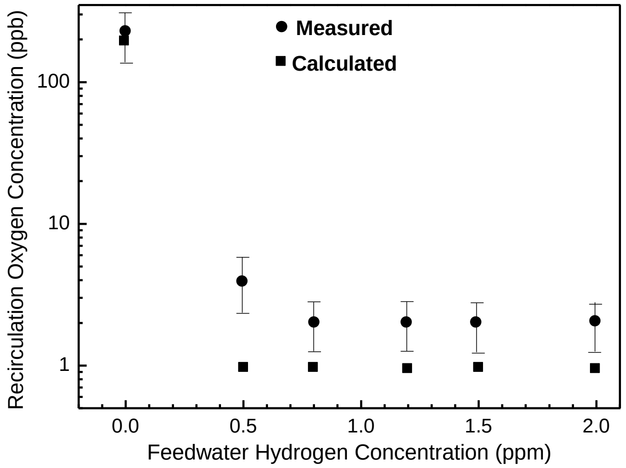
Figure 56. Calculated redox potential as a function of radiation dose rate according to [29].

- **ECP highly dependent on burn cycle and radiation dose rate.**
- **ECP similar to that in BWR under comparable conditions.**

Expected Corrosion Issues in ITER

- Similar to those in BWRs.
- IGSCC in austenitic stainless steels.
- Irradiation-assisted IGSCC in stainless steels.
- Corrosion of copper alloys.
- Radiolysis leads to net oxidizing environment.
- Modification of redox conditions of the coolant.
- ECP is the key.
- ECP can be calculated from $[O_2]$, H_2O_2, and $[H_2]$ using the MPM.





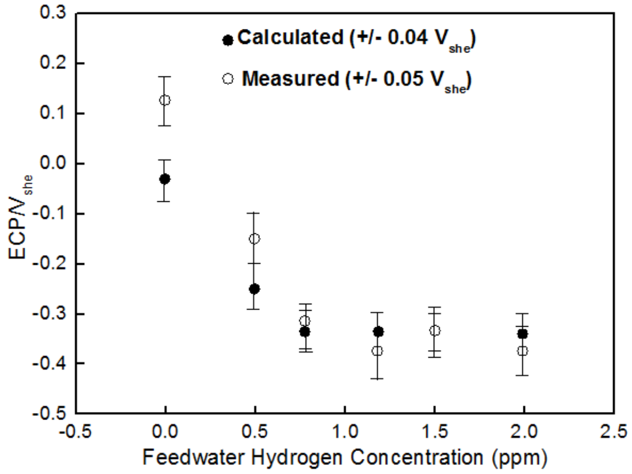
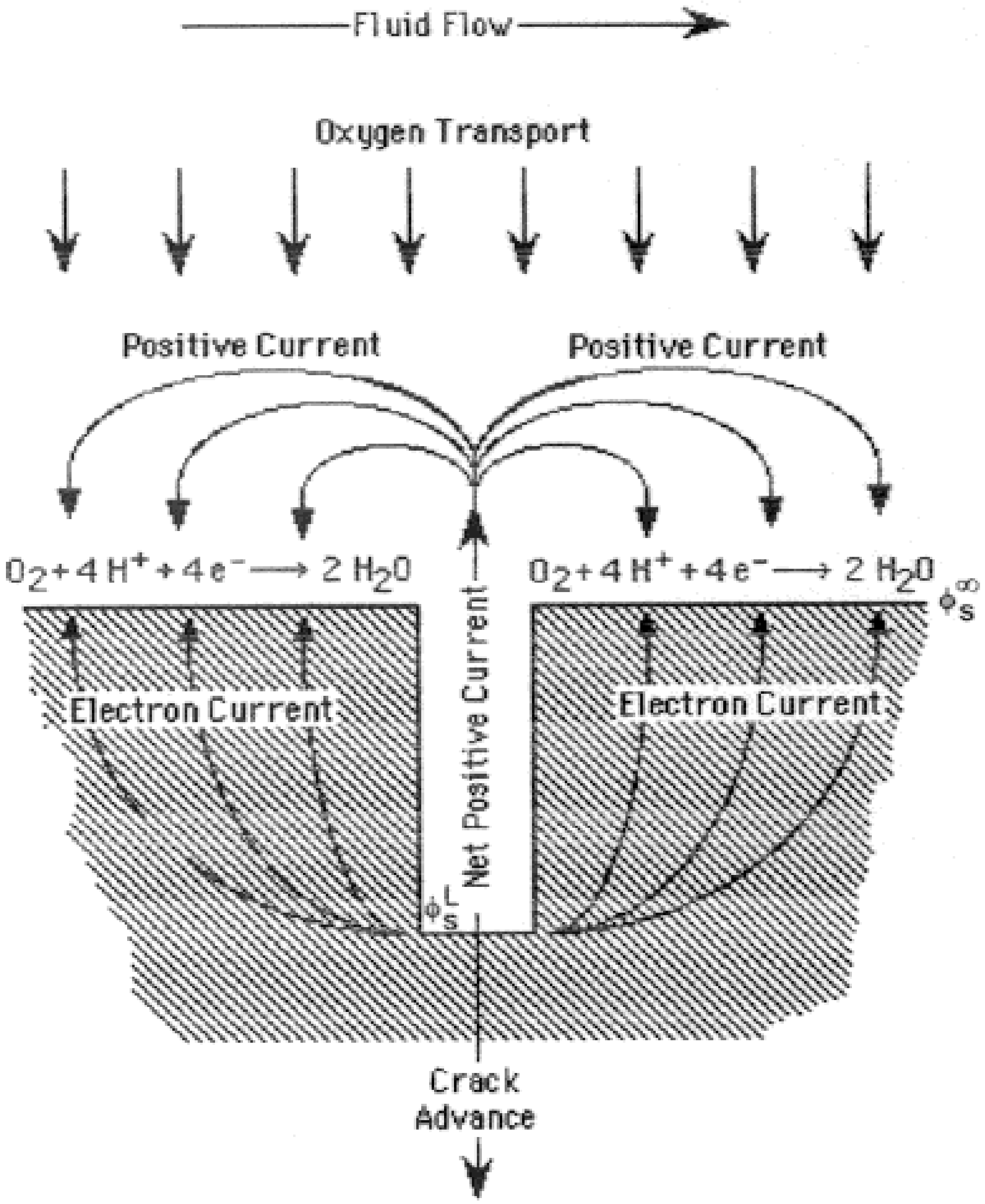


Figure 1. Comparison of calculated and measured (a) $[H_2]$, (b) $[O_2]$, and (c) ECP for the Leibstadt BWR under HWC conditions. The "measured" data were acquired in a test cell attached to the recirculation piping.

