Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

Deterministic analyses in support of nuclear fusion system/facilities early stage design

15th EMUG meeting – Unicersità la Sapienza Roma, 17/04/2024

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Outline

Context: deterministic Safety analysis in early design stages

DEMO Plant Divertor system study case

DONES Facility Lithium System loop

Context: deterministic safety analysis in early design stages

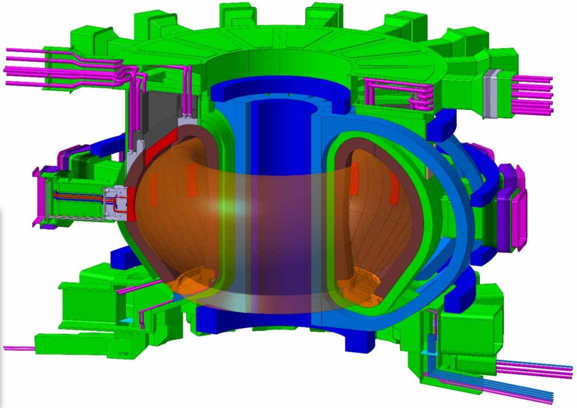
Fusion Plant preliminary safety analysis

Identification of:
- Plant Safety objectives
- Safety functions

Plant design

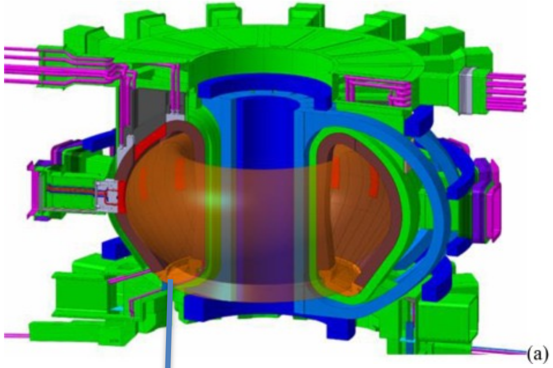
Identification of plant:
- Hazards / risks
  - Reference accident definition Design Basis Accident- Design Extension Conditions
    - Scoping analysis on identified DBA-DEC

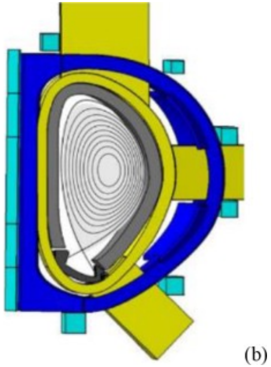
Case study examples from: EUROFusion Nuclear Fusion DEMOnstration plant



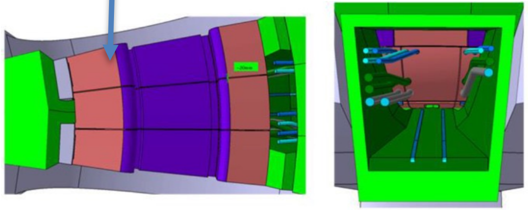
- Perspective:
  - early validation of design and identification of issues/showstoppers
  - assumptions/sensitivities on undefined design parameters (dimensioning/settings/isolation classification)

DEMO Divertor system: in Vacuum Vessel components

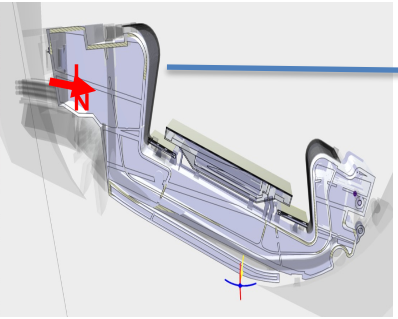




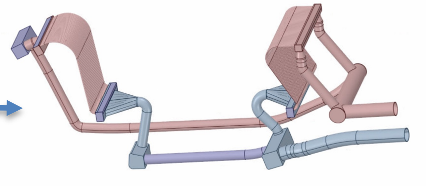
16 sectors x 3 = 48 modules



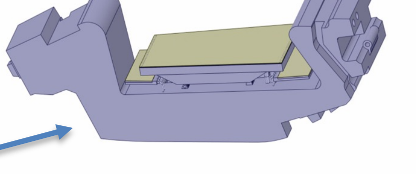
Each module

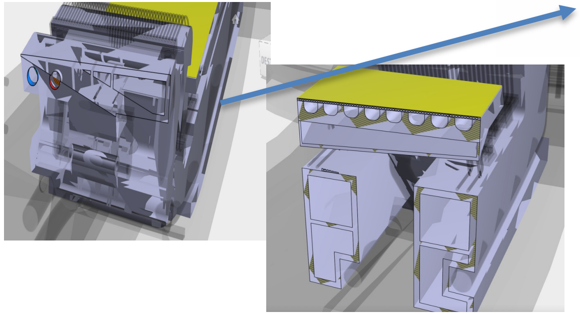


1 Plasma Facing Unit



1 cassette

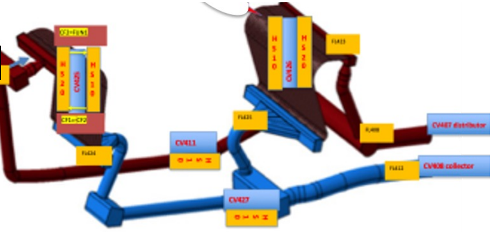


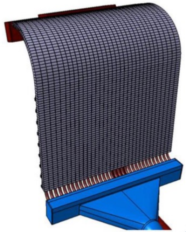


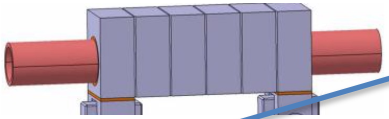
https://doi.org/10.1016/j.fusengdes.2022.113010

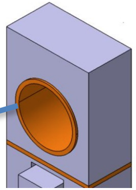
Melcor Model development DEMO Divertor system

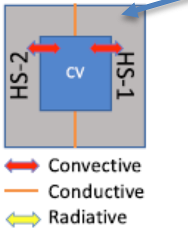
Development of model for in VesselDiverto PFU components:
1- Channels with both convective and conductive
2- Swirled pipes - higher HTC with respect to melcor self-calculated







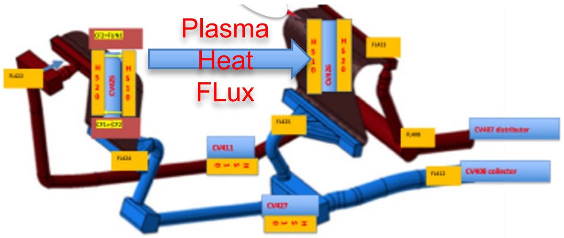


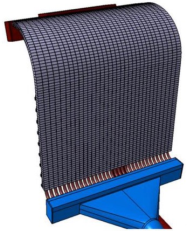


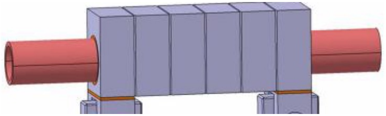
- MELCOR FUN1 functions have been used to represent the conductive contact between the plasma-side and cassette-side HS of IVT and OVT volumes.
- Melcor calculated HTC much lower than actual one in Steady State conditions > need for compensation

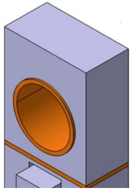
Heat Transfer Coefficient	
Temp [K]	HTC [$Wm^{-2}K^{-1}$]
278.15	105790
378.15	134860
474.37	145680
579.03	225040

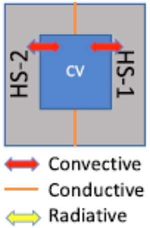
Melcor Model development DEMO Divertor system











```
* HS10 - Tile OuterVT side (where disruption occurs) - hs plasma on left/cv415 on right
….
hs42610001    'PFU_1OVTplasma'              * Name of Structure,
…..
hs42610201   TUNGSTEN       1              *
hs42610202   Cu               2               *
hs42610203   CuCrZr        3               * material Name, Mesh Interval number
hs42610300   9420   -1    1.                  * POWER SOURSE VOLUMETRIC- ref to CF420, power sourc distr. data to enter, fraction of power from CF/TF to apply
….
hs42610400   -7721  100 ext 0.5 0.5    * LEFT SIDE Convective exchange HTC self-calculated + power source from plasma in function CF421,
…
hs42610600   -7656  426 int 0.1 0.9      * RIGHT SIDE Convective+ cond+rad fun1 cf304 , *SWIRL COMPENSATION HERE
…..
```

Issue: *convective boundary with HTC dependency on temperature* && surface power source flux (disruption etc.)

