Failure analysis of leaks due to cracks in hydrogen transfer lines of ESS cryogenic moderator

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Abstract. The ESS cryogenic Moderator System (CMS) has been designed to slow down the high-energy neutrons by means of two hydrogen moderators (to be increased to four in the future) by using forced flow of subcooled liquid hydrogen with a temperature of 17 K at 1.0 MPa. A liquid hydrogen leak is considered the most severe failure for the CMS. A leak scenario from the transfer line to its vacuum envelope through a crack have been analyzed and the expected results will be presented in this paper. An analysis code has been developed and calculated the pressure and temperature changes in the CMS process line and its vacuum envelope. The effect of the crack sizes is clarified. The consequential temperature changes along the vacuum envelope as well as the pressure drops were calculated. The required size of the safety relief device in the hydrogen transfer line and its vacuum envelope have thereby been determined and implemented.

1. Introduction

The European Spallation Source ERIC (ESS) will provide long-pulsed cold and thermal neutron fluxes at very high brightness to the research community. In the beginning, the ESS will install two hydrogen moderators above the target wheel and the current plan is to replace them with four (two above and two below, respectively) in the future. Two flat butterfly shaped hydrogen moderator vessels have been designed and optimized to achieve a maximum neutron brightness under the condition of parahydrogen fraction higher than 99.5% [2]. A cryogenic moderator system (CMS) has been designed to continuously supply subcooled liquid hydrogen with a temperature of 17 K and a parahydrogen fraction of more than 99.5% to the moderators and to maintain an average temperature rise at the moderators within 3 K [3]. Figure 1 shows an overview of the ESS CMS where the design pressure is 1.7 MPa and the nominal operational pressure is 1.0 MPa. The CMS cold box consists of two centrifugal pumps in series, a pressure control buffer (PCB) with a volume of 0.065 m³, an ortho-parahydrogen convertor with a catalyst bed of 0.035 m³, and two kinds of heat exchangers. The liquid hydrogen is transferred to a distribution box (DB) via a main transfer line (HTL) and split into each moderator transfer line (DTL). An online ortho- and parahydrogen fraction measurement system (OPMS) where a Raman spectroscopy will be used is placed in a bypass line in the distribution box [4]. There are five separate vacuum spaces: the CMS cold box, the main transfer lines, the distribution box and distributed transfer lines, the OPMS and the moderators. The overall liquid hydrogen inventory is 0.344 m³. The CMS is cooled by a helium refrigeration plant, which is called the Target Moderator Cryoplant (TMCP) [5]. All the relief devices and active control release valves are connected to a hydrogen vent line (HVL).
with a total length of 36 m. The HVL maintains a helium atmosphere with positive pressure by a check valve with a cracking pressure of 3.7 kPa [6].

In this study, a liquid hydrogen leak from the HTL to its vacuum envelope is considered as the most severe failure event. A safety relief device will discharge the hydrogen to the atmosphere without exceeding the design pressures. An analysis code that estimates the pressure changes caused by hydrogen leakage was developed. The pressure rise behaviors were analyzed and the consequential temperature changes along the vacuum envelope as well as the pressure drop were calculated. The required size for the safety device in the vacuum envelope were determined based on the analysis results.

2. Development of a pressure rise simulation
The vacuum loss caused by the hydrogen leak results in applying a huge heat load to the process line. When the process pressure reaches 1.43 MPa, the hydrogen is released from the safety relief valve (PRV) (SV-62009, SV-82093, SV-82094 or SV-82099). Subsequently, the leaked hydrogen flows through the HTL vacuum envelope to the both ends where the vacuum safety relief devices (VSDs) (SV-85010 and SV-85020) are located. The hydrogen from SV-85020 is released to the atmosphere on the roof top through the main hydrogen vent line (MHVL), while that from SV-85010 goes through the sub hydrogen vent line (SVHL) and the MHVL as shown in figure 1. In this study, the failure analysis was implemented using the following three kinds of simulations.

