CO₂-based System in NEST

SAFETY ISSUES OF A CO₂-BASED SYSTEM IN NEST

TECHNICAL REPORT
August 2016
NEST - EMPA

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1 Summary

The concept of CO\textsubscript{2} system in the NEST research and innovation building extends the approach developed by the refrigeration industry by giving access of the CO\textsubscript{2} network to the floors of allegedly inhabited buildings and neighbourhoods.

The main implication on safety results from the larger amount of pressurized working fluid and the presence of people living or working in the vicinity.

In consequence, the installation shall be designed according to the relevant safety and security standard and the service personnel shall be trained in the safety rules. The standard EN 378-1\[37\] requires to adapt the load of the CO\textsubscript{2} system according to the concentration limit of the refrigerant in the volume of the machinery room (0.1 kg/m\textsuperscript{3} or 50'000 ppm).

People working inside technical rooms and galleries where the network passes should be equipped with portable CO\textsubscript{2} detectors. Odorisation of the CO\textsubscript{2} could also be used. Moreover, the installation should be designed in order to prevent damages caused by third parties.

All the necessary actions should be undertaken to prevent a pipe failure that would put the network out of operation. In the case of such event, the placement of safety valve to slow down pressure drop should be set in order to guarantee that the quantity of CO\textsubscript{2} released remains beneath the maximum tolerable limit.

In the event of an accidental loss of a large quantity of CO\textsubscript{2}, an appropriate ventilation system is required in order to eliminate any risk of suffocation, particularly in spaces below ground level.

CO\textsubscript{2} detectors should be installed inside the building, especially in technical rooms and galleries, to control appropriate exhaust ventilation. In technical room, nozzles should be located at ground level and the access door release or blocking may be activated by a sensor state monitoring device.

Carbon dioxide gas dissolved in water to form a weak acid. In consequence, the use of efficient dryers is required to avoid corrosion and guarantee an isothermal phase change.

The equipment of the NEST CO\textsubscript{2} system should, as far as possible, be designed within the category (I) of the pressure equipment directive (PED) where self-certification principle apply. In any case, care must be taken to verify the certificates of conformity of each component.
2 Introduction

This technical report makes a synthesis of the safety issues identified from previous studies and experience gained from LENI and IPESE-EPFL on district heating and cooling network (DHC) using carbon dioxide (CO\(_2\) or R744) as heat transfer fluid. It is based mainly on the following safety study on CO\(_2\)-based DHC[20] and preparatory report for the design and build of an experimental facility of a CO\(_2\) network:

- S. Henchoz. Safety issues of the CO\(_2\) network - a review of the current application of CO\(_2\), focusing on safety when it is used as a refrigerant. 6 avril 2012[20];


The technical concept of CO\(_2\) network makes use of the latent heat between liquid and solid phase of the fluid. The CO\(_2\) network is therefore built around two tubes, maintained at a working pressure of about 50 bar, with the CO\(_2\) flowing at \(~ 13^\circ C\) in the liquid form and \(~ 15^\circ C\) in the vapour form (Figure 1).

![Flowsheet of a typical CO\(_2\) district heating and cooling network](image-url)

Figure 1: Flowsheet of a typical CO\(_2\) district heating and cooling network [41, 19].
The use of the CO\(_2\) as a natural refrigerant has many advantages:

- it is inert and compatible with both metals and plastics or elastomers, non-flammable, non-toxic and abundant in the environment, therefore, requiring no recovery or recycling
- it possesses a high volumetric thermal capacity of 2'600 kJ/m\(^3\) at 0\(^\circ\)C, which is 7.8 times higher than R134a and 5.2 times higher than Ammonia (NH\(_3\)), making it an efficient refrigerant\(^{[25]}\).

However, its use raises safety issues since:

- CO\(_2\) is colourless and odourless and an asphyxiate at strong concentrations;
- high operating pressures are more hazardous and increase the leak potential

This requires to consider safety and security measures as well as to train the service personnel in the safety rules.

This report is structured in four parts. First, the thermodynamics and phase behaviour of CO\(_2\) is exposed for the range of pressure of the network. Then, the state of the art and the future evolution of DHC CO\(_2\) networks are presented, emphasising the safety aspects of the CO\(_2\) system in the NEST building. Third, general hazards resulting from the use of large quantities of carbon dioxide at high pressure are reviewed and safety measures proposed accordingly. Finally, as the first safety measures focus on preventing the risks, applicable standard and directives are presented towards the design and certification process of the CO\(_2\) network.
3 Thermodynamic property of CO₂

At normal pressure and temperature (1 bar, 20°C), CO₂ is a gas 1.53 times heavier than air ($M_{CO₂}=44$ g/mol). When it is cooled down above −78.4°C at normal pressure, it forms solid "dry ice". CO₂ liquefies when it is compressed above the triple point pressure (5.18 bar) and cooled down under the temperatures of the saturated liquid to gas line. At 50 bar, this temperature is 14.2°C. Above the critical temperature of 31°C, CO₂ only exists as a supercritical fluid.

These phase transitions are shown in the pressure–enthalpy diagram of Figure 2 with a closer view of the saturation dome included in Annex A, p. 30. The latent heat of vaporization/condensation of CO₂ at 50 bar is 180 kJ/kg.

The depressurisation of CO₂ from 501 bar to 1 bar, for example by accident in a safety valve, will produces gaz and solid reaching a temperature of −78.4°C. If the depressurisation occurs in the liquid line, 56% of the mass will reach a solid state. If it occurs in the vapour line, 5% of the mass will reach a solid state. Solid CO₂ formed within systems could cause blockages and subsequent hazards, as well as leading to the embrittlement of materials due to low temperature, causing fractures and cracks.

As CO₂ density is sensitive to temperature changes, especially close to the critical point, a relatively small increases in temperature can leads to system over pressurisation.

Figure 2: CO₂ pressure–enthalpy diagram with phase transition.

