EUROfusion

STATUS OF DESIGN BASIS ACCIDENT ANALYSES FOR EUROPEAN DEMO

IAEA TM on Fusion Design Safety and Regulation
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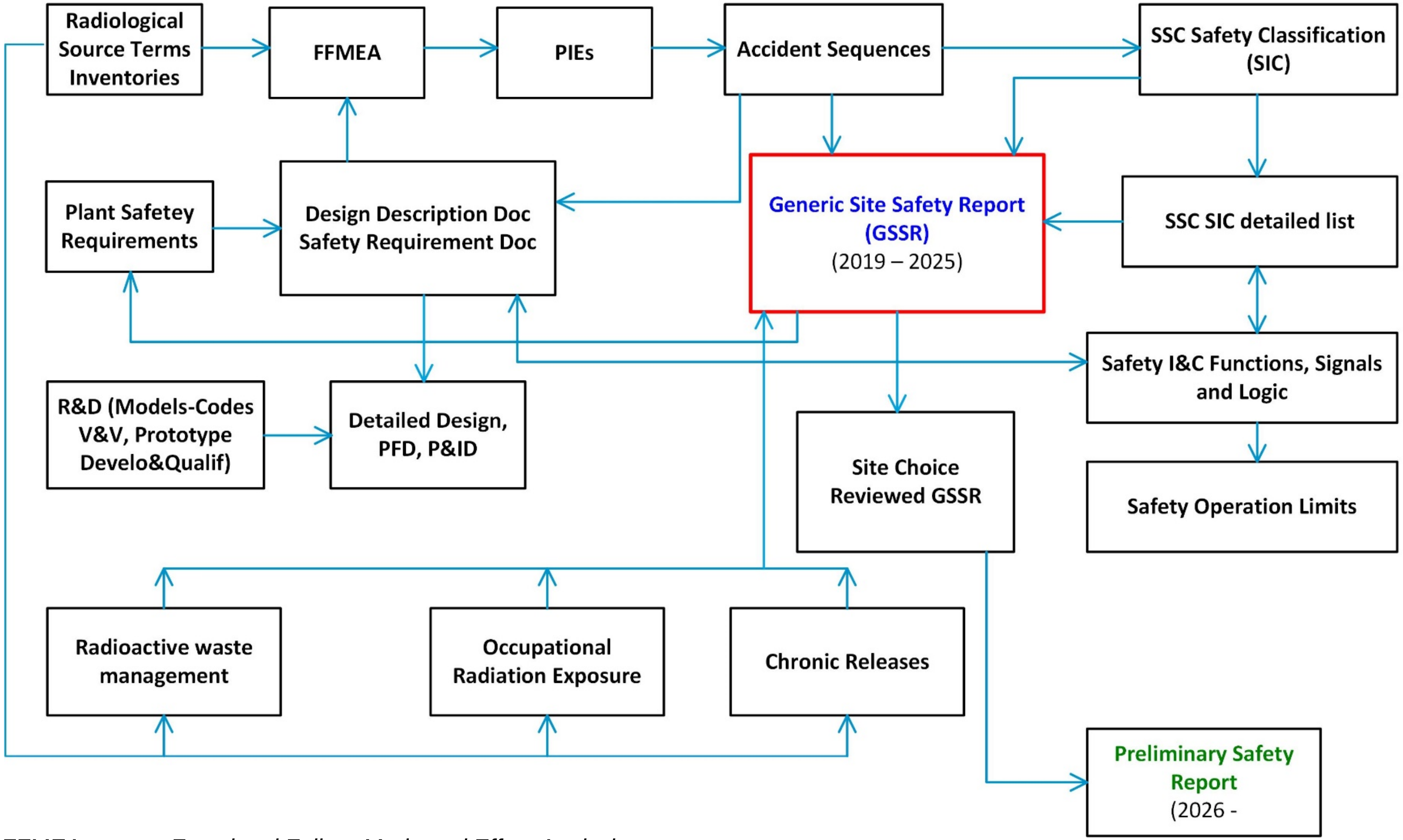
Outline

- **DEMO safety approach**
  - Generic Site Safety Report (GSSR)
- **Design Basis Accidents (DBA) – GSSR Vol. 7**
  - Requirement
  - Category
  - Purpose
- **DBA events**
  - Pre-concept Design Phase (PCDP, – 2020)
  - Concept Design Phase (CDP, 2021 – 2027)
  - Tools for the analyses
  - Main safety issues
- **Summary and outlook**
  - Event ranking
  - Requirements for following investigation
  - Design Extension Condition (DEC)

DEMO safety approach



FFMEA	*Functional Failure Mode and Effect Analysis*
PFD	*Process Flow Diagram*
P&ID	*Piping and Instrumentation Diagram*
PIE	*Postulated Initiating Event*
SSC	*Structures, Systems and Components*
V&V	*Verification and Validation*

Ref. 1

Generic Site Safety Report (GSSR)

- Vol. 1 Safety Principles and Approach
- Vol. 2 Overview of Design and Safety Features
- Vol. 3 Radiological and energy source terms
- Vol. 4 Occupational Safety
- Vol. 5 Environmental impact of routine operations
- Vol. 6 Accident Sequence Identification (PIEs)
- Vol. 7 Analysis of accident scenarios within design basis and design extension conditions
- Vol. 8 Analysis of *beyond design basis events* → design extension conditions
- Vol. 9 Assessment of impact of external hazards
- Vol. 10 Documentation of validation and verification of safety codes
- Vol. 11 Assessment and strategies for reducing radioactive waste hazard

Requirement

- **Requirement 19 Design Basis Accidents** in *IAEA Specific Safety Requirements 2012* (Ref. 2) is **valid for fusion:**

  "A set of accident conditions that are to be considered in the design shall be derived from postulated initiating events for the purpose of establishing the boundary conditions for the nuclear power plant to withstand, without acceptable limits for radiation protection being exceeded."

