EUROfusion

STATUS OF DESIGN BASIS ACCIDENT ANALYSES AND SAFETY CODES APPLICATION FOR EUROPEAN DEMO

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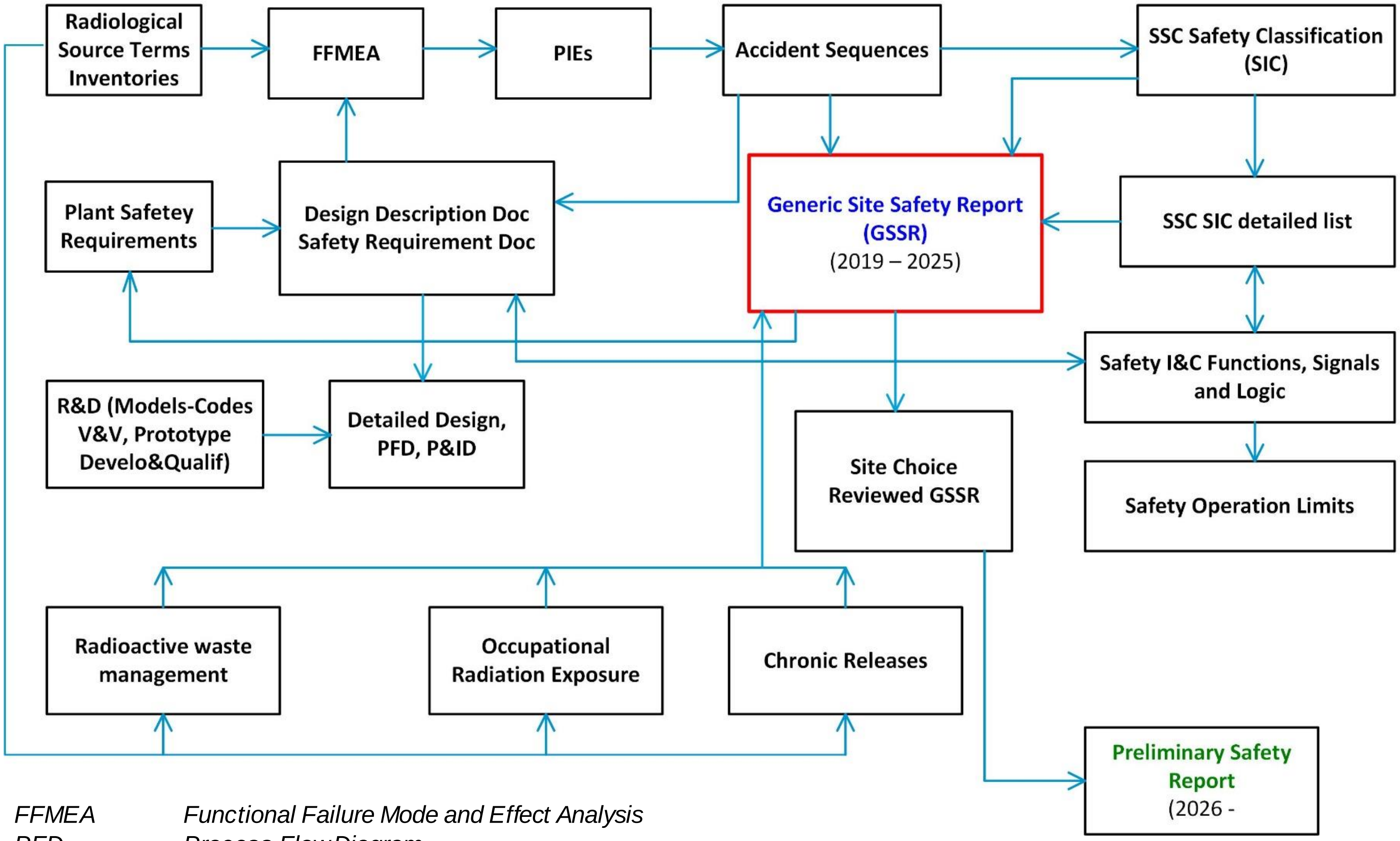
Outline