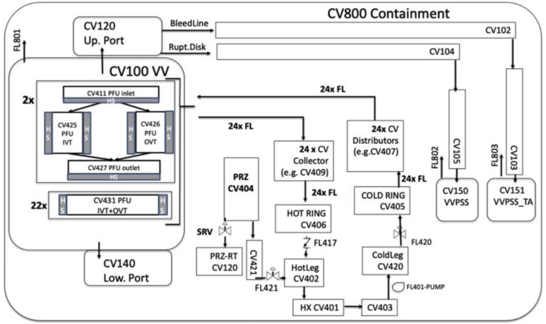
```
*Extra heat transfer because of swirl inserts
cf65600 htotal add 2 1.0 0.0 * power removed from hs
cf65601 0.0
cf65610 1.0 0.0 cfvalu.304 * conduction
cf65611 -1.0 0.0 cfvalu.655 * compensation for swirl inserts
```

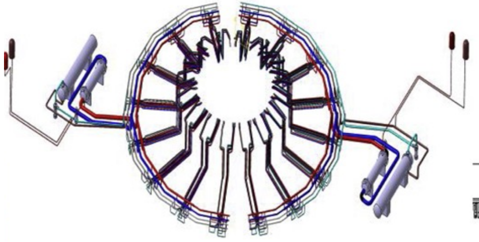
CF 655 logic accounting for:
-- additional heat removal derived from swirled-pipes / Experimental Temperature dependency HTC
-- dependency on flow/pool fraction, i.e. this additional heat is not considered after LOCA/LOFA event

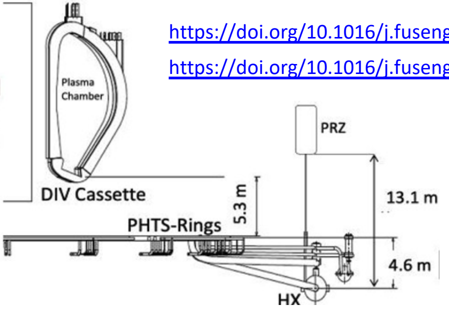
```
*********************************************************************************
cf30400 'OVTBRK10' FUN1 5 1.0 0.0 * radiation+conduction function
cf30401 0.000e0                   * initial value
cf30410 1.0 0.0 hs-temp.4262001   * temp1 CuCrZr layer HS2
cf30411 1.0 0.0 hs-temp.4261004   * temp2 CuCrZr layer HS1
cf30412 0.0 8967.291667 time        * A3 = f*ks/dx' ; dx'=dx*J, J=1.15
cf30413 0.0 0.1054 time           * * A4
cf30414 0.0 0.74855088 time         * A5 area
```

Initial Divertor HTS layout: PFU LOCA , LOFA

- 2 loops for PFU (8 sectors each)
- 2 loops for Cassette (8 sectors each)
- HX, rings, PRZ at lower elevations







https://doi.org/10.1016/j.fusengdes.2021.112475

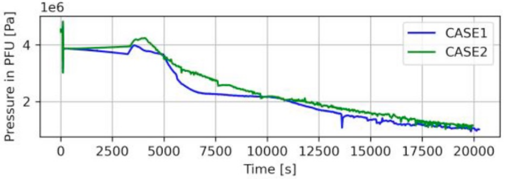
https://doi.org/10.1016/j.fusengdes.2022.113025

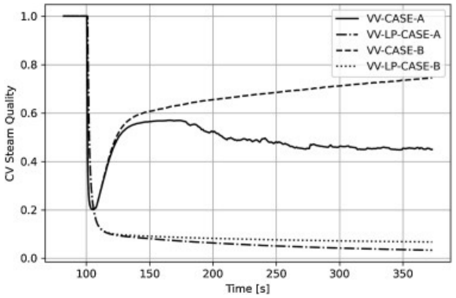
In **PFU** - LOCA scenario: pressure accommodation capability provided by VVPSS

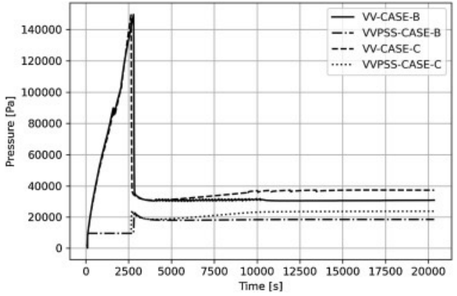
CASE A - Vacuum Vessel Walls at 40 °C, with PFU HTS valves

CASE B - Vacuum Vessel Walls at 200 °C, with PFU HTS valves

CASE C - Vacuum Vessel Walls at 200 °C, no valves.





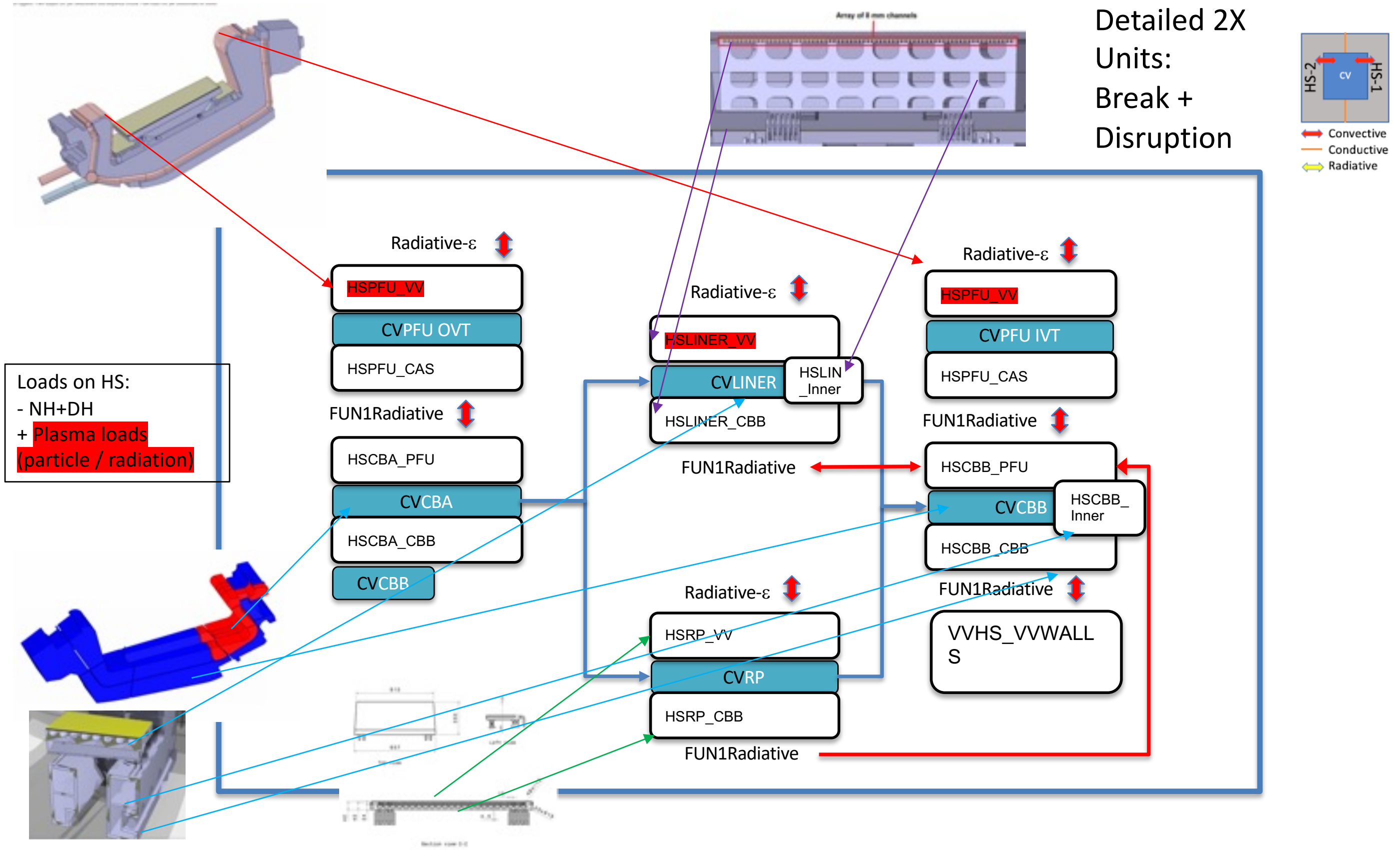


In LOFA: pressure accommodation capability provided by pressurizer, despite <u>not favoured by the loop layout in terms of relative elevations</u>

Melcor Model development DEMO Divertor system

Development of model for in Vessel components: FUN1 coupling across PFU-CASSETTE

Detailed 2X Units:
Break +
Disruption



Loads on HS:
- NH+DH
+ Plasma loads (particle / radiation)

Radiative-ε
HSPFU_VV
CVPFU OVT
HSPFU_CAS
FUN1Radiative
HSCBA_PFU
CVCBA
HSCBA_CBB
CVCBB

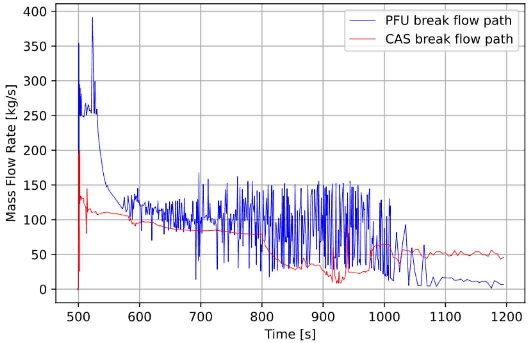
Radiative-ε
HSLINER_VV
CVLINER
HSLIN_Inner
HSLINER_CBB
FUN1Radiative

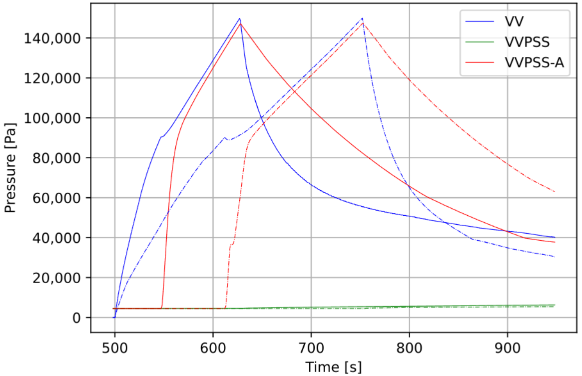
Radiative-ε
HSRP_VV
CVRP
HSRP_CBB
FUN1Radiative

Radiative-ε
HSPFU_VV
CVPFU IVT
HSPFU_CAS
FUN1Radiative
HSCBB_PFU
CVCBB
HSCBB_Inner
HSCBB_CBB
FUN1Radiative
VVHS_VVWALLS