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1 This pressure is close to the 55 bar commonly found at 21° within CO₂ fire extinguishers.
4 Overview of current and future trends of CO₂ systems

CO₂ has covered up to 80% of the refrigerant market for marine applications until 1960[32]. Even having been used by the refrigeration and chemical industries without much greater problem than any other refrigerant, it has been replaced in the 60’s by new competing refrigerants, such as R12 and R22. The main reasons were the rapid loss of capacity at high cooling-water temperatures in the tropics, and the failure of the manufacturers to design compact and price-effective high-speed CO₂ compressor design[24].

In the last 20 years, the environmental issues linked with CFC and HFC refrigerants and the habitability of the manufacturers to follow modern trends in CO₂ compressor design have contributed to a renewed interest in CO₂ refrigeration and heat pumping systems[33].

4.1 State of the art of CO₂ systems

There are about 3’000 CO₂ trans-critical booster systems installed worldwide with more than 90% in Europe[28]. The majority of these systems have been installed in the last few years.

Heat Pump Water Heater for Household Use

Since 2001 in Japan, more than 2.8 millions EcoCute¹ CO₂ domestic hot water preparation units[4], reaching COP higher than 3.9, have been produced. This represents 98% of all the new residential heat pump water heaters in Japan. In these machines, gaseous CO₂ is heated to around 100°C under pressure of 100 bar.

Large scale CO₂ heat-pumps

The heating capacity of large scale CO₂ heat-pumps lie between 45 and 1000 kWth. Therma²[11] is producing such chillers and combined heat and cold units using piston or screw compressors. These machines are used in large buildings, district heating networks and industrial applications with CO₂ circuit designed for a possible pressure of about 115 bar and temperature of 120°C.

CO₂ refrigeration systems

Across Europe, uptake of natural refrigerants in food retail has doubled in the past years[27]. In Switzerland, 373 CO₂ refrigeration units have been installed from 2002 to 2013 and since 2010, CO₂-only refrigeration systems have been the standard in all new and retrofitted stores[28]. Carrier published the list of their refrigeration units installed in Swiss supermarkets since 2002[8].

In a SPAR supermarket in Schüpfen³ (Bern), a fully integrated system allows to recover the heat from the refrigeration process and transports it around the entire store to cover the full annual heating requirements.

In Schlachtbetrieb Zürich⁴, the largest CO₂ heat pump system in Switzerland (800 kWth) is

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¹ http://www.atmo.org/presentations/files/553_27_shigeru_yoshida_mitsubishi.pdf
³ http://www.carrier.com/commercial-refrigeration/hr/hr/news/news-article/carrier_announces_the_100th_co2oltec_integral_system_installation_in_a_spar_store_in_switzerland.aspx
used to produce hot water at 90°C for the slaughterhouse based on waste heat from refrigeration systems. These installations circulate evaporating CO₂ at high pressure (20-40 bar) inside fridges and freezers in which customers are taking out food. So far, to the best knowledge of the author, no major accident has been reported.

CO₂ transportation

Currently there are more than 6'500 km of CO₂ pipeline built and operated worldwide[29], mainly used for enhanced oil recovery. Indeed, except in the USA, most countries have little experience with CO₂ pipelines or CO₂–Enhanced oil recovery operations. To be transported in a pipeline, CO₂ should be compressed to ensure that single-phase flow is achieved. Pipelines, which transport CO₂ in the supercritical state (operating pressure 74-210 bar), have shown up a lower rate of casualty per km of pipeline than their natural gas counterpart[31]. However these pipelines are all located in low populated areas, so the incidents did not cause any reported casualties or fatalities.

4.2 The future of CO₂ systems

The sales of CO₂ refrigerant have increased of 88% between 2008 and 2010 and its share among natural refrigerants is expected to rise from 35% to 42%[26]. Furthermore, according to a survey carried out in 2014[28], a majority of experts believes that the share of CO₂ will be at least over 20% in the field of residential heating, commercial refrigeration and mobile air conditioning across Europe in 2020. This means that in the immediate future, new CO₂ network pipes will inevitably be built close to population centres.

Regarding industrial refrigeration, commercial & industrial heating and stationary air conditioning, the panel of experts views NH₃, CO₂, H₂O and HC as serious contenders.

The concept of DHC CO₂ system extends the approach developed by the refrigeration industry[8, 11] by giving access of the CO₂ network to the floors of allegedly inhabited buildings and neighbourhoods. The main implication on safety results from the larger amount of working fluid and the presence of people living or working in the vicinity.
5 General hazards of large quantities of carbon dioxide at high pressure

According to the safety group classifications SN EN 378-1:2008+A2:2012[37], presented in Table 2), CO₂ is in group A1 for which toxicity(A) has not been identified at concentrations less than or equal to 400 ppm and flammability(1) does not show flame propagation when tested in air at 21°C and 1.01 bar. According to the PED directive 2014/68/EU, CO₂ is a group 2 fluid (not explosive, nor extremely flammable or highly flammable, nor very toxic, toxic or oxidizing).

Table 2: Information on CO₂ refrigerant from standard EN 378-1, Annex E (§6.1.1).

<table>
<thead>
<tr>
<th>Number of Refrigerant</th>
<th>Chemical formula</th>
<th>Group of fluids</th>
<th>Flammable in air</th>
<th>LFL in air</th>
<th>Mass of molecule</th>
<th>GWP at 100-year</th>
<th>Temp. of auto-inflammation</th>
</tr>
</thead>
<tbody>
<tr>
<td>717 Ammoniac</td>
<td>NH₃</td>
<td>A1</td>
<td>0,000 35.1</td>
<td>1,000 22.7</td>
<td>0,116</td>
<td>0,111</td>
<td>N.D.</td>
</tr>
<tr>
<td>744 Dioxide Carbon</td>
<td>CO₂</td>
<td>A1</td>
<td>0,000 22.7</td>
<td>0,116</td>
<td>0,116</td>
<td>0,116</td>
<td>N.D.</td>
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5.1 Hazards of large quantities of inhaled carbon dioxide

5.1.1 Toxicity

The concentration of CO₂ in the atmosphere is about 350 ppm (0.035%). According to NIOSH[9], OSHA[30], ACGIH[3], HSE[15], the Threshold Limit Values (TLV) for CO₂ and the Permissible Exposure Limit (PEL) is 5'000 ppm (0.5%). The Immediately Dangerous to Life and Health limit (IDLH) is considered generally at 50'000 ppm (5%), but a more restrictive limit of 15'000 ppm is given by HSE[15].

