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Safety Important Classification of EU DEMO components

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The identification of structures, systems and components (SSCs) performing safety functions is of paramount importance for an EU DEMO development in all phases of the project: design, fabrication, commissioning, operation, maintenance, inspections and tests. Early identification of safety relevant SSCs contributes in the correct definition of systems requirements, preliminary layout and design integration. It may also be exploited as a supporting criterion for selection among the plant variants, e.g. alternative blanket concepts. Those SSCs assigned to a safety importance class (SIC) will receive adequate attention during the different developing phases.

A graduation of safety important SSCs is adopted for DEMO on the basis of the IAEA Guide No. SSG-30, on SSCs classification. Three safety importance classes (SIC-1, SIC-2 and SIC-3) are assigned on the basis of: a) the consequences the loss of the safety function could lead to, b) the involvement of the SSCs in preventing, detecting or mitigating incident or accident and, c) the involvement of the SSCs in bringing and maintaining the plant in a safe state. In this paper, the provisional safety classification of the Primary Heat Transfer System (PHTS) related to the Helium Cooled Pebble Bed (HCPB) and Water Cooled Lithium Lead (WCLL) blankets of DEMO is presented.

Keywords: Safety class, DEMO, Accident sequence, HCPB, WCLL

1. Introduction

The identification of systems, structure and components (SSCs) performing safety functions is required for DEMO development in order to identify the associated implications for the design, fabrication, commissioning, operation, maintenance, inspections and tests. Those SSCs of safety relevance identified with a safety important class (SIC) will receive adequate attention during all the different developing phases. The objective is to ensure and demonstrate that they will meet the minimum performance and reliability requirements throughout their intended lifecycle so that the safety function is provided when required.

Safety classification process defined for DEMO [1] is based on the IAEA Guide No. SSG-30 [2]. The objective of this activity is to define a provisional safety classification of the primary heat transfer system (PHTS) of the helium cooled pebble bed blanket (HCPB) [3] and the Water Cooled Lithium Lead (WCLL) [4] reactor models.

2. Safety classification process

The DEMO safety classification process [1] focuses on the identification/estimation of the following items:

- 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 lose safety functions, including the severity of consequences;
- Failure event probability or failure event category

2.1. Plant breakdown structure (PBS)

SSCs to classify are identified by the PBS, whose hierarchy is detailed up to a level enabling component classification. An excerpt of PBS is reported in Table 1.

Table 1 – Excerpt of PBS for the HCPB BB PHTS

50 - PHTS of HCPB breeding blanket (BB)
50-1 - BB PHTS segments (He loops)
50-1-1 - Supply and Distribution
50-1-2 - Cooling trains
50-1-2-1 - Piping, joints and valves
50-1-2-2 - Steam Generator/Heat Exchangers
50-1-2-3 - Pressure relief devices
50-1-2-4 - Expansion volume
50-1-2-5 - Helium Cooling Circuit (HCS)-Circulator

2.2. Safety Functions

Safety relevant SSCs shall perform safety functions, i.e. those functions necessary to ensure that exposures to hazards for public and workers are well within acceptable limits during both normal operations and accident conditions over the full lifetime of the facility. A hierarchical breakdown of safety functions is defined in terms of fundamental and supporting functions on the basis of the ITER functional breakdown [5]. An excerpt of such breakdown is reported in Table 2.

2.3. Categorization of safety functions

Important contribution in performing the SSCs safety classification is the categorisation of the functions on the basis of the following factors [2]:

- *Consequence of failure of the SSC;*
- *Frequency of occurrence of the IE (Initiating Event) for which the function will be called upon;*

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- *Significance of the contribution of the function in achieving either a controlled state or a safe state.*

Table 2 – Excerpt of safety functions

S1 Provide confinement of radioactivity
- S1a) Provide process confinement barriers
- S1b) Provide building confinement barriers including systems for maintaining depression and filtering/detritiating effluents

S2 Provide limitation of radioactive exposure to direct radiation including electromagnetic radiation fields
- S2a) Shield to limit radioactive and/or magnetic field exposure
- S2b) Provide Access control in operating area

S3 Provide protection of systems for safe confinement and limiting exposure
- S3a) Provide management of pressure
- S3b) Provide management of chemical energy
- S3c) Provide management of magnetic energy

……….