- control DBA conditions to **return the plant to a safe state** and mitigating the consequences of any accidents
- Key plant parameters shall not exceed the specified **design limits**
- manage DBAs to have **no, or only minor radiological impacts**, on or off the site, and do not necessitate any off-site intervention measures
- DBA analysis in a **conservative manner** with respect to postulating certain failures in safety systems, specifying design criteria and using conservative assumptions, models and input parameters in the analysis
- Fusion regulation: **no need for public sheltering**

Category

DEMO Off-site Consequence Limits / Targets for Off-Normal Events

	Anticipated events	**Unlikely events**	**Extremely unlike events**	**Hypothetical bounding events**
Category	1 – 2	3	4	DEC
Anticipated	> 10^{-2}	10^{-2} – 10^{-4}	10^{-4} – 10^{-6}	< 10^{-6}
Early dose			10mSv/event	50mSv/event
Chronic dose	Treat as normal operation	5mSv/event	50mSv/event	No cliff-edge effects; counter measures limited in time and space

Category 1 ~ operational events

Category 2 ~ likely events

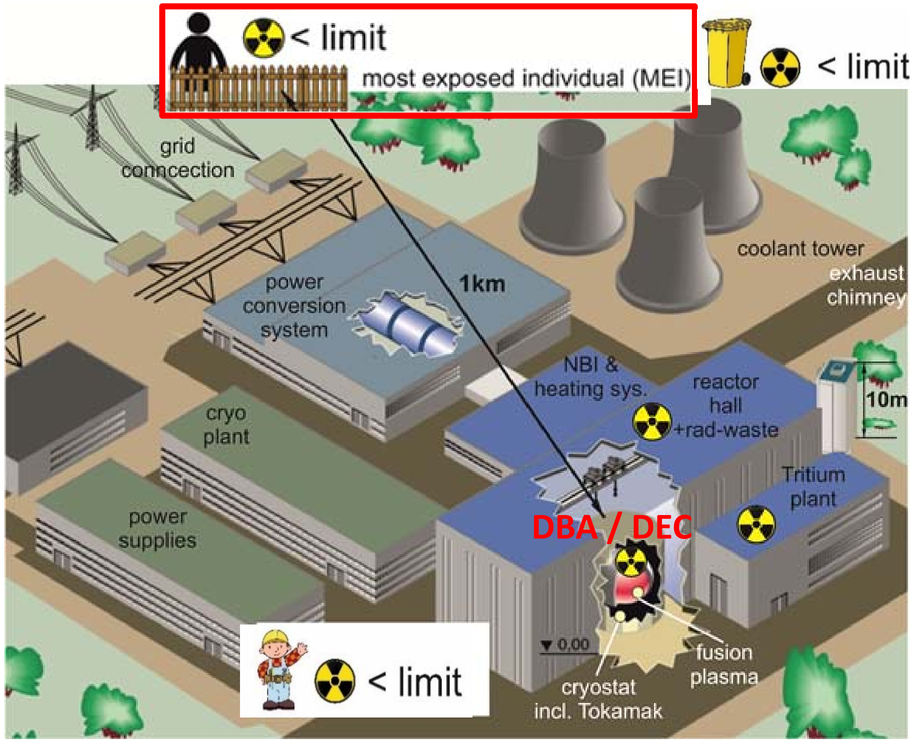
Category 3 ~ DBA

Category 4 ~ postulated multiple failure events

DEC: Design Extension Condition

Purpose

- Identify drivers for design from DBA analysis results:
  - o Evaluation of **thermal-hydraulic results** (pressure, temperature, mass, etc.) in transient
  - o **Dose to the public** based on the environmental releases of source terms
  - o **H_2 production** → flammability / detonation risk
- input and outcomes from DBA analysis in an iterative process to improve DEMO design progressively



Events performed in the PCDP – IVCs

Events selected from the PIEs in GSSR Vol. 6:

- in-BB LOCA (HCPB / WCLL)
- ex-vessel LOCA (HCPB / WCLL / DIV)
- in-vessel LOCA (HCPB / WCLL / DIV)
- Loss of Flow Accident (LOFA) (HCPB / WCLL / DIV)
- Loss of heat sink (HCPB / WCLL)

MELCOR1.8.6 for fusion

- IVCs, Primary Heat Transfer Systems (PHTSs, BB, DIV) , Vacuum Vessel (VV) , VV Pressure Suppression System (VVPSS), *Tokamak cooling room (TCR)*