Table 3 report the symptoms and limits recommended by health Agencies.

Table 3: Standards for CO₂ in the workplace.

<table>
<thead>
<tr>
<th>CO₂ concentration in the atmosphere</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady-state CO₂ concentrations found in typical office buildings</td>
<td>350 ppm</td>
</tr>
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</table>
| 700 ppm | Continue on the next page...

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1 National Institute for Occupational Safety and Health, USA
2 Occupational Safety and Health Administration, USA
3 American Conference of Governmental Industrial Hygienists, USA
4 Health and Safety Executive, UK
Table 3: Standards for CO\textsubscript{2} in the workplace.

<table>
<thead>
<tr>
<th>Definitions &amp; Symptoms</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum concentration for continuous exposure (EPA)\textsuperscript{1}</td>
<td>1000 ppm</td>
</tr>
<tr>
<td>Low end CO\textsubscript{2} concentration, permissible exposure limit (PEL) in the workplace for an 8-hour workday</td>
<td>5'000 ppm</td>
</tr>
<tr>
<td>High-end CO\textsubscript{2} concentration limit for a 10 minute period [HSE-WEL]</td>
<td>15 000 ppm</td>
</tr>
<tr>
<td>Shortness of breath, deep breathing</td>
<td>20'000 ppm</td>
</tr>
<tr>
<td>High-end CO\textsubscript{2} concentration limit for a 10-15 minute period [9, 30, 2]</td>
<td>30'000 ppm</td>
</tr>
<tr>
<td>Immediately dangerous to life and health limit (IDLH) – Breathing becomes heavy, sweating, pulse quickens</td>
<td>50'000 ppm</td>
</tr>
<tr>
<td>Headaches, dizziness, restlessness, breathlessness, increased heart rate and blood pressure, visual distortion</td>
<td>75'000 ppm</td>
</tr>
<tr>
<td>Lethal concentration of CO\textsubscript{2} over 5-10 minutes</td>
<td>90'000 ppm</td>
</tr>
<tr>
<td>Impaired hearing, nausea, vomiting, loss of consciousness, death for exposure greater than 10 minutes</td>
<td>100'000 ppm</td>
</tr>
<tr>
<td>Permanent heart damage for 20-30 seconds exposure, coma, convulsions, death</td>
<td>300'000 ppm</td>
</tr>
</tbody>
</table>

For a long time, CO\textsubscript{2} was considered as totally neutral for the human metabolism (below its lethal concentration). However, recent studies\cite{18, 16} showed that chronic and/or long term intermittent exposure to concentrations substantially higher than the ambient concentration might induce pathological states. These kinds of exposures are normally excluded in technical rooms where the prescriptions for standard central heating forbids long lasting presence of persons. However, in the case of the NEST research and innovation building, regular presence of person achieving experiment, work or maintenance in technical rooms and galleries must be considered.

About a possible release in the street along the network, the risk of chronic exposure to high concentrations is virtually null, because such concentration implies large, thus detectable, leak. In the case of a small continuous leak, the dispersion due to the turbulent mixing provoked by air movements makes high concentration very unlikely.

Proposed safety measures:

It is important to install inside the building, especially in technical rooms and gallery, CO\textsubscript{2} sensors with incremental values such as 0, 5, 300, 1'000, 20'000 ppm, controlling appropriate exhaust ventilation. In technical room, nozzles should be located at ground level and the access door release or blocking may be activated by a sensor state monitoring device.

5.2 Hazards of carbon dioxide at high pressure

In addition to the hazard posed by CO\textsubscript{2} if inhaled, there are additional hazards associated with large quantities of dense CO\textsubscript{2} at high pressure. These can arise when a release occurs and the pressure suddenly falls or is lost completely. These hazards include cryogenic burns,
embrittlement of pipe work, toxic contamination and possibly "grit blasting" of neighbouring plant (although information suggests that CO\textsubscript{2} snow also needs to be compressed in order to give a grit blasting effect)[18].

5.2.1 Corrosion

CO\textsubscript{2} is an acid gas and will react with water to form carbonic acid. Carbonic acid corrosion of carbon steels has been recognized for years as a major source of damage in oilfield equipment and gas pipelines, and is commonly referred to as "sweet gas" corrosion[6]. In the case of high pressure CO\textsubscript{2} saturated with water (40-80 bar at 50\textdegree{}C), the corrosion rate is in the order of 0.2 mm/year[10]. In any case, and has to be as limited as possible

Proposed safety measure:

The use of efficient dryers are required in order to limit in any case, as for any standard compression chiller or heat-pump, the contamination of the working fluid to guarantee an isothermal phase change and avoid corrosion.

5.2.2 Boiling Liquid Expanding Vapour Explosion (BLEVE)

A special type of accident might occur with CO\textsubscript{2} in the case of the rupture of one of the component filled with liquid, resulting in a rapid pressure reduction causing a nearly instantaneous transition from liquid to vapour with a corresponding energy release. This is called Boiling Liquid Expanding Vapour Explosion (BLEVE) and is likely to occur if the liquid is stored at a pressure high enough for the superheated liquid to reach the spinodal point (Figure 3) during depressurisation.

In 2011, a thermodynamic analysis[34] and small scale experiment[7] of BLEVE have been performed. The pressure at which this might occur was estimated to be between 22 and 45 bar[1], which is above the limit of the proposed CO\textsubscript{2} network, but also of the existing CO\textsubscript{2} chillers and heat-pumps.

