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# Commissioning of the cryogenic safety test facility PICARD

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**Abstract.** The sizing of cryogenic safety relief devices requires detailed knowledge on the evolution of the pressure increase in cryostats following hazardous incidents such as the venting of the insulating vacuum with atmospheric air. Based on typical design and operating conditions in liquid helium cryostats, the new test facility PICARD, which stands for **P**ressure **I**ncrease in **C**ryostats and **A**nalysis of **R**elief **D**eVICES, has been constructed. The vacuum-insulated test stand has a cryogenic liquid volume of 100 liters and a nominal design pressure of 16 bar(g). This allows a broad range of experimental conditions with cryogenic fluids. In case of helium, mass flow rates through safety valves and rupture disks up to about 4 kg/s can be measured. Beside flow rate measurements under various conditions (venting diameter, insulation, working fluid, liquid level, set pressure), the test stand will be used for studies on the impact of two-phase flow and for the measurement of flow coefficients of safety devices at low temperature. This paper describes the operating range, layout and instrumentation of the test stand and presents the status of the commissioning phase.

**Keywords:** Cryogenics, liquid helium, safety, test setup, heat flux, relief flow rate

## 1. Introduction

The dimensioning of cryogenic safety relief devices requires detailed knowledge on the evolution of the pressure increase in cryostats following hazardous incidents such as the venting of the insulating vacuum with atmospheric air. However, the process dynamics are often not considered in the established design codes. Rather, the codes are based on constant (maximum) heat flux data, yielding safe but potentially oversized dimensions of safety devices. General design steps are the following:

- (i) Determination of the maximum heat flux to the cryogenic fluid from experimental data, e.g. for helium (He) found in
  - Lehmann and Zahn [1]: heat transfer to He I, with and without multi-layer insulation (MLI), venting of the insulating vacuum with air,
  - Harrison [2]: heat transfer to He II, with and without composite insulation, venting of the insulating vacuum with air,
  - Bosque et al. [3]: heat transfer to He II, without MLI, venting of the insulating vacuum with gaseous nitrogen.



- (ii) Determination of the resulting discharge mass flow rate, e.g. from models based on
  - Varghese and Zhang [4]: Calculation of the maximum discharge mass flow rate from the maximum heat flux<sup>1</sup>,
  - Chorowski et al. [6]: Calculation of the time-dependent discharge mass flow rate from the maximum heat flux<sup>2</sup>.
- (iii) Determination of the required discharge diameter of the safety relief device, e.g. based on DIN EN ISO 4126 [8], API 520-1 [9] or AD-2000 [10][11].

The analytic approach presented in [12] is based on theoretical considerations and differential equation modeling and includes a time-dependent heat flux caused by desublimating air<sup>3</sup>. By consideration of the process dynamics between step (i) and (ii), a reduction of the required diameter of safety relief devices is possible. Besides savings in both spending and space, a smaller diameter also reduces gas leakage through safety relief devices, which especially in liquid helium cryostats contributes significantly to the overall leakage.

The model [12] contains some simplifying assumptions concerning the kinetics of desublimation, heat transfer and thermal equilibrium in the inner vessel. Therefore, the new test facility PICARD, which stands for **P**ressure **I**ncrease in **C**ryostats and **A**nalysis of **R**elief **D**evelopments, has been constructed. This paper discusses the aims and possibilities of measurements at PICARD, presents the design and construction of the experimental setup and instrumentation before giving an overview on the status of the commissioning and an outlook on the R&D collaboration between KIT and CERN.

## 2. Purpose and Operating Range

With a cryogenic liquid volume of 100 liters and a nominal design pressure of  $p_N = 16$  bar(g), the cryogenic test facility PICARD allows a broad range of experiments. In order to complement the existing data on the processes following hazardous incidents, detailed flow rate and heat flux measurements under various conditions will be conducted. In the course of the experiments, the impact of the venting diameter, the insulation, the liquid level and the set pressure on the heat flux and hence on the process dynamics will be investigated. The results will be