Initial Divertor HTS layout: Cassette & PFU LOCA

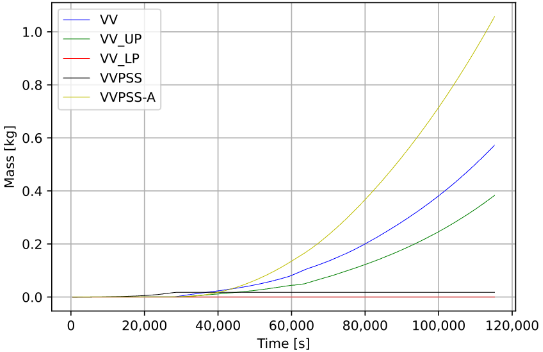
CASE1. In-vessel LOCA in the DIV primary cooling circuit for the cassette module

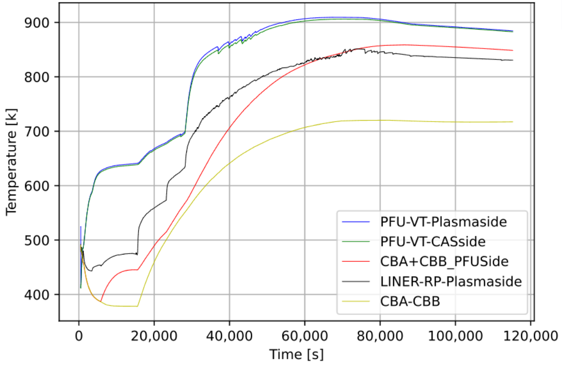




Case 1 (dashed line)

CASE2. In-vessel LOCA in the DIV primary cooling circuit for the cassette module and target PFU loop





Long-term Hydrogen mass inventory resulting from steam - W reactions ($W + 3 H_2O \rightarrow 3 H_2 + WO_3 - 156$ kJ/mol)

Equation for H2 production	Unit
RR = 15140 * exp(-16720/T); T in K	[l/m^2_s]

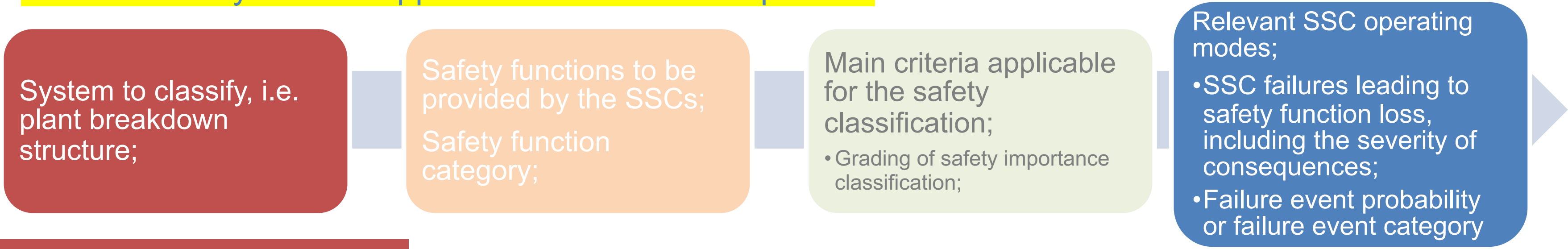
https://doi.org/10.1016/S0022-3115(98)00169-X

Hydrogen production relevant at high temperature only, long term pattern

System Classification – motivation and application

To support early safety classification an example of application to DEMO plant of the approach to SSCs safety classification derived from IAEA Guide No. SSG-30 is presented,

-> Melcor analysis can support definition of consequences



System to classify, i.e. plant breakdown structure;

Safety functions to be provided by the SSCs;

Safety function category;

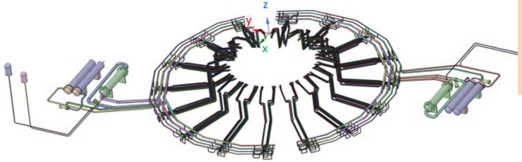
Main criteria applicable for the safety classification;

- Grading of safety importance classification;

Relevant SSC operating modes;

- SSC failures leading to safety function loss, including the severity of consequences;
- Failure event probability or failure event category

DEMO Divertor Cassette PHTS
- Assumed 0.015 g-T /m3 inVV water cooling loops: 2.35g-T
- 7 kg of Activated Corrosion Products (**ACP**)

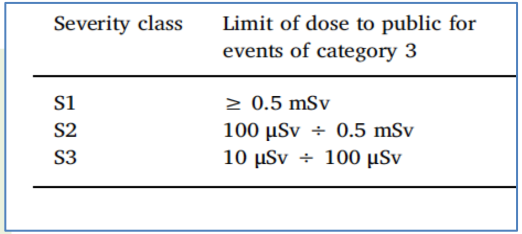


https://doi.org/10.3390/en15238879

Confinement of radioactivity Limitation of radioactive exposure

SIC-1.

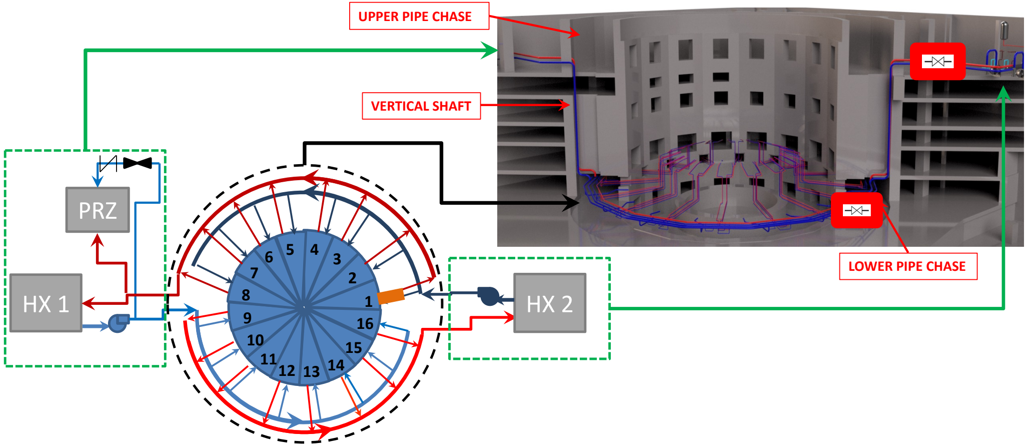
- If SSC failure could lead to an event with consequences exceeding one-tenth of the limits set out in plant safety requirements



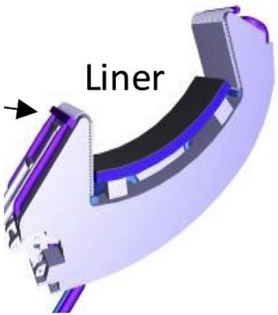
Severity class	Limit of dose to public for events of category 3
S1	≥ 0.5 mSv
S2	100 µSv ÷ 0.5 mSv
S3	10 µSv ÷ 100 µSv

ref->Technical Meeting on Fusion Design Safety and Regulation, IAEA Headquarters 23-25 October 2023

Example of sensitivity studies supporting classification: DEMO Divertor cassette Primary Heat Transfer System

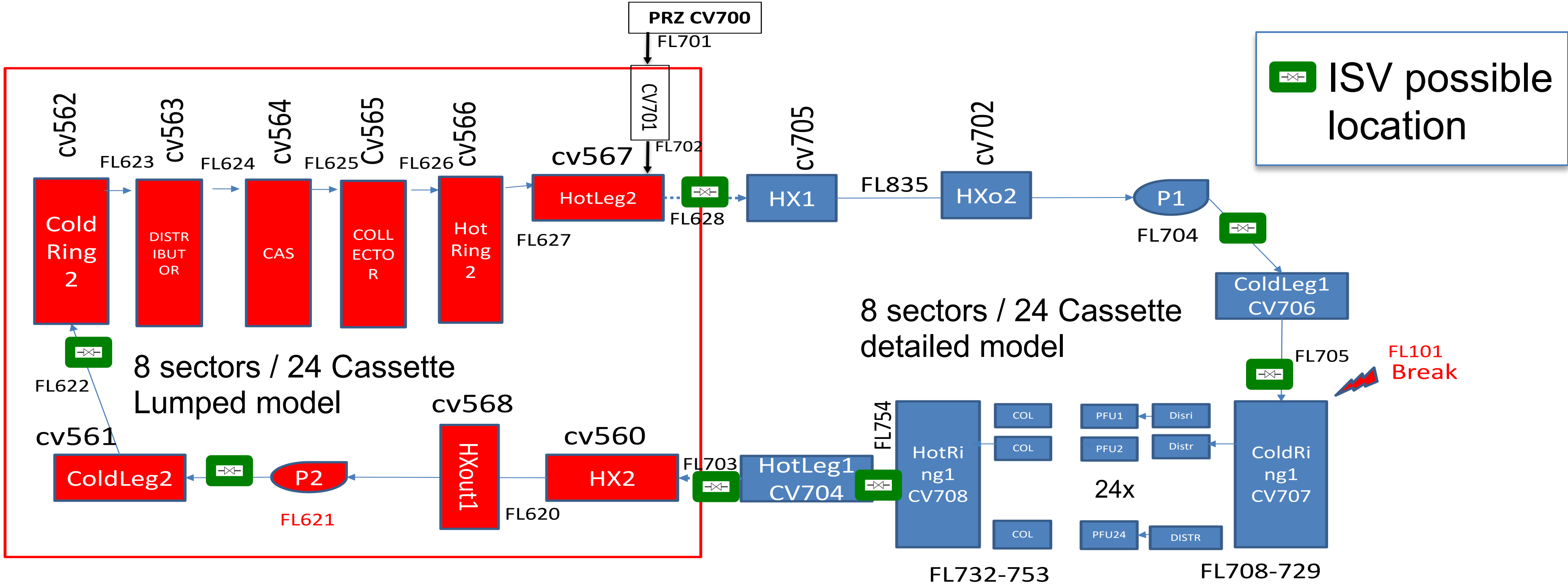


DIV CASSETTE PHTS main data	
Thermal power [MW]	185.0
Total water volume [m^3]	156.8
Total piping length (In+Ex-VV) [m]	3042
Cooling loops [-]	1