Even if, over the past 50 years, two BLEVEs with CO\textsubscript{2} have been reported in the chemical industry\textsuperscript{1}[1], the use of CO\textsubscript{2} in the refrigeration industry did not leads to accidents of this type. It seems that high pressure liquid pipelines are much less susceptible to end up in a BLEVE than in the case of spherical or cylindrical storage. This could be explained by the large source of nucleation sites on the rough surface of the pipes, making the boiling process to start earlier, thus reducing the risk of explosive boiling.

The risk linked with the potential breakage of a component containing CO\textsubscript{2} in the gaseous phase seems not to be of a greater concern than its liquid counterpart. However, care has still to be taken in the design and operation of such components, as in any chemical plant or gas pipe.

Proposed safety measures:

Relief valves shall be sized to release pressure fast enough to prevent it from increasing beyond the strength of the vessel, but not so fast to avoid an explosion. The valves should maintain a

\textsuperscript{1}One due to overfilling of a 35 tons vessel and the other to corrosion in a 10 kg vessel
constant pressure until all the liquid has boiled and the vessel empties.

Figure 3: Pressure/volume graph with the spinodal point X and curve – dashed red line (source: Global CCS Institute\(^1\)).

5.2.3 Leakages in pipes

Risk assessment of CO\(_2\) pipelines\(^2\) consists in:

1. imagining a failure scenario and modelling the release of CO\(_2\);
2. modelling its dispersion to obtain a spatial and time distribution of the concentration of CO\(_2\) in the atmosphere;
3. comparing the result to a Probit function of the toxicity of CO\(_2\) for human health.

Obviously each step has its own model, assumptions and uncertainties which are cascaded to the following steps of the process. This explains the large range of variation in the 10-6 individual risk contour\(^2\) (radius from 0 to 204 m around the leak). A major difficulty lies in defining an accurate dispersion model\(^1\).

Two major categories of failure can be distinguished:

- Low Flowrate Leakage
- High Flowrate Leakage


\(^2\)The 10-6 individual risk contour is the distance from the pipeline, for an ever-present person to have a probability to die lower than 1/1'000'000 per year
5.2.3.1 Low Flowrate Leakage

Low flowrate leakage could appear in operation, without being detected, under the following circumstances:

a) Default of a seal;

b) Default of a welded joint;

c) Leakage along shafts (mainly in the case of non-hermetic machines).

The main danger of such small leak is a potential rise in the concentration of CO\textsubscript{2} in enclosed rooms. Heavier than air, CO\textsubscript{2} tends to accumulate in basements and underground facilities such as technical galleries. Although CO\textsubscript{2} is not considered as a dangerous fluid for human health (PED category 2, safety group A1) according to NF EN 378-1, the main danger remains suffocation provoked by ambient air depletion with carbon dioxide.

Proposed safety measures:

This kind of leakage might occur for a rather long time before becoming a danger for human health. Hence, safety measures consist in:

- Primarily facilitating the detection and location of the leaks, in order to fix or replace the leaking component;

- Enclosing the heat-exchanger at the user substation in a gas tight containment, in order to prevent leakage into the central/cooling heating room. This containment would also protect the installation from damages provoked by a third party;

- Installing CO\textsubscript{2} detector inside the containment. They should be installed preferably at the bottom, for buoyancy reasons. Considering that sensors are very cheap, two units could be used in parallel, hence allowing a very high degree of reliability, at a reasonable cost. An alarm should be installed outside of the room, triggered by a positive measurement of the sensors. It should warn people not to enter the room without ensuring good ventilation;

- Using an odorisation of the CO\textsubscript{2}, in order to warn people from the presence of gas. For instance, in CO\textsubscript{2} based fire protection systems, a wintergreen scent is mixed with the CO\textsubscript{2} as it is being discharged[3];

- Equipping people working inside technical rooms and galleries with portable CO\textsubscript{2} detectors. (The flame of a candle or lighter could also help to detect the lack of oxygen);

- Determining, by testing, the minimum audible diameter for holes. With a pressure differential of \(\sim\)50 bar, even very small holes will likely generate audible leaks, facilitating the detection and location of the faulty component. Tests should also be done to see from which diameter dry ice will appear near the hole. Small leaks will probably be visually detectable through this phenomenon.
5.2.3.2 High Flowrate Leakage

The distinction between this mode of failure and the first one comes from the fact that this one should be detected very quickly, mainly under the form of a downward pressure change. This mode could occur under a partial or total rupture of a pipeline subsection, of a pressure vessel or of a large component. The main reasons of the rupture could be\cite{29}:

a) Relief valve failure

b) Weld, gasket or valve packing failure;

c) Carbonic acid corrosion of carbon steels;

d) Outside force: Damage caused by a third party (ex. work in progress);

e) Large pressure fluctuations (ex. liquid hammer);

f) Metal fatigue.

Proposed safety measures:

Contrarily to its low flowrate counterpart, this kind of leakage constitutes a major danger as soon as it appears. The safety measures should focus first on preventing it from occurring, and secondly on stopping it as quickly as possible. Hence, safety measures consist in:

- Preventing corrosion, by monitoring the water content of the CO$_2$ and using efficient dryers. In the case of abnormal activity of the dryer over a long period of time, the source of water should be searched for. However, because of the large pressure differential between the CO$_2$ and the water, a contamination by water penetrating into the network seems unlikely. A leakage from the CO$_2$ network into a water loop is more probable. To detect this, a pH sensor at the water outlet of the heat-exchanger may be envisaged. The corrosion at the outside of the pipeline should be prevented using standard technologies already in use for oil and gas pipelines (per ex. cathodic shielding);

- Preventing damages caused by third parties, by installing the network into technical galleries or, if this is not possible, by keeping a sufficient depth for the pipeline. This should avoid possible damages from small works in progress, (which are not necessarily submitted to authorization). A sufficient depth will also reduce the impact of repeated mechanical stresses provoked by heavy vehicles when the network is under a road (Inspired by EN 14161);