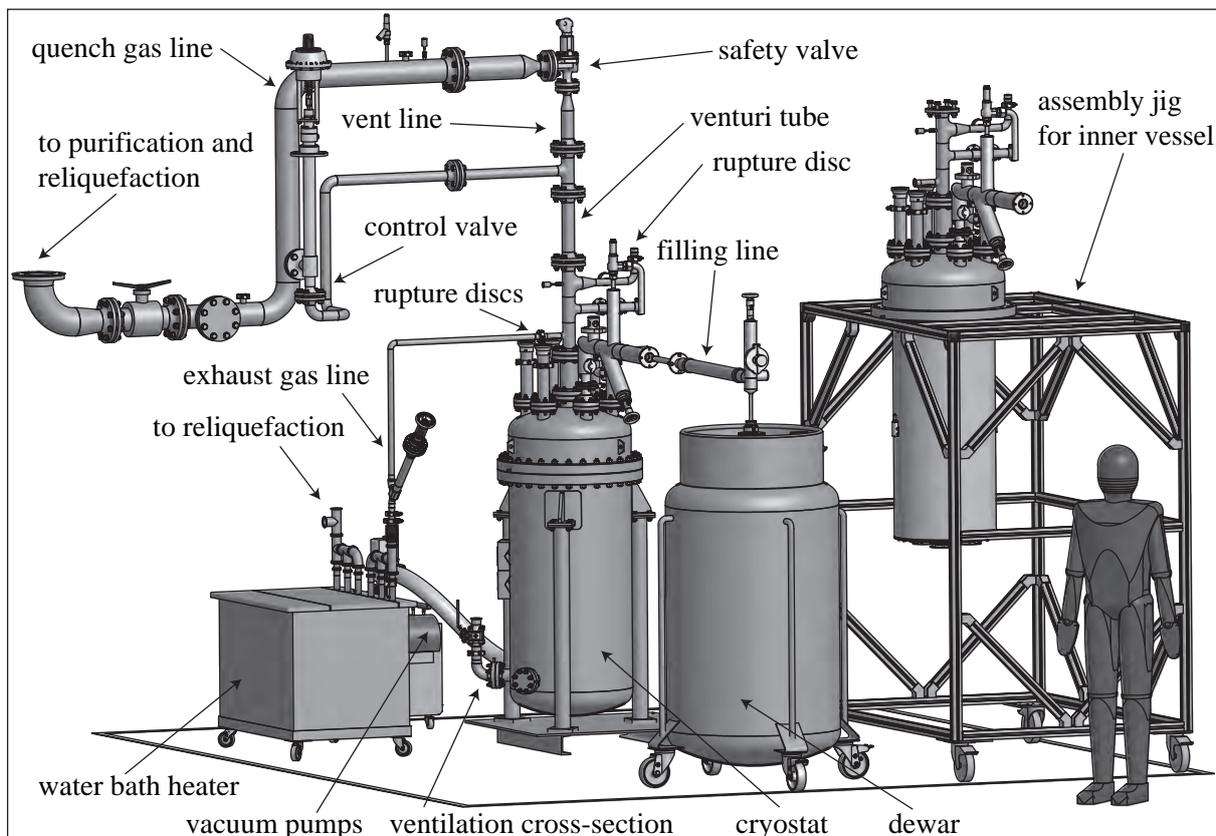
<sup>1</sup> This model is used in DIN EN 13648 [5].

<sup>2</sup> This model was used for the dimensioning of the safety relief devices at the KATRIN experiment [7].

<sup>3</sup> This model is used in DIN SPEC 4683 [13].

**Table 1.** Scope of the planned experiments at the PICARD test facility.

Parameter	Range
Venting diameter	1 . . . 40 mm
Insulation	0 . . . 30 layers of superinsulation, with/without radiation shield
Liquid level	20 . . . 80 %
Set relief pressure	2 . . . 12 bar(g)
Cryogenic fluid	Helium, nitrogen, neon, argon
Venting fluid	Air, nitrogen
Safety relief device	Safety valve, rupture disk, control valve
Heating	With/without simulating the quench of a superconducting magnet
Relief mass flow	Single-phase, two-phase
Discharge coefficient	Of different safety relief devices at 4 . . . 300 K