S4 Provide supports for implementing safety functions
- S4a) Provide auxiliaries essential for implementing safety functions (electrical power supply, compressed air, etc.…)

……….

Three safety function categories are defined in [1] on the basis of the guidelines in [2]. These three categories have been here elaborated in a table form (Table 3) on the bases of: i) conditions and frequency the function could be lost; ii) significance of the function in achieving either a controlled state or a safe state; iii) severity of the consequences caused by the loss of function. Table 3 also identifies, the three categories (S1, S2, S3) by different colours (respectively red, orange, green). Accordingly, the category to the safety functions provided by the SSCs shall be assigned on the basis of:
- the significant loss of safety function event;
- the purpose of requiring the security function;
- the failure likelihood (e.g. expected operational event, basic design incident);
- the consequences induced by the significant event.

Table 3 – 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**		

(a) The term "design extension conditions" is used to describe those accidents, beyond the design basis, for which additional prevention and mitigation provisions are required.

2.4. Criteria to check eligibility of SSC as SIC

To identify if the SSC is a safety relevant component, the following three top level criteria is used:
- Criterion **A** the SSC failure can directly initiate an incident or accident, leading to risks of exposure or contamination,
- Criterion **B**: the SSC operation is required to limit the consequences of an incident or accident that would lead to risks of exposure or contamination, or
- Criterion **C**: the SSC operation is required to ensure the functioning of other SIC components.

If one or more than one of the above criterions is applicable to the SSC, the SSC shall be classified as SIC.

2.5. Grading of safety importance classification

A gradation in the SIC classification for DEMO SSCs is defined in [1] by means of three safety importance classes, SIC-1, SIC-2 or SIC-3:

SIC-1. If SSC failure could lead to an event with consequences exceeding one-tenth of the limits set out in plant safety requirements [7] (see Table 4), or SSC needs to prevent, detect or mitigate an accident from resulting in consequences exceeding the above limits, or SSC is needed to bring and maintain the plant into a safe state.

SIC-2. If SSC failure could lead to an event with consequences exceeding a dose of 100 µSv to the most exposed individual member (MEI) of the public, or SSC is needed to prevent, detect or mitigate an incident or accident, although not required to reach a safe state, or SSC is needed to ensure adequate shielding from radiation during normal operation.

SIC-3. If SSC failure could lead to an event with consequences exceeding a dose of 10 µSv to the MEI of the public, or although not needed to prevent, detect or

Table 4 – Proposed DEMO Off-Site Consequence Limits/Targets for Off-Normal Events [7]

	Anticipated events [(b)]	Unlikely events	Extremely unlikely events	Hypothetical bounding events
Event Category	1-2	3	4	BDBE
Yearly Event	f>1E-02	1E-02>	1E-04	f<1E-06

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	Anticipated events (b)	Unlikely events	Extremely unlikely events	Hypothetical bounding events
Frequency		f>1E-04	>f>1E-06	
Early Dose			10mSv/ event	50mSv/ event
Chronic Dose	As normal operations	5mSv/ event	50mSv/ event	

(b) Category 1 refers to Operational events and Category 2 refers to likely event sequences

mitigate an incident or accident, SSC helps to further reduce the consequences of such an event.

All other components are defined as "non-SIC". They shall not impair SIC functions in any condition.

3. Safety classification of PHTSs

3.1. Operating modes

For the PHTS analysed in this study, two operating modes result relevant for the SSCs safety classification:

- Normal Operations (NOp), for all cooling and source terms confinement phases.
- Incident (Inc) or accident conditions (for SSCs required in case of abnormal/accidental events).

3.2. Possible failures of the SSCs

Some typical failure modes of the PHTS SSCs are [6]: I&C – Erratic/No output; Loss of power supply; Pipe/channel clogging; Spurious pressure relief from safety device; SSC – Failure to open/operate; SSC Leak/Rupture; Valve - Failure to remain in position.

Some of these events could lead to the loosing of safety functions. The ones leading to the worst radiological consequences shall be selected as representative events for the safety classification. An example is a coolant pipe failure. It could be either a small leak or a guillotine pipe break (i.e. large loss of cooling accident - LOCA). Clearly, the reference event to consider in the safety classification shall be the large LOCA.

3.3. Event category

Based on Table 4 data, five event categories have been defined (Table 5) for our study. The following items are considered in defining event category:

- SSC failure mode;
- Related SSC failure rate;
- Number of elements inducing the same type of event and their reliability wise correlations, i.e. series and/or parallel configurations in defining effects on the loss of function;
- Yearly time in which SSC provides safety function.