- inVV coolant inventory for divertor cassette 45% of 157m3.
- Radionuclide inventory in coolant:
  - 7 kg of Activated Corrosion Products (**ACP**)
  - Assumed 0.015 g-T /m3 inVV water cooling loops: 2.35g-T

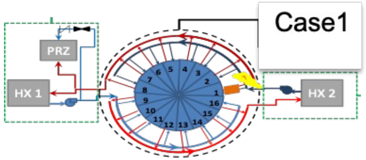
MELCOR code INPUT overview

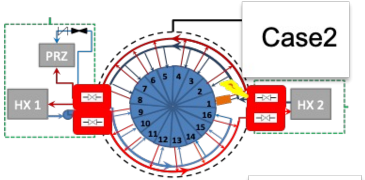


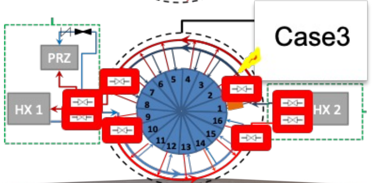
+ Vacuum Vessel and Tokamak Building

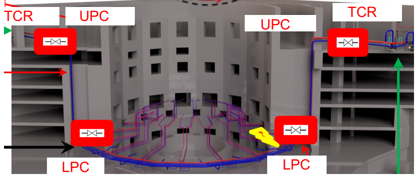
Layout and considered accident

Studied Postulated Initiating Accident: Ex-vessel LOCA: DOUBLE END GUILLOTINE BREAK of Divertor Cassette HTS loop in the cold leg







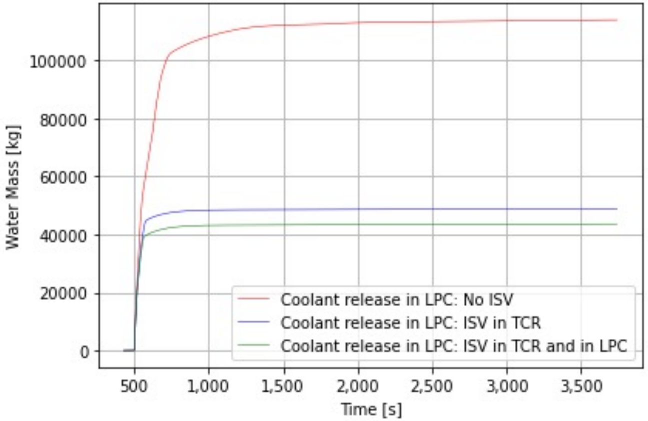


1. CASE 1: NO Safety Isolation Valves (SIV)
2. CASE 2: Safety Isolation Valves (SIV) upstream HXs
    1. SIV Contributes to mitigate consequences and reach controlled state
3. CASE 3: Safety Isolation Valves (SIV) upstream HXs AND in LPC
    1. SIV contributes to mitigate consequences and reach controlled state

Scoping analysis results

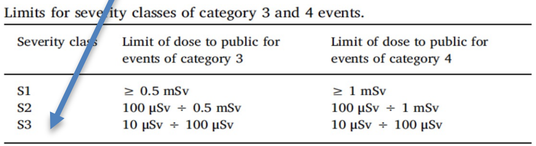
Studied Postulated Initiating Accident: Ex-vessel LOCA: DOUBLE END GUILLOTINE BREAK of Divertor Cassette HTS loop in the cold leg

CASE	HTO [g] release in LPC 10s ISV (5s ISV)[3s ISV]
#1 No ISV	13.99 (-)
#2 ISV UPC	5.76 (5.52) [5.48]
#3 ISV UPC+LPC	5.10 (5.10) [5.10]



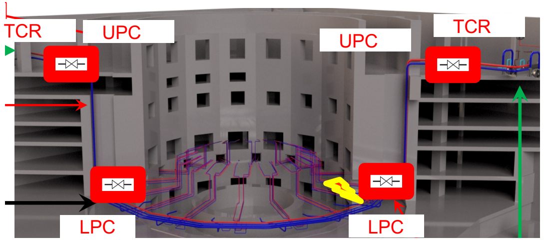
Release of HTO to
environment after 1 week from
IE on coolant loop
(HTO g -> DCF) < 30 [μSv]

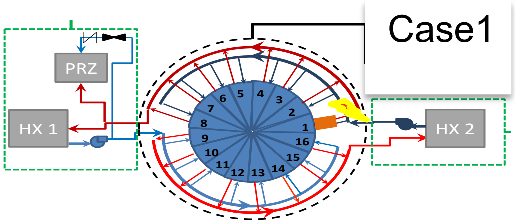
Severity S3

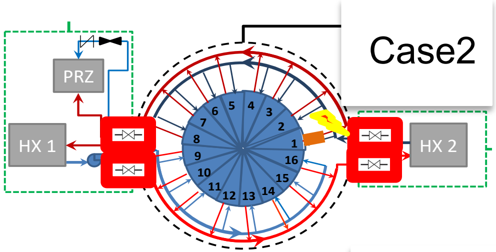


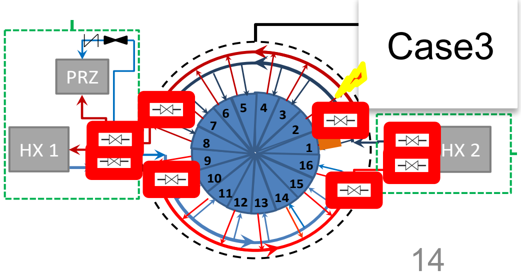
Limits for severity classes of category 3 and 4 events.

Severity class	Limit of dose to public for events of category 3	Limit of dose to public for events of category 4
S1	≥ 0.5 mSv	≥ 1 mSv
S2	100 μSv ÷ 0.5 mSv	100 μSv ÷ 1 mSv
S3	10 μSv ÷ 100 μSv	10 μSv ÷ 100 μSv





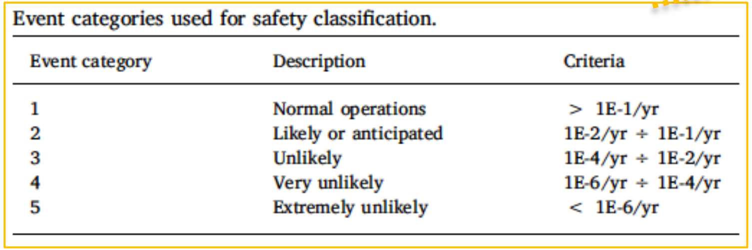




Example of application of IAEA SSG-30 to DEMO Divertor

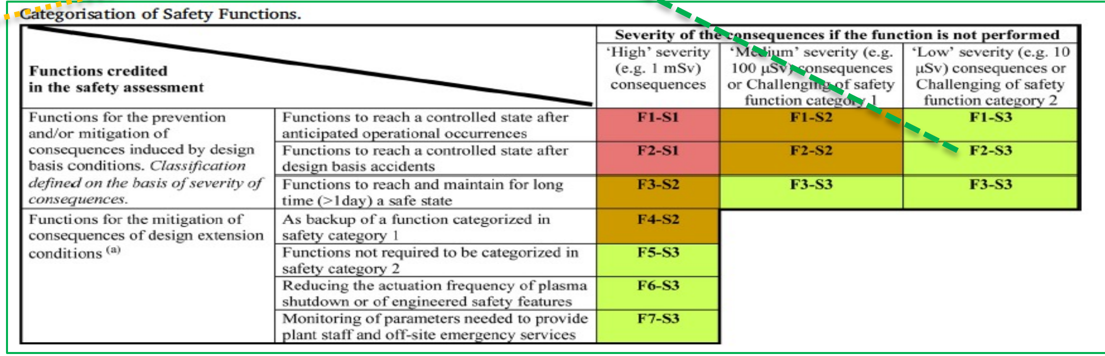
Merging information

PBS elements (Components)	Safety function	Op. Md.	Possible Failure of SSC	Event Category	Significant event	Safety Classific Criteria	Function safety category	Safety Class	Failure Rate	FR Unit	Yearly Failure Rate
55 - Divertor (DIV) Primary Heat Transfer System (PHTS)											
55-1 - Divertor PHTS segments (Water loops to cool-down DIV cassettes)											
55-1-1 - Supply and Distribution											
55-1-1-1 - Pipe work (In cryostat)			Leak/Rupture	4	Large LOCA	A	F2-S3	SIC-3	2,50E-11	/h	5,78E-06
55-1-1-2 - Pipe work (In PC & shaft to cooling room)	S1a) - Provide process confinement barriers		Leak/Rupture	4	Large LOCA	A	F2-S3	SIC-3	2,50E-11	/h	9,63E-08
55-1-1-3 - Segment supply line isolation valves	S1a) - Provide process confinement barriers		Leak/Rupture	3	Large LOCA	B	F2-S3	SIC-3	2,66E-08	/h	3,07E-04



Event categories used for safety classification.

