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Vertical displacement events: A serious concern in future ITER operation

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ABSTRACT

Material damage to plasma-facing components due to the frequent loss of plasma confinement remains a serious problem for tokamak reactors and in particular for ITER-like design. The deposited plasma energy during major disruptions, edge-localized modes (ELM), and vertical displacement events (VDE) causes significant surface erosion, possible structural failure, and frequent plasma contamination. Surface erosion damage consists of vaporization, spallation, and liquid splatter of metallic materials. Structural damage includes large temperature increases and high thermal stresses in structural materials and at the interfaces between surface coatings and structural components. A comprehensive fully 3D model (contained in the HEIGHTS computer simulation package) is developed to specifically study the longer plasma instabilities that cause VDE. The model includes detail deposition processes, surface vaporization, phase change and melting, heat conduction to coolant channels, and critical heat flux criteria at the coolant channels. The design requirements and implications of plasma-facing components are discussed along with recommendations to mitigate and reduce the effects of plasma instabilities on reactor components.

1. Introduction

Analysis of material erosion and damage from intense energy deposition on target surfaces is important for many applications such as space studies, discharge and laser-produced plasma sources, high-energy physics applications, thermonuclear and inertial fusion studies, etc. An important application of this understanding is in future tokamak fusion devices during plasma interaction with plasma-facing materials (PFM).

Damage to PFM as a result of plasma instabilities remains a major obstacle to a successful tokamak reactor design. Plasma instabilities take various forms, such as major disruptions, which include both thermal and current quench (sometimes producing runaway electrons); edge-localized modes (ELM), and vertical displacement events (VDE). The extent of the damage depends on the detailed physics of the disrupting plasma, the physics of plasma/material interactions, and the design configuration of plasma-facing components (PFC) [1]. Plasma instabilities such as hard disruptions and ELM, because of their short durations, will mainly cause surface damage to PFM. Surface damage includes high erosion losses from vaporization, spallation, and melt-layer erosion. Plasma instabilities with longer duration, such as VDE, and those with deeper deposited energy, such as runaway electrons, can cause serious structural damage due to the high heat flux values to coolant channels and possibly causing burnout of these tubes [2]. Other bulk damage includes large temperature increases in structural materials and at the interfaces between surface coatings and structural materials. These large temperature increases can cause high thermal stresses, possible melting and detachment of surface material, and material fatigue and failure. In addition to these effects, the transport and redeposition of the eroded surface materials to various locations on PFC are a major concern for plasma contamination, safety (dust inventory hazard), and successful and prolonged plasma operation after instability events [3].

The strongly elongated plasma configuration in ITER-like devices ($\kappa \approx 2$) is vertically unstable unless an active control feedback at the vertical position is applied. A malfunction of this feedback system for variety of reasons can lead to a rapid plasma vertical displacement at full plasma current. As the plasma contacts the top or bottom of the vacuum vessel, the current is rapidly forced to zero, similar to the behavior of the plasma after the thermal quench of a disruption. This phenomenon constitutes the VDE. The thermal energy of the plasma is expected to be lost at the contact point. The area of strong wall contact with the plasma will absorb considerable fraction of the total plasma energy and can result in melting and vaporization of the PFC as well as melting of the copper substrate and coolant channel burnout that could be of a serious concern.

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Plasma-facing surfaces are rapidly heated during plasma instabilities by direct impact of energetic plasma particles and radiation. The deposited energy in the bulk material is calculated using models that include the physics of energy loss by plasma ions and electrons in target materials. HEIGHTS package calculates in detail the spatial and time dependence of beam energy deposition in various target materials [1]. The thermal response of the material is calculated by solving a multidimensional (up to 3D) time-dependent heat-conduction equation, with moving boundaries, i.e., the receding eroded surface and the solid-liquid interface, with boundary conditions that include heats of melting and vaporization [2]. All of the calculations presented in this study are 3D time-dependent analysis.