- **DEMO safety approach**
  - Generic Site Safety Report (GSSR) - main achievements during the Pre-Concept Design (PCD) phase (2014 – 2020)
- **Design Basis Accidents (DBA) – GSSR Vol. 7**
  - Requirement
  - Category
  - Purpose
  - DEMO reference design
  - Performed events
- **Safety codes – GSSR Vol. 10**
  - Category
  - Description template
  - V&V status of MELCOR in fusion
- **Outlook** (DBA, DEC, code validation plan)

DEMO safety approach (Ref. 1)



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*

GSSR (PCD 2020)

- 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
- Vol. 9 Assessment of impact of external hazards
- Vol. 10 Safety models and codes
- Vol. 11 Assessment and strategies for reducing radioactive waste hazard

DBA – 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 an evacuation** on technical grounds for all plant states

DBA – Category (Ref. 1)

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	BDBE
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	

Category 1 ~ operational events

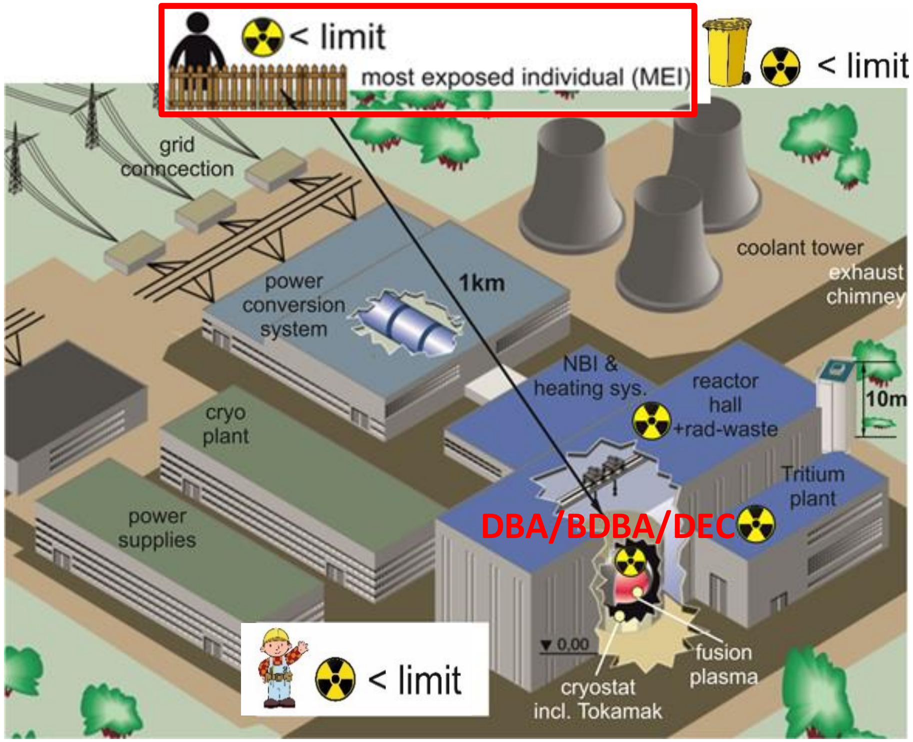
Category 2 ~ likely events

Category 3 ~ DBA

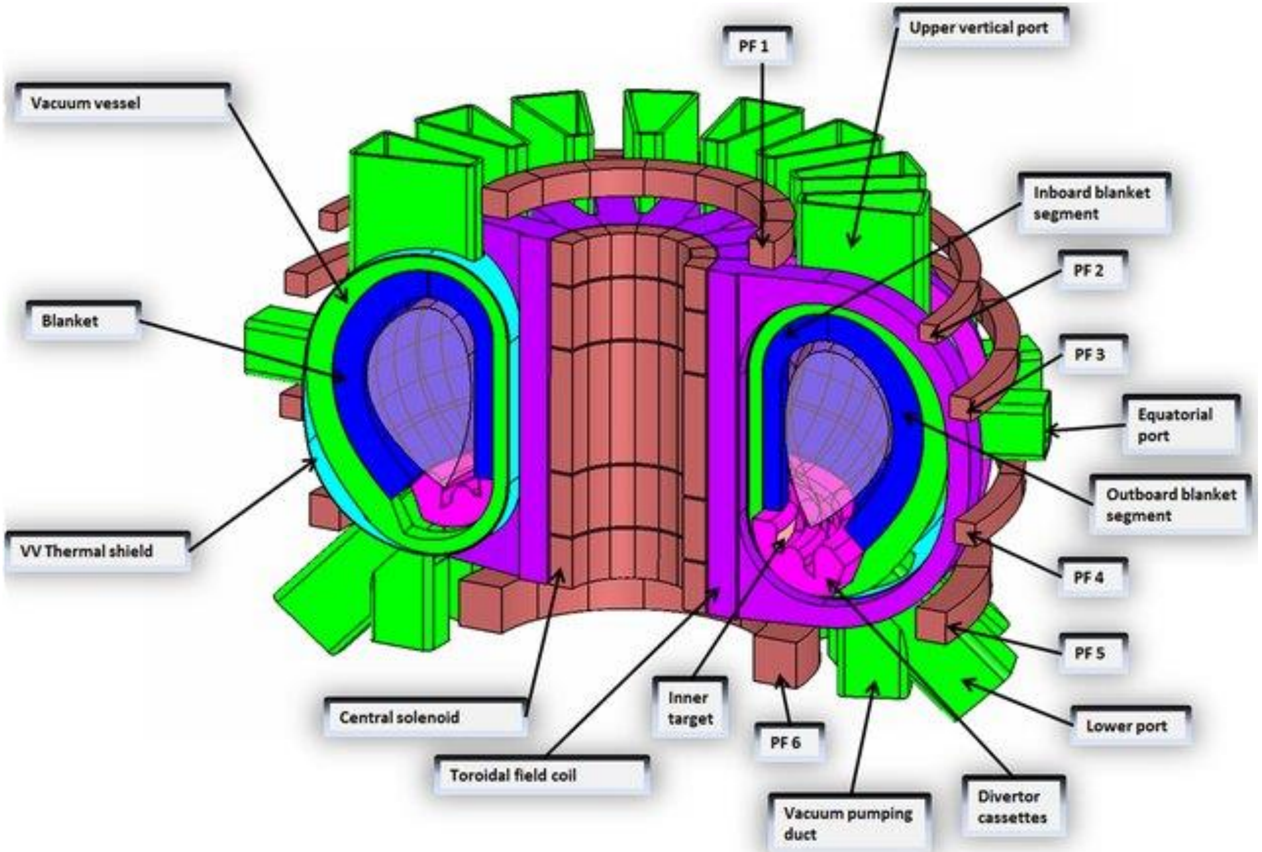
Category 4 ~ postulated multiple failure events

DBA – Purpose

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



DBA – DEMO reference design



- **Baseline 2015 (18 Toroidal Field (TF) coils)**
- **Baseline 2017 (16 TF coils)**
- **Vacuum Vessel (VV)**
- **In-vessel components (IVCs)**
  - 2x Breeding Blanket (BB) concepts:
    - Helium Cooled Pebble Bed (HCPB)
    - Water Cooled Lithium Lead (WCLL)
  - Divertor (DIV, single-null, water)
- **Primary Heat Transfer System (PHTS)**
  - BB-PHTS (indirect / direct coupling with power conversion system)
  - DIV-PHTS
  - VV-PHTS
- **VV Pressure Suppression System (VVPSS) (He / water)**
- **Tokamak Cooling Room (TCR)**

Fig.