**Figure 1.** Overview of the PICARD test facility.

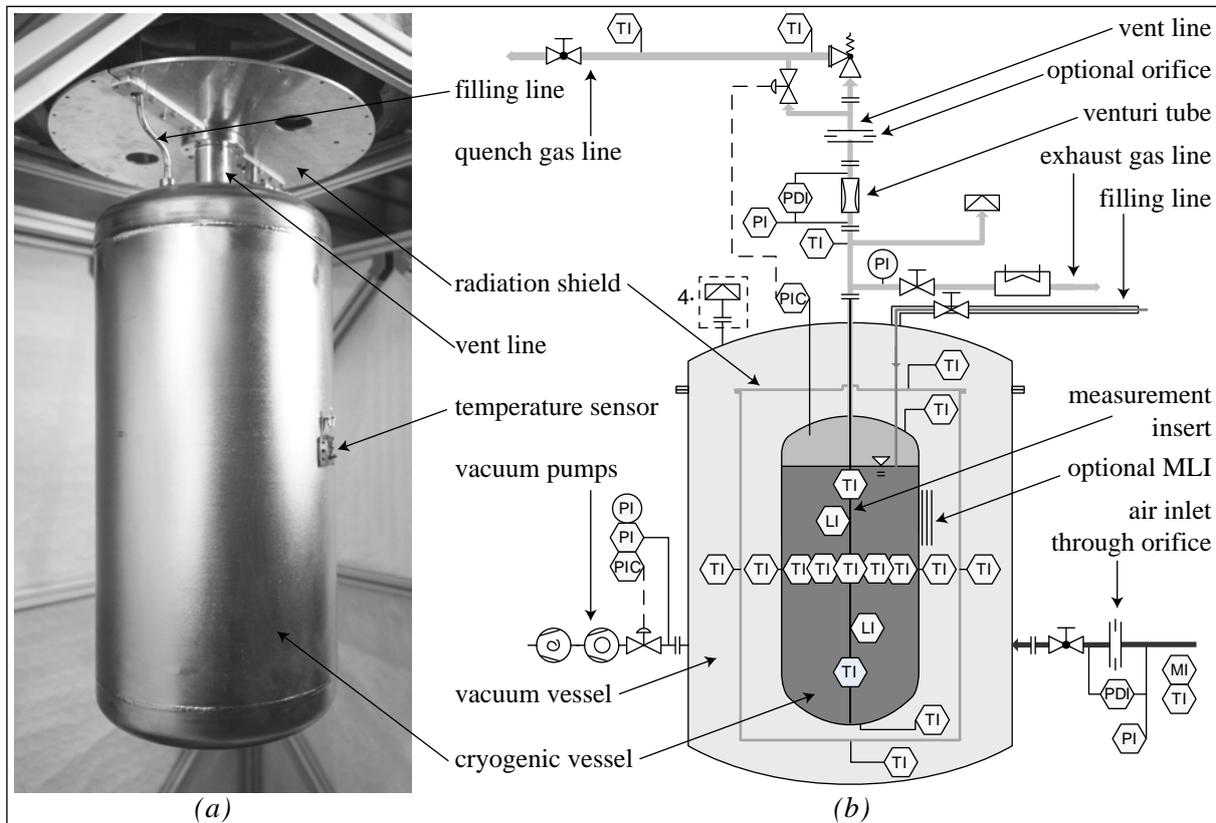
implemented in the form of fit parameters in the analytic model [12]. Experiments with different working fluids such as helium and nitrogen as well as with the venting fluids air and gaseous nitrogen will complement the data set. Specifically, a detailed investigation on the occurrence and effects of two-phase flow during helium discharge will be conducted. Furthermore, the discharge coefficients of safety relief devices in a temperature range between  $T = 4 \dots 300$  K and with relief pressures between  $p = 2 \dots 12$  bar(g) will be investigated. In case of helium, mass flow rates through safety valves and rupture disks up to about 4 kg/s can be measured. Additionally, the blow-off at constant pressure through a control valve shall be studied as an alternative to the established safety valves, where the pressure fluctuates because of constant relief cross sections. The scope of the planned experiments is summarized in table 1.

### 3. Design and Construction

#### 3.1. Experimental Setup

Figure 1 shows a CAD drawing of the PICARD test setup with its main components: the cryostat, the piping, the dewar and the assembly jig. From the dewar, cryogenic liquid is transferred through a filling line into the inner vessel of the cryostat. A picture of the inner vessel is shown in figure 2(a). The dimensions of the cryostat are given in table 2.

During the filling process, the evaporating cryogenic fluid cools down the inner vessel and the exhaust gas line. In order to avoid air condensation, the exhaust gas is heated up in a water bath heater. When the required liquid level in the inner vessel of the cryostat is reached, the filling line is disconnected manually.