In this study it is shown that vapor flux from the PFC surface can remove significant part of the incident plasma energy and therefore, can protect the copper substrate and coolant channels from overheating. The upgraded HEIGHTS-3D simulation package is used to simulate in full 3D laboratory simulation experiments and the response of an entire ITER module to a VDE. A typical ITER-like VDE will have an incoming energy of 6 kJ/cm^2 deposited in 0.5 s (i.e., VDE power of 120 MW/m^2). The initial temperature distribution of the PFC and the bulk substrate prior to the VDE is calculated according to steady state heat flux, module design, and initial coolant temperature. The models used in the upgraded HEIGHTS-3D were recently benchmarked against VDE simulation experiments using powerful electron beam and have an excellent agreement with the data [4].

2. Effects of longer-duration VDE instabilities

During any intense and fast power deposition (<10 ms) on target materials such as during a disruption or ELM, a vapor cloud from the target debris will form above the bombarded surface. This shielding vapor layer, if well confined, will significantly reduce the net energy flux to the originally exposed target surface to only a few percent of its initial incident value; thereby substantially reducing the net vaporization rate [2]. In this case, most of the incident plasma energy is reradiated to nearby surfaces and components and little energy is conducted away from the surface to the bulk structure. However, VDE (duration 100–500 ms), and runaway electrons (deeper penetration depth), do not produce intense localized vapor cloud capable of stopping the incident plasma particles and re-radiating the plasma energy. Therefore, VDE and runaway electrons, in addition to causing severe surface melting and erosion, can substantially damage the structural materials and coolant channels. Major concern is the higher temperature observed in the structural material, particularly at the interface with the coating materials. Elevated temperatures and high thermal stresses in the structure can seriously degrade the integrity of the interface bonding; this may lead to detachment of the coating from the structural material. This can result in a major downtime, unsafe and uneconomical reactor operation. In ITER-like devices, low-z materials such as beryllium and carbon are preferred for first wall coating/tile design while tungsten is preferred for baffle/dome region since it can withstand higher heat fluxes.

3. Heat transfer processes in structural materials

Heat removal from PFC is achieved through channels with forced flow of sub-cooled liquid, using of heat transfer principle at sub-cooled boiling. At sub-cooled boiling, the bulk liquid temperature in channels can significantly be lower than the saturation temperature. Accordingly, the contribution of single-phase forced convection into heat exchange is considerable. While channel wall temperature is lower than saturation temperature, the heat transfer is determined only by the single-phase forced convective heat exchange. Nucleate boiling processes at channel wall can be possible if the wall temperature exceeds the saturation temperature by some value. In this case vapor bubbles are formed on the internal channel surfaces, rushed into bulk liquid and condensed. As the temperature difference is increased nucleate boiling plays more important part in the heat transport. At this stage bubbles accumulation and condensation rate at the wall surface will increase. As a result thin elongated bubbles and then a denser vapor blanket are formed at the internal wall surface. This makes difficult for the liquid to remove the heat efficiently and therefore, heat sink from wall is decreased rapidly. As a result, the wall temperature is significantly increased [5]. The value of the heat flux at which this situation occurs is known as the critical heat flux (CHF). If the coolant fluid has high mass velocity and the bulk liquid temperature is much lower than the saturation temperature, film boiling will occur where fluid core consist of sub-cooled liquid and isolated from the wall by a thin vapor film. The maximum wall temperature will depend on the heat flux, fluid mass velocity, and pressure. In case of sub-cooled boiling the CHF is high and the heat transfer is dissipated by burning of the channel walls.

4. Mathematical model

The time-dependent heat-conduction equation in 3D Cartesian coordinates is given by:

$$\rho c\frac{\mathrm{D}T}{\mathrm{D}t} = \frac{\partial}{\partial x}\left(\chi(x,y,z,T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\chi(x,y,z,T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\chi(x,y,z,T)\frac{\partial T}{\partial z}\right) + Q(x,y,z,t). \quad (1)$$

In case of PFC surface, the net volumetric energy deposition rate $Q(x,y,z,t)$ depends on the deposited plasma heat energy and the energy loss due to evaporation:

$$Q_{\mathrm{surface}}(x,y,t) = Q_{\mathrm{in}}(x,y,t) - Q_{\mathrm{vapor}}(V_{\mathrm{surface}}), \quad (2)$$

where V_{surface} is the velocity of receding surface as result of the evaporation process. The surface velocity is given by [6,7,9] (we use Gaussian units unless otherwise indicated):

$$V_{\mathrm{surface}}(x,y,t) = 5.8\times 10^{-2}\frac{\alpha\sqrt{A}P_{\mathrm{v}}(T_{\mathrm{v}})}{\rho(T_{\mathrm{v}})\sqrt{T_{\mathrm{v}}}}\left[0.8+0.2\ \exp\left(\frac{-t}{10\tau_c}\right)\right], \quad (3)$$

where α is the sticking probability (usually = 1); A is the atomic mass number of target material; P_{v} is the vapor pressure; τ_{c} is the vapor collision time.

