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Rationale for the selection of the operating temperature of the DEMO Vacuum Vessel

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The Vacuum Vessel (VV) of DEMO has to fulfil various requirements. The main function is to provide the high vacuum environment essential for plasma operation. Likewise, it has important safety functions: it acts as the first and main nuclear confinement barrier and the main constituent to the neutron and radiation shielding function protecting other components in particular the superconducting coils and all maintenance areas. It has to remove the heat load from nuclear heating also in the unlikely event of a major technical malfunction. The VV is well designed to provide the mechanical support and attachment for the in-vessel components (IVCs). This paper addresses the effect of the VV temperature on the functions and issues described, and the approach to define the best suitable temperature window. Following a qualitative assessment, the finding is that a lower operating temperature around 40°C is advantageous for most of the issues.

Keywords: DEMO Vacuum Vessel, VV, temperature, baking

1. Introduction

The EU fusion roadmap Horizon 2020 [1] foresees as next step after ITER a demonstration fusion power plant (DEMO). It advises an approach of a pulsed tokamak based on matured technologies and dependable operational plasma regimes. Therefore, the technological and physical developments undertaken for ITER should be exploited in the development of DEMO.

In magnetically confined fusion devices the plasma operation takes place in a hermetically sealed vacuum vessel (VV) of unconventional size and shape that enables the crucial high-vacuum environment. Additionally to the basic scope the DEMO VV has to fulfil several additional requirements, due to its design and constructional concept.

DEMO will be classified as nuclear facility in which the VV is part of the nuclear first confinement barrier. One of the main safety functions of the VV is the protection by shielding of the superconducting magnets, all the maintenance areas and the environment against neutron radiation. Therefore wall irritation and damage by neutrons need to be considered.

It has to provide mechanical support to the in-vessel components (IVCs) in all envisaged operational conditions. In addition, the usage of the hydrogen isotope tritium (T) as component of the fusion fuel requires additional safety and material compatibility considerations. T surface retention and bulk permeation contribute also to the overall T inventory.

The temperature for operation or conditioning of conventional vacuum chambers is generally chosen to provide excellent vacuum conditions. Due to the additional functions of the DEMO VV the arguments for the temperature selection are multifaceted.

2. Vacuum Vessel assembly

The intended design of the DEMO VV is based on the concept chosen for the ITER VV [2]. Presently it is foreseen to build the VV assembly with all the attached ports in stainless steel 316L(N). The main reasons for this choice are the good manufacturability, satisfactory mechanical properties, experience gained by ITER, and the fact that this material is included in several nuclear code frameworks, e.g. RCC-MRx Edition 2015, [3]. The material selection has to be considered preliminary given the early phase of the DEMO project.

The VV is planned to be constructed as a double shell structure. In between the inner and outer shells a sufficient amount of ribs for reinforcement are foreseen. The properly dimensioned interspace is planned to be filled with ≈55%, by volume, steel plates and cooling water for neutron and radiation shielding.

The VV is obliged to safely withstand any anticipated loading conditions, including disruptions, gravity, coolant pressure, and any combinations thereof.

3. Operating temperatures of fusion devices

The criteria according to which the operational temperature windows of VVs in other fusion facilities have been specified often are not well traceable or documented. Furthermore, they are often no longer valid, as specific modifications were implemented since then, e.g. change of in-vessel materials, but present operational parameters could not be adapted to that effect.

This is the case, for example with JET. Initially, temperatures were determined for carbon IVCs and reduced later, with the transition to tungsten IVCs, also for financial reasons. As summarized in Table 1, in present

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fusion devices no preferential VV temperature is observed.

Table 1: Overview VV temperatures of fusion devices

Device	Active since	Cryo-stat	Operation Temp. [°C]	Baking Temp. [°C]	Baking time [days]	Tri-tium
JET	1983	No	200 320 (DTE)	320		Yes
AUG	1991	No	20	150	8	No
W7-X	2016	Yes	20	150	8	No
ITER	>2025	Yes	100	200		Yes
DEMO	>2045	Yes				Yes

4. Rationale for VV temperature selection

The multifaceted specification on the DEMO VV operating temperature affect the functions required in different ways.