Table 5 – 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

The likelihoods of component failures are estimated by data extracted from the fusion component failure rate database (FCFRDB), which collects data useful for probabilistic assessment in nuclear fusion and fission field [8], [9]. Due to the heterogeneity of FCFRDB data sources, for a large set of components, more than one failure rate data was available to be taken as reference in defining the component failure rates. Relying on the high quality of the components and items that will be used in DEMO, the most promising failure rates have been selected from the range of available data.

The number of elements in the plant that could cause the same event (e.g. length of pipes, length of welds, number of similar components that could induce loss of coolant from the circuit) have been estimated by the design documents [3], [4].

3.4. Radiological consequences of events

Outcomes from dedicated deterministic analyses should be used to quantify the possible consequences related to accident events. At the current state of the art, deterministic estimations of accident sequences related to the two PHTSs are ongoing, but results are not yet available. Then, for the purpose of this first safety class assignment, very simplified calculations have been performed to estimate the order of magnitude of the possible dose to public due to SSCs failures. Conservative data are used to estimate the releasable source term of tritium.

10 g and 200 g of tritium/loop are, respectively, considered for the source terms in the two HCPB and WCLL PHTSs. The last design estimations [10] foresee about 2 g and 60 g of tritium, respectively, for the two PHTSs. The values assumed in addition to producing a very conservative estimate should also compensate for the approximation made in neglecting other source terms as activated products.

Three different events have been considered for the loss of confinement in the PHTS: Large ex-vessel loss of cooling accident (LOCA), small ex-vessel LOCA with isolation of the loop after the detection of the initiating event, ex-vessel leak. In all considered cases, the radiological content of the coolant is released into the tokamak cooling room (TCR) and from here to the environment through the vent detritiation system (VDS) effluents and through building leaks. For the three events, different releases in TCR have been assumed:

- 100% of coolant inventory in TCR for large LOCA;
- 33% of coolant inventory in TCR for small LOCA;
- 10% of coolant inventory in TCR for ex-vessel leak.

Table 6 summarises the resulting amounts of tritium released in TCR in the three cases of failure.

Table 6 – Tritium released in TCR on a PHTS loop failure

BB model	Large ex-vessel LOCA		Small ex-vessel LOCA with isolation		Ex-vessel leak	
	g of T	[Bq]	g of T	[Bq]	g of T	[Bq]
HCPB	10	3.57E+15	3.3	1.18E+15	1	3.57E+14
WCLL	200	7.14E+16	66	2.36E+16	20	7.14E+15

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The amount of tritium released into the environment after the initiating event has been determined, using the following assumptions and data from safety data list (SDL) [12]:

- Flow capacity of VDS = 5000 m^3/h
- Detritiation efficiency of VDS = 99.0%
- Free volume of TCR = 60700 m^3 [11]
- Leak rate from the TCR building = 1% of total TCR volume / day [11]

The dose to public has been estimated considering all the tritium released in HTO form. The worst dose HTO conversion factor estimated for ITER in [12] has been used: 8.3E-2 mSv/g of HTO. The data was calculated on the basis of: i) weather conditions with wind speed of 2 m/s and no rain; ii) long term dose for an adult at the distance of 2.5 km; iii) 0 m release height.

The maximum tritium release to the environment was found to take place already after 1 week from the IE. Some results are reported in table 7. It is confirmed that our reference event is the large ex-vessel LOCA.

Table 7 – Release of tritium to environment and dose to public

BB model	Release of HTO to environment			Dose to public		
	Large ex-vessel LOCA	Small ex-vessel LOCA	Ex-vessel leak	Large ex-vessel LOCA	Small ex-vessel LOCA	Ex-vessel leak
	[Bq]			**[µSv]**		
HCPB	5.35E+13	3.53E+12	1.07E+12	12	1	0.2
WCLL	1.07E+15	3.53E+14	1.07E+14	249	82	25

To associate a class of severity to the consequences of the events, the limits reported in Table 8 have been considered. They have been defined by limits fixed in Table 4 and Table 3. Then, the severity class of consequences related to loss of safety function has defined for both the categories 3 and 4 of the IEs, as reported in table 9. As the large ex-vessel LOCA in a loop of the HCPB PHTS induces 12 µSv of dose to public, for both frequency categories 3 and 4, the severity class is S3. While, for the WCLL PHTS, being the dose to public 249 µSv, the severity class is S2. In terms of safety classification, such severity classes are reflected in SIC-3 level classification for the HCPB PHTS SSCs and SIC-2 level classification for the WCLL PHTS SSCs.