(1) A pressure rise analysis in the process and vacuum envelope caused by liquid hydrogen leak through a crack, which is developed in this paper.
(2) Transient temperature and pressure rise along the HTL vacuum envelope are analyzed using a modified version of the one-dimensional transient thermal transport code for the HVL analysis developed by Tatsumoto et al. [6].
(3) Transient temperature and pressure rise along the HVL are analyzed, where the one-dimensional code developed by Tatsumoto et al. [6] is used.

2.1. Pressure rise analysis in the process line and vacuum envelope

2.1.1 Analytical model. The HTLs have a coaxial pipe structure with a length of 37.6 m. The outer diameter of the process line is 60.3 mm and its thickness is 2.0 mm. The HTL vacuum envelope has an outer diameter of 139.7 mm and a thickness of 2.0 mm. The vacuum envelopes of the supply and return HTL are connected at both ends to form one overall vacuum space, whose volume is 0.823 m³, and are
physically isolated from the CMS cold box and the DB. Figure 2 shows an analysis model that estimates pressure changes caused by a hydrogen leaked to the vacuum envelope through a crack. The whole process volume is divided into two sections: liquid phase (0.344 m$^3$) and gaseous phase (0.05 m$^3$), which corresponds to the volume of gaseous phase in the PCB tank. Various crack sizes are considered.

The flow diameter of the PRV (SV-62009) was selected to be 12.76 mm at a set pressure of 1.43 MPa according to EN ISO 21013-3:2006. The required discharge mass flow rate through the VSDs (SV-85010 and SV-85020) is estimated by this simulation to avoid exceeding the design pressure of 0.15 MPa. The required size of the VSDs is determined based on this analysis result.

As a maximum crack size, half the cross-sectional area of the process pipe (0.00141 m$^2$) is postulated in this analysis. A rhombic shape crack with the length of 188.5 mm, which corresponds to a perimeter of the pipe, is applied as shown in figure 2. The width is calculated to be 15 mm for the postulated area. The hydraulic diameter, $d_H$, is 15 mm.

![Figure 2. Analytical model for the pressure rise analysis.](image)

2.1.2. Equations. The leaked flow rate through the crack is calculated by the equation of an orifice flow meter.

$$\dot{m} = \frac{C_d}{\sqrt{1 - \beta^4}} \varepsilon \frac{\pi d_H}{4} \sqrt{2\Delta P \rho}$$  \hspace{1cm} (1)

where $\dot{m}$ is the mass flow rate, $\rho$ is the fluid density, $C_d$ is the coefficient of discharge, $\beta$ is the diameter ratio of orifice diameter to pipe diameter, $d_H$ is the hydraulic diameter which corresponds to the orifice diameter and $\Delta P$ is the differential pressure. The subscript of 1 denotes the upstream part.

Released flow rate via the PRV is calculated according to EN ISO 21013-3 design code guideline.

$$\dot{m} = 8.008 \times 10^{-5} C_{d_{dr}} A_{\nu} \sqrt{P \rho_1}$$  \hspace{1cm} (2)

$$C = 3.948 \sqrt{\frac{\gamma \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{\gamma - 1}}}{\gamma}}$$  \hspace{1cm} (3)

where $K_{d_{dr}}$ is the discharge coefficient, $A_{\nu}$ is the actual orifice area and $\gamma$ is the heat capacity ratio.

Natural convection heat transfer on the horizontal pipe is calculated by the following correlation [7].

$$Nu = 0.53(Gr Pr)^{0.25}$$  \hspace{1cm} (4)

where $Nu$ is the Nusselt number from isothermal surface of a long horizontal cylinder, $Gr$ is the Grashof number, $Pr$ is the Prandtl numbers.
2.1.3. Numerical procedure. Initially, the liquid hydrogen in the process line is set at an average liquid temperature of 19 K and the operational pressure of 1.0 MPa. The temperature in the gaseous phase is set to 40 K. The pressure of the vacuum envelope is set to 10⁻⁵ Pa.