Event category	Description	Criteria
1	Normal operations	> 1E-1/yr
2	Likely or anticipated	1E-2/yr ÷ 1E-1/yr
3	Unlikely	1E-4/yr ÷ 1E-2/yr
4	Very unlikely	1E-6/yr ÷ 1E-4/yr
5	Extremely unlikely	< 1E-6/yr



Categorisation of Safety Functions.

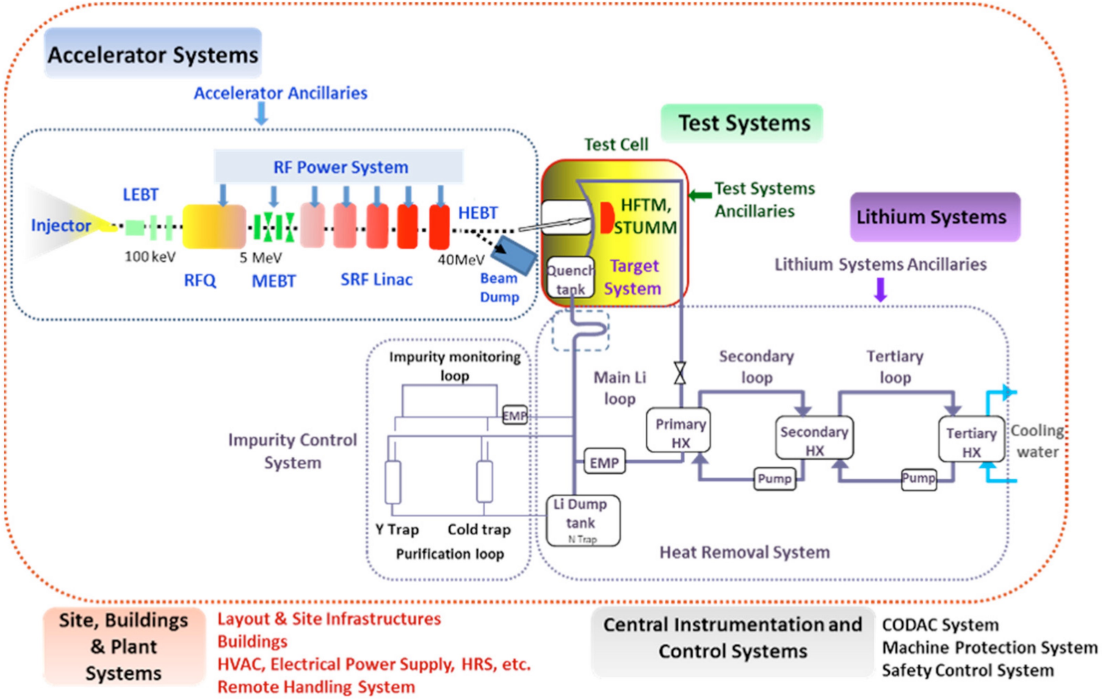
Functions credited in the safety assessment		Severity of the consequences if the function is not performed		
		'High' severity (e.g. 1 mSv) consequences	'Medium' severity (e.g. 100 µSv) consequences or Challenging of safety function category 1	'Low' severity (e.g. 10 µSv) consequences or Challenging of safety function category 2
Functions for the prevention and/or mitigation of consequences induced by design basis conditions. *Classification defined on the basis of severity of consequences.*	Functions to reach a controlled state after anticipated operational occurrences	**F1-S1**	**F1-S2**	**F1-S3**
	Functions to reach a controlled state after design basis accidents	**F2-S1**	**F2-S2**	**F2-S3**
	Functions to reach and maintain for long time (>1day) a safe state	**F3-S2**	**F3-S3**	**F3-S3**
Functions for the mitigation of consequences of design extension conditions [(a)]	As backup of a function categorized in safety category 1	**F4-S2**		
	Functions not required to be categorized in safety category 2	**F5-S3**		
	Reducing the actuation frequency of plasma shutdown or of engineered safety features	**F6-S3**		
	Monitoring of parameters needed to provide plant staff and off-site emergency services	**F7-S3**		

Outline

Context: deterministic Safety analysis in early design stages

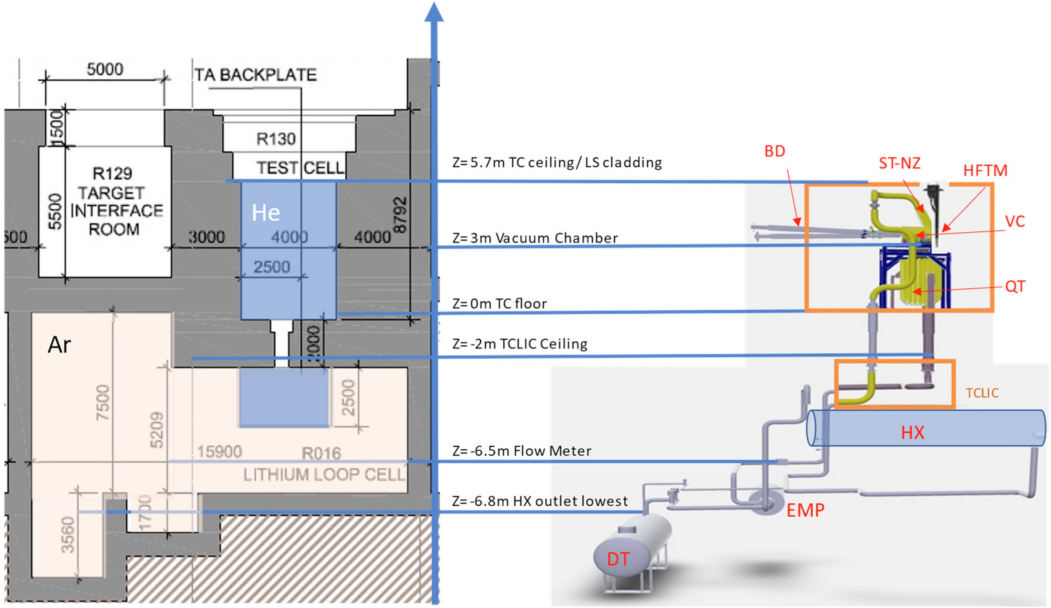
DEMO Plant Divertor system study case

DONES Facility Lithium System loop



Design problem position: safety case 1

Water cooled liner in DONES Test cell with possible lithium spills and potential lithium –water reactions in case of liner failure

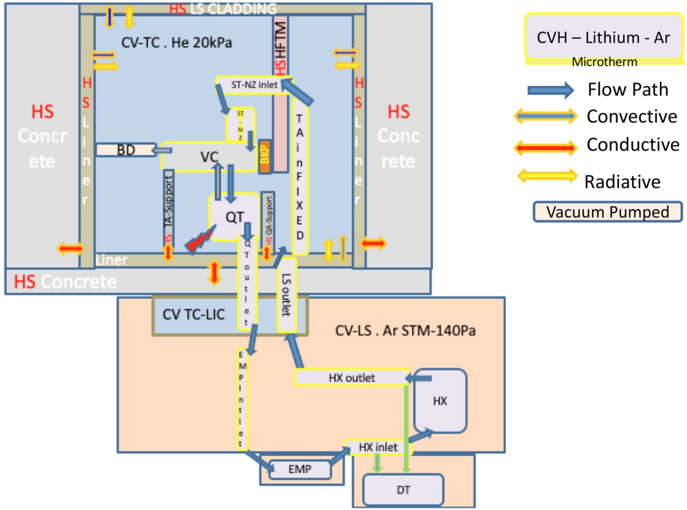


(a) (b)