Results evaluation focused on

- Thermal hydraulic transient behaviour
  - Pressurization in the VV / *TCR*
  - Increase of FW temperature
- Transport of source terms and potential environment release
  - W-dust, tritium (HCPB)
  - W-dust, HTO, activated corrosion product (ACP) (WCLL)
- Start to perform dose calculation

DEMO baseline

- 2015 (18 toloidal fields)
- 2017 (16 toloidal fields)

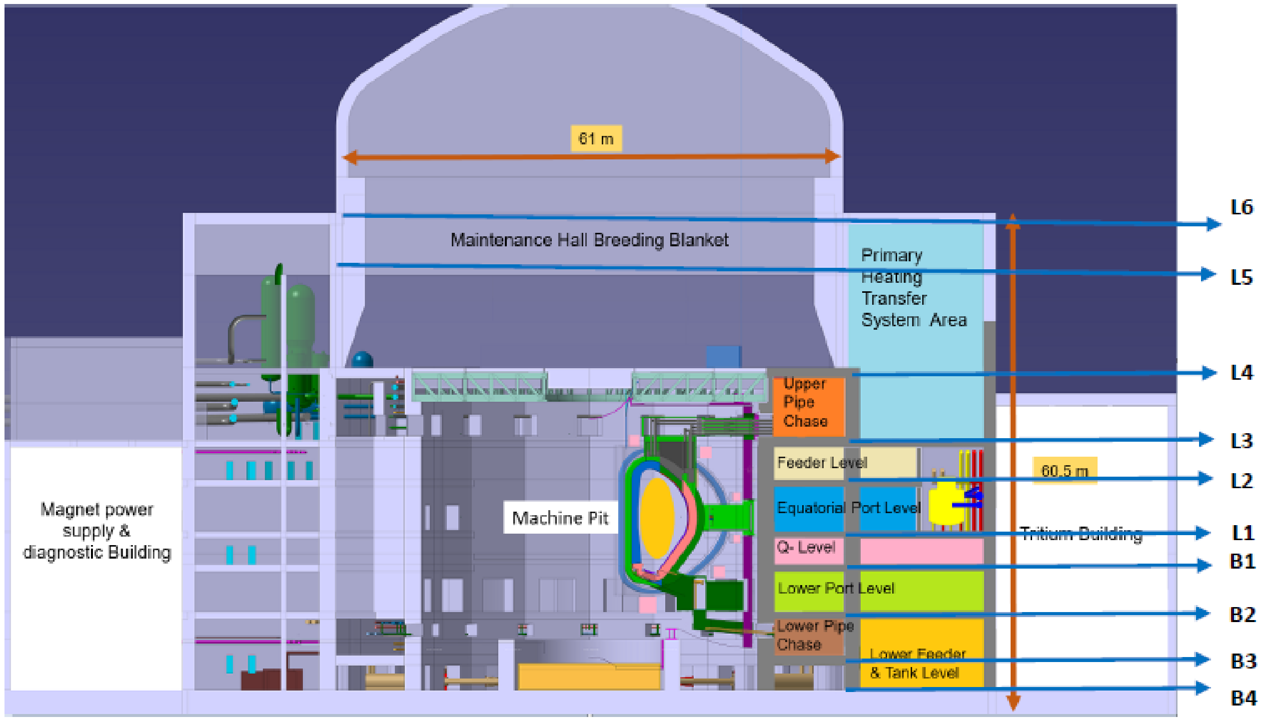
In-vessel components (IVCs)

- 2x Breeding Blanket (BB) concepts:
  - Helium Cooled Pebble Bed (HCPB)
  - Water Cooled Lithium Lead (WCLL)
- Divertor (DIV)

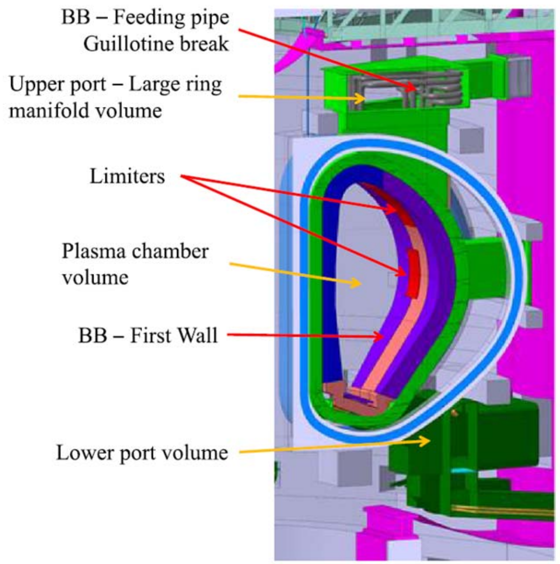
Ref. 1

DEMO reference design

- **Concept Design Phase (CDP, 2021 – 2027)**
- **DEMO baseline 2017**
- **Tokamak building**
  - IVCs (BB, DIV, limiters)
  - VV, VVPSS (He / water)
  - PHTSs for BB, DIV, VV
  - Cryostat, upper pipe chase (UPC), low pipe chase (LPC), PHTS vault, galleries, dome and top hall
  - leak rate conditions, detritiation efficiencies and flaps