The leaked liquid hydrogen would expand uniformly across the entire vacuum space in isenthalpic process. The leaked flow rate of liquid hydrogen is calculated using eq. (1). Lehmann et al [8] reported that a transient heat flux for loss of insulation vacuum for LHe cryostat and LHe containers with MLI was 6 kW/m². In this analysis, the heat flux of 6 kW/m² is always applied to the process line, regardless of the vacuum pressure. All the heat load by the vacuum loss is applied to the liquid phase in the subcooled condition and is consumed in the temperature rise of it up to its saturated temperature. At saturated condition, the heat load is consumed in the vaporization. If the process pressure exceeds the PSV set pressure of 1.43 MPa, which is higher than its critical pressure of 1.28 MPa, supercritical hydrogen is released via the PSV at the flow rate calculated by equations (2) and (3). If the pressure increases to the critical pressure, the hydrogen in the process line is treated as a single phase. Averaged enthalpies and densities are obtained by a mass balance and energy balance. The temperature and the pressure are given by GASPAK [9] using the density and enthalpy as a parameter.

On the other hand, the leaked liquid hydrogen is evaporated on the vacuum envelope where film boiling is dominating. The film boiling heat flux of 1 × 10⁵ W/m² [10] is applied in this analysis. The natural convection heat transfer between the vacuum envelope and surrounding air maintained at 300 K is calculated by eq. (4). Once the vacuum pressure increases to 0.15 MPa, which is the design pressure of the vacuum envelope, the hydrogen is released maintaining the vacuum pressure at 0.15 MPa and hydrogen is released in this analysis. Averaged enthalpy is calculated by the energy balance at the pressure of 0.15 MPa. The average temperature and densities are given by GASPAK using the pressure of 0.15 MPa and the average enthalpy. The released flow rate is calculated by the mass balance.

This calculation explicitly repeats with 1 ms time steps until the process hydrogen temperature increases up to 45 K, where 90% of hydrogen has been released.

2.2. Transient forced flow heat transport of the leaked hydrogen along the HTL vacuum envelope
In order to analyze the transient phenomenon of the HVL during the release of liquid hydrogen, Tatsumoto et al. [6] have developed a one-dimensional transient thermohydraulic simulation code, where an enthalpy equation is solved considering not only single-phase flow but also two-phase flow with forced flow heat transfer. The simulation code can be also applied to this transient process analysis along the HTL vacuum envelope by modifying the dimensional parameters and the boundary conditions.

The vacuum envelopes of the HTLs with a total length of 37.6 m are routed from the CMS cold box in the hydrogen room to the DB in the A2T access room. MLI with a thickness of 8.3 mm is wrapped on the process pipe. In this analysis, the crack part is postulated at the middle of the HTL. The cold hydrogen would travel to both end of the HTL vacuum envelope and be released from the VSDs. Therefore, the cold hydrogen with half release flow rate given in the analysis described in 2.1 flows through half the length of the HTL vacuum envelope (L = 19 m).

The details of the analysis procedures have been described in [6]. The heat transfer and pressure drop of the two-phase forced flow [11] are considered. Single-phase forced flow heat transfer is calculated by the Dittus-Boelter equation [12]. The natural convection heat transfer from ambient air is considered by using equation (4), where the properties of nitrogen are used instead of air. The effect of the condensation of moisture in air is ignored.

The length of the HTL vacuum envelope is divided into 76 grids and the volume of a grid is 2.45×10⁻³ m³. An enthalpy equation is solved by the finite volume method. The convection term is discretized by applying a central differencing scheme. Time integration is explicitly performed with a time step of 50 ms. The fluid properties are calculated using GASPAK [9]. The stainless-steel properties are given as polynomial functions of temperature, which are provided by NIST [13] within an error of 1.0%. An initial temperature of the vacuum envelope is set at 300 K. The inlet temperature is set to saturated temperature at 0.1 MPa due to the isenthalpic expansion process. Half release flow rate given in the analysis described in 2.1 is applied to the inlet.
The pressure drop through the VSDs (SV-85010 and SV-85020) is calculated by a convergent nozzle model. The VSD with the diameter of 100 mm is selected.

\[
\dot{m} = A \sqrt{\frac{2y}{y-1} \rho_1 P_1 \left(\left(\frac{P_2}{P_1}\right)^\frac{y}{y-1} - \left(\frac{P_2}{P_1}\right)^\frac{y+1}{y-1}\right)}
\]

(5)

The subscripts, 1 and 2, donate vacuum space and backpressure region.