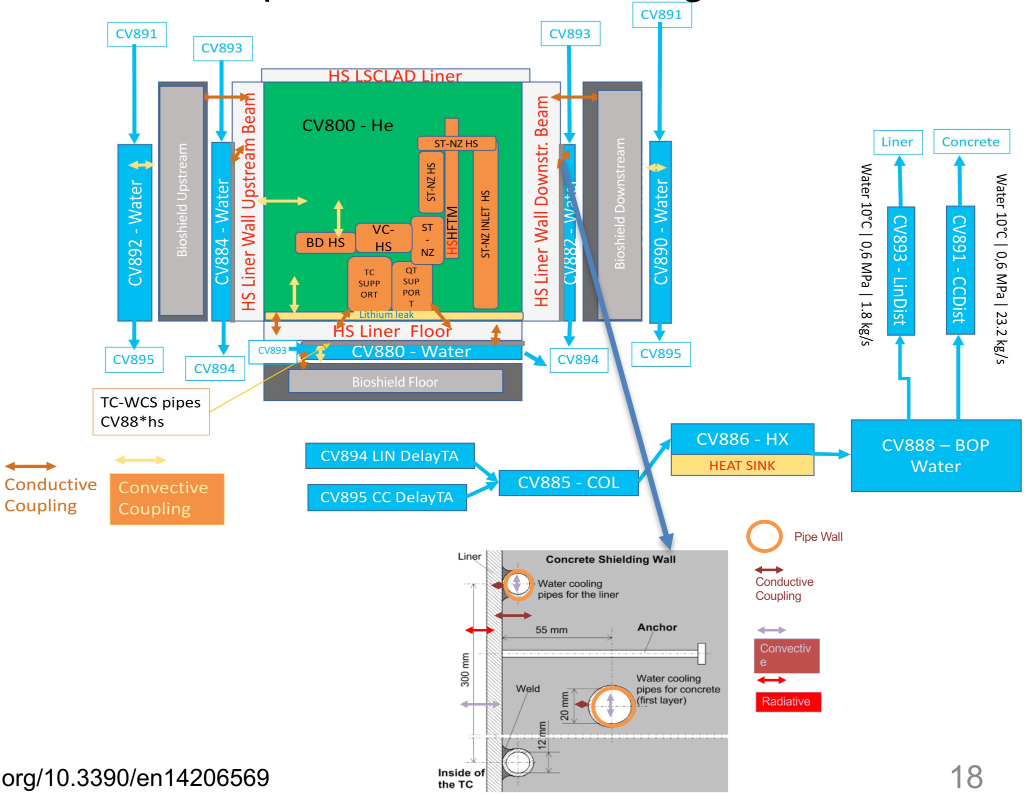
Approach

Creation of two melcor models

Lithium loop with Li as working fluid



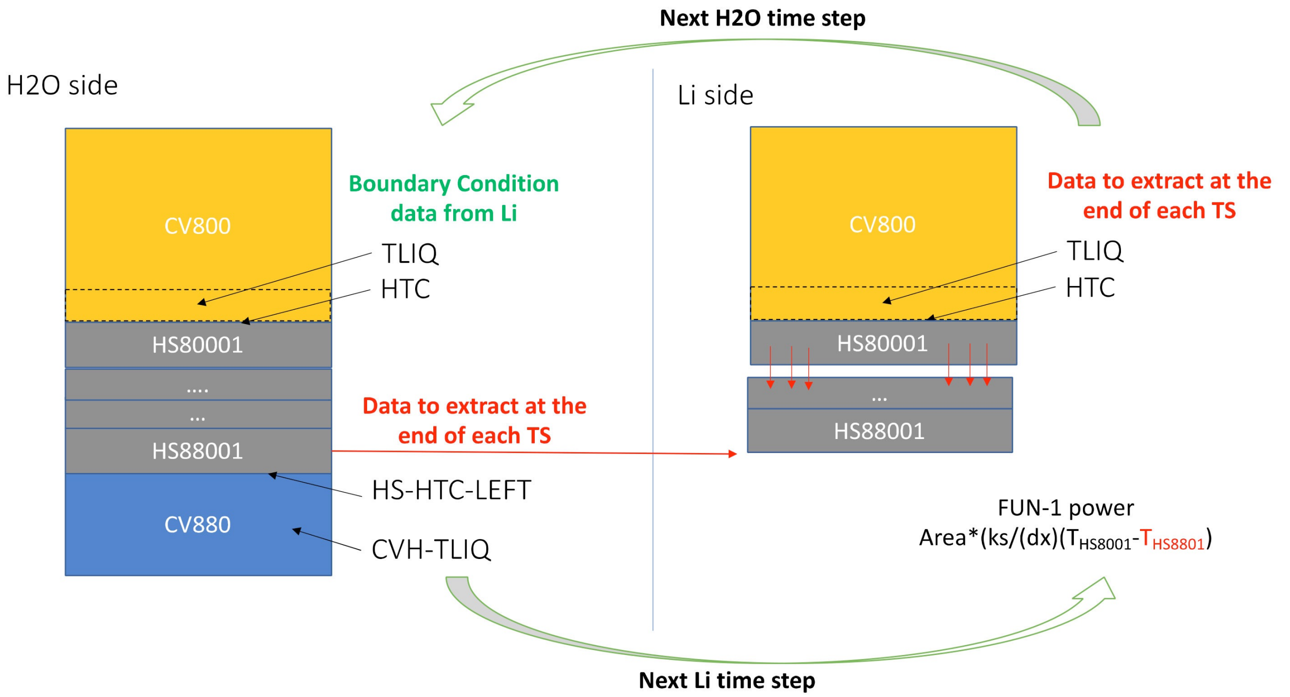
Liner loop with water as working fluid



https://doi.org/10.3390/en14206569

Approach

To overcome the Melcor limitation to 1 working fluid, a numerical coupling of two melcor runs was performed by means of EDF



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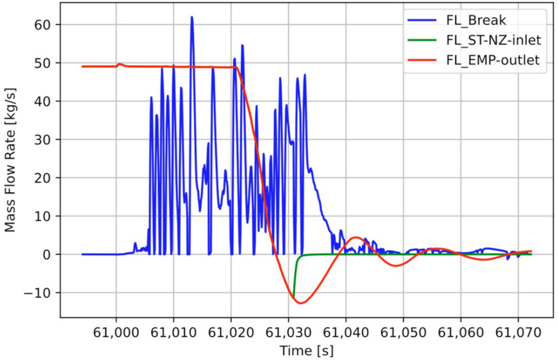
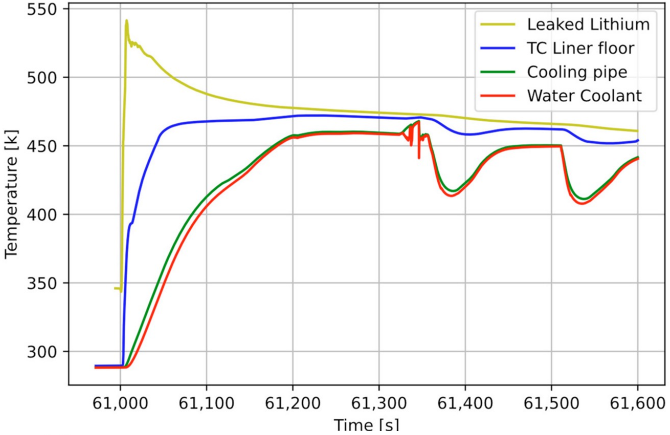
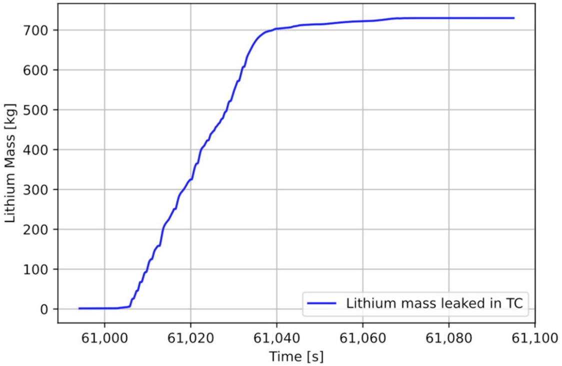
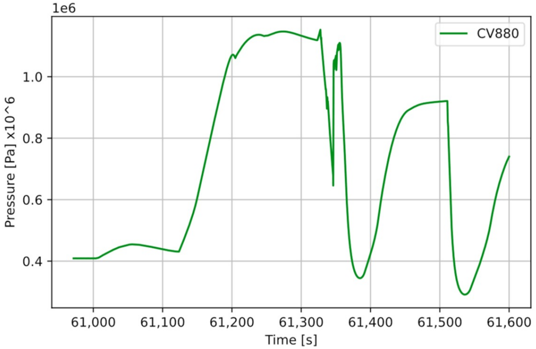
Design Feedback





- despite the occurrence of water vaporization transient in the cooling loop under the floor liner, the reached pressure peak at about 1.14 MPa appears withstandable within the cooling pipe design pressure
- Given the high temperature difference between released liquid lithium inventory (546 K) and liner temperature (287 K), the temperature rise has a steep pattern reaching more than 3 K/s temperature rise velocity, possibly posing structural resistance concerns to such thermal shock events



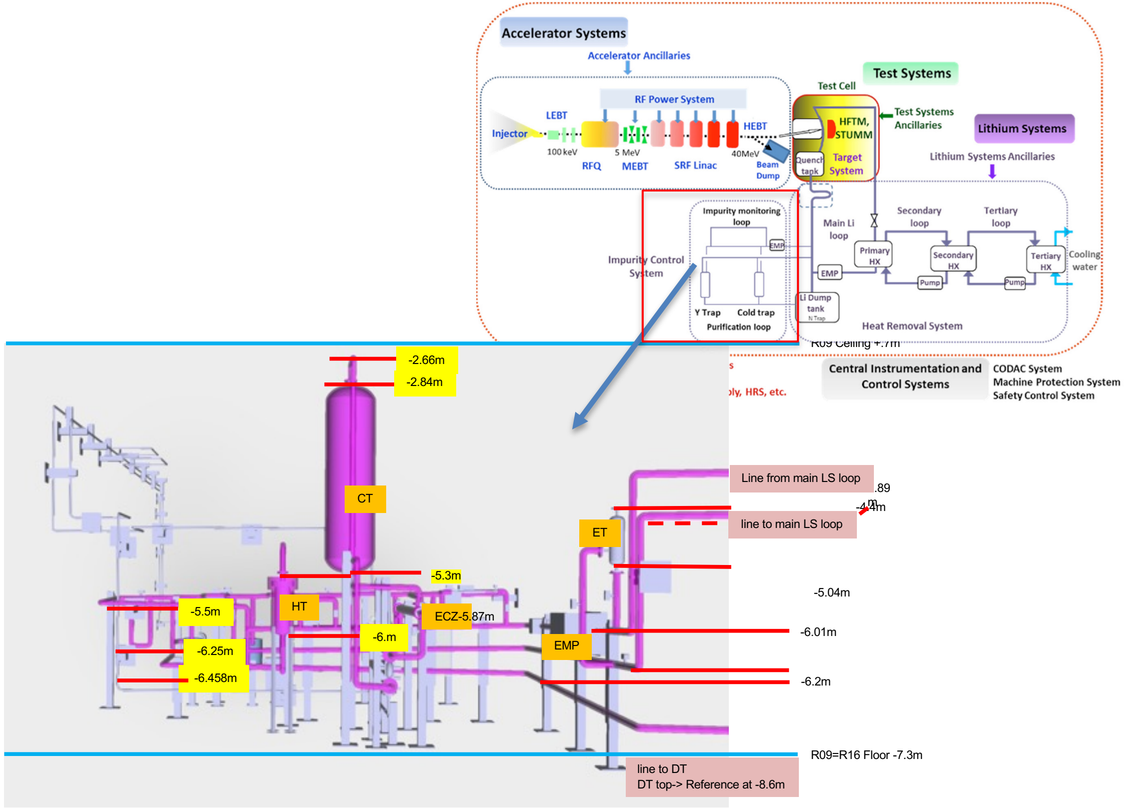


Water coolant pressure in the liner cooling loop water pipes after IE

https://doi.org/10.3390/en14206569

Design problem position: safety case 2

- Background: Lithium loop provided with Impurity control system, with radionuclides/contaminant inventory.
- Considered Postulated Initiating Event BDBA:
    - Loss of Li in Impurity Control System due to break in Cold Trap outlet. Break Area assumed to be at Cold Trap outlet towards ECZ above DT discharge, section 0.0003 m2 *2 (double break)
    - Co-Occurrence of Ar Atmosphere loss resulting in Fire event
- Objectives:
    - Lithium release rate
    - Lithium inventory released depending on detections and isolation
    - Temperature of Lithium at release
    - Possible fire events