Coupled Environment Fracture Model.



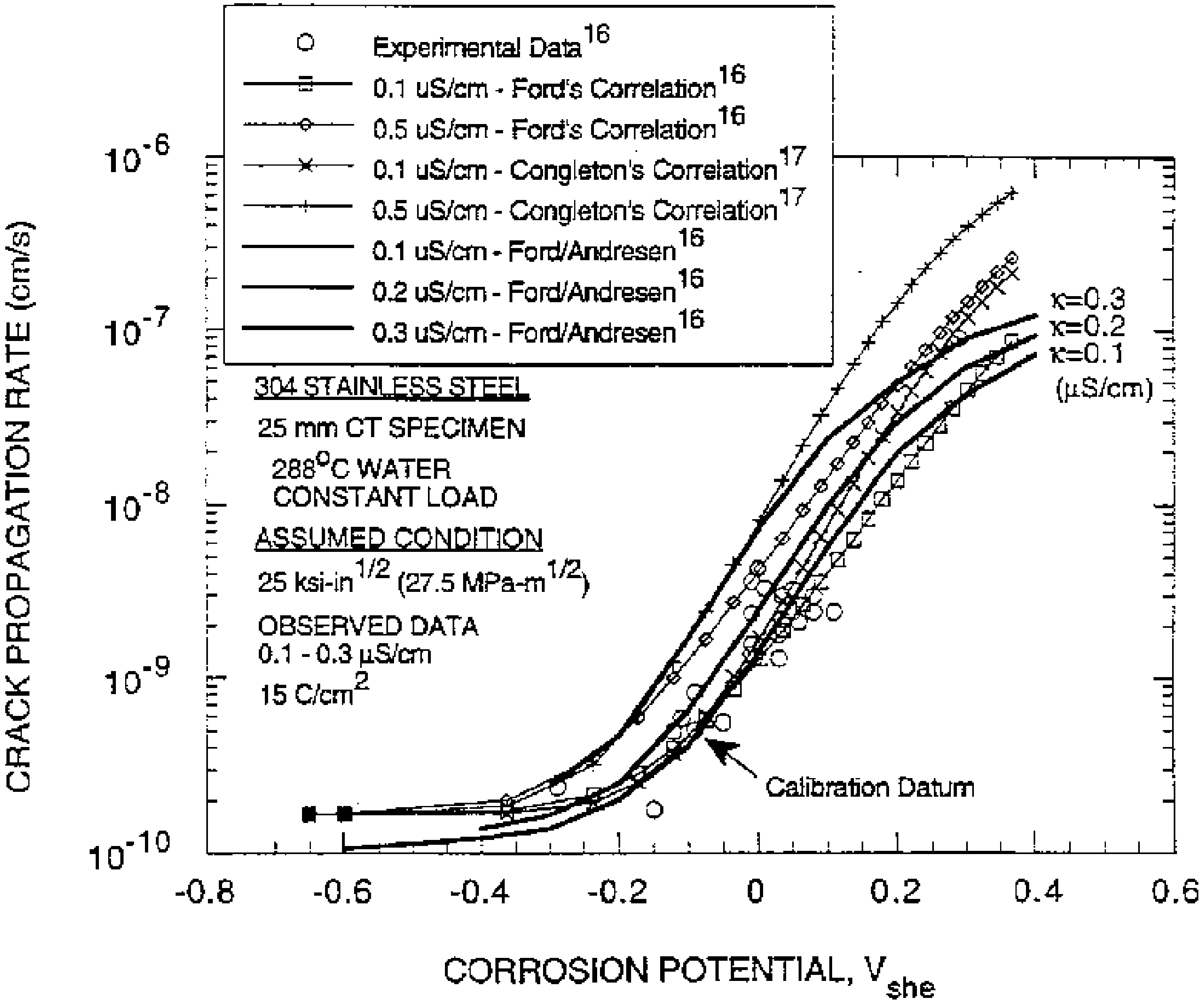
Schematic of the origin of the coupling current in stress corrosion cracking. The coupling current is required by the differential aeration hypothesis for localized corrosion, and the conservation of charge requires that the electron current flowing from the crack to the external surface must be equal to the positive ionic current flowing through the solution from the crack to the external surface.

The only physically viable solution for Φ is that which charge is conserved.

$$\int_S i\,dS = 0$$

That is the basis of the Coupled Environment Fracture Model (CEFM).

Measured and calculated (via the CEFM) crack growth rates for sensitized Type 304 SS in high temperature aqueous solutions as a function of ECP and conductivity. The citations refer to references in the original source [2] .



