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Integration of DEMO hazard piping into the tokamak building

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ABSTRACT

Because of the complexity of the design of a Fusion Power Plant like the EU DEMOnstration power plant the study of the plant layout must proceed in parallel with the design of the major systems. This is necessary to ensure that the design of the plant incorporates from the very beginning sound considerations on:

- Safety and licensing,
- Personnel security in context with operation and maintenance,
- Adequate plant availability, and
- Safe performance operation including delivery of few hundred MW net electric power to the electrical grid.

Though it is a process of trial and change that follows the design evolution, this approach allows a better and continuous control of the numerous physical and functional interfaces among the systems and structures assuring an optimization of the overall design focused on the above targets.

Some of the fluid systems inside the tokamak building are activated e.g., water coolant circuits of in-vessel components containing activated corrosion products (ACPs), radioactive N^{16} and N^{17} isotopes generated from neutron irradiation of oxygen, as well as the Lithium-Lead (LiPb) system containing ACPs and radioactive isotopes generated by neutron activation of the LiPb alloy. The layout of the corresponding circuits must consider constraints such as shielding, inspection, maintainability and irradiation lifetime of some equipment of other plant systems located in the tokamak building, e.g. electric and electronic equipment, organic seals of valves, and relevant actuators. Furthermore the personnel exposure during operation and maintenance has to be as low as reasonable achievable.

The experiences of Nuclear Power Plants and ITER (International Thermonuclear Experimental Reactor) are an important input to the layout of the DEMO coolant circuit. This paper presents some initial considerations on the criteria to be used for the layout criteria inside the tokamak building.

1. Introduction

Designing the layout of plant in a power reactor proceeds in parallel with the studies of the performance and design of plant. Though it is a process of trial and change, there is a logic to the work.

DEMO has the objective to demonstrate electricity production from fusion power, with a certain efficiency and plant availability [1]. This goal depends upon not only successful plasma operation but also the reliable operation of the numerous plant systems supporting the function of the tokamak components. DEMO represents an important and ambitious step between ITER and the fusion power plant [1]. Being a first of a kind, DEMO cannot rely on detailed design and technological

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knowledge, as available for nuclear power plants (NPP). Typically, designing the layout of the fusion plant is a process of trial and improvement and it proceeds in parallel with the performance analysis of the various systems. Regarding the plant systems very little analysis of this process has been published [2], although the work is a substantial part of the engineering development of a project. Considering the complexity of the design of a fusion power plant, the layout development has to follow the design evolution of the different DEMO design options since the early phase in order to provide the necessary design basis to develop a technically feasible, operable and maintainable conceptual plant design and to identify areas in which there are significant technical or cost uncertainties [3].

2. Systematic approach

The EU DEMO design is benefitting from some of the lessons learned from the ITER design and construction phase, In particular, the importance to give sufficient attention from the very beginning on:

- o Integrated design neutronic analyses of the all plant, taking into account sufficient design margin in some areas (e.g., shielding of 16N and 17N, streaming).
- o Development of a sound maintenance plan, including provisions to access areas where contamination and or activation is higher than originally considered.
- o Development of a plant layout, providing sufficient space to integrate all equipment and auxiliary systems, particularly in the tokamak building

DEMO follows a systematic sequence to tackle the integration task of systems that represent potential hazards to DEMO:

- o Identification of systems representing potential risks to DEMO, its personnel or the environment
- o Identification of hazards potentially originating from these systems
- o System analysis to evaluate consequences based on the systems' technical specifications
- o Definition of targets and limits for the specific hazards based on conventional standards. In case no conventional standard exists limits applied in ITER or fission are considered at this stage.
- o Definition of mitigation actions and verification for all relevant machine states, e.g. plasma operation, dwell, or maintenance.

3. Design variants of DEMO plant systems

Two design variants are considered for the plant layout inside the tokamak complex building with different main and auxiliary systems. One option considers a helium-cooled breeding blanket with beryllium and Lithium ceramic pebble beds (HCPB) [1]. This breeding blanket (BB) concept requires specific auxiliary systems such a primary heat transfer system (PHTS) operated with Helium and a tritium extraction system operated with helium as purge gas, see Fig. 1.

The second option considers a water-cooled breeding blanket with a lithium lead loop (WCLL) [1]. This BB concept requires different auxiliary systems such as PHTS operated with water and a tritium extraction system operated with a liquid eutectic of Lead and Lithium (LiPb), see Fig.2. In both cases, the divertor, the protection limiters, the vacuum vessel are cooled with water.