2.3. Released hydrogen flow through the hydrogen vent line

The leaked hydrogen is released from the two VSDs at both ends. As shown in Figure 3, the released hydrogen from the SV-85020 close to the DB goes through the main HVL with an outer diameter of 168.3 mm and a thickness of 3.0 mm, meanwhile that from the SV-85010 above the CMS cold box is merged to the MHVL through the SHVL with the length of 6.5 m and the thickness of 7.0 mm.

The initial temperature and pressure are set to 300 K and 0.1 MPa over the entire HVL. The released flow rate, \(\dot{m}/2\), and the temperature at the VSD, which are given by the second analysis described in 2.2, are applied as the inlet condition. Downstream of the merging point (at \(x = 31\) m), the cold hydrogen passes through the HVL at the flow rate of \(\dot{m}\).

The volume of a grid is \(2.56 \times 10^{-3} m^3\). The MHVL and SHVL are divided into 288 and 52 grids, respectively. An enthalpy equation is solved by the finite volume method. The convection term is discretized by applying a central differencing scheme. Time integration is explicitly performed with a time step of 50 ms. The details of the analysis procedures have been described in [6].

3. Results and discussion

Figure 4 shows the analysis result for the postulated maximum crack size. The process pressure rapidly decreases and is 0.66 MPa when the vacuum pressure increases to 0.15 MPa at \(t = 2.5\) s. The flow rate of the leaked liquid hydrogen does not match that of the released hydrogen. This is because a part of the leaked hydrogen is consumed in the vacuum envelope pressure rise. The liquid hydrogen temperature rises due to the vacuum loss and reaches the saturated temperature at \(t = 15\) s. The liquid temperature is decreased with decrease in the pressure, because it is under saturated condition. The VSD opens at \(t = 2.5\) s and the released flow rate of the cold hydrogen is 0.4 kg/s. The maximum flow rate of 0.7 kg/s appears around \(t = 10\) s. For such a large crack, the PSV doesn’t work and most of the hydrogen is released from the VSD within 40 s.

Figure 5 shows the effect of the crack size, \(d_H\), on the peak release hydrogen flow rate from the VSD and the PSV. For higher \(d_H\), all the hydrogen is released from the VSD and the peak release flow rate decreases with decreasing in \(d_H\). For \(d_H < 8\) mm, the liquid hydrogen is mainly released from the PSV and the maximum flow rate is 0.43 kg/s and is smaller than that via the VSD for \(d_H = 15\) mm.
Figure 6 shows the transient hydrogen temperature profiles along the HTL vacuum envelope where the released flow rate shown in figure 4 (b) is applied as the inlet flow condition. Figure 7 shows the wall temperature profile of the vacuum envelope for each time step. In these graphs, $t = 0$ means when the VSD is activated. The two-phase region spreads to 7.5 m away from the crack at $t = 40$ s and the hydrogen temperature drops down to 91 K at the location of the VSD. The wall temperature reduction gets smaller after $t = 10$ s, because the peak release flow rate appears at around $t = 7.5$ s. The lowest wall temperature is 60 K at the crack location and the wall temperature at the location of the VSD decreased down to 176 K at $t = 40$ s. The layout of the HTL vacuum envelope has been designed under the condition of thermal stress between 300 K and 80 K, based on this analysis result.