Control of redox conditions in BWRs

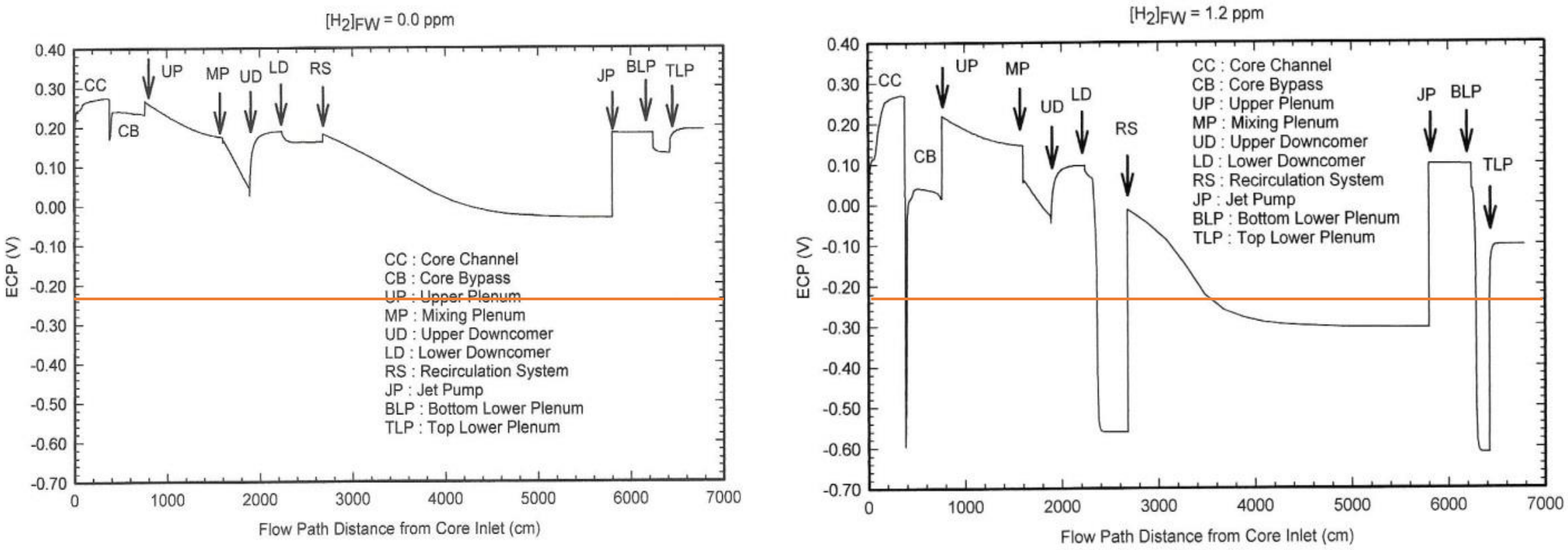


Figure 2. Predicted ECP vs flow path distance from the bottom of the core for (a) 0 (NWC) and (b) 1.2 ppm of hydrogen (HWC) added to the feedwater of the Leibstadt BWR.

- HWC in BWRs.
- 0.5 – 1.0 ppm H_2 added to feedwater.
- Critical ECP for IGSCC in weld-sensitized Type 304 SS is -0.23 V_{she} (red line).

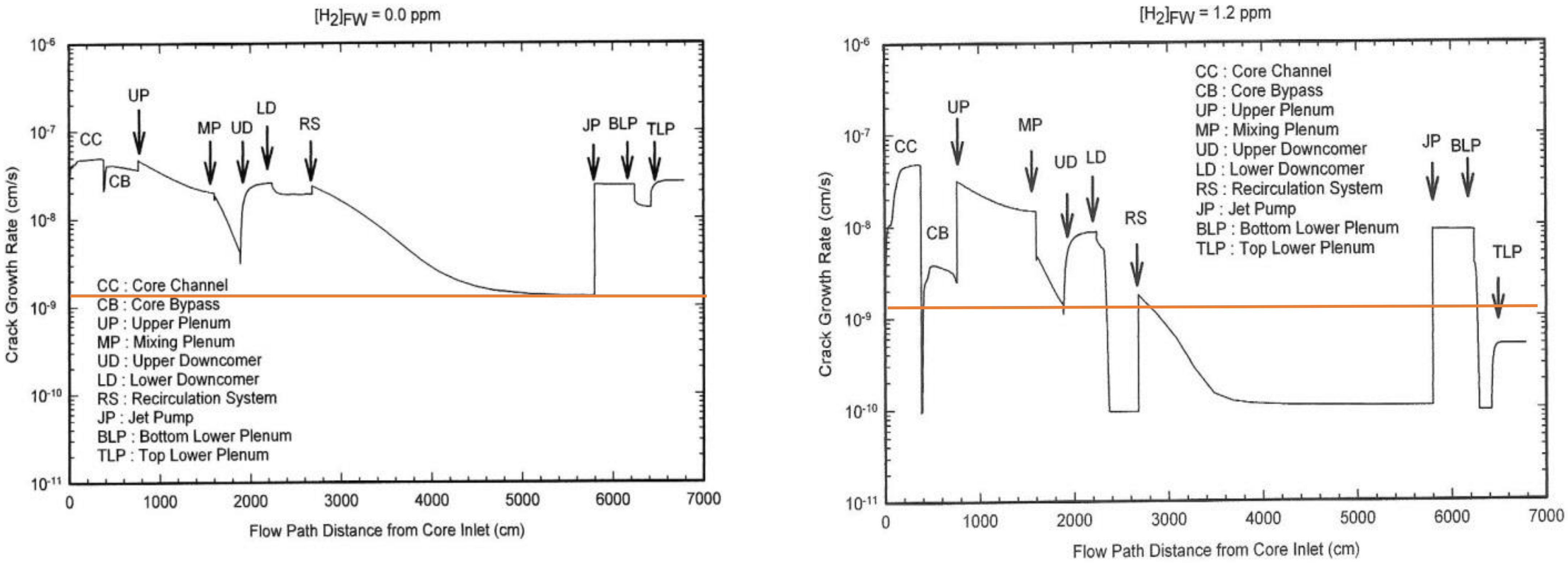


Figure 3. Predicted crack growth rate vs flow path distance from the bottom of the core for NWC (0 ppm H_2) (a) and HWC (1.2 ppm of H_2) (b) added to the feedwater of the Leibstadt BWR.