Therefore, two different hazard conditions are to be taken into account for the plant layout and building integration. Of course, integration of common plant systems for both variants with the associated pipework into the building must be done, which contribute to the environmental condition of rooms and shafts. The specific components and pipes in number and size for each variance have an impact on the building layout in terms of volume of the occupied rooms (Figs.1&2). In addition, the dimension of building systems, like the detritiation system (DS) and heating, ventilation and air conditioning system (HVAC) are related to the amount of pipework and to the room sizes.

4. Hazards assessment criteria

Hazards originated from the coolant loops and LiPb loops have to be assessed according to their safety relevance to personnel and equipment.

Radiation caused by N^{16} and N^{17} isotopes in the cooling water of in-vessel components will exist during plasma operation only. In dwell time or maintenance shutdown these isotopes have decayed (half-life in the order of seconds).

Other hazards remain also during dwell time and maintenance shutdown like radiation from active corrosion products (ACPs), fluid pressure, leakage of tritium, and radiation from activated LiPb. In case a plant system is drained during shutdown and the pipework is purged the radiation risk will be reduced drastically.

Other hazards are linked to accidental scenarios such as pipe whipping or over-pressurization of a room, see Table 1.

5. Plant systems inside tokamak building and their specific hazards

5.1. Plant system hazards based on machine status

5.2. Specific hazards

The chronical tritium release of plant systems is a severe issue. This release must be mitigated to ensure the access for staff during maintenance phase and to prevent a hydrogen explosion risk. Technical solution is to connect the detritiation system to the affected rooms in the tokamak building and if possible to make a double enclosure around the leaking pipe work or component. The coolant purification system minimizes the tritium content, which could leak from the coolant. [4]

Coolant leakage is expected to be large from a helium loop (i.e., up to about 10 % of the inventory could be loss per year) [13]. The key

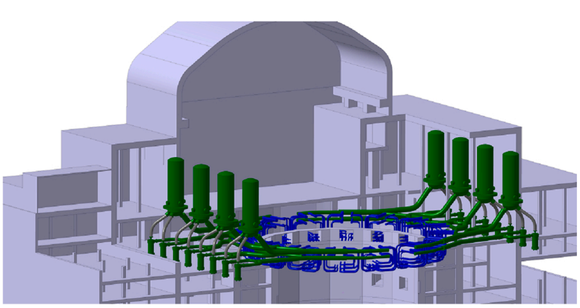

Fig. 1. Building for HCPB with 8 Heat Exchangers (HEX).

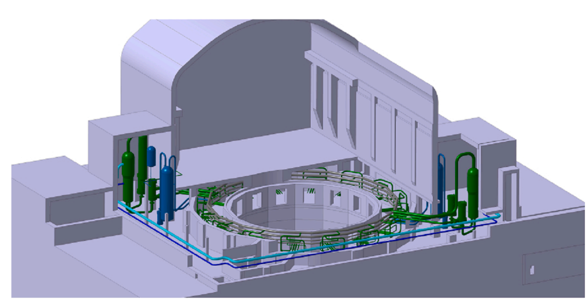

Fig. 2. Building for WCLL with 2 HEX (green) and 2 steam generators (blue) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Plant system hazards based on machine status.

Plant Systems	Machine Status			
	Plasma operation	Dwell	Shutdown	Accident
Divertor / limiter PHTS BB (WCLL) PHTS	Neutron and gamma radiation (N^{16}, N^{17}, ACPs)	Gamma radiation (ACPs)		Gamma radiation Pipe whipping Tritium / ACP release Rise of room pressure
BB (HCPB) PHTS	Chronical tritium release			Pipe whipping Tritium release Rise of room pressure
WCLL LiPb loop	Gamma radiation (radioactive isotopes from LiPb neutron activation, ACPs) Chronical tritium release			Gamma radiation Tritium / ACP release Chemical reaction with O_2
HCPB He purge loop	Chronical tritium release			Tritium release
Tritium system - DT pipework	Chronical tritium release			Tritium release
Cryo-distribution - 4K / 80K lines	n/a			Rise of room pressure Freezing adjacent services

difference from an occupational dose perspective is that the tritium in the helium system exists as tritium gas and that in the water system as tritiated water. Tritiated water and water vapor is about 10,000 times more hazardous than tritium gas. Once released into the cooling system equipment rooms, however, tritium gas will slowly convert to vapor by surface interactions, thus creating a significant airborne concentration of tritiated vapor. Detritiation equipment would be required to keep airborne tritium concentrations and environmental releases within safe limits for both helium and water cooling systems. The investigation of this issue has been just started.