Room09 Atmosphere Ar,
Pressure -140Pa

Melcor Model

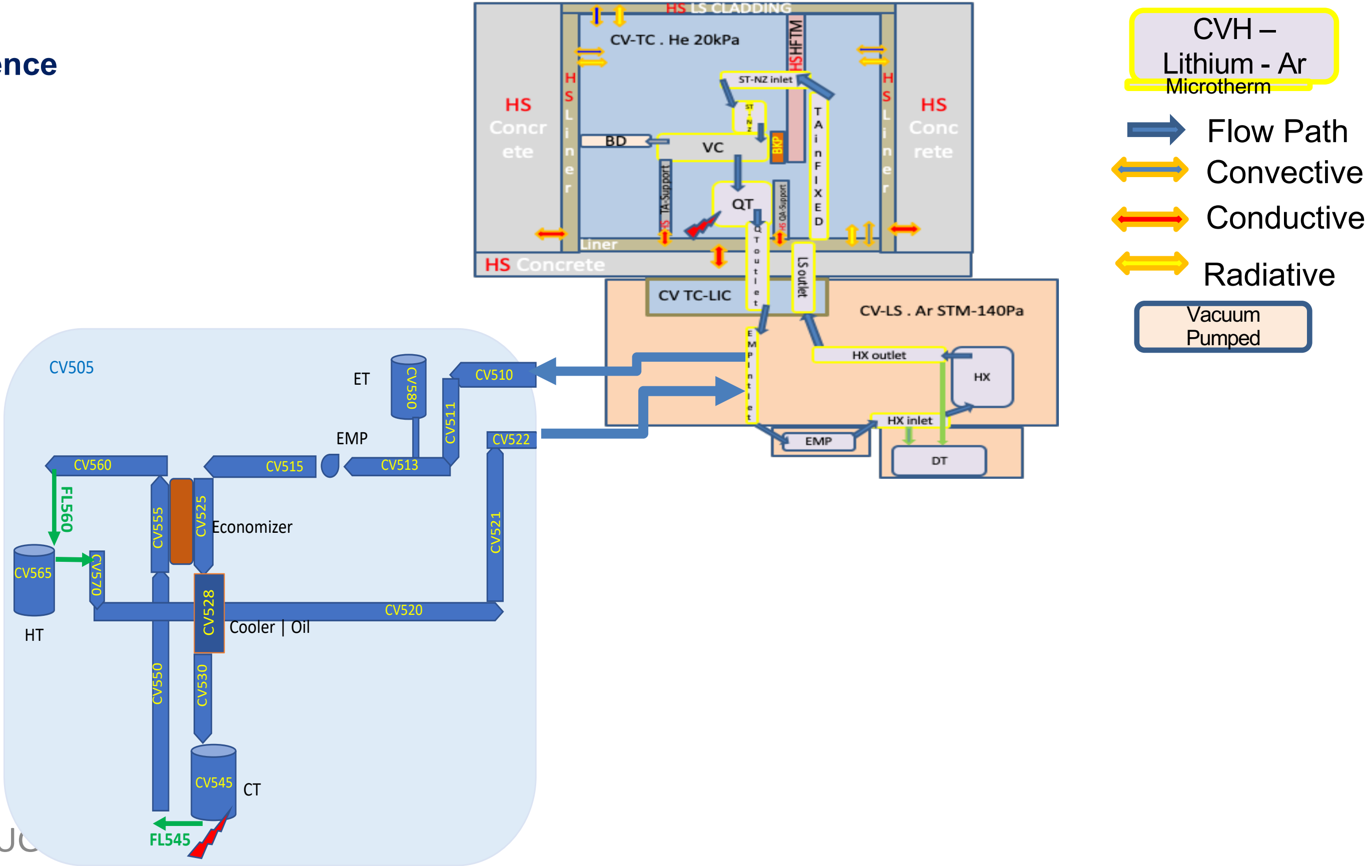
Melcor Model, Reference

fluid: lithium :

- TC/ TA

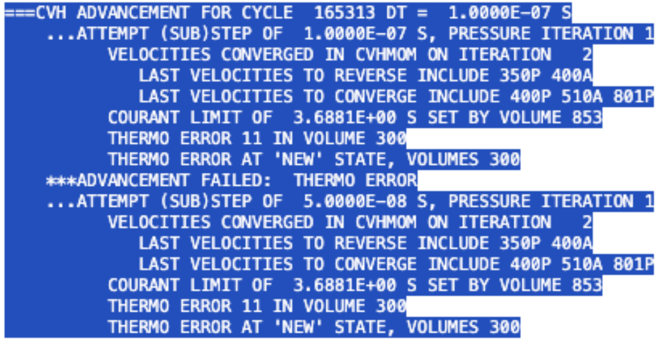
- LS-MAIN

- LC-ICS



Issues Melcor

Frequent THERMO ERROR 11 runtime errors



```
===CVH ADVANCEMENT FOR CYCLE  165313 DT =  1.0000E-07 S
    ...ATTEMPT (SUB)STEP OF  1.0000E-07 S, PRESSURE ITERATION 1
          VELOCITIES CONVERGED IN CVHMOM ON ITERATION   2
             LAST VELOCITIES TO REVERSE INCLUDE 350P 400A
             LAST VELOCITIES TO CONVERGE INCLUDE 400P 510A 801P
          COURANT LIMIT OF  3.6881E+00 S SET BY VOLUME 853
          THERMO ERROR 11 IN VOLUME 300
          THERMO ERROR AT 'NEW' STATE, VOLUMES 300
    ***ADVANCEMENT FAILED:  THERMO ERROR
    ...ATTEMPT (SUB)STEP OF  5.0000E-08 S, PRESSURE ITERATION 1
          VELOCITIES CONVERGED IN CVHMOM ON ITERATION   2
             LAST VELOCITIES TO REVERSE INCLUDE 350P 400A
             LAST VELOCITIES TO CONVERGE INCLUDE 400P 510A 801P
          COURANT LIMIT OF  3.6881E+00 S SET BY VOLUME 853
          THERMO ERROR 11 IN VOLUME 300
          THERMO ERROR AT 'NEW' STATE, VOLUMES 300
```

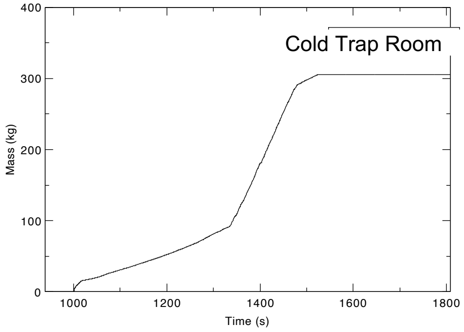
Guessed as related to Li gas phase / ATM too small

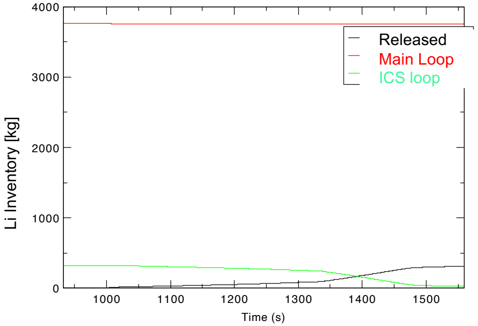
Run correct termination helped by SC coefficients

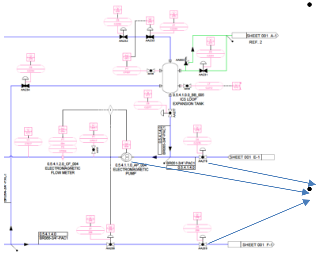
- 4411
  ```
  *Minimum (estimated) volume fraction of the pool or the atmosphere below
  *which equilibrium thermodynamics will be enforced,
  ```
- 4400
  ```
  *Number of iterations after which velocities will be considered converged if
  *there is no significant effect (less than 0.05%) on pressures.
  ```

Design feedback

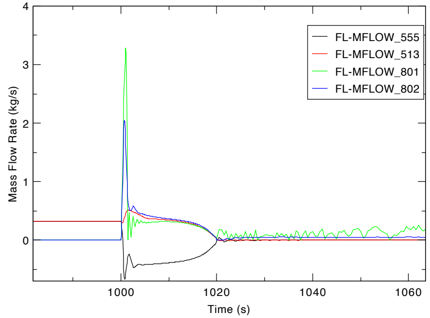
Released inventory, efficacy of sensors loop isolation