- Avoiding large magnitude transients pressure waves, by regulating the network in order to reduce the risks of damages caused by liquid hammer effects. In the event of a high flowrate leak, safety devices should ensure its stopping under the shortest delay. The pipeline should be divided into subsection, by safety valves, the closure of these valves being triggered by a pressure differential sensor. Figure 4 displays schematically
an example of a potential system. The probes being located on each side of a symmetrical Venturi restriction. In the case of a large leakage, the massflow through the closest venturi restrictions will increase rapidly; consequently the pressure drop through these restrictions will increase and command the closure of the safety valves. Symmetrical Venturi probes are particularly interesting, since they generate a low pressure drop at low flowrate (normal operations) and are able to deal equally with flows going in both directions. The Venturi probes may also be useful to measure flowrates in normal operations, and help monitoring the operation of the network. The location of these pipes sectioning safety valves should be done according to the two following criteria:

1. Spatial distribution of the leaking CO\textsubscript{2}:
   The quantity of CO\textsubscript{2} released will be proportional to the distance between the two subsection valves that are the closest. Hence, the distance between the valves should be the result of a tradeoff between the tolerable risk and the cost associated with the installation and servicing of the safety valves. A worst case analysis is a possible method to define the distance between the valves. An option could be to compute the spatial distribution of the CO\textsubscript{2} concentration in the case of a rupture of pipe on a day with a little or no wind. Individual risk contours will have to be compared to the population density, so as to evaluate the danger to which the population is submitted.

2. Energy / Impulse liberated by the explosion:
   Large releases are likely to have similar characteristic as explosions. A short distance between safety valves may reduce the impulse of a quasi instantaneous release of CO\textsubscript{2}. Too large an impulse might propels parts of the soil in all direction thus severely injuring people. In fact, the diameter of the pipe may play a more important role than the length of the subsection. A criterion on the maximum kinetic energy of fragment liberated during the explosion should also be considered to estimate potential damages. The study might leads to the conclusion that, for safety reason, pipes with a diameter larger than a critical value should be forbidden in some given areas.
5.3 Hazard identification

The risk assessments will focus first on identifying all the risks, and then propose a set of measures such that all the residual risks remain under a tolerance threshold. Such an analysis is required by the directive 2006/42/CE[13].

The results of the risk analysis will affect the choice of the control devices. The required performance level (PL) indicator, ranging from PL “a” (low) to PL “e” (high), has to be evaluated as a function of the severity of the potential injury, the frequency of exposition to the risk and the possibility to avoid the hazard/harm.

An overview of the minimal set of triggering factors, protection objectives and prevention measures to consider for the realisation of a CO$_2$ network in the NEST building are reported in Table 4 below. These factors are extracted from the risk assessment (Annex C) of an experimental CO$_2$ network, build by LENI-EPFL in 2015 (Annex B).

Table 4: Extract from the risk assessment of an experimental CO$_2$ network (Annex C).

<table>
<thead>
<tr>
<th>Triggering factors</th>
<th>Protection objectives</th>
<th>Prevention measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>While filling, pipe bursting due to the high pressure in the CO$_2$ bottle (200 bar)</td>
<td>Keep control of the pressure while filling</td>
<td>Use a flow restrictor and secure the flexible pipe by a cable</td>
</tr>
<tr>
<td>Excessive increase in pressure, beyond what the system can accommodate, explosion</td>
<td>Prevent any dangerous pressure from developing</td>
<td>Mount a valve or a dump valve on every pipe sections that can be isolated</td>
</tr>
<tr>
<td>Emission of CO$_2$ in the technical room</td>
<td>Quickly detect the presence of CO$_2$ and to halt the loss</td>
<td>Installation of a CO$_2$ detector and of pilot operated blanking valves</td>
</tr>
<tr>
<td>Continue on the next page...</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4: Extract from the risk assessment of an experimental CO$_2$ network (Annex C).

<table>
<thead>
<tr>
<th>Triggering factors</th>
<th>Protection objectives</th>
<th>Prevention measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emission of CO$_2$ in the technical room</td>
<td>Avoid trapping of valve pintle</td>
<td>Blanking valves pneumatically activated, piloted by EV 24V</td>
</tr>
<tr>
<td>Blanking valve do not close up because of a power shortage</td>
<td>Under pressure</td>
<td>Valves are normally-closed valve</td>
</tr>
<tr>
<td>Blanking valve do not close up because of failure of</td>
<td>To ensure nonetheless the closing up of the blocking valve</td>
<td>Link am active ventilation to the detection system</td>
</tr>
<tr>
<td>the controller module or the valves are spewing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission of CO$_2$ and ventilation malfunction</td>
<td>Prevent the entry of people in the technical room when the concentration of CO$_2$ is</td>
<td>CO$_2$ detection with sound and light alarm mounted on secured electricity supply or inverter</td>
</tr>
<tr>
<td></td>
<td>excessive, warn the people in the room that they must get out</td>
<td></td>
</tr>
<tr>
<td>Back flow of CO$_2$ into the general ventilation</td>
<td>Avoid collaborator entering in contact with CO$_2$</td>
<td>Ventilation with dedicated channel for the evacuation</td>
</tr>
<tr>
<td>CO$_2$ gas reflux in the exhaust duct of the ventilation of</td>
<td>Avoid any excess of the maximum concentration allowed in the room</td>
<td></td>
</tr>
<tr>
<td>a neighbouring local</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure increase following a machine stoppage, valves are</td>
<td>Avoid any pressure increase</td>
<td>The machine keeps the NC blanking valves open and maintain old water supply in the heat exchanger; contacting phases achieves a buffer effect</td>
</tr>
<tr>
<td>spewing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6 Applicable standards and directives

The rules and technical standards for refrigeration and heat pumping equipments apply to the central plant and to all substations. For all these equipments, the foundation of the safety analysis is given by the pressure equipment directive (PED)[12] (§ 6.2, p. 23) [78].