Preliminary study have been made to understand the issue of activation of water and the production (inside plasma facing components) and decay of short-lived N^{16} and N^{17} radiation. The radiation caused by N16 asks for dedicated shielding to protect equipment from this high radiation source. This issue is a driving factor for the upper pipe chase layout and the routing of this high-activated water. N^{17} is also a neutron emitter, which can activate components [5]. Currently analysis are performed to evaluate the dose level, which challenge the limits of valves and electronic equipment [4,6,7].

Radiation emitted from ACPs in plasma facing component (PFC) coolant is an issue for access of maintenance personnel. The relevant shutdown dose rate (SDDR) depends on the machine operating time. A chemical volume control system (CVCS) can reduce substantially the ACPs, which are an important source of the gamma radiation. In addition a chemical oxidation decontamination during plant life time and before maintenance can reduce substantially the active inventory inside the plant systems. A loss of coolant accident (LOCA) would release the ACPs into the building. Therefore, the access of personnel in the affected area will be limited or forbidden.

In LiPb the Gamma-radiation sources are coming from the radionuclide inventory generated from Lead and impurities by neutron activation inside the vacuum vessel (VV) and ACPs. The radiation dose of this system is also a function of the machine operating time.

Pipe whipping as a consequence of a guillotine break of a high-energy pipe might endanger the integrity of adjacent systems.

An accident scenario of pipe break (e.g. LOCA in the PHTS) might cause an over pressurization of the room or entire building.

A loss of cryogenic fluid at 4 [K] or 80 [K] due to a pipe break can endanger adjacent systems and over pressurize the building.

6. Introduced mitigation actions to cope with the hazards

6.1. General mitigation strategies

DEMO follows several strategies to mitigate hazards inside the tokamak complex building:

(i) Improve n-shielding and reduce n-streaming
(ii) Implementation of system segregation
(iii) Definition of adequate thicknesses of the separating walls between segregated plant systems
(iv) Minimization of affected building areas by segregation of rooms
(v) Cleaning process and cleaning systems. (E.g. DS)

Because of the limited space available in this paper, no considerations are made on the results of design activities in progress to ensure sufficient margins in shielding.

6.2. Specific mitigation strategies

6.2.1. Radiation doses

Further work is required to improve the design of the WCLL PHTS to ensure that the radiation dose rate and the end-life integrated radiation dose is within the limits defined for electrical and electronic qualified equipment.. An example of recent work done to study radiation field caused by ^{16}N and ^{17}N. Using comprehensive methodologies coupling novel modelling tools coupling n-transport codes with fluid-dynamics code is described elsewhere [6,7]

Accurate shielding wall design, location of sensible equipment in lower radiation field areas, e.g. actuators of valves located behind a wall with adequate thickness, are some of the adopted mitigation strategies. Fig. 5 identifies the upper pipe chase area.

The target values of radiation are for non-critical (10 Gy) and critical electronic equipment (1 Gy). Analyses are ongoing to evaluate the benefit of using special concrete with higher shielding capacity to meet this criteria in the adjacent rooms to the upper pipe chase [7].

The divertor and limiter coolant water pipes run vertically inside the bioshield, see Fig. 3, in order to increase the delay time where the bioshield is the radiation protection towards ports and galleries. As lesson learnt from ITER [9] the PFC water pipes in DEMO are not routed inside the port cells but instead enter directly from the VV port into the lower pipe chases, see Fig. 4.

As an additional way of radiation protection, electrical equipment (e.g. cubicles) might be placed on intermediate non-radioactive levels (Fig. 5): Q-level & upper feeder level away from any radiation hazard pipework. Furthermore the intermediate levels do not provide access into the VV, therefore transport of activated in-vessel components (IVCs) does not take place on these levels, and the relevant huge dose will not affect significantly the cubicles.