An example of the data treated in the study and the classification obtained for the single components is reported in table 10.

Table 8 – 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

Table 9 – Severity classes for events

BB Model	**Large ex-vessel LOCA**			**Small ex-vessel LOCA with isolation**			**Ex-vessel leak**		
	Dose to public	Severity class for events		Dose to public [µSv]	Severity class for events		Dose to public	Severity class for events	
	[µSv]	Cat. 3	Cat.4		Cat. 3	Cat.4	[µSv]	Cat. 3	Cat.4
HCPB	12	S3	S3	1	-	-	0.2	-	-
WCLL	249	S2	S2	82	S3	S3	25	S3	S3

4. Conclusions

Despite very preliminary, because of poor design detail and still on-going deterministic assessment of accident sequences, the presented analyses gives a first picture on possible safety classification of DEMO SSCs, as well as a first application of the criteria defined for DEMO SSCs safety classification [1].

The main outcomes obtained are the following:

- The main safety function for both PHTSs of HCPB and WCLL is the confinement of radioactive products at the level of process barrier;
- SSCs of HCPB PHTS can be classified as SIC-3;
- SSCs of WCLL PHTS can be classified as SIC-2.

Safety classification of DEMO plant SSC is going-on with priority to the most critical systems from safety and layout point of view according to the progress of their design and safety analyses. The safety classification is an important element for the design of the DEMO systems and for the definition of layout, buildings and auxiliary systems to be performed since the early stage of the design and it has to follow the evolution of the design.

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Table 10 – Excerpt of safety classification of SSCs of the PHTSs of the HCPB and WCLL BB models

PBS elements (Components)	Safety function	Op. Md.	Possible Failure of SSC	Event Category	Significant safety event	Safety Classific. Criteria	Failure rate		Yearly Failure	Function safety category	Safety Class
50-1-2 - Cooling trains of HCPB BB PHTS											
50-1-2-1 - Piping, joints and valves		NOp	Small size leak		No						
	S1a		Rupture; Clogging	3	Large LOCA	A	2.50E-11	/h	7.33E-4	F2-S3	SIC-3
			Valve-Fail to remain in position		No						
50-1-2-2 - Steam Generator/HX		NOp	Small size leak		No						
	S1a		Multiple tubes rupture	3	Large LOCA	A	1.00E-07	/h	8.76E-4	F2-S3	SIC-3
			Shell rupture		No						
50-1-2-3 - Pressure relief devices	S1a	NOp	Leak/Rupture	4	Large LOCA	A	3.00E-10	/h	5.26E-6	F2-S3	SIC-3
			Spurious pressure relief		No						
	S3a	Inc	Failure to open on demand	5	Large LOCA	C	6.00E-07	/h	3.15E-9	F1-S3	SIC-3
50-1-2-5 - HCS-Circulator		NOp	Small size leak		No						
	S1a		Rupture	3	Large LOCA	A	1.00E-08	/h	1.75E-4	F2-S3	SIC-3
			Blower trip		No						
52-1-2 - Cooling trains of WCLL BB PHTS											
52-1-2-1 - Piping, joints and valves		NOp	Small size leak		No						
	S1a		Rupture; Clogging	3	Large LOCA	A	2.50E-11	/h	1.77E-4	F2-S2	SIC-2
			Valve-Fail to remain in position		No						
52-1-2-2 - Pressurizer		NOp	Small size leak		No						
	S1a		Rupture	5	Large LOCA	A	1.00E-10	/h	8.76E-7	F2-S2	SIC-2
52-1-2-5 - Steam Generator/HX		NOp	Small size leak		No						
	S1a		Multiple tubes rupture	3	Large LOCA	A	1.00E-07	/h	8.76E-4	F2-S2	SIC-2
		Inc	Shell rupture		No						
52-1-2-6 - Main Coolant pump	S1a	NOp	Small size leak		No						
			Pump trip		No						
	S1a		Rupture	4	Large LOCA	A	3.00E-10	/h	2.63E-6	F2-S2	SIC-2

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