- Crack growth rate calculated with the CEFM.
- CGR mirrors ECP as CGR is exponential function of ECP.
- CGR at creep limit for ECP < 0.6 V_{she}. No IGSCC.

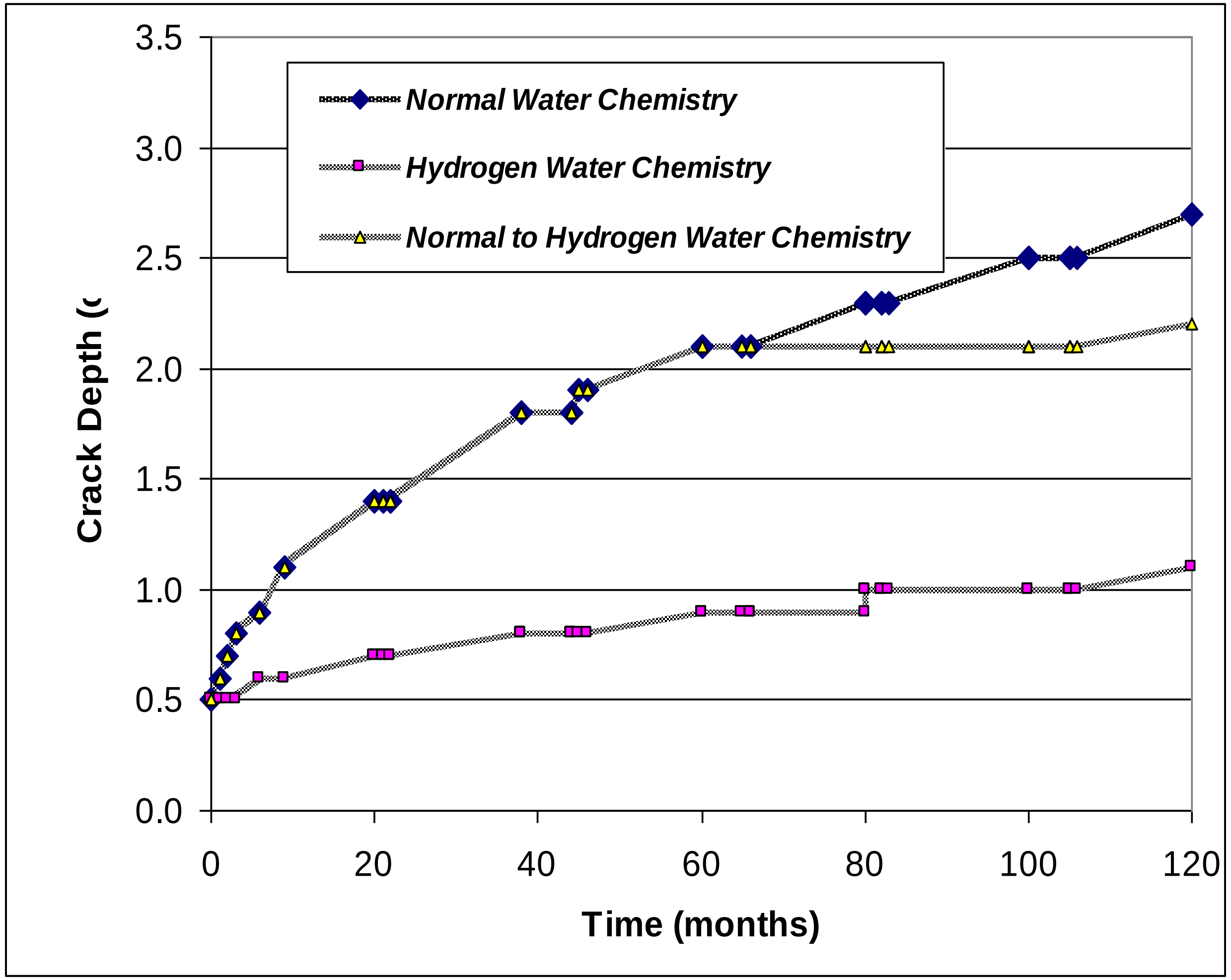
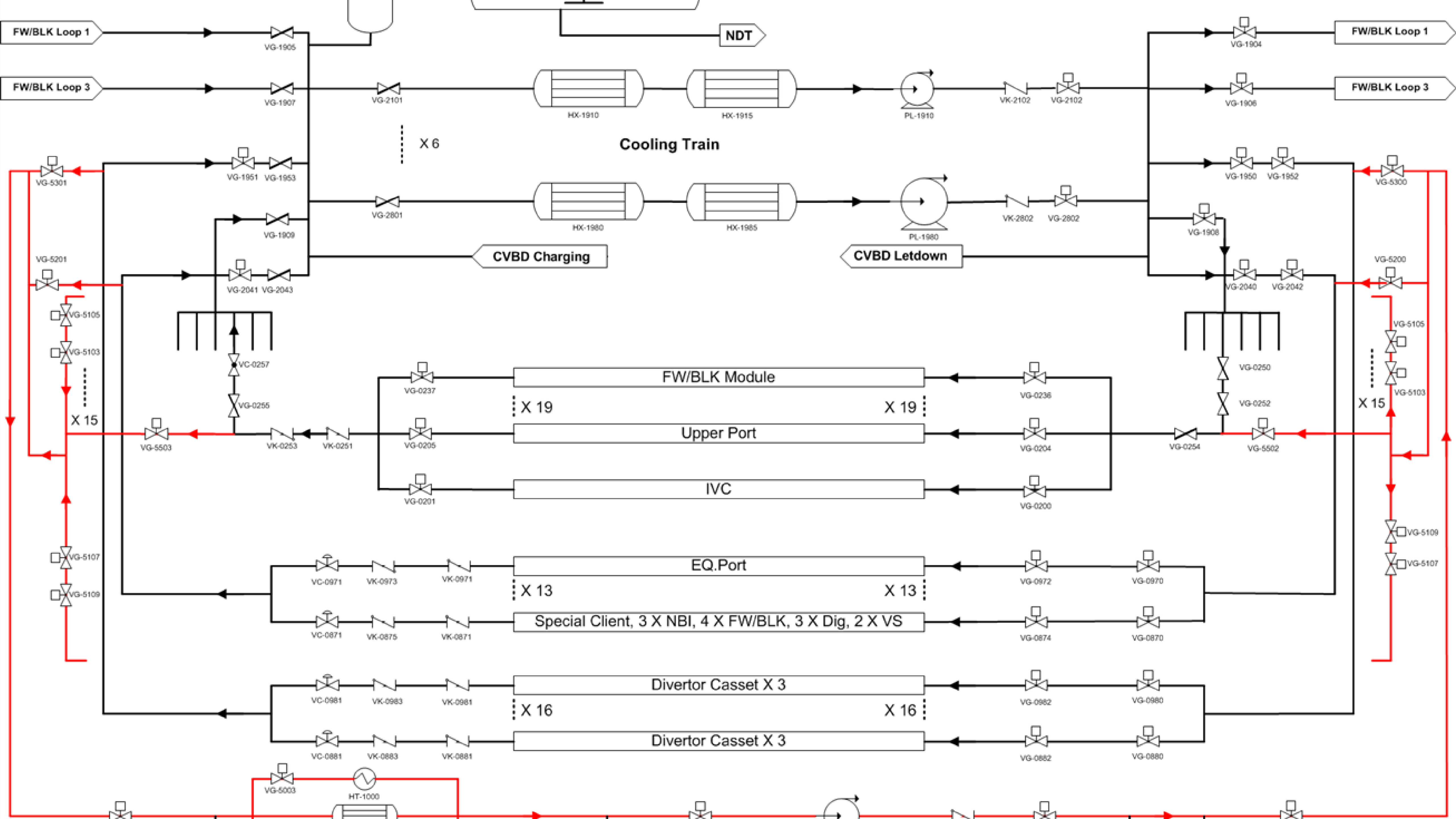