6.1 Standards

The following standards apply for the realization of a CO\textsubscript{2} system in NEST:

- **EN 378**: Refrigerating systems and heat pumps;
- **EN 14276**: Pressure equipment for refrigerating systems and heat pumps;
- **EN 13480**: Metallic industrial piping;
- **EN 14511**: Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling;
- **EN 15450**: Heating systems in buildings;
- **EN ISO 13849**: Safety of machinery.

6.1.1 EN 378 : Refrigerating systems and heat pumps

The standards EN 378[37, 35, 36] applying for the design of refrigerating systems and heat pumps are reported in Table 5. It differentiates equipments installed in unoccupied or occupied machinery rooms and system with (indirect) or without (direct) secondary distribution loop. Direct system requires a dedicated ventilation system controlled by a gas detection.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 1736:2008</td>
<td>Flexible pipe elements, vibration isolators, expansion joints and non-metallic tubes – Requirements, design and installation</td>
</tr>
<tr>
<td>EN 12263:1998</td>
<td>Safety switching devices for limiting the pressure – Requirements and tests</td>
</tr>
<tr>
<td>EN 12693:2008</td>
<td>Safety and environmental requirements – Positive displacement refrigerant compressors</td>
</tr>
<tr>
<td>EN 13136:2013</td>
<td>Pressure relief devices and their associated piping – Methods for calculation</td>
</tr>
<tr>
<td>EN 13313:2010</td>
<td>Competence of personnel</td>
</tr>
</tbody>
</table>
The standard EN 378-1 requires to adapt the load of the system according to the practical limit of the refrigerant in the volume of the machinery room. The Refrigerant Concentration Limit (RCL) of CO₂ is 0.1 kg/m³ (50'000 ppm), representing the highest concentration which does not hinders emergency evacuation procedures. The Acute Toxicity Exposure Limit (ATEL) is 0.07 kg/m³ (35'000 ppm).

Figure 5, p.22, shows the decision tree of the security standards SN EN 378-1[37].

6.1.2 EN 14276: Pressure equipment for refrigerating systems and heat pumps

The standards applying for the design of pressure equipment for refrigerating systems and heat pumps are reported in Table 6.

Table 6: Standards for pressure equipment for refrigerating systems and heat pumps.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
</table>

6.1.3 EN 13480: Metallic industrial piping

The standards applying for the design of metallic industrial piping are reported in Table 7.

Table 7: Standards for metallic industrial piping.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 13480-1:2012</td>
<td>Part 1: General</td>
</tr>
<tr>
<td>EN 13480-2:2012</td>
<td>Part 2: Materials</td>
</tr>
<tr>
<td>EN 13480-3:2012</td>
<td>Part 3: Design and calculation</td>
</tr>
<tr>
<td>EN 13480-4:2012</td>
<td>Part 4: Fabrication and installation</td>
</tr>
<tr>
<td>EN 13480-5:2012</td>
<td>Part 5: Inspection and testing</td>
</tr>
<tr>
<td>EN 13480-6:2012</td>
<td>Part 6: Additional requirements for buried piping</td>
</tr>
<tr>
<td>EN 13480-8:2012</td>
<td>Part 8: Additional requirements for aluminium and aluminum alloy piping</td>
</tr>
<tr>
<td>EN 13480-8:2012/A2:2015</td>
<td>Part 8: Additional requirements for aluminium and aluminum alloy piping</td>
</tr>
</tbody>
</table>
6.1.4 EN 14511: Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling

The standards applying for the design of air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling are reported in Table 8.

Table 8: Standards for air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 14511-1:2013</td>
<td>Part 1: Terms, definitions and classification</td>
</tr>
</tbody>
</table>

6.1.5 EN 15450: Heating systems in buildings

The standards applying for the design of heating systems in buildings are reported in Table 9.

Table 9: Standards for heating systems in buildings.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 15450:2007</td>
<td>Design of heat pump heating systems</td>
</tr>
</tbody>
</table>

6.1.6 EN ISO 13849: Safety of machinery

The European norm on safety of machinery addresses the issues reported in Table 10:

Table 10: Standards for safety of machinery.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 13849-2:2012</td>
<td>Safety-related parts of control systems – Part 2: Validation[22]</td>
</tr>
</tbody>
</table>
Figure 5: Decision tree for the security standards SN EN 378 (source: Federal Office for the Environment\textsuperscript{a} (FOEN, BAFU, OFEV), 23.12.2013.

\textsuperscript{a}http://www.bafu.admin.ch/chemikalien/01415/01426/index.html?lang=de
6.2 Directives

The directives, listed in Table 11, apply for the CO$_2$ system in NEST. They determine the category of equipments, describing the conformity assessment process and the notified bodies involved.

Table 11: Directive applying for the design of CO$_2$ network.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Date</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014/68/EU$^1$</td>
<td>July 19, 2016</td>
<td>The Pressure Equipment Directive (PED)</td>
</tr>
<tr>
<td>2006/42/EC$^2$</td>
<td>17 May 2006</td>
<td>European directive on machinery</td>
</tr>
<tr>
<td>SR 819.121[38]$^3$</td>
<td>20 November 2002</td>
<td>Verordnung über die Sicherheit von Druckgeräten - Ordonnance sur la sécurité des équipements sous pression</td>
</tr>
<tr>
<td>(Stand am 1. Juli 2015)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR 734.27[38]$^4$</td>
<td>7 November 2001</td>
<td>Verordnung über elektrische Niederspannungsinstallationen (NIV) - Ordonnance sur les installations électriques à basse tension (OIBT)</td>
</tr>
<tr>
<td>(Stand am 20. April 2016)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR 814.012[39]$^5$</td>
<td>27 February 1991</td>
<td>Major accidents ordinance (MAO) - Störfallverordnung (StFV) - Ordonnance sur les accidents majeurs (OPAM)</td>
</tr>
<tr>
<td>(Stand am 1. April 2013)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RS 814.81[40]$^6$</td>
<td>18 May 2005</td>
<td>Ordinance on the Reduction of Risks relating to the Use of Certain Particularly Dangerous Substances, Preparations and Articles (ORRChem)</td>
</tr>
<tr>
<td>(Stand am 1. Januar 2016)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Further details on the Machinery Directive (2006/42/EC) are given on the guide of application$^7$[14].