The heat flux in the case of forced convection is determined by

$$q_{\mathrm{conv}} = \alpha_{\mathrm{conv}}(T_{\mathrm{w}} - T_{\mathrm{b}}), \quad (4)$$

where T_{b} is the bulk water temperature in coolant; α_{conv} is the heat transfer coefficient.

Usually turbulent liquid flow is realized to get higher heat transfer coefficient. Therefore, Sieder–Tate [8] equation for fully developed turbulent flow inside smooth round tube was implemented.

The Sieder and Tate correlation for the heat transfer coefficient is given by:

$$\mathrm{Nu} = \frac{\alpha_{\mathrm{conv}}d}{\kappa} = 0.027\ Re^{0.8}Pr^{1/3}\left(\frac{\mu_{\mathrm{b}}}{\mu_{\mathrm{w}}}\right)^{0.14}, \quad (5)$$

where the tubular Reynolds number determined as $\mathrm{Re} = Gd/\mu_{\mathrm{b}}$; Prandtl number is $\mathrm{Pr} = c_{\mathrm{p}}\mu_{\mathrm{b}}/\kappa$; G is the coolant mass velocity; d is the tube diameter; μ_{b} is the bulk water dynamic viscosity; μ_{w} is the

water dynamic viscosity at wall; c_p is the specific heat at constant pressure; κ is the thermal conductivity.

This correlation takes into account the variation in water properties from the bulk temperature to the wall temperature.

The bulk water temperature along tube is determined from the thermal balance equation:

$$T_b(y) = T_{in} + \frac{2\int_0^y q(y)dy}{c_p r G}, \quad (6)$$

where T_{in} is the inlet temperature in coolant; r is the coolant tube radius; y is the distance along tube.

The heat exchange in the case of nucleate boiling is given by

$$q_b = \alpha_b(T_w - T_{sat}). \quad (7)$$

The heat flux to coolant channel in fusion reactor is one-sided. Araki et al. [10] proposed the following correlation for fully developed nucleate boiling regime in case of one-sided heating based on their experiments:

$$T_w - T_{sat} = \frac{25.72 q_b^{1/3}}{\exp(P/8.6)}, \quad (8)$$

where q_b is the heat flux in MW/m^2 and P is the water pressure in MPa.

The heat transfer coefficient from this correlation is then calculated as

$$\alpha_b = \frac{10^6 (T_w - T_{sat})^2 \exp(3P/8.6)}{(25.72)^3}. \quad (9)$$

For regimes when the heat transfer to coolant is determined by forced convection and nucleate boiling at wall surface, Bergles and Rohsenow [11] proposed the following correlation:

$$q = q_{conv}\left[1 + \left\{\frac{q_b}{q_{conv}}\left(1 - \frac{q_{bi}}{q_b}\right)\right\}^2\right]^{1/2}, \quad (10)$$

where q_{bi} is the boiling heat flux at point of incipient boiling.

A correlation for boiling incipience was also proposed by Bergles and Rohsenow. To start the nucleate boiling process wall temperature has to exceed the saturation temperature by a certain value ΔT, and the heat flux q_i to coolant in this case is given by

$$q_i = 1082\, P^{1.156}\left(\frac{T_w - T_{sat}}{0.556}\right)^{2.1598/p^{0.0234}} \quad (11)$$

At the same time this heat flux is equal to that derived from wall to coolant by forced convection. From this equality, using the last Eqs. (11) and (4), it is possible then to calculate wall temperature T_w at boiling incipient point. The boiling heat flux at this point is determined by substituting T_w in Eq. (7).