DBA – performed events

Events selected from the PIEs in GSSR Vol. 6:

- **in-BB LOCA** (HCPB / WCLL) due to failure of related channels / pipes
- **ex-vessel LOCA** (HCPB / WCLL / DIV) due to guillotine break of a main pipe in the PHTS
- **in-vessel LOCA** (HCPB / WCLL / DIV) due to failure of the first wall / IVT (Inner Vertical Target) channels
- Loss of Flow Accident (**LOFA**) due to pump / blower trip (HCPB / WCLL / DIV)
- **Loss of heat sink** due to loss of condenser vacuum (HCPB / WCLL)

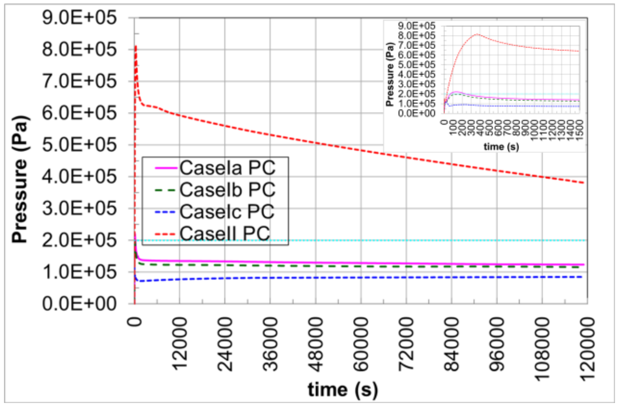
Ref. 1

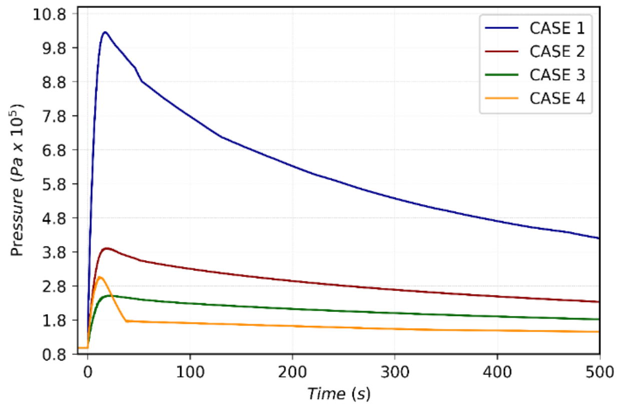
Analysis for each event performed and documented

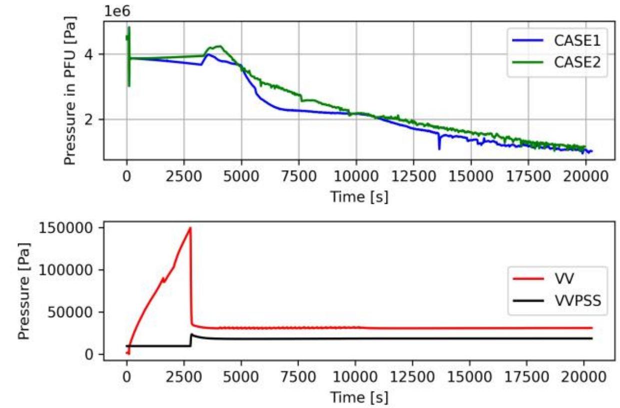
- Identification of causes, accident description, and assumptions for different scenarios;
- Generation of analysis model with proper computer code (MELCOR186 for fusion);
- Implementation of the initial conditions, assumptions and control methods to the model;
- Simulation of scenarios and evaluation of transient results;
- Analysis of radiological releases;
- Indication of uncertainties in the modelling;
- Recommendations for model improvement and to the designers;
- Summary for different scenarios

DBA – performed events (Ref. 1)

In-vessel LOCA HCPB	Ex-vessel LOCA WCLL	LOFA / In-vessel LOCA PFU-loop of DIV







- Pressurization of the VV exceeds the defined limit (200kPa)
- Both wet and dry expansion volumes with adequate volumes are required to suppress the VV pressure.