**Figure 2.** (a) Picture of the PICARD inner vessel mounted on the assembly jig and connected to the radiation shield and to the lid of the vacuum vessel by the vent line. (b) P&ID of the PICARD experiment that is equipped with 18 TVO temperature sensors (TI), three fast pressure transducers (PI) where one is connected to the control valve (PIC), two vacuum pressure transducers (PI) where one controls the closure of the vacuum valve in order to protect the turbo pump from pressure surge when venting the insulating vacuum (PIC), two manometers (PI), two fast differential pressure transducers (PDI) for mass flow measurements, two liquid level probes (LI), and one combined temperature-humidity probe (TI with MI). The instrument symbols in circles indicate a display on site, those in combs specify that the sensors are connected to a computer where the data is recorded and processed with the Labview<sup>TM</sup> software [14].

Different measures have been taken to prevent fast evaporation of the cryogenic fluid inside the cryostat due to unwanted heat inleak caused by convection, conduction and radiation. The vacuum pumping station is flanged to one side of the vacuum vessel and provides an insulating vacuum of  $p = 10^{-6}$  mbar. The inner and outer surfaces of the cryogenic vessel have been electropolished. An additional radiation shield made of aluminum is cooled by thermal conduction through contact with the vent line. Depending on the type of experiment, either the radiation shield or the MLI can be attached to the inner vessel at the assembly jig.

During the experiments, the cryogenic fluid is released through a safety valve. The set pressure is at least 20 % below the nominal design pressure of 16 bar(g), considering the tolerances of the rupture disk and the safety valve. The escaping cryogenic fluid is conducted through a quench gas line to be collected in the helium facilities of the Institute for Technical Physics (ITEP). The ultimate safety device of the pressurised volume is a rupture disk with a burst pressure of  $p = 16$  bar(g).

**Table 2.** Dimensions of the main PICARD components.

Component	Parameter	Value
Inner vessel	Height	900 mm
	Diameter	400 mm
	Typical liquid volume	100 l
	Nominal pressure	16 bar(g)
Outer vessel	Height	1500 mm
	Diameter	600 mm
	Vacuum volume	300 l
	Nominal pressure	10 bar(g)
Radiation shield	Height	1050 mm
	Diameter	500 mm
Vent line	Inner diameter	60 mm
Quench gas line	Inner diameter	100 . . . 150 mm

### 3.2. Instrumentation

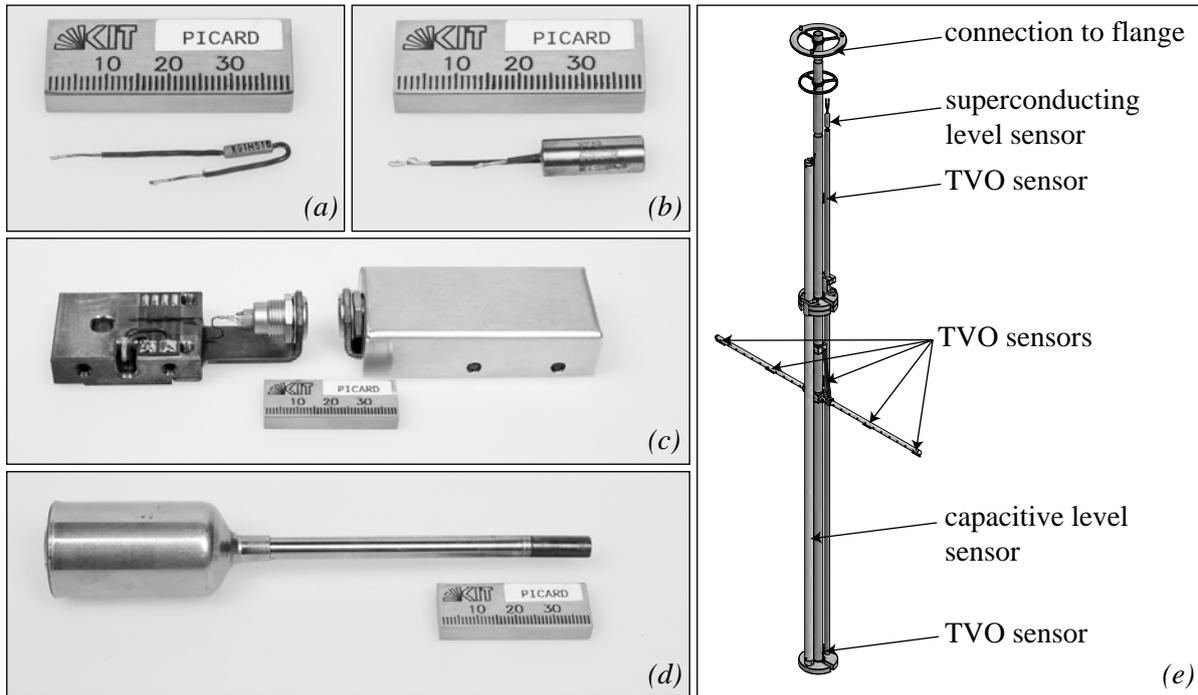
In order to perform heat flux and flow rate measurements under various specified conditions, studies on the impact of two-phase flow and measurements of flow coefficients of safety devices at low temperature, a variety of valves, orifices, venturi tubes, temperature sensors, (differential) pressure transducers and liquid level probes have been installed at the PICARD test stand. The Piping and Instrumentation Diagram (P&ID) is shown in figure 2(b).