The purpose of the Ordinance SR 814.012 on Protection against Major Accidents (MAO, StFV, OPAM) is to protect the public and the environment against serious harm or damage resulting from major accidents. According to Annex 1.1–41, the ordinance applies above the threshold quantities of 20'000 kg CO$_2$ and should then not concern the NEST-CO$_2$ project.

In accordance with the Annex 2.10 of the ORRChem (RS 814.81), installations containing more than 3 kg of natural refrigerant are to have a maintenance book.

The Annex II of the pressure equipment directive (2014/68/EU and SR 819.121) categorize unfired pressure vessels and piping in different hazard categories with corresponding conformity
assessment modules. The classification is based on the service pressure (PS), the volume (V) for the vessels, the nominal diameter for the piping (DN) and the working fluid. Since part of the system is in the gas phase it is considered, in a restrictive manner, as using gas. For the NEST-CO\textsubscript{2} project, the equipment categories reported in Table 12 may be encountered:

Table 12: Conformity assessment for a CO\textsubscript{2} network in NEST (2014/68/EU-Annex II).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>&lt;50</td>
<td>&lt;32</td>
<td>&lt;1000</td>
<td>Sound Engineering practice</td>
</tr>
<tr>
<td>I</td>
<td>&lt;200</td>
<td>&lt;100</td>
<td>&lt;3500</td>
<td>Internal production control (A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Risk assessment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Design calculation report</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Manufacturing drawings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Material certificate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Pressure test report</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• EC declaration of conformity of the safety relief devices</td>
</tr>
<tr>
<td>II</td>
<td>&lt;1000</td>
<td>&lt;250</td>
<td>&lt;5000</td>
<td>supervised pressure equipment checks at random intervals (A2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Quality assurance of the production process (D1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Quality assurance of final pressure equipment inspection and testing (E1)</td>
</tr>
</tbody>
</table>

6.3 Certification procedure

The certification procedure requires the following steps\cite{19}:

1. Preliminary risk analysis according to 2006/42/CE “machines”;

2. Evaluation of the safety category according to PED EC 2014/68;

3. Control chains with safety functionalities: determine the required performance level (PLr) based on the preliminary risk analysis and the standard ISO 13849\cite{21, 22};

4. Ordinance on low voltage electric installations (OIBT): check the conformity of the wiring by a certified inspector;

5. Preparation of the documentation: include the operation manual, filling procedure, safety procedures and the list of responsible persons;

6. Pressure integrity test: test resistance of the system to 1.1 time the service pressure using nitrogen.

The equipment of the NEST CO\textsubscript{2} system should stay, as far as possible, within the category (I) of the PED EC 2014/68\cite{12} where self-certification principle apply. Consequently, the design should be guided by the following principles:
• **Plate heat exchanger should be duplicated, if necessary,** to decrease the relevant volume in order to satisfy the PS×V constraint. This action could also facilitate the control of the system during part load operation;

• **The diameter of shell and tube heat exchanger should be kept within the bounds of the directive,** by increasing if necessary the pressure level in tubes;

• **The pipe should be designed with nominal diameter lower than DN100.** Under DN32, the pipe has to be designed in accordance with the country sound engineering practice.

In all cases, *care must be taken to verify the certificates of conformity of each component before placing order.*
7 Conclusion

This study addresses the safety issue for the realization of a CO\textsubscript{2} heat distribution system in the NEST research and innovation building. It is based on consideration around the concept of CO\textsubscript{2} network developed at LENI/IPESE–EPFL\cite{41, 19} and takes advantage from the realization of an experimental CO\textsubscript{2} network.

CO\textsubscript{2} is increasingly used as a refrigerant in the commercial and food retail industries. In Switzerland, employees and customers are actually moving freely around high pressure CO\textsubscript{2} equipment in more than 378 shopping centre, without particular concerns over safety (§ 4.1, p. 8). Compared to these applications, the specificity of the NEST CO\textsubscript{2} system is that:

\begin{itemize}
  \item it uses CO\textsubscript{2} not solely as a working fluid in a refrigeration cycle, but also to distribute, recover or harvest heat either in the indoor or outdoor environment of the building;
  \item the system is located in a multi-use building where technician and scientists are at work and researchers reside permanently.
\end{itemize}

The CO\textsubscript{2} demonstration system in NEST will be safely operated under the following conditions:

\begin{itemize}
  \item the design follows the appropriate standard and directives (§ 6, p. 19) and the proposed safety measures (§ 5.1, p. 10). The certificates of conformity should be verified for each component of the system;
  \item the equipments are protected against damage from third party;
  \item the technical rooms and galleries are equipped with sensors connected to appropriate exhaust ventilation;
  \item the personnel is trained in the safety rules.
\end{itemize}

The evaluation of conformity will be facilitated if the equipments are designed in the lowest category (category I) according to the pressure equipment directive (§ 6.3, p. 23).
References


[20] S. Henchoz. Safety issues of the CO2 network – a review of the current application of CO2, focusing on safety when it is used as a refrigerant. 6 avril 2012.