- efforts should be made to reduce the pressure peak inside the TCR
- provide additional volume for steam expansion in the TCR

- LOFA (top): melting temperature of cooling channels is not reached. Recommendation of loop layout to reduce trapping of steam within IVCs volume
- In-vessel LOCA (low): the pressurization is controlled by the VVPSS (H2O)
- integrated analysis of both cassette and PFU (Plasma Facing Unit) loops

The main uncertainties

- Reference design data
- Level of MELCOR geometric and phenomenological modelling details

DBA – performed events (Ref. 1)

Dose assessment

- Codes UFOTRI (tritium) and COSYMA (W-dust, activation corrosion products (ACP)
- Historic weather conditions from Cadarache (ITER) in 1991
- S1: WCLL, ex-vessel LOCA, DBA (tritium, ACP)
- S2: HCPB, loss of heat sink, BDBA (W-dust, tritium)
- S3: WCLL, FW-PHTS ex-vessel LOCA, BDBA (W-dust, tritium, ACP)
- S4: DIV PFU, in-vessel LCOA ,DBA (W-dust, tritium)

Dose in mSv at selected distance

Scenario	95%percentile	0.5 km	1.0 km	5.0 km	10.0 km
S1 (WCLL)	Early dose	1.6E-03	8.7E-04	6.0E-05	1.2E-05
	ED with ingestion	6.8E-03	3.6E-03	2.8E-04	7.9E-05
S2 (HCPB)	Early dose	1.0E-01	3.9E-02	7.1E-03	3.9E-03
	ED with ingestion	1.3E-00	4.8E-01	9.3E-02	6.0E-02
S3 (WCLL)	Early dose	1.1E-02	6.3E-03	4.0E-04	1.4E-04
	ED with ingestion	5.4E-02	3.5E-02	2.8E-03	1.4E-03
S4 (DIV)	Early dose	6.0E-02	3.4E-02	1.7E-03	7.2E-04
	ED with ingestion	2.8E-01	1.6E-01	1.3E-02	9.5E-03

Fig.

Dose calculation will be continued wrt. Tokamak building arrangement, leak conditions and detritiation efficiency.

Safety codes – GSSR Vol. 10

- **Summary of information on all computer codes for DEMO safety investigation**
  - Codes used in DEMO and ITER
  - Fission codes, which intend to be used in DEMO potentially
- **Codes are categorized for different DEMO safety application purposes**
- **Code description with a defined template**
  - Key model description applied for the DBA and BDBA (GSSR)

Safety codes – Category

- **System codes**
  MELCOR186 for fusion, ASTEC, RELAP5-3D, GETTHEM, ATHLET, TRACE, CONSEN, ECART
- **Codes for plasma interaction**
  MEMOS, TOKES
- **Containment codes**
  COCOSYS
- **Source terms codes** (activation, decay heat, tritium, ACP, neutron sputtering products, etc.)
  FISPACT-II, ACAB, TMAP, ECOSIMPRO, UFOTRI, OSCAR-Fusion v1.3, PACTITER, SPUTTER_II
- **Codes for radiological release**
  JRODOS, MACCS, COSYMA
- **Sensitivity codes**
  SUSA, BEST-EST, RAVEN
- **CFD codes**
  ANSYS CFD, GASFLOW, SIMMER, DET3D, FDS
- **Thermal-structural codes**
  ANSYS Mechanical
- **Process codes**
  APROS
- **Neutronic codes**
  cR2S

Codes used / developed in EUROfusion WPSAE tasks

Safety codes – Description template

- **Overview**
  - Code version / origin / availability
  - Code's capability / range of application / past history of application (in or out of fusion)
  - Code structure, its generic models and empirical correlations
  - linkages to other codes
  - document
- **Key model description for DEMO**
  - DBA (Vol. 7) and BDBA (Vol. 8)
- **Key input data description**
- **Key validation studies**
  - Previous V&V studies (results of major validation studies)
  - DEMO validation studies (for code used for DEMO)
- **Improvements requested for DEMO scopes**

Safety codes – V&V status of MELCOR in fusion

- **MELCOR182 modified for ITER**
  - the ingress-of coolant event (ICE) facility in Japan (Ref. 9)
  - the European Vacuum Impingement Test Apparatus (EVITA) facility in France (Ref. 10)
- **MELCOR186 for fusion**
  - code-to-code benchmark analysis of DEMO in-vacuum vessel LOCA scenarios (Ref. 11)
- **MELCOR-TMAP** (Ref. 12)
  - Multi fluids capability benchmark
  - Vacuum permeator problem
  - Water cooled PbLi heat exchanger problem
- **Common MELCOR fission-fusion-version in future**
  - European MELCOR User Group (EMUG11) (Ref. 13)