6.2.2. Pipe whipping and cryo-releases

In order to mitigate the consequences of pipe whipping due to a guillotine break of a high-energy pipe, these pipes are routed in dedicated vertical shafts, Fig. 6. Safety-sensitive pipes containing tritium are thus protected from this hazard. Also the 4 K and 80 K helium pipes of the cryo-distribution will be arranged inside dedicated shafts and areas in order to mitigate the relevant hazard to avoid damage due to the chilliness on other system, equipment and pipework.

Here Segregation of pipes and equipment of the LiPb system can reduce the SDDR for maintenance to adjacent systems during shutdown (<< 100μSv/h of dose for workers) [5]. A concrete wall thickness 1.25–1.5 m is necessary to be able to place non-critical electronic

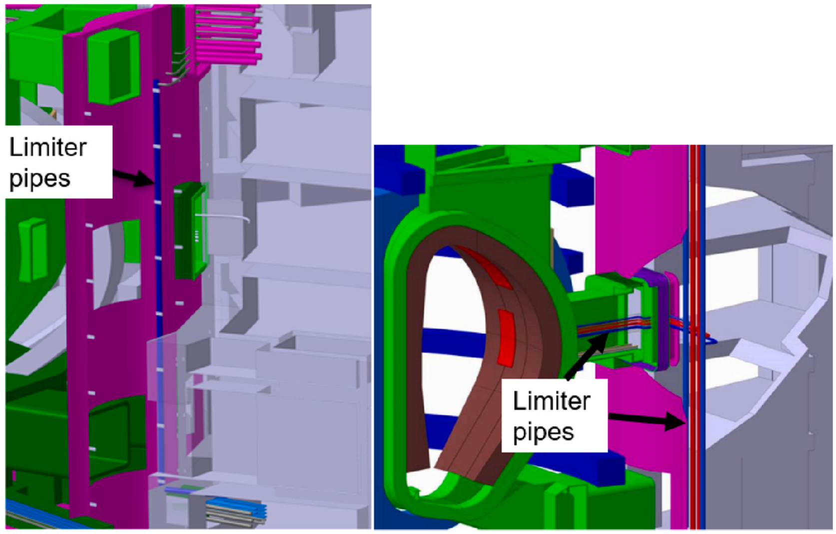

Fig. 3. Divertor and limiter pipes carrying activated cooling water routed inside the bioshield to protect radiation-sensitive electronics inside the tokamak complex.

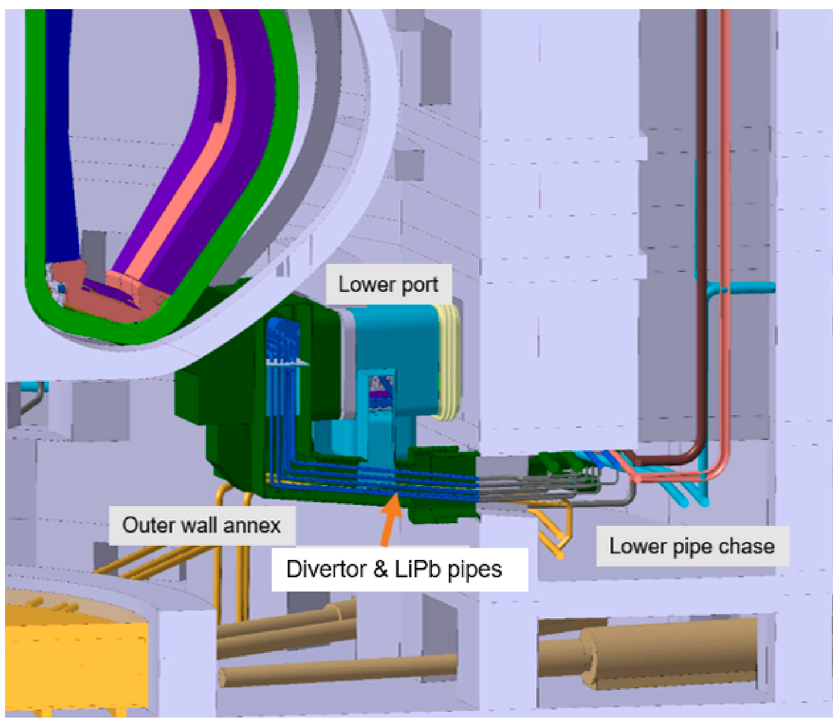

Fig. 4. Pipe routing through outer wall annex to lower pipe chase.

equipment in the next room and allow man access 2 weeks after shut-down [1].