The above-stated calculation method of heat transfer to coolant channel is only correct if the heat flux does not exceed the CHF value. If, however, the heat flux at certain location of the channel exceeds the critical value, the heat exchange in this place is reduced and must be described by a different formula. Tong [12] proposed the following correlation for the CHF calculation

$$q_{CHF} = 0.23 f_0 G H_{fg}\left(1 + 0.00216\left(\frac{P}{P_c}\right)^{1.8} Re^{0.5} Ja\right), \quad (12)$$

where f_0 is the fanning friction factor, $f_0 = 8\mathrm{Re}^{-0.6}(d_h/d_0)^{0.32}$; Ja is the Jakob number, $\mathrm{Ja} = -\chi(\rho_l/\rho_v)$; χ is the quality of sub-cooled liquid bulk, $\chi = (-c_p(T_{sat} - T_b))/(H_{fg})$; H_{fg} is the latent heat of vaporization of water; P is the water pressure in coolant; P_c is the critical pressure of water, $P_c = 22.089$ MPa; d_h is the hydraulic diameter of coolant channel; d_0 is the reference diameter, $d_0 = 0.0127$ m; ρ_l is the density of liquid bulk; ρ_v is the density of vapor at saturation temperature.

In our developed model the CHF value is determined at each time step. This value is time-dependent and location-dependent along the tube according to the water properties in the coolant channel. If the heat flux to coolant (calculated with correlations for forced convection and nucleate boiling) exceeds the CHF, then the heat flux at this channel location is calculated using Marshall [13] correlation in the following way:

$$q = q_{CHF}\left(\frac{T_w - T_{sat}}{T_{CHF} - T_{sat}}\right)^{-0.23}, \quad (13)$$

where T_{CHF} is the local wall temperature at CHF.

5. Validation and benchmarking

Recent experimental data [14] were used to benchmark HEIGHTS package. Experiments simulated the process of the loss-of-flow accident (LOFA) in coolant channel. In these experiments the circulation pump of the water flow loop was disabled after achieving steady-state condition. This resulted in almost linear decrease in flow velocity to 0 m/s in ~8 s. The mockup was then heated by electron beam with the same intensity. The temperature change is monitored by the thermocouple. When the temperature in the thermocouple achieved 700 °C, the electron beam heating was discontinued. The purpose of these experiments was to determinate the time it takes between start of flow velocity decrease and mockup heating up to the above temperature. It is mockup time-to-burnout (TBO), which characterizes mockup's survivability. In our simulation we took into account the linear velocity decrease that affected both the forced convective heat transfer and the CHF value. At each time step the heat exchange and the CHF were recalculated with the new velocity value, as well as the change in water properties. Fig. 1 shows our HEIGHTS simulation results of the thermocouple temperature rise compared to the experimental data as a result of decreasing flow velocity from 1 m/s to zero in about 8 s.

6. VDE simulation of ITER

Plasma disruptions and ELM will have no significant thermal effect on the structural materials or coolant channels because of their short deposition time. However, VDE with much longer duration time (fraction of a second), or runaway electrons (deeper penetration depth), in addition to causing severe surface melting and erosion, can substantially damage the structural components. Major concern is the higher temperature in the structural material, particularly at the interface with the coating materials. Elevated temperatures will seriously degrade the interface bonding and may cause detachment of the coating from the structural material.

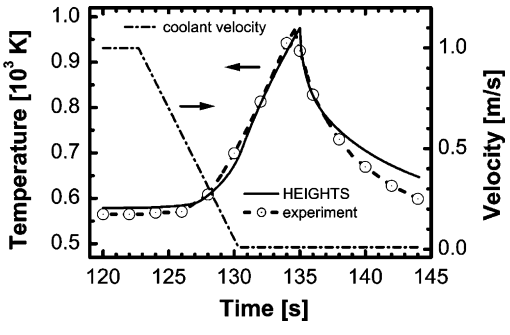

Fig. 1. HEIGHTS modeling of LOFA and comparison with experimental data.

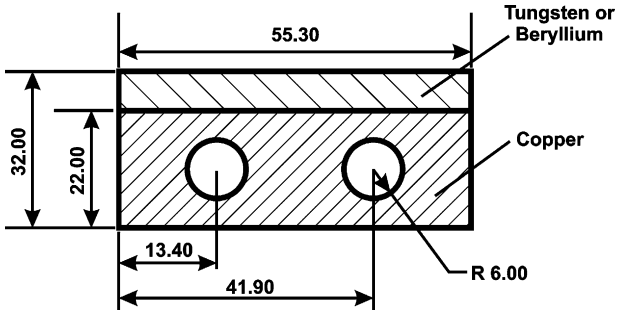

Fig. 2. Schematic illustration of ITER-like divertor module.