Figure 57. Integrated damage functions (crack length) vs reactor operating time for three operating scenarios: (1) NWC, (2) HWC (1 ppm H_2 in the reactor feedwater), and (3) NWC for 5 years followed by HWC for the remaining 5 years (Macdonald and Balachov).

- Data for a BWR but is expected to hold for ITER with modification for intermittent operation of burn/dwell.
- Shape of crack depth vs time is due to the impact of crack length and hence IR potential drop down the crack on the crack growth rate.
- Illustrates the Law of Decreasing Returns; the benefits of HWC decrease the later it is started.
- Similar studies need to be performed for ITER.

Comprehensive Model of ITER Coolant Circuit. (Macdonald and Engelhardt, 2017).

- Work funded by US ITER, ORNL.
- Predicted species concentrations only, no ECP or crack growth rate predictions were included in the project.
- Work follows extensive work over 30 years in modelling the coolant circuits of BWRs and PWRs.
- Codes developed for predicting specie concentrations at closely spaced points around the entire coolant circuit.
- Because of the complexity of the circuit (next slide) it was necessary to use a simpler analog, but with the residence times in the plasma zone and the out-of-plasma zone and the hydrodynamic parameters being as for the real circuit.



FW/BLK Loop 1
FW/BLK Loop 3
NDT
VG-1905
VG-1907
VG-2101
HX-1910
HX-1915
PL-1910
VK-2102
VG-2102
VG-1904
VG-1906
X 6
Cooling Train
VG-5301
VG-1951
VG-1953
VG-1950
VG-1952
VG-5300
VG-2801
HX-1980
HX-1985
PL-1980
VK-2802
VG-2802
VG-1909
VG-1908
CVBD Charging
CVBD Letdown
VG-5201
VG-2041
VG-2043
VG-2040
VG-2042
VG-5200
VG-5105
VG-5103
X 15
VC-0257
VC-0255
VG-0250
VG-0252
FW/BLK Module
VG-0237
VG-0236
X 19
Upper Port
VG-5503
VK-0253
VK-0251
VG-0205
VG-0204
VG-0254
VG-5502
IVC
VG-0201
VG-0200
VG-5107
VG-5109
EQ.Port
VC-0971
VK-0973
VK-0971
VG-0972
VG-0970
X 13
Special Client, 3 X NBI, 4 X FW/BLK, 3 X Dig, 2 X VS
VC-0871
VK-0875
VK-0871
VG-0874
VG-0870
Divertor Casset X 3
VC-0981
VK-0983
VK-0981
VG-0982
VG-0980
X 16
VC-0881
VK-0883
VK-0881
VG-0882
VG-0880
VG-5003
HT-1000

Energy deposition rates in water from the plasma for various IBED PHTS components

Table 23. Energy deposition rates in water from the plasma for various IBED PHTS components