Figure 8 shows the effect of the size of the VSD on the pressure drop via the VSD, $\Delta P_{VSD}$, which is calculated by equation (5) at the maximum release flow rate of 0.35 kg/s where the hydrogen temperature at the VSD, $T_{VSD}$, is 170 K. The pressure drop, $\Delta P_{VSD}$, remarkably gets much higher for VSD diameters lower than 100 mm. Based on

![Figure 4. Analytical results for the postulated maximum crack ($d_H = 15$ mm).](image1)

![Figure 5. Effect of the crack size on the release hydrogen flow rate.](image2)

![Figure 6. Hydrogen temperature distributions along the HTL vacuum envelope.](image3)

![Figure 7. HTL vacuum envelope temperature distributions.](image4)
the analytical result, the diameter of the VSD is determined to be 100 mm where the pressure drop is 3.8 kPa at 350 g/s. Figure 9 shows the time variations in the pressure drops of the vacuum envelope, $\Delta P_{VE}$, and the VSD, $\Delta P_{VSD}$. The peak pressure drop, $\Delta P_{VE}$, is 15.4 kPa at around $t = 11$ s for a short duration of 5 s. The sum of $\Delta P_{VE}$ and $\Delta P_{VSD}$ is 19.2 kPa. Therefore, the set pressure of the VSD should be set to 0.13 MPa in order to maintain the vacuum envelope pressure below the design pressure.

The released hydrogen from SV-85010 on the CMS cold box through the SHVL is mixed with that from SV-85020 on the DB through the MHVL at the merging point ($x = 31$ m). The pressure drops through the two different ways ($\Delta P_{VE} + \Delta P_{VSD} + \Delta P_{MHVL}$ and $\Delta P_{VE} + \Delta P_{VSD} + \Delta P_{SHVL}$) should be equal at $x = 31$ m. The ratios of the flow rate of the distributed flow rate toward SV-85010 and SV-85020 through the vacuum envelope are correctly estimated to be 50.6% and 49.4%, respectively. It can be considered that the postulated half flow rate used in this analysis would be reasonable.

Figure 10 shows the temperature distributions along the MHVL for each time step which are calculated using the released flow rate and the hydrogen temperature at the VSD, $T_{VRD}$, shown in figure 9 as the inlet conditions. There are large temperature drops at the merging point, because the hydrogen coming from the CMS cold box is colder. There is a guide pipe at the roof penetration to prevent the building wall from direct contact with the cooled HVL. The wall temperature at the penetration drops down to 234 K. However, it is much higher than the lowest allowable temperature of 175 K where the guide pipe temperature can be maintained above 253 K [6].

**Figure 8.** Effect of the VSD size on the pressure drops, $\Delta P_{VSD}$.

**Figure 9.** Time variations in the pressure drops for the leak at postulated maximum crack size.

**Figure 10.** Temperature distributions through the HVL.

(a) Released hydrogen temperature  
(b) HVL wall temperature
The pressure drop through the HVL, \( \Delta P_{HVL} \), is also shown in figure 9. The pressure drop, \( \Delta P_{HVL} \), increases up to 5.8 kPa when the release flow is at 0.35 kg/s and, after \( t = 8 \) s, it decreases down to 1.2 kPa. The HVL size is sufficient to limit the backpressure below the design pressure. It turns out that, for the hydrogen leak failure on the HTL, the maximum total pressure drop, \( \Delta P_{TE} + \Delta P_{VSD} + \Delta P_{HVL} \), is no more than 24 kPa for a few seconds and the leaked hydrogen can be released to the atmosphere without exceeding the design pressure of not only the HTL vacuum envelope but also the HVL.

4. Conclusions

As the most severe failure event for the ESS CMS, a liquid hydrogen leak to the HTL vacuum envelope was considered. A pressure rise analysis code has been developed and simulated the behaviors of the process line and vacuum envelope. The transient process calculations through the HTL vacuum envelope and the HVL were calculated using release flow rate given by the pressure rise analysis. The one-dimensional simulation code has been already developed by Tatsumoto et al. [6]. For the crack size, \( d_H \), larger than 8 mm, all the hydrogen is released via the VSD. It turns out that the HVL wall temperature should be kept above the lowest allowable value of 175 K at the roof penetration.

The required VSD cross sectional diameter was determined to be 100 mm based on the analysis result. The total pressure drop was lower than the design pressure for the postulated crack size. The analysis made it clear that the cold hydrogen could be released safely even if the severe failure happened.

5. References

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