A typical design of ITER-like plasma-facing and structural materials is schematically shown in Fig. 2. The structural material is copper coated by tungsten or beryllium with water being the coolant. Fig. 2 also shows the actual design dimensions and parameters for an ITER-like module that will be exposed to a VDE. A typical plasma energy density of 60 MJ/m^2 is deposited over 0.5 s was considered in this analysis. The pressure in the 1.5 m length coolant channel was constant 3.6 MPa. The water flow velocity and water temperature at inlet were varied.

The surface temperature of the copper-structure during a VDE was calculated for different surface coated materials of tungsten and beryllium. As an example, Fig. 3 shows the surface temperature of a 5-mm-thick copper substrate at its interface with 5- and 10-mm-thick tungsten and beryllium coatings during a typical VDE delivering to the surface about 60 MJ m^{-2} in 500 ms. The water flow velocity is assumed 20 m/s and the water inlet temperature is 413 K. For reactor conditions, the tile thickness is determined by the surface temperature limitations during normal operation. With a tungsten coating, the copper surface interface can actually melt during VDE. For the given conditions, only beryllium coatings of reasonable thickness (about 5–10 mm) can withstand the acceptable temperature rise in the copper structure, because most of the incident plasma energy is removed by beryllium's higher surface vaporization rate, which leaves less energy to be conducted through the structural material. Therefore, low-z materials such as beryllium and carbon coatings will suffer significant surface erosion while protecting the structural copper substrate.

Figs. 4 and 5 show the time dependence of the maximum heat flux to the coolant and the wall temperature at the maximum flux location, respectively. Initially the wall temperature is lower than the water temperature in coolant and the water flow heats up the copper wall (negative values in Fig. 4). In the case of 5 and 10 mm W coatings and 5 mm Be coating, the heat flux to the coolant reaches the critical value. In case of 5 mm tungsten coating the fast propagating heat flux area causes burnout of the copper coolant channel

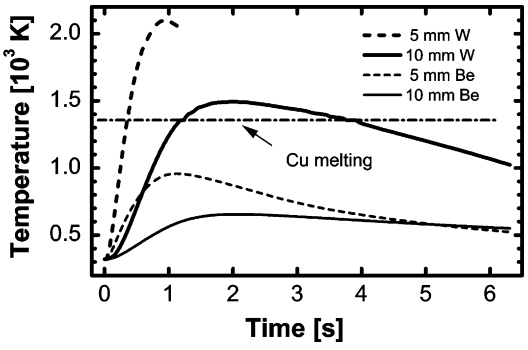

Fig. 3. Copper surface temperature under 5 or 10 mm coating of W or Be.

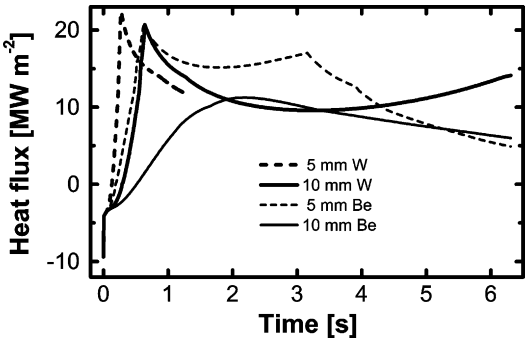

Fig. 4. Heat flux to coolant tube in mockups with 5 or 10 mm coating of W or Be.

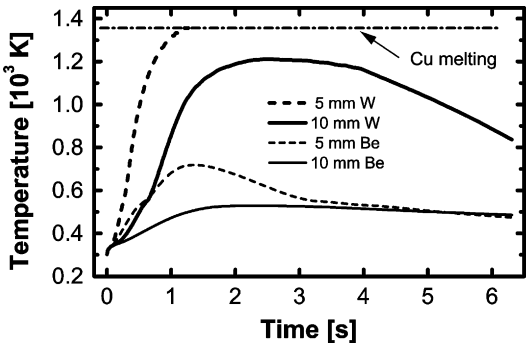

Fig. 5. Coolant wall temperature in mockups with 5 or 10 mm coating of W or Be.