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A  CO₂ pressure-enthalpy diagram
B Schematic layout - experimental CO₂ network[19]
### Risk Assessment - experimental CO\textsubscript{2} network

| x.1 | While filling, pipe bursting due to the high pressure in the CO\textsubscript{2} bottle (200 bar) | Pressure | Assembler | Assembler injured |
| x.2 | Excessive increase in pressure, beyond what the system can accommodate | Pressure | Assembler | Assembler injured |
| x.3 | Emission of CO\textsubscript{2} in the technical room | Suffocation due to CO\textsubscript{2} | Assembler/Technical collaborator | Assembler/Technical collaborator suffocate due to lack of oxygen |
| x.4 | Emission of CO\textsubscript{2} in the technical room | Suffocation due to CO\textsubscript{2} | Assembler/Technical collaborator | Assembler/Technical collaborator suffocate due to lack of oxygen |
| x.5 | Blankning valve do not close up because of a power shortage | Suffocation due to CO\textsubscript{2} | Assembler/Technical collaborator | Assembler/Technical collaborator suffocate due to lack of oxygen |
| x.6 | Blankning valve do not close up because of failure of the controller module or the valves are spewing | Suffocation due to CO\textsubscript{2} | Assembler/Technical collaborator | Assembler/Technical collaborator suffocate due to lack of oxygen |
| x.7 | Emission of CO\textsubscript{2} and ventilation malfunction | Suffocation due to CO\textsubscript{2} | Assembler/Technical collaborator | Assembler/Technical collaborator suffocate due to lack of oxygen |
| x.8 | Back flow of CO\textsubscript{2} into the general ventilation | Suffocation due to CO\textsubscript{2} | Assembler/Technical collaborator | Assembler/Technical collaborator suffocate due to lack of oxygen |
| x.9 | CO\textsubscript{2} gas reflux in the exhaust duct of the ventilation of a neighbouring local | Suffocation due to CO\textsubscript{2} | Technical collaborator | Technical collaborator suffocate |
| x.10 | Pressure increase following a machine stoppage, valves are spewing | Thermal energy | Assembler/Technical collaborator | Assembler/Technical collaborator injured by ejection of CO\textsubscript{2} |

#### Source of danger

- Special operating conditions
- Assembly/default factory settings
- Transport
- Commissioning
- Deployment
- Adjustment
- Production
- Cleaning
- Maintenance
- Diagnosis / Repair
- Shut-down

#### Persons concerned

- Depending on the mode of exploitation

#### Incident (worse case)

- Assembler
- Assembler injured
- Assembler/Technical collaborator
- Assembler/Technical collaborator suffocate due to lack of oxygen
- Assembler/Technical collaborator suffocate due to lack of oxygen
- Assembler/Technical collaborator suffocate due to lack of oxygen
- Assembler/Technical collaborator suffocate due to lack of oxygen
- Assembler/Technical collaborator suffocate due to lack of oxygen
- Assembler/Technical collaborator suffocate due to lack of oxygen
- Technical collaborator

#### Gravity of damage

- Low
- Medium (reversible)
- High (irreversible)

#### Probability

- Rare
- Quite often
- Frequent

#### Triggering factor

- Pressure
- Excessive increase in pressure
- Emission of CO\textsubscript{2}
- Blankning valve do not close up
- Emission of CO\textsubscript{2} and ventilation malfunction
- Back flow of CO\textsubscript{2}
- CO\textsubscript{2} gas reflux
- Pressure increase following a machine stoppage

#### Before measure

- Before measure
| Numbering of the risk | Special operating conditions | Triggering factor | Protection objective (to avoid incident) | Prevention measures | After measure | Gravity of damage | Probability | Residual risks |
|-----------------------|-----------------------------|------------------|-----------------------------------------|---------------------|--------------|------------------|-------------|----------------|----------------|
| x.1                   |                             | While filling, pipe bursting due to the high pressure in the CO2 bottle (200 bar) | Keep control of the pressure while filling | Use a flow restrictor and secure the flexible pipe by a cable | x | x | Reducution Gearbox Failure |
| x.2                   |                             | Excessive increase in pressure, beyond what the system can accommodate, explosion | Prevent any dangerous pressure from developing | Mount a valve or a dump valve on every pipe section that can be isolated | x | x | Valves spewing, CO2, risk of suffocation from oxygen deprivation |
| x.3                   |                             | Emission of CO2 in the technical room | Quickly detect the presence of CO2 and block the flows | Installation of CO2 detector and of pilot operated blanking valves | x | x | Slide Gate Values no longer function under working pressure |
| x.4                   |                             | Emission of CO2 in the technical room | Avoid trapping of valve pintle Under pressure | Blanking valves pneumatically activated, piloted by EV 24V | x | x | Programmable logic controller failure or electrical power shortage |
| x.5                   |                             | Blanking valve do not close up because of a power shortage | To ensure nonetheless the closing up of the blocking valve | Valves are normally-closed valve | x | x | None |
| x.6                   |                             | Blanking valve do not close up because of failure of the controller module or the valves are spewing | Detect any concentration above 5000 ppm and ventilate | Link an active ventilation to the detection system | x | x | Inadequate ventilation |
| x.7                   |                             | Emission of CO2 and ventilation malfunction | Prevent the entry of people in the technical room when the concentration of CO2 is excessive, warn the people in the room that they must get out | Detection de CO2 et sound and light alarm mounted on secured electricity supply or inverter | x | x | None |
| x.8                   |                             | Back flow of CO2 into the general ventilation | Avoid collaborator entering in contact with CO2 | Ventilation with dedicated channel for the evacuation | x | x | Electrical power failure; backflow of CO2 in the evacuation channel |
| x.9                   |                             | CO2 gas reflux in the exhaust duct of the ventilation of a neighbouring local | Avoid any excess of the maximum concentration allowed in the room | Determine the maximum possible amount of CO2 before exceeding the high-end CO2 concentration limit and reflect it in the technical documentation and on the equipment | x | x | None |
| x.10                  |                             | Pressure increase following a machine stoppage, valves are spewing | Avoid any pressure increase | The machine keeps the NC blanking valves open and maintain old water supply in the heat exchanger; contacting phases achieves a buffer effect | x | x | Electrical power failure: blanking valves close, the pressure increases and the valves spew, see risk x.7 |