

RISK ANALYSIS OF HEATING AND REFRIGERATION SYSTEMS WITH NATURAL WORKING FLUIDS

Felix K. Gmünder, Martin Wolfer, and Esther Seitz

Basler & Hofmann, Consulting Engineers, Forchstrasse 395, CH-8029 Zürich, Switzerland

ABSTRACT

This paper deals with the risk of natural working fluids (refrigerants) thought to replace halogenated hydrocarbons (CFHC, FHC) in heating and refrigerating machinery such as heat pumps in homes and freezers in markets. Halogenated hydrocarbons are safe for man but destroy the ozone layer in the stratosphere and contribute to the greenhouse effect. In contrast, natural working fluids are environmentally friendly, but they are either toxic (ammonia) or flammable (hydrocarbons). To find out if the risk of natural working fluids for installers, maintenance staff, homeowners, and shoppers is acceptable, quantitative risk analysis of generic model-systems was performed. The following systems were investigated: (i) a heat pump in a single-family home with 1 kg of propane or ammonia, (ii) a central refrigerator system in a supermarket with 20 kg of propene or ammonia, and (iii) 50 refrigeration/freezer-units (in the shopping area) in a supermarket with 200 g of working fluid in each single unit (ammonia or propane).

Heat pumps in homes using propane as a working fluid were found acceptable for both homeowners and installers/servicing staff. If ammonia is used, the risk for installers and servicing staff is not negligible. The estimated societal risk for a central cooling system in supermarkets displayed as a frequency consequence curve is acceptable for both ammonia and propene as working fluids with respect to fatalities, injuries and damage to building. The risk of individual freezers/refrigerators was more difficult to model and calculate. Nevertheless, the results suggest that the application of propane is a safety issue whereas the risk of ammonia is negligible when societal risk criteria are