The tokamak building, represents the secondary and ultimate confinement barrier for the radioactive material contained inside the building. The relevant safety function could be challenged by an over pressurization of the building beyond 2 bar absolute. To avoid this over pressurization, sufficient volume inside the building has to be made available for accidental scenarios. LOCA of PFC – PHTS or loss of 4[K] & 80[K] inventories.

In case of an ex-vessel LOCA in the PHTS equipment area, around 50,000 m^3 and 120,000 m^3 are available for the WCLL and HCPB plant options, respectively. -Analyses are on-going to assess whether the pressure peak after the reference accident can be kept under the limit of 2 bar [10,11].

6.2.3. ACPs radiation

Cleaning processes might be necessary in the DEMO tokamak building to reduce the SDDR due to ACPs inside the IVC coolant loops. A chemical oxidation decontamination used in the fission plants will reduce substantially active inventory inside the plant system. This minimizes the radiation dose during maintenance and at the end of the plant.

7. Conclusion

The paper describes the initial study of the layout of the DEMO buildings aiming to assure an optimization of the overall design focused on the main targets: nuclear licensing, availability and minimization of radiation dose to the staff according to as low as reasonable achievable (ALARA) criterion. The tokamak building is the most important building

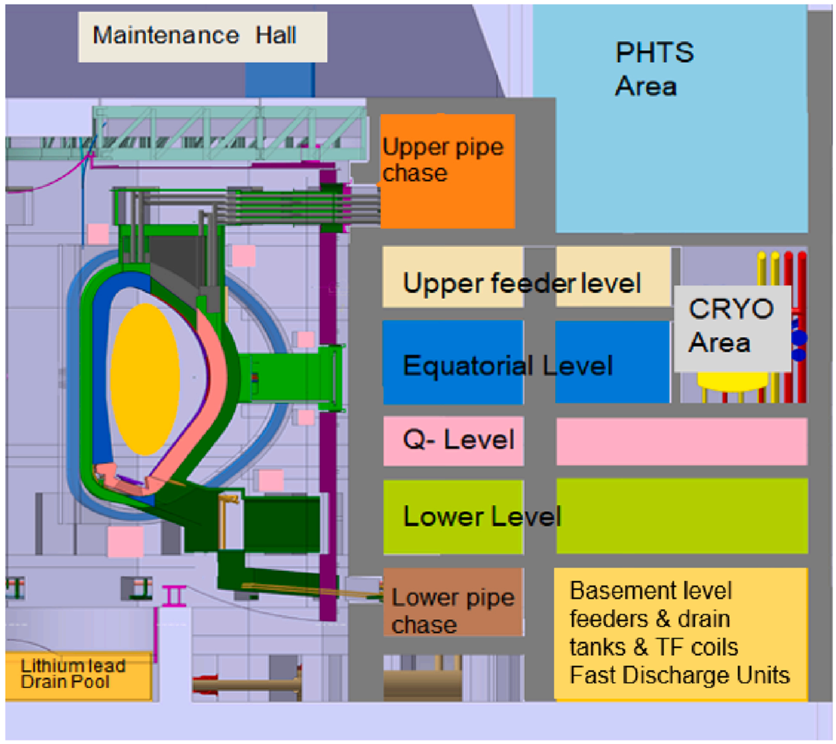

Fig. 5. DEMO Tokamak building level.