Component	Energy deposition, W/cm³		References
	Neutron	Gamma	
Normal Heat Flux Module(a)			[28–30]
Manifold In(3)	0.306	0.054	
First Wall (FW)(3)	3.437	0.607	
Shield Block (SB)(3)	0.884	0.156	
Manifold Out(3)	0.306	0.054	
Enhanced Heat Flux Module(a)			
Manifold In(3)	0.714	0.126	
FW(3)	6.712	1.184	
SB(3)	1.819	0.321	
Manifold Out(3)	0.714	0.126	
Edge Localized Mode/Vertical Stabilization Coils(a)	0.187	0.033	
Divertor			[31], [32]
Cassette Body (Steel)(4)	0.175	0.031	
Inner Vertical Target (IVT) (PFUs)(4)	1.482	0.262	
IVT (Steel)(4)	0.591	0.104	
Outer Vertical Target (OVT) (PFUs)(4)	1.640	0.289	
OVT (Steel)(4)	0.615	0.109	
Dome (PFUs Outer)(4)	1.015	0.179	
Dome (PFUs Umbrella)(4)	1.310	0.231	
Dome (PFUs Inner)(4)	1.265	0.223	
Dome (Steel Outer)(4)	0.494	0.087	
Dome (Steel Umbrella)(4)	0.293	0.052	
Dome (Steel Inner)(4)	1.148	0.203	
Upper Port Plugs(b) (6)	1	4.6	33
Equatorial Port Plugs(b) (6)	3.2	4.3	
Lower Port Plugs(b) (6)	10^{-6}	10^{-6}	34
Neutral Beam Injector Duct Liners(b) (6)	0.2	0.8	35

(a) Average values across the module depth.
(b) Maximum (conservative) values.

- Latest data available for radiation parameters during the plasma burn.
- Energy deposition rates assumed to be zero during dwell.
- However, long-lived radiolysis products are transported to out of radiation zone areas of the coolant circuit and will persist, albeit at lower levels, during the dwell.

Simplified Coolant Circuit

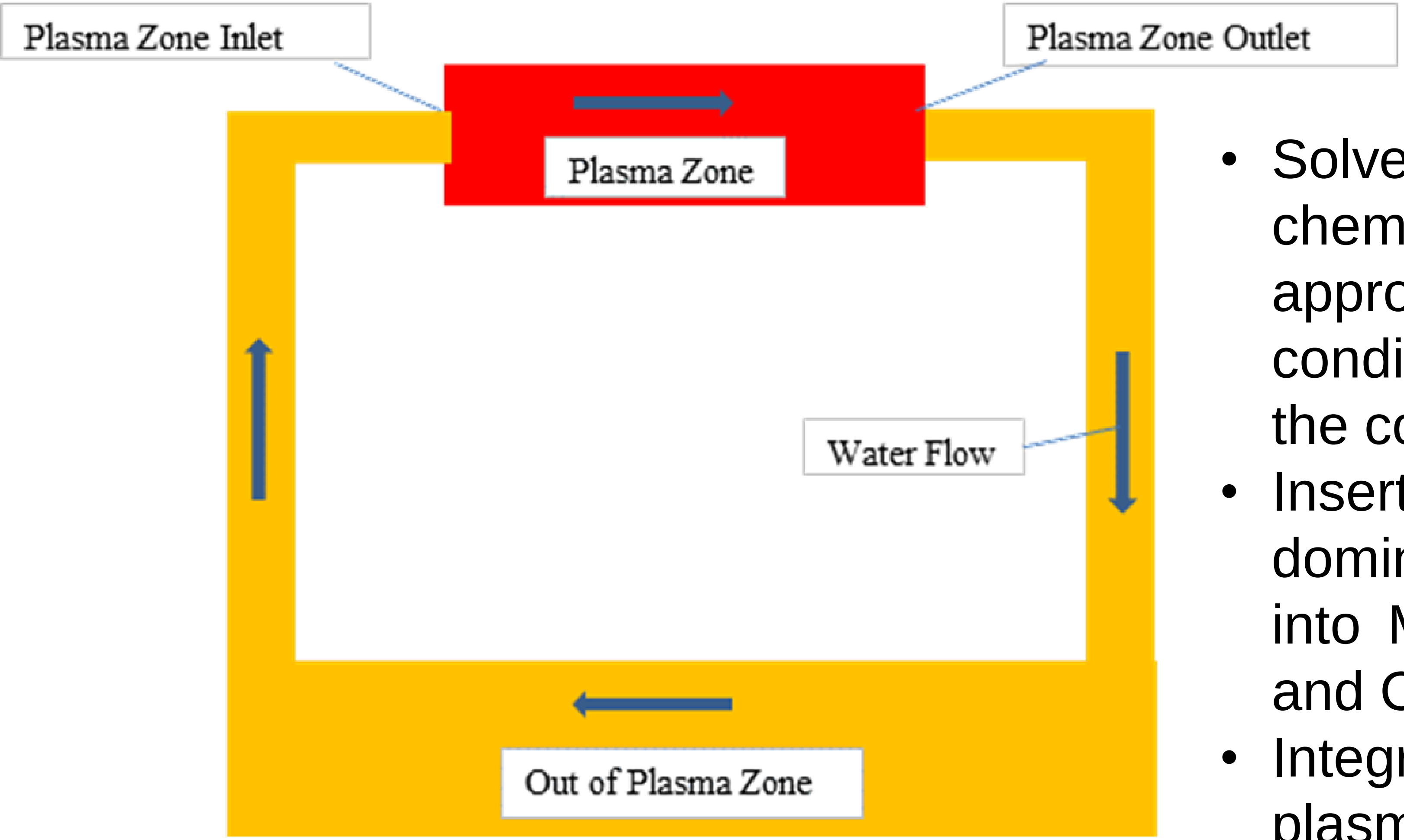


Figure 24. Simplified representation of the IBED PHTS.

- Solve couple mass transport, chemical reaction equations with appropriate initial boundary conditions for each species to yield the concentration.
- Insert concentrations of the most dominant species (H2, O2, H2O2) into MPM and CEFM to yield ECP and CGR.
- Integrate CGR over successive plasma burn/dwell cycles to predict damage (crack length vs operating time).