4.1 VV cooling concept and energy generation

The main additional scope of DEMO compared to today's fusion devices is to be the step towards commercial power plant with high thermal power and a nearly-continuous plasma operational time of hours. This results in a constant heating by neutron radiation of the IVCs, and the VV by ≈65 MW [4]. Consequently a permanent cooling of the VV is required (rather than to heat the VV to a suitable temperature). If operated at elevated temperature the heat removed from the VV could potentially be used in the power conversion system for pre-heating. To be attractive the temperature therefore should be at least 150°C. The VV may then contribute by ≈4 % of the total produced electrical power. If cooled near ambient temperature the heat removed from the VV must be transferred to a re-cooling system that exchanges the heat to a natural water source or to air using a cooling tower. To allow for the heat transfer to natural sources, not using an additional chiller water system, the VV operational temperature must not be lower than ≈40°C. For DEMO, as still a prototype plant, it is conceivable to leave this energy potential unexploited.

4.2 Structural requirements

The construction of a double walled structure like the VV becomes increasingly complex. Consequently cost increase with load bearing capacity corresponding to increased wall thickness, number of reinforcement ribs, and the total weld volume.

For mechanical design (strength and mechanical stability) lower temperatures are favourable. For example, the ultimate tensile strength (UTS) of SS316 typically is reduced by ≈10% between a temperature of 50°C and 200°C [5]. This has to be compensated by constructive measures for higher temperature design options.

4.3. Compressive strength requirements

According to the saturated steam table (see Table 2) it is obvious that the required pressure to prevent the cooling water from boiling increases non-linearly with the temperature. As result of the overall height of the VV there have to be an additional pressure resulting from the water column of ≈1.5 bar considered.

Table 2: Saturated steam table (excerpt)

T [°C]	P [bar]	Increase to lower temp [bar]	Increase to lower temp [%]
100	1.01		--
120	1.98	0.97	96
140	3.61	1.63	82
160	6.18	2.57	71
180	10.02	3.84	62
200	15.54	5.52	55
220	23.18	7.64	49
240	33.45	10.27	44

4.4 Heat loads - thermal shielding

The thermal radiation analysis of the DEMO Vacuum Vessel Thermal Shield (VVTS) and Cryostat Thermal Shield (CTS) was performed by Končar [6] based on conceptual CAD model data.

The analyses were preformed assuming a base case VV temperature of 200°C and the still valid estimate of a liquid helium cooled VVTS at 80 K. In this combination a net radiation heat flow Q^{rad} from the VV to the VVTS of ≈890 kW was calculated.

$$Q^{rad} \sim (T_{hot}^{4} - T_{cold}^{4}) \qquad (1)$$

As the thermal radiation is proportional to the power of 4 with the (absolute) temperature (see eq. 1), this flow is reduced significantly (by a factor of ≈5) in case of a reduction of the VV temperature from 200°C to 40°C.

Contributions from other effects such as the thermal conductance at the VVTS supports were found to be negligible.

The cost of cryogenic refrigeration as criterion has to be considered. A very extensive compilation of cost data for a number of commercial two-stage and single-stage coolers was done by Green [7]. This data allows estimating the capital costs of coolers as a function of refrigeration for different temperatures. For a refrigeration at 77 K, the capital costs are ≈150 $/W. It is expected that the cost of larger systems do not linearly increase with the power but it is still a significant cost factor.

Depending on design choice for the cooler the efficiency η (defined as refrigeration produced / electrical power consumed) of the Cryoplant is expected to ≈20 % at 4 K and ≈25 % at 80 K. For the complete process including the Carnot cycle this implies that for the removal of 1 W heat flux an electrical power of ≈335 W at 4 K, and of ≈10 W at 80 K are necessary, respectively.

These values above show that the heat loads to the VVTS contribute significantly to both, the construction costs and the operational costs of the Cryogenic plant.

Compared to the rough calculation in paragraph 4.1 there would be still an energy surplus with higher VV

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operating temperatures from the viewpoint of overall plant efficiency.

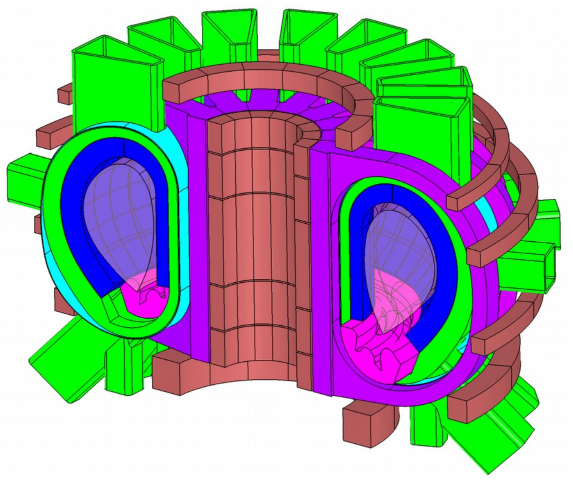

Fig. 1: Sectional drawing of DEMO; VV (green), BB (blue), Divertor (pink), VVTS (cyan), and Magnetic coil-system (brown, purple).