Ref.3



Ref. 4

Events in the current CDP

- **Loss of vacuum (LOVA)**
  - In the VV due to air ingress (HCPB / WCLL)
  - In the cryostat due to helium ingress
- **Tritium plant and fuel cycle events**
  - Breaking of pumping line in the torus pumping system
  - Break / leak in Isotope Rebalancing and Protium Removal (IR/PR)
- **Loss of cryogenic helium** outside the cryostat
- **Ex-vessel LOCA** (Revised HCPB, BB PHTS & Tritium Extraction Removal System)
- **Fire accident** (PbLi loop room)
- **H_2 mitigation in the VVPSS** (WCLL Ref. 5 / HCPB Ref. 6)
- **Combination of events** → DEC
  - Small LOCA and LOVA (WCLL)
  - Small in-vessel LOCAs in the BB and DIV (HCPB)
  - Ex-vessel LOCA with concurrent loss of heat sink (HCPB)
- **Event in the long term** → DEC
  - Loss of heat sink (HCPB)
  - Loss of power supply (HCPB)

Tools for the analyses

- **MELCOR1.8.6 for fusion**
  - Thermal-hydraulic behaviour with CVH-FL and HS packages
  - Transport of source terms with RadioNuclide (RN) package
  - W – steam reaction → H_2 production
  - H_2 mitigation with Passive Autocatalytic Hydrogen Recombiner (PAR) package
- **UFOTRI** (tritium) **& COSYMA** (W-dust, ACP)
  - Dose calculation
  - the environmental impact of releases
- **Fire Dynamic Simulator (FDS)** for fire accident
- **RAVEN** (Reactor Analysis and Virtual control Environment)
  - Sensitivity and uncertainty quantification analyses

➡ **GSSR Vol. 10 Safety Codes**
  - Key model description applied for the DBA and DEC (former BDBA)

Main safety issues

- **Pressurization, if**
  - BB / DIV pressure > design limit (HCPB 9.2MPa, WCLL 18.6MPa, DIV >5MPa)
  - VV pressure > design limit of 200kPa → VVPSS design
  - Cryostat pressure > design limit of 105kPa
  - PbLi loop pressure > design limit of 4.6MPa
  - rooms in the Tokamak building (UPC, LPC, PHTS vault, galleries, dome, etc.)
  - Glove box in the tritium building
- **Temperature increase, if**
  - T_FW > T_limit of Eurofer
  - T_BZ > T_limit of Eurofer, breeding material, Neutron Multiply Material (NMM)
  - T_DIV > T_limit of Eurofer, CuCrZr, Cu-OFHC
  - T_glovebox > T_limit
- **Chemical reactions**
  - W – air → WO_3
  - W – steam → WO_3 + H_2 production → flammability / detonation risk
- **Transport of the source terms** (tritium, dust, ACP)
  - Environmental releases
  - Dose to the population

Summary – Event ranking

- Category / Event
- Selected code
- Baseline / modelled system / component
- Important parameters
- Important phenomena
- Release / leak path
- Radiological release
- Mitigation methods
- Recommendation

➡ **Ranking** for study priority wrt. potential design drivers

Outlook – Requirements for following investigation

- **Updated baseline design**
  - IVCs' decay heat
- **Inventories**
  - Coolant (He / Water)
  - Cryogenic liquid
  - Tritium in the fuel cycle
  - Source terms (tritium, dust, ACP in the VV / PHTS / structure)
- **Plasma behavior**
  - Fast / soft shutdown
  - Mitigated / unmitigated disruption (time, loading)
- **VVPSS design** (HCPB / WCLL)
- **Revise leak & detritiation conditions**
- **Material properties**
  - Temperature for structure failure
  - Melting temperature
- **Tokamak building**
  - Free volume of system / room
  - Chimney design
- **Refine assumptions / parametric study**
- **Use improved / new codes**
  - common MELCOR fission-fusion-version in future (Ref. 11)
  - JRODOS with tritium functionalities of UFOTRI
  - explosion code

Outlook – DEC

- Identify design extension conditions (DECs) for DEMO in consensus with stakeholders
- Investigate accident analyses due to DECs (multiple failure scenarios)
- Requirement 20 DEC in *IAEA Specific Safety Requirements 2012* (Ref. 2):

  "A set of design extension conditions shall be derived on the basis of engineering judgement, deterministic assessments and probabilistic assessments for the purpose of further improving the safety of the nuclear power plant by enhancing the plant's capabilities to withstand, without unacceptable radiological consequences, accidents that are either more severe than design basis accidents or that involve additional failures."
- DECs in *IAEA TECDOC 2016* (Ref. 7):

Plant state	Indicative expected frequency of occurrence
Normal operation	-
Anticipated operational occurrences	> 10^{-2}
Design basis accidents	10^{-2} – 10^{-6}
DEC without significant fuel degradation	10^{-4} – 10^{-6}
DEC with core melt	< 10^{-6}

Extend DEC for the design of Fusion Power Plant (FPP) in IAEA document

Reference

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Contributors

- **DEMO DBA analyses**

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Thank you!