Table 24. IBED PHTS chemistry parameters [10]

Parameter	IBED PHTS
Conductivity @ 25 °C, µS/cm	≤0.2
pH @ 25 °C	7.0–9.0
Sodium, ppb	≤5
Chloride, ppb	≤5
Hydrogen, ppb	≤350
Catalyzed Hydrazine, ppb	≤30
Ammonia, ppb	≤1000
Oxygen, ppb	≤10
ORP @ 25 °C, mV	-(400)–(-100)
Iron, ppb	≤10
Copper, ppb	≤10

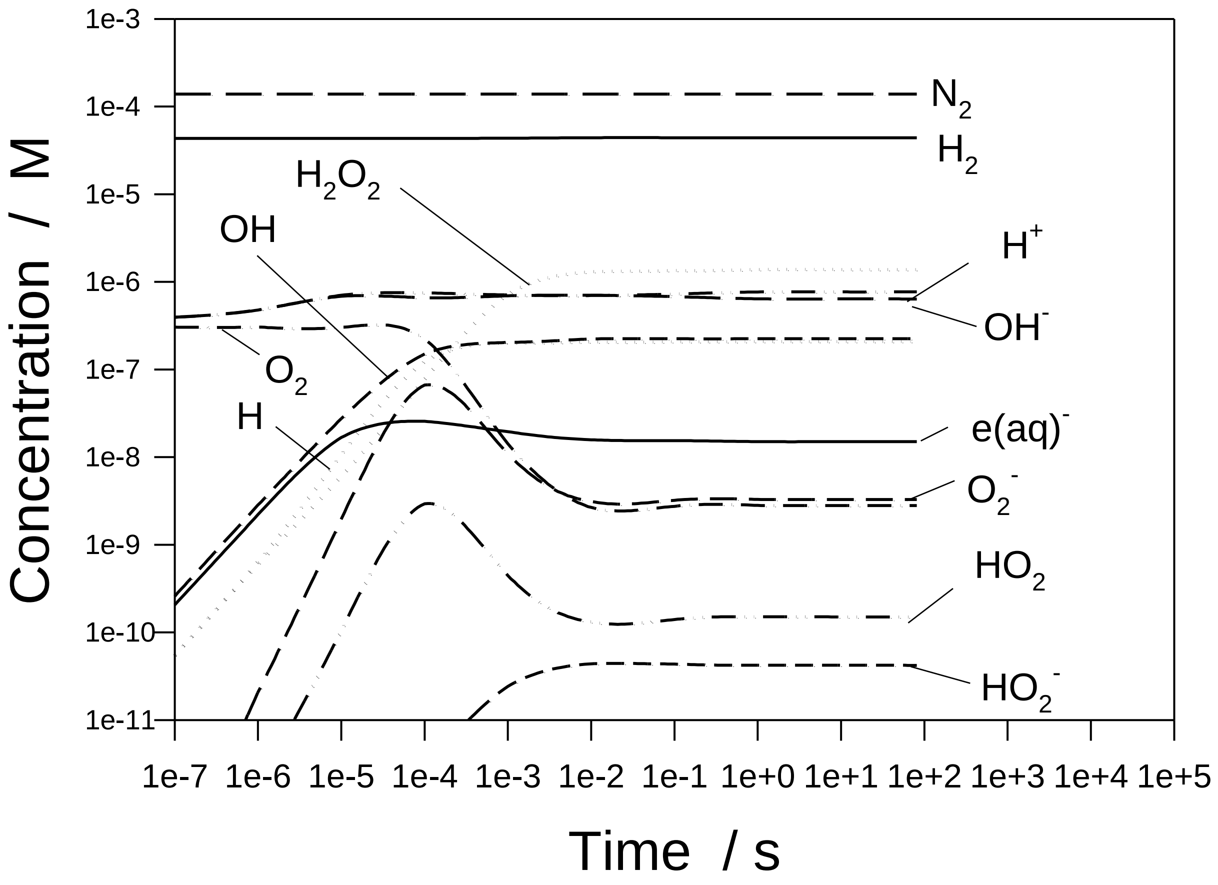


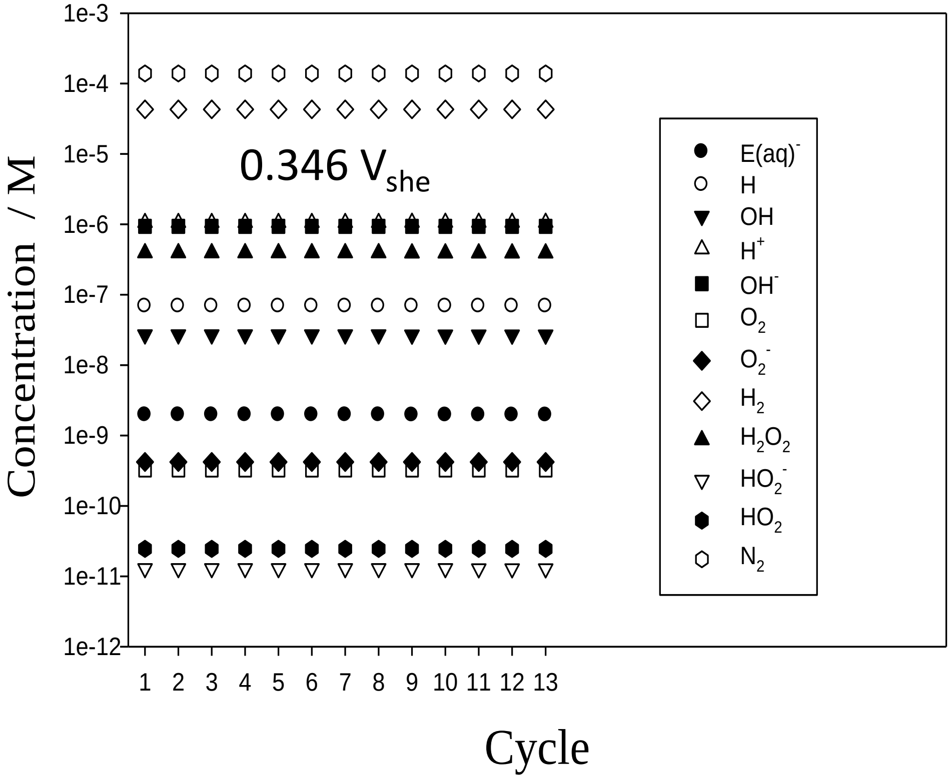
Figure 15. Concentrations of species in the model block (see Table 24) as functions of time. Note added ammonia for pH control, pH = 9.5 at 25 °C and hydrazine to scavenge O_2.