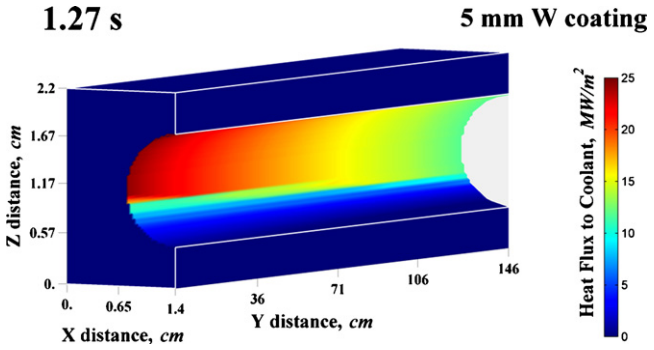

Fig. 6. Heat flux to coolant along channel for mockup with 5 mm W coating.

in ~1–1.5 s. This time depends on the coolant system parameters such as the mass velocity, inlet sub-cooling, and the pressure in the coolant, which influences the occurrence of the critical flux.

Figs. 6 and 7 show the heat flux to the coolant along the channel for 5 mm W and 10 mm Be coatings, respectively. In the case of 5 mm

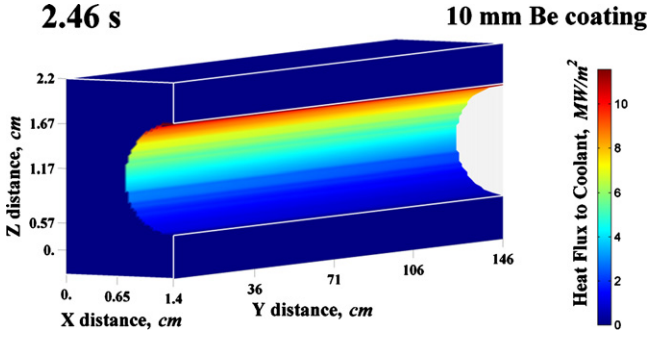

Fig. 7. Heat flux to coolant along channel for mockup with 10 mm Be coating.

W coating, the high heat flux to coolant channel generates dense vapor blanket near the wall. This reduces heat sink to water and leads to a rapid increase in wall temperature. The CHF value at the channel outlet is lower than at the inlet since sub-cooling and the pressure are less. Therefore, heat sink to coolant is decreased and wall temperature is increased more rapidly. Higher temperature is spread around the tube. These processes result in rapid destruction of channel walls at the outlet.

The 10-mm Be coating protects the copper block from plasma energy deposition and prevents the occurrence of the critical heat flux condition at channel walls. The heat transfer to coolant is mainly determined by the forced convection and nucleate boiling of sub-cooled water at the wall surface.

7. Conclusion

We have developed full three-dimensional models that simulate plasma-facing materials thermal response during plasma instability events in fusion reactors. The models include detail plasma energy deposition on plasma-facing materials, thermal conduction processes, coating and structural material phase changes, coating materials evaporation, and thermal hydraulics of coolant tubes. The models also consider the heat exchange between PFC and coolant for smooth channel and sub-cooled water. Processes of heat transfer to coolant as results of forced convection and sub-cooled boiling were also modeled. Time and spatial dependence of changes in water properties are taken into account when heat transfer coefficient and critical heat flux are calculated.

HEIGHTS package was benchmarked for a set of regimes with various incident heat flux, water flow velocity, and water inlet temperature and showed excellent agreement with experimental data in steady-state conditions as well as in high power plasma transient cases.

Thermal response of ITER-like design modules to plasma vertical displacement event was studied in detail. Results of plasma energy deposition transient of 60 MJ/m^2 over 0.5 s indicate that if copper block covered by 5 or 10 mm tungsten or 5 mm beryllium heat flux to coolant achieves the critical value. The high heat fluxes in case of tungsten coating lead to coolant channel burnout in ~1–1.5 s after the start of VDE. Thicker Be or C coating or using liquid lithium surface will protect the coolant channels against VDE.

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