4.5 Neutron irradiation and self-healing

The influence of the neutron irradiation on mechanical properties depends on (irradiation) temperature. For metals a classification in relation to the melting temperature is common. The DEMO VV candidate materials are operated in the "low-temperature" regime (0.06-0.3 of melting temperature), i.e from ≈106 K to ≈260°C for SS316. Kozlov [8] describes the characteristic features: the temperature provides some mobility to the interstitials created by neutron irradiation, however is too low for mass motion of the corresponding vacancies through the crystal. The average lifetime of interstitials before migration τ and a quasi-equilibrium, reached in short time, both go exponentially with $1/T$, $\tau \sim \exp(1/KT)$. Then following this basic behaviour, dislocation loops are formed that increase linear with time.

The question of "self-healing or annealing" of defects (e.g. the question to which extend Cr-Carbide precipitations causing embrittlement and degradation of properties can be "resolved") was investigated by Agrawal [9] for SS 304 (similar in properties to the current candidate SS316LN). The studies were done in a temperature range above 450°C and the results show that (significant) effects of sensitisation and de-sensitisation appear at temperatures over 600/650°C. Therefore, in the intended operational temperature range significant influence of self-healing is not expected. During the ongoing selection process of VV candidate materials (and its optimum operational temperature) criteria such as the temperature dependent degradation of properties under n-irradiation (e.g. embrittlement and loss of ductility) and healing strategies of defect by baking should be addressed with selection.

4.6 Adsorption, desorption and baking

Depending on their individual desorption energy (E_{des}) - related to the combination of gas species and wall material - the mean residence time τ of particles on a surface covers a very wide range. Gases with a low E_{des} (< 71 kJ/mol) desorb within minutes after starting evacuation, whereas gases with high E_{des} (> 105 kJ/mol) stay stable over months. The gases in the medium range of E_{des} account considerably over a long-term period to the vacuum pressure. This is an issue especially after venting of a vacuum chamber with air for maintenance purposes. For water (E_{des} ≈90 kJ/mol on stainless steel) at room temperature, τ is ≈8 minutes, whereas at 177°C it is only 3 msec. This means that for the vacuum conditioning during commissioning the technical possibility for a temperature increase (baking) of the VV is desirable. The baking temperature should be at least around 180°C to limit the necessary baking time to a period of a few days (see Table 1). Based on the experience of other devices an intermediate baking not following an event with air intrusion is not envisaged as long as plasma operation is still possible.

The E_{des} of Hydrogen (H_2) is even higher (≈135 kJ/mol on stainless steel) and $\tau \approx 3 \cdot 10^{10}$ sec. at room temperature. Therefore, it can be assumed that a long-term stable and remaining monolayer of gas is built up within less than a second [10]. At 177°C, τ is only ≈8 minutes, therefore more mobility is likely. Options to decrease the amount of particles depend on the probability that they were pumped out of the VV or recycled into the plasma. Therefore, mainly the conductance to the pumping system is accountable as the conductance to the plasma is expected to be low.

Under the given conditions it is expected that the highest developing surface load is a monolayer (multilayers are not probable). This means a maximum of $\approx 10^{19}$ particle/m^2. The surface of the DEMO VVs inner shell is ≈2000 m^2 including ducts. For structural materials the real surface in microscopic dimensions has to be calculated by a factor 50 higher because of the surface roughness. This finally results in ≈1.66 mol particles and thereby a calculated maximum wall surface T inventory of 10 g in the unlikely case that every surface particle is a T molecule.

4.7 Tritium penetration and permeation

It needs to distinguish between plasma driven permeation (PDP) and gas driven permeation (GDP). As the VV is completely shielded by the IVCs, PDP is not considered to occur to the VV inner walls. GDP compared to PDP is in the orders of magnitude less efficient [11].

The transport of hydrogen isotopes in structural materials has been a wide subject of research for decades as it is of general interest.

The flux of hydrogen isotopes through a metallic wall depends on the permeability of the wall material, the gas exposed area und the thickness of the wall and the driving forces – the pressure difference. These forces for

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permeation are proportional to the square root of the pressure [12] and strongly limited by surface coatings.