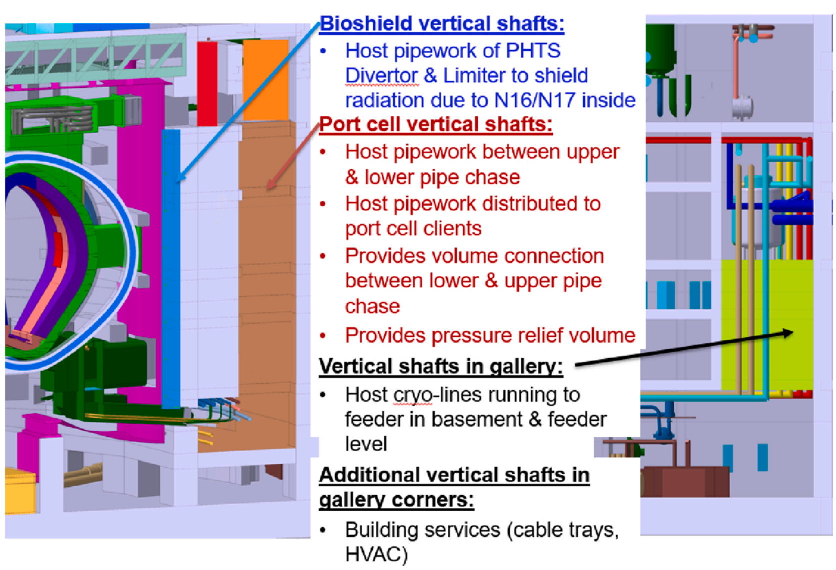

Fig. 6. Vertical shafts in tokamak building.

for the many systems it integrates, the complex interfaces, radioactive inventories, and significant energies. A number of accidental scenarios must be considered that could mobilize the radioactive inventories and challenge the leak tightness of the building that represents the ultimate confinement barrier to the environment.

This article highlighted main issues relevant to coolant and LiPb loops, i.e. high radiation areas in the surrounding of equipment, particularly those due to N^{16} and N^{17}, the risk of pipe whipping, over-pressurization of areas and of the building itself in case of ex-vessel LOCA. It addresses the relevant mitigation measures adopted in DEMO: adequate shielding and segregation of WCLL PHTS and LiPb pipes, as well as the cryo-pipes from cooling pipes to avoid synergism in pressurization of the building in accidental condition.

Segregation of plant systems is applied also in different levels and rooms. Adequate expansion volumes are foreseen for accidental scenarios. Common integration rules are applied to minimize accidental consequence scenarios [12]. Selected main plant systems have been integrated into the tokamak building considering two options of the breeding blanket, HCPB and WCLL, with the associated ancillary systems, e.g. the PHTS [4] The task of plant system integration and building layout provides the input data for several safety and functional assessments in the DEMO project that enable the iterative process required to identify a feasible solution to this complex problem.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] E European Research Roadmap to the Realization of Fusion Energy [https://www.eurofusion.org/fileadmin/user_upload/EUROfusion/Documents/2018_Research_roadmap_long_version_01.pdf].
[2] C. Gliss, et al., Initial layout of DEMO buildings and configuration of the main plant systems, Fusion Eng. Des. 136 (2018) 534–539.
[3] G. Federici, et al., Nucl. Eng. 59 (2019), 066013.
[4] F. Cismondi, et al., Progress of the conceptual design of the European DEMO breeding blanket, tritium extraction and coolant purification systems, in: Presented at the 14th International Symposium On Fusion Nuclear Technology, Budapest, Hungary, 2019.
[5] Iole Palermo et.al., Guidelines to estimate neutron fluency and dose rate in building.
[6] P. Chiovaro, et al., Investigation of the DEMO WCLL breeding blanket cooling Water activation, in: Presented at the 14th International Symposium On Fusion Nuclear Technology, Budapest, Hungary, 2019.
[7] P. Chiovaro, et al., Assessment of the dose rates due to Water activation on an isolation valve of the DEMO WCLL breeding blanket primary heat transfer system, in: Presented at the 14th International Symposium On Fusion Nuclear Technology, Budapest, Hungary, 2019.
[9] Z. Ghani, et al., Radiation levels in the ITER tokamak complex during and after plasma operation, Fus. Eng. Des. 96–97 (2015) 261–264.
[10] M. D'Onorio, et al., Sensitivity analysis for the hydrogen production during an Ex-vessel LOCA without plasma shutdown for the EU DEMO WCLL blanket concept, in: Presented at the 14th International Symposium On Fusion Nuclear Technology, Budapest, Hungary, 2019.
[11] S. D'Amico, et al., Preliminary thermal-hydraulic analysis of the EU-DEMO helium-cooled pebble bed fusion reactor by using the RELAP5-3D system code, in: Presented at the 14th International Symposium On Fusion Nuclear Technology, Budapest, Hungary, 2019.
[12] E. Zorla, et al., Radiation shielding properties of high performance concrete reinforced with basalt fibers infused with natural and enriched boron, Nucl. Eng. Des. 313 (March) (2017).
[13] Helium leak and chemical impurities control technology in HTTR Daisuke Tochio, Atsushi Shimizu, Shimpei Hamamoto, Nariaki Sakaba, J. Nucl. Sci. Technol. 51 (11-12) (2014) 1407–1412.