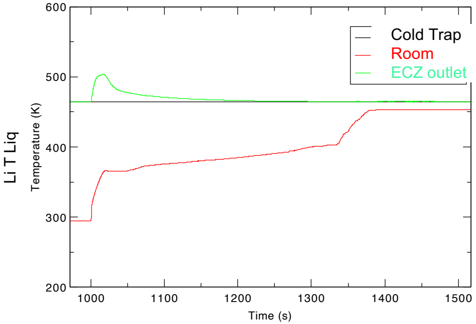






- Trigger:
  - CT level (TBD)
  - Flow, Pressure on EM-FM in loop
  - dPressure on DT
  - Leak sensors (TBD)
- Actuation:
  - EMP-ICS stops
  - Isolation valves close





About 10 kg of Li lost from main loop till isolation becomes effective

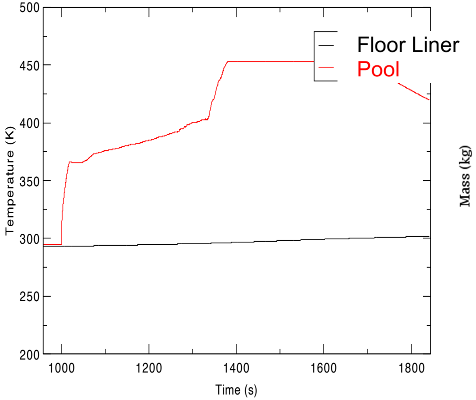
About 303 kg of Li released inventory in about 530s

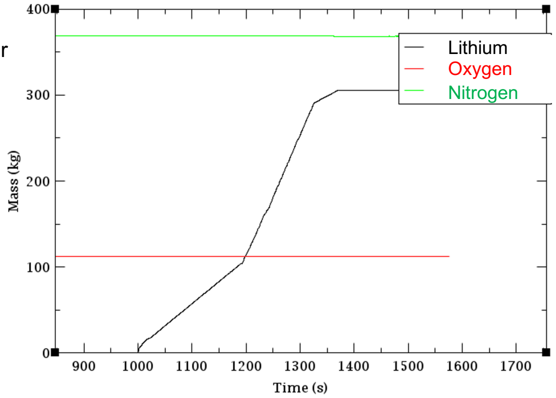
Released lithium temperature at about 450-453K (177-180°C)
Note: floor surface (50m2), initial temperature 293.15K

Design feedback

Thermal load on liner floor in case of fire

- R09 filled in Air,
- 303 Kg of lithium on room floor





In normal humidity air, lithium pools spontaneously ignite for temperatures above 243 ° C. FIRE Handbook reports above 180°C. [Piet et al, Fusion Engineering and Design 5 (1987) 273-298]

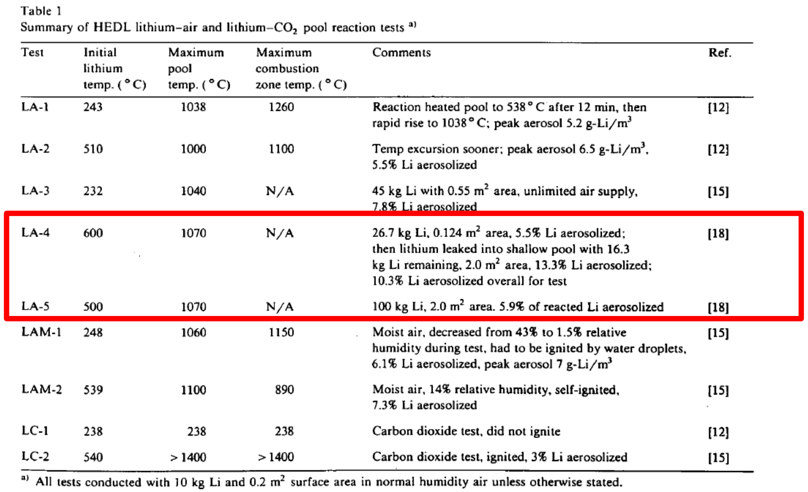


Table 1
Summary of HEDL lithium–air and lithium–CO_2 pool reaction tests [a)]

Test	Initial lithium temp. (° C)	Maximum pool temp. (° C)	Maximum combustion zone temp. (° C)	Comments	Ref.
LA-1	243	1038	1260	Reaction heated pool to 538 ° C after 12 min, then rapid rise to 1038 ° C; peak aerosol 5.2 g-Li/m^3	[12]
LA-2	510	1000	1100	Temp excursion sooner; peak aerosol 6.5 g-Li/m^3, 5.5% Li aerosolized	[12]
LA-3	232	1040	N/A	45 kg Li with 0.55 m^2 area, unlimited air supply, 7.8% Li aerosolized	[15]
LA-4	600	1070	N/A	26.7 kg Li, 0.124 m^2 area, 5.5% Li aerosolized; then lithium leaked into shallow pool with 16.3 kg Li remaining, 2.0 m^2 area, 13.3% Li aerosolized; 10.3% Li aerosolized overall for test	[18]
LA-5	500	1070	N/A	100 kg Li, 2.0 m^2 area. 5.9% of reacted Li aerosolized	[18]
LAM-1	248	1060	1150	Moist air, decreased from 43% to 1.5% relative humidity during test, had to be ignited by water droplets, 6.1% Li aerosolized, peak aerosol 7 g-Li/m^3	[15]
LAM-2	539	1100	890	Moist air, 14% relative humidity, self-ignited, 7.3% Li aerosolized	[15]
LC-1	238	238	238	Carbon dioxide test, did not ignite	[12]
LC-2	540	> 1400	> 1400	Carbon dioxide test, ignited, 3% Li aerosolized	[15]

[a)] All tests conducted with 10 kg Li and 0.2 m^2 surface area in normal humidity air unless otherwise stated.

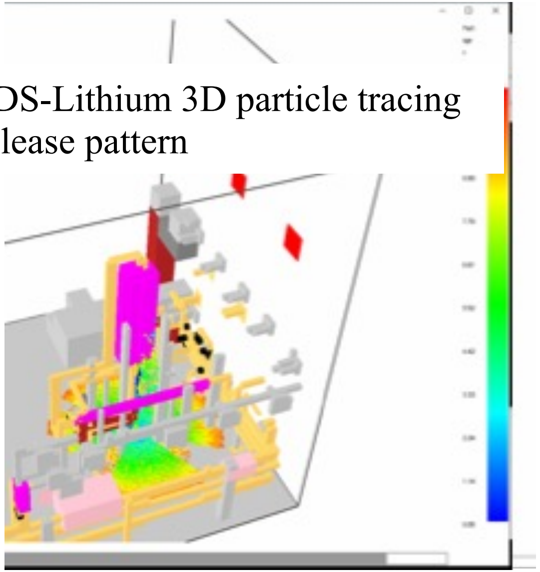
No Li-air reactions occur at considered pool temperature.
Need to trigger higher Li pool temperatuers (e.g. LA-4/LA-5)
(https://www.osti.gov/servlets/purl/764178)

Design feedback

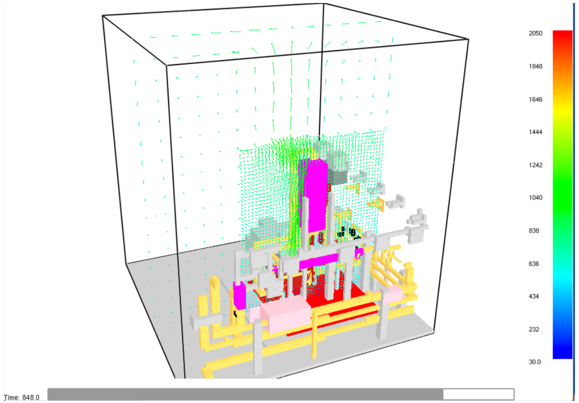
Though conservatively assuming reactions from initially spilled droplets of lithium and most conservative ignition temperature reported in literature (i.e. >=180°C)

Melcor release rate data provided in input to Fire Dynamic Simulation code, with Li-O2 reaction Heat Release Rate

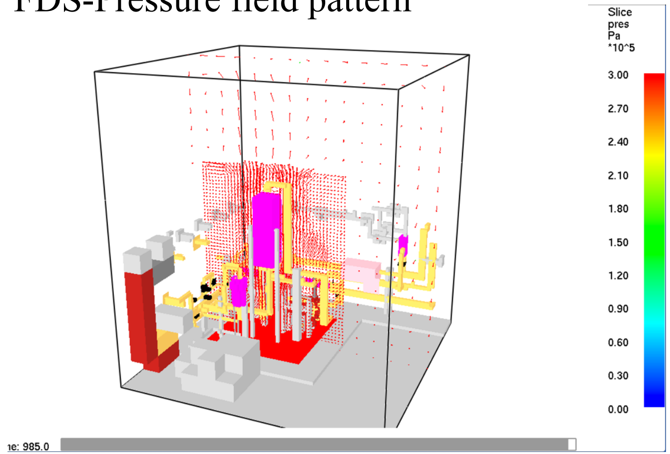
FDS-Lithium 3D particle tracing release pattern



FDS-Temperature field pattern



FDS-Pressure field pattern



Pressure increase peak (with respect to initial value of slight under pressurization over STD) allowing for atmosphere leakage is at about +142.kPa

Thanks for your attention

danilo.dongiovanni@enea.it

***Disclaimer**:*
The presentation provides examples of safety analysis for practical design support activity in fusion plants/research facilities components.

Reference to EUROFusion DEMO-DONES / ITER plant systems is provided to merely exemplify specific cases of safety support to design.

The content here presented reflects the views only of the authors.