The penetration and further permeation generally is dependent on various material properties as well as on the surface as within the bulk material. Experimental studies revealed that hydrogen permeation is significantly influenced by surface conditions, particularly oxide films, and internal defects and impurities that trap diffusing hydrogen. Hydrogen embrittlement mainly is related to the amount of hydrogen absorbed and its distribution within the metal lattice and finally the temperature. Therefore, the enrichment of T is an ongoing process over the lifecycle of a fusion device. Measurements show that in the relevant range investigated between 40°C and 220°C the change of permeability is proportional in an Arrhenius-plot (i.e. follows an exponential 1/KT law) and is in the order of 3 to 4 orders of magnitude [13].

The T permeated through the inner shell of the VV solutes to a high degree in the cooling water. For minimized T inventory this water may has to be de-tritionated. The level of T concentration as influx to the outer shell is therefore estimated to be very low and thereby causes a negligible permeation flow into the Cryostat.

The effect of temperature to T retention was studied qualitatively by Matsuyama [14] comparing the x-ray spectra after exposure plates of bare 316L at temperatures of 120°C and 350°C. The results indicate that the T concentration in the plates exposed to T at the lower temperature is significantly lower than that exposed at the higher temperature. The x-ray intensity peaks at the lower temperature are ≈1/3 compared to the higher temperature (where the ratio of peaks not necessarily represents one-to-one the T concentration).

4.8 Diagnostics and control

For the operation of DEMO still various diagnostics are foreseen, whereby the requirements on reliability and accuracy are even higher than on any existing fusion device. They are still in an early stage of development and will be based on very different principles and technical solutions. Therefore only some general suggestions on the influence of the VV temperature could be made for devices that are mounted within or close to the VV. The frontend will often consist of metals where the same estimations are valid than for the VV. So usually a lower temperature also here leads to less irradiation under neutron influence. Cable and other plastic electrical insulations usually have limited temperature resistance; electronic components usually are easier to operate at lower temperatures.

4.9 Construction - Mechanical Engineering

A decision for the DEMO Breeding Blanket (BB) has not yet been finally taken. The BB intentionally has to be replaced at least once during the operational phase of DEMO. For efficiency reasons it shall be operated at an inlet temperature of at least ≈300°C [15]. For improved neutrons shielding it is generally aimed to minimize gaps between the IVCs where larger gaps for better removal are however desired. This could be assisted by a high temperature difference (ΔT) between the VV and the IVCs during operation. In the case the BB is operated at (minimum) 300°C and the VV at 40°C ($\Delta T \geq 260$ K) and assuming both components to be at 20°C during maintenance the relative thermal contraction of the 12 m high BB inside the VV is ≈33 mm. The additionally gained space is especially useful for the installation and removal procedure of the BB modules.

The conditioning of all the vacuum components at increased temperature (see chapter 4.6) must be envisaged. During the baking process the VV does not have to withstand operational loads such as from magnetic fields, disruptions, hence the cumulated forces may be lower. The layout of the cooling system also is expected to be simplified by operating at lower temperatures due to the possibly use of more standard components (pumps, valves, etc.) compared to specialized high pressure and temperature devices.

4.10 Safety aspects

In general in the case of a VV loss of coolant accident (LOCA) the less enthalpy within VV cooling water would be expected to lead to a milder course of the accident. In the event of a station blackout (no electrical energy) a VV at lower temperature will be more effective against the in-vessel components temperature increase due to the decay heat. Both issues could be seen as a small advantage for a lower VV temperature.

Conclusions

The issues investigated predominantly show an advantage of a lower VV operating temperature down to approximately 40°C as summarized in Table 3. A higher temperature is of benefit for the overall plant efficiency: the usage of the energy produced in the VV in the steam cycle could contribute up to 4 %. Therefore an operating temperature of 150°C and above is attractive for future power plants.

Table 3: Compared influence of VV temperature

Issue	40°C	>150°C
Energy efficiency	-	+
Mechanical requirements	+	-
Thermal shielding	+	-
Neutron irradiation	0	0
Adsorption, desorption, baking	+	-
Penetration, permeation	+	-
Diagnostics and control	+	-
Mechanical Engineering	+	-
Safety	+	-

In Table 3 an overview is given of the positive (+) or negative (-) effects of the lowest appropriate and a useful higher temperature.

In the process of bringing ITER into operation and developing DEMO in more detail it is likely that other issues emerge that have to be considered. To rate these

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issues also on financial aspects, what is definitely necessary for a future power plant, more detailed investigations have to be started.

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