Table 27. Rate of hydrogen peroxide production by different modules

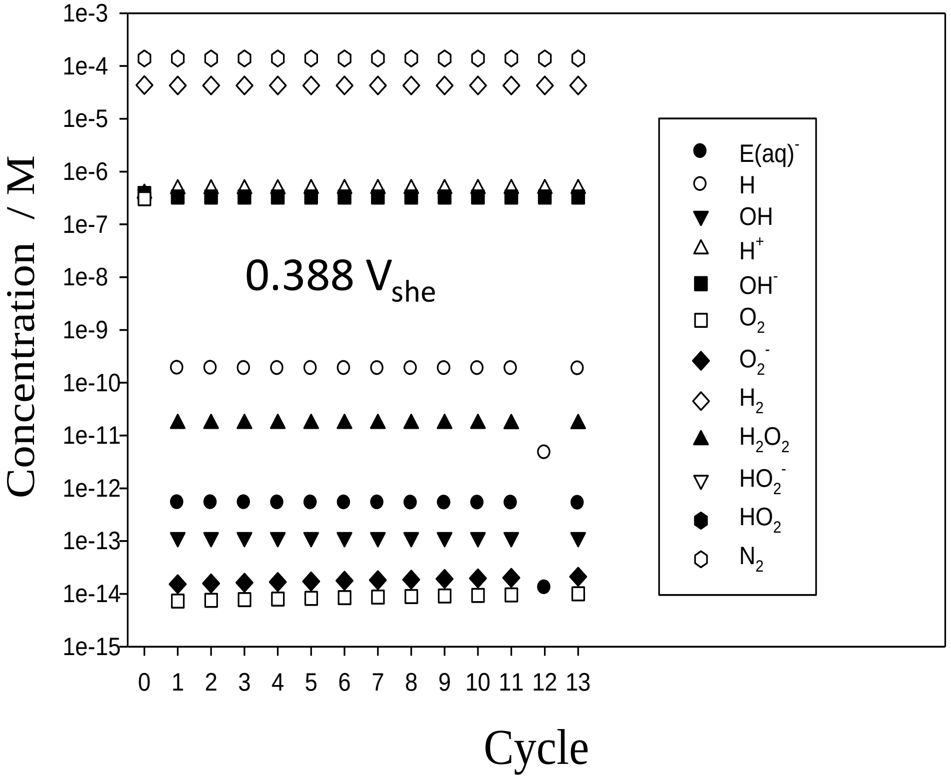
No.	Module	H_2O_2 production rate (g/s)
1	Divertor (D)	5.73E+00
2	Normal Heat Flux (NHF)	1.31E+01
3	Enhanced Heat Flux (EHF)	2.47E+01
4	18 Upper Ports (Ups)	1.22E–06
5	27 Edge Localized Modes	5.09E–01
6	Upper Vertical Stabilization (VS)	5.67E–02
7	15 Equatorial Ports (Eps)	1.59E+01
8	Lower VS 4T	5.67E–02
9	3 Lower Ports	2.29E–06
10	3 Neutral Beam Injector Duct Liners (NBIDLs)	2.35E+00
11	NHF	9.14E–01
12	EHF	1.29E–01
	All Modules	63.5

- Hydrogen peroxide (H_2O_2) is the most deleterious species, because on a per mole basis it elevate the ECP much more than oxygen (O_2).
- Highest generation rate of H_2O_2 is predicted to occur in the Enhanced Heat Flux module that also has the highest *n* and *γ* dose rate.
- Plasma zone comprises D, NHF, EHF, and NBIDLs. The out-of-plasma zone comprises the rest.

Predicted Concentrations at the Inlet to and the Outlet



Outlet of Plasma Zone



Inlet of Plasma Zone

- System is predicted to come to steady-state within one cycle of the coolant.
- $[H_2]$ essentially constant, but $[O_2]$ and $[H_2O_2]$ are predicted to be reduced by a factor of > 10^4 at the inlet to the plasma zone compared with the outlet.

Summary and Conclusions

- In fusion reactors (e.g., ITER), the coolant will be subjected to intense, high energy *n* and *γ* irradiation that will produce a myriad of electroactive radiolysis products that can participate in corrosion processes. The dominant products are predicted to be H_2, O_2, and H_2O_2.
- The currently proposed coolant chemistry is similar to that of a BWR primary coolant under HWC conditions at low temperatures (100 ^oC vs 288 ^oC for a BWR), with the exception that NH_3 and N_2H_4 may be added for pH and redox control, respectively.
- The most likely corrosion problems are IGSCC of weld- and irradiation-sensitized austenitic stainless steels and general corrosion of Cu alloys.
- Radiolysis and mixed Potential Models have been developed for predicting species concentrations, electrochemical corrosion potential (ECP), and crack growth rate (CGR) at closely-spaced points around the coolant circuit of the ITER.
- During the plasma burn, the ECP of Type 304 SS in the radiation zone is predicted to be 0.10 – 0.35 V_{she}, well above the critical potential for IGSCC of -0.23 V_{she} while during the dwell, the ECP is predicted to be about -0.45 V_{she}, a value at which IGSCC cannot occur.
- Accordingly, crack growth is predicted to be cyclical corresponding to the plasma burn cycles.
- Estimates are made of the crack growth rate over multiple burn/dwell cycles and the growth in the crack length as a function of operating time is estimated taking into account the impact of increasing crack length on the CGR.

Acknowledgments

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