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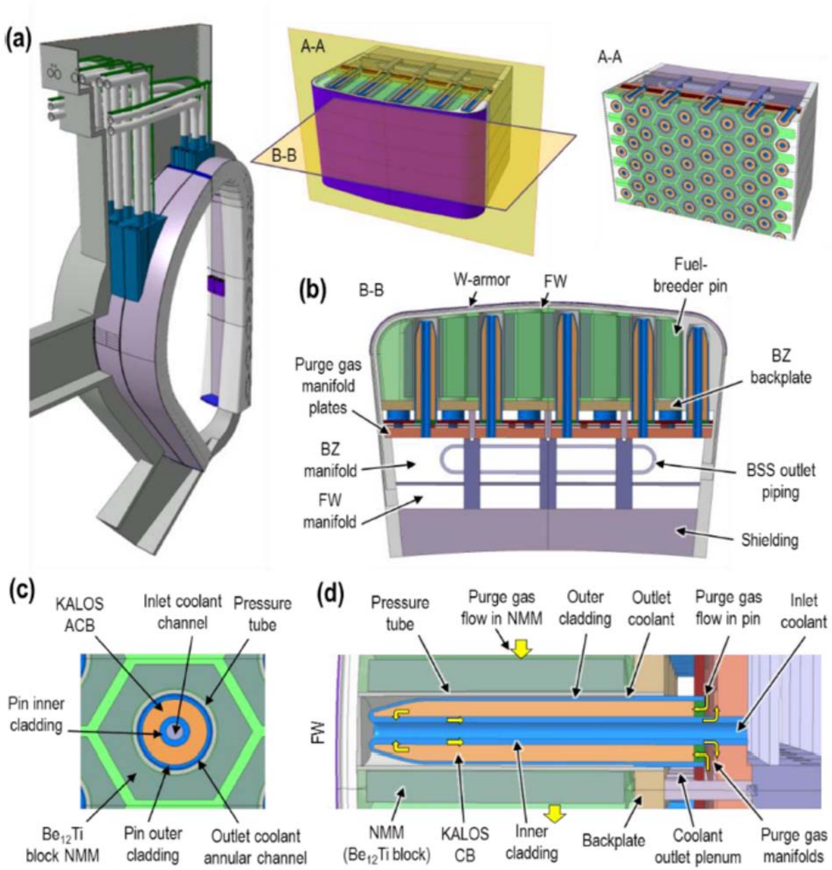
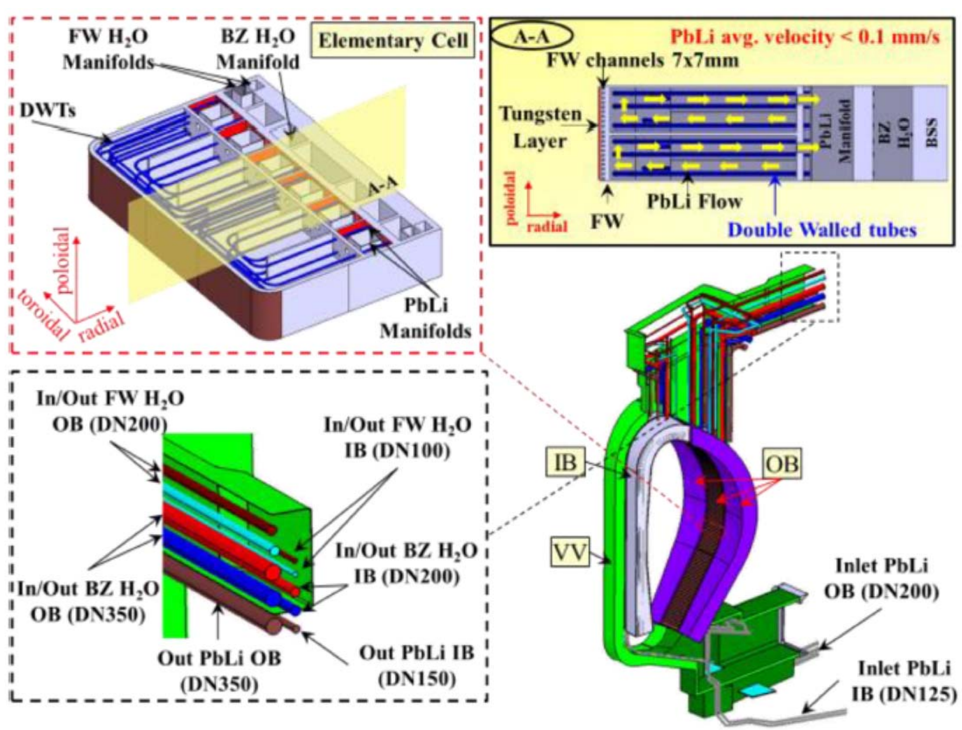
DEMO reference design – BB