Outlook – DBA

- **Continue DBA analyses in the on-going Concept Design Phase (CDP, 2021 - 2027)**
    - updated IVCs and systems wrt. the identified issues from the performed analyses and design
    - updated source terms inventories
    - updated plasma, confinement and pressure suppression conditions, etc.
    - Tokamak building arrangement including leak rate conditions, detritiation efficiencies and flaps
- **Further events to be performed**
    - tritium process systems
    - blanket system connecting to the tritium extraction removal system
    - PbLi loop (WCLL)
    - loss of vacuum (VV, cryostat)
    - release of cryogenic fluid
    - fire and explosion accidents
    - seismic safety, etc.
- **Dose assessment for the radiological impact based on the environmental releases of source terms**

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

Outlook – codes

- **Update and extend the safety codes list**
  - Improve existing codes following code development
    - e.g. integration of UFOTRI functionalities in JRODOS for public dose calculation
  - Additional codes relevant for DEMO safety
- **Propose code validation plan for DEMO**
  - validation status in fusion
  - identify gaps between the performed validation and DEMO requirement
- **In long term, the validation details for each of the computer codes used in the safety analysis for DEMO are required**

Reference

1. G. Caruso, S. Ciattaglia, B. Colling, L. DiPace, D.N. Dongiovannie, M. D'Onorio, M. Garcia, X.Z. Jin, J. Johnston, D. Leichtle, T. Pinna, M.T. Porfiri, W. Raskob, all contributors to the WPSAE, **DEMO – The Main Achievements of the Pre–Concept Phase of the Safety and Environmental Work Package and the development of the GSSR**, Fusion Engineering and Design, Volume 176, March 2022, 113025.
2. IAEA, **Safety of Nuclear Power Plants: Design**, Safety Standards No. SSR-2/1, 2012.
3. L.V. Boccaccini, et. al., **Status of maturation of critical technologies and systems design: Breeding blanket**, Fusion Engineering and Design 179 (2022) 113116.
4. J.H. You, et. al., **Divertor of the European DEMO: Engineering and technologies for power exhaust**, Fusion Engineering and Design 175 (2022) 113010.
5. I. Moscato, et. al., **Tokamak cooling systems and power conversion system options**, Fusion Engineering and Design 178 (2022) 113093.
6. G.A. Spagnuolo, et. al., **Integrated design of breeding blanket and ancillary systems related to the use of helium or water as a coolant and impact on the overall plant design**, Fusion Engineering and Design 173 (2022) 112933.
7. C. Gliss, et. al., **Integrated design of tokamak building concepts including ex-vessel maintenance**, Fusion Engineering and Design 177 (2022) 113068.
8. IAEA, **Considerations on the Application of the IAEA Safety Requirements for the Design of Nuclear Power Plants**, TECDOC 1791, 2016.

Reference

9. T. Marshall, et. al., **Fusion safety codes: international modeling with MELCOR and ATHENA/INTRA**, Fusion Engineering and Design 63/64 (2002) 243-249.
10. B. J. Merrill, **Benchmarking MELCOR 1.8.2 for ITER Against Recent EVITA Results**, INL/EXT-07-13521, November 2007.
11. M. D'Onorio, et. al., **Benchmark analysis of in-vacuum vessel LOCA scenarios for code-to-code comparison**, Fusion Engineering and Design, Volume 173, December 2021, 112938.
12. B. J. Merrill, et. al., **Modifications to the MELCOR-TMAP code to simultaneously treat multiple fusion coolants**, Fusion Engineering and Design, Volume 146, Part A, September 2019, Pages 289-292.
13. F. Mascari, et. al., **Physical models necessary to be implemented in MELCOR_2.2 for fusion reactor safety analyses and the current model already implemented in MELCOR fusion**, EMUG11, April 2019.

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- **GSSR Vol. 7**

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- **GSSR Vol. 10**

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Thank you!

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