An overview of the different TVO temperature sensors that have been calibrated at the calibration facility at ITEP is given in figure 3(a)-(d). For fast temperature measurements, seven plain TVO temperature sensors (figure 3(a)) have been chosen and fixed at the measurement insert shown in figure 3(e). Four of them are attached to horizontal wings of the measurement insert that unfold once having passed through the vent line. They are complemented by three additional plain TVO sensors hanging freely at different heights of the measurement insert to verify the simplifying assumption of a homogenous temperature profile within the cryogenic fluid.

The design of eight additional TVO sensors for surface temperature measurements is shown in figure 3(c). The copper blocks were mounted on the top, bottom, left and right side of the outer surface of both the inner vessel and the radiation shield. The temperature measurement at the outer surface of the inner vessel shall provide information concerning the heat transfer resistance within the inner vessel. Three more TVO sensors were prepared for in-tube temperature measurements of the cryogenic fluid inside the vent line and quench gas line (figure 3(d)).

A capacitive level sensor, attached to the measurement insert shown in figure 3(e), was designed for experiments with e.g. nitrogen. For helium level measurements, an additional superconducting level sensor has been installed.

Due to fast pressure and temperature changes and the possible occurrence of two-phase flow, two different methods are applied for measuring the discharge mass flow. The first method is a flow measurement with a venturi tube according to DIN EN ISO 5167-4 [15]. The venturi tube was installed right before the safety valve, since the expected two-phase flow after the safety valve would make a downstream measurement impossible. The second method is based on the measurement of the temperature  $T$  and the pressure  $p$  inside the inner vessel. By means of thermodynamic correlations and fluid property data [16], the changes in the mass within the inner vessel  $m$  over time  $\tau$  (and therefore also the discharge mass flow  $\dot{m}$ ) can be calculated with



**Figure 3.** (a) Picture of a plain TVO sensor for fast temperature measurement of the cryogenic fluid inside the inner vessel, and (b) of a TVO temperature sensor casted into a copper case. (c) Picture of a casted TVO temperature sensor that has been inserted into a copper block to be mounted on the surface of the inner vessel and the radiation shield. The copper block is protected from heat radiation by an aluminum shield. (d) Picture of a casted TVO temperature sensor at the tip of a stick to measure the temperature of the cryogenic fluid inside the vent line and the quench gas line. (e) CAD drawing of the measurement insert with TVO temperature sensors as well as capacitive and superconducting level probes.

a constant total volume  $V$  and the time-dependent density  $\rho$  by:

$$\dot{m}(\tau) = \frac{dm(\tau)}{d\tau} = \frac{d(V \cdot \rho[p(\tau), T(\tau)])}{d\tau}. \quad (1)$$

The expected uncertainties in the range of 20% were judged sufficiently accurate under the difficult conditions. However, large temperature gradients within the cryogenic fluid could make an evaluation difficult, if not even impossible following this procedure.

For the air or nitrogen venting mass flow rate in the vacuum vessel, an orifice measuring section has been chosen. Since both critical and subcritical flow is expected, the measured data will be evaluated based on calibration. The composition of the ambient air will be measured with a combined hygrometer and temperature sensor in order to consider the influence of humidity. Using orifices of different diameters, the heat flux into the pressure vessel can be adjusted.

#### 4. Status and Outlook

All components have been manufactured and assembled. Their specified leak tightness and the pressure resistance have been verified. Within the next month, the approval by the notified body is scheduled. The further commissioning with measurements of the evaporation rates and temperature gradients during stand time will be conducted, before first data of venting

experiments will be taken. Later this year, the experiments will concentrate on the occurrence and the influence of two-phase flow, which is the focus of a R&D collaboration between KIT and CERN.

### Acknowledgments

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