HCPB BB



WCLL BB



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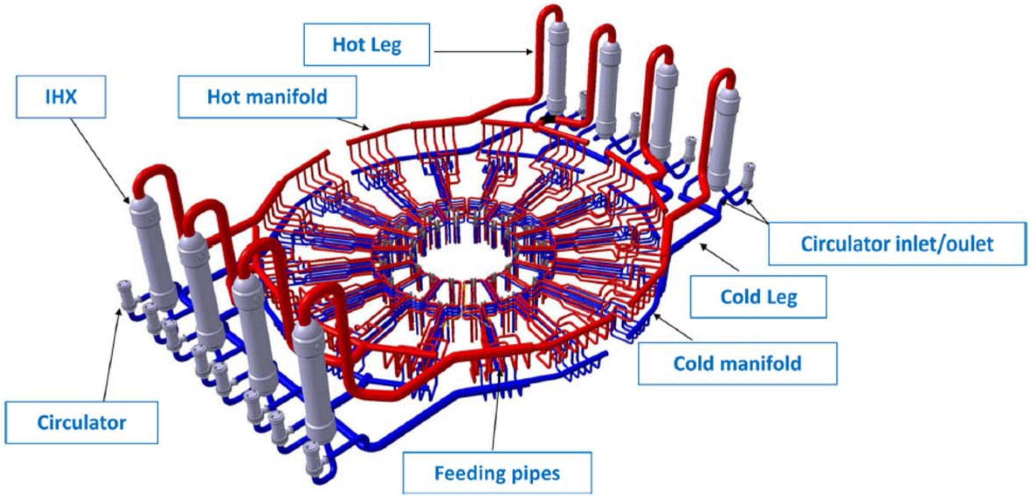
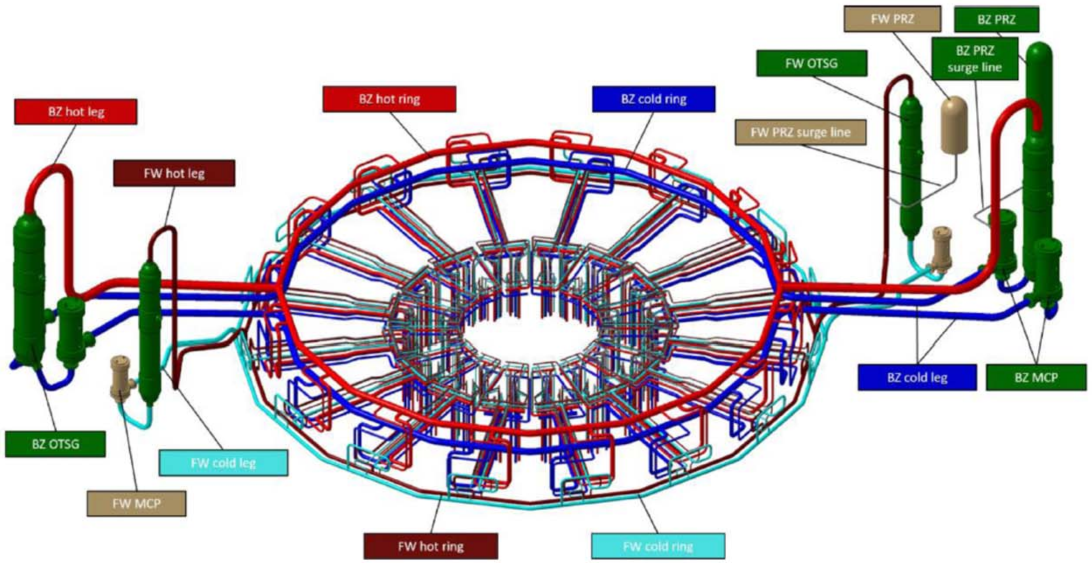
DEMO reference design – BB-PHTS

HCPB-PHTS (indirect coupling)



WCLL-PHTS (direct coupling)



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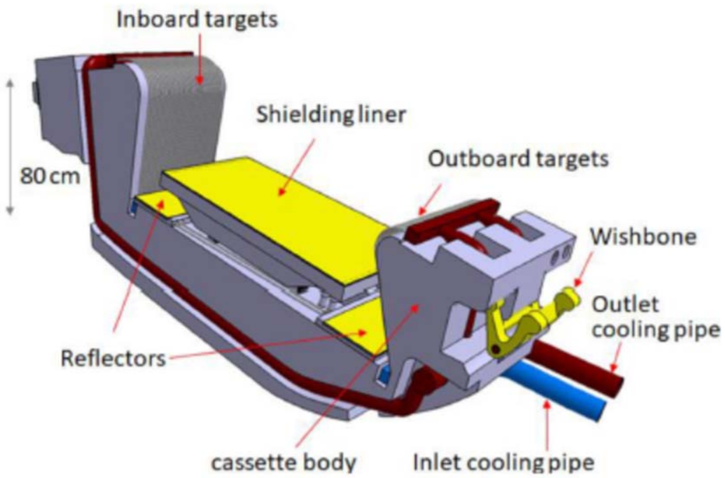
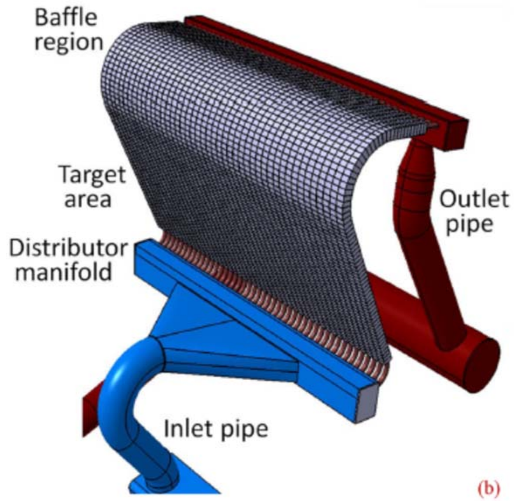
DEMO reference design – DIV

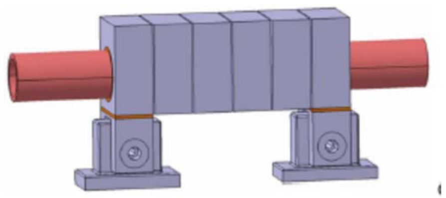
Divertor cassette module



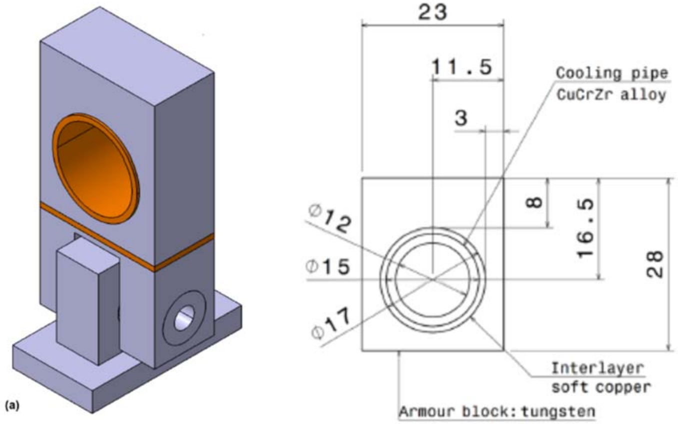
Outboard target



target element segment

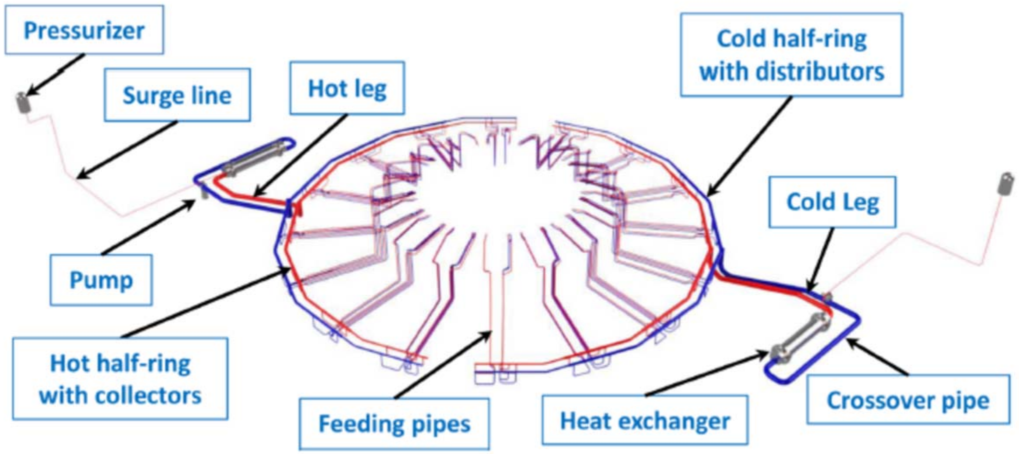


Single monoblock unit

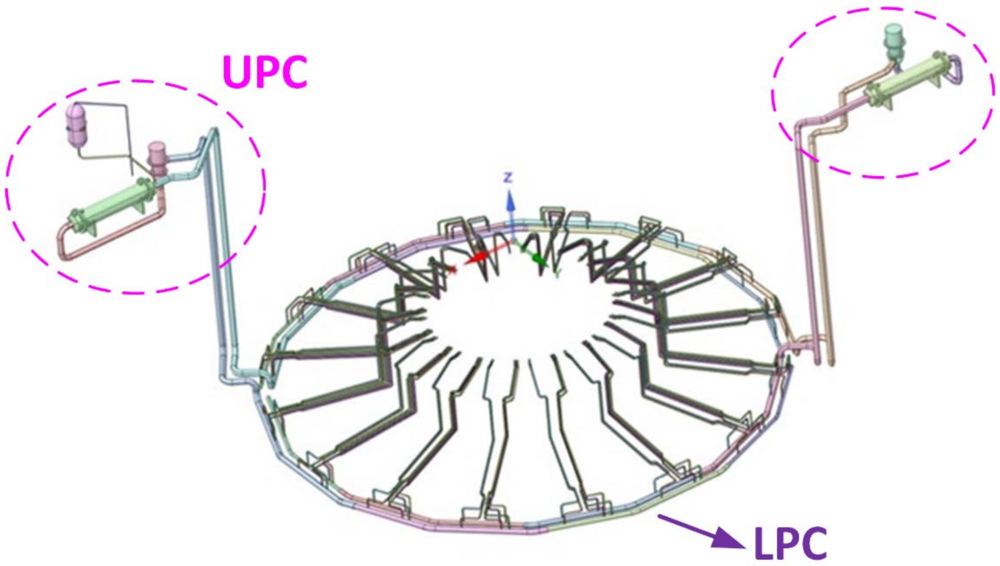


Ref. 10

DEMO reference design – DIV-PHTS

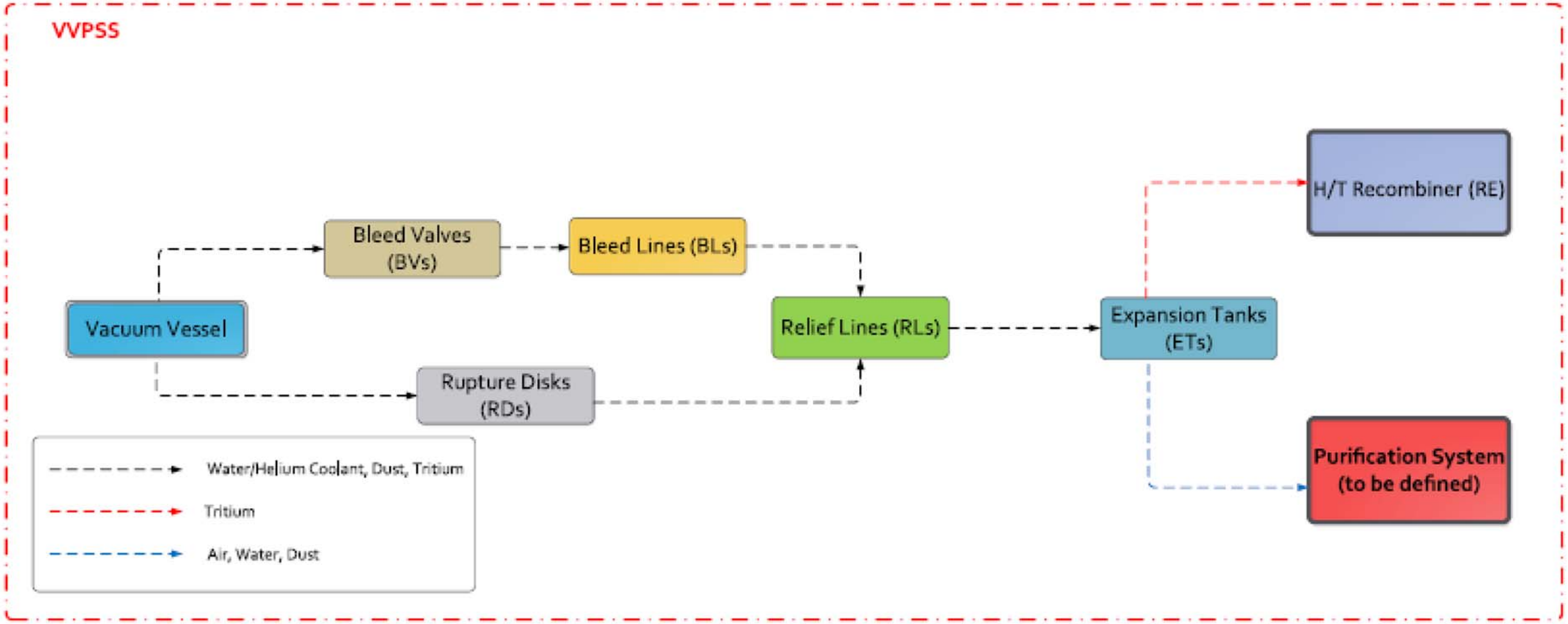


Ref. 10



DEMO reference design – VVPSS

Schematic drawing of the VVPSS



Ref. 4

Safety codes in GSSR Vol. 10

- **System codes**
  MELCOR186 for fusion, ASTEC, RELAP5-3D, GETTHEM, ATHLET, TRACE, CONSEN, ECART
- **Codes for plasma interaction**
  AINA, MEMOS, TOKES
- **Containment codes**
  COCOSYS
- **Source terms codes** (activation, decay heat, tritium, ACP, neutron sputtering products, chemical equilibrium)
  FISPACT-II, ACAB, GammaFlow & ActiFlow, TMAP, ECOSIMPRO, FUS-TPC+, OSCAR-Fusion v1.3, SPUTTER_II, CEA
- **Codes for radiological release**
  JRODOS, MACCS, UFOTRI and COSYMA, CERES
- **Sensitivity codes**
  SUSA, BEST-EST, RAVEN
- **CFD codes**
  ANSYS CFD, GASFLOW, SIMMER
- **Thermal-structural codes**
  ANSYS Mechanical
- **Process codes**
  APROS
- **Fire codes**
  FDS, CDI, SYLVIA
- **Explosion codes**
- DET3D, COM3D
- **Neutronic codes**
  cR2S&AdvancedD1S

Codes used in WPSAE tasks
Codes developed in EUROfusion tasks
ITER codes

Design temperature limit and melting temperature for the materials

Material	Design temperature limit (°C)	Melting temperature (°C)	IVC
Tungsten (WO_3)	-	3410 (1473)	HCPB,WCLL, DIV
EUROFER97	550	1325 – 1530	HCPB,WCLL, DIV
PbLi (liquid)	800	234 – 237	WCLL
ACB	920	1200	HCPB
$Be_{12}Ti$	900 – 1000	1570	HCPB
CuCrZr	450	1081	DIV
Cu-OFHC	*tbd*	1083	DIV

FW / pin failure: 1000°C → 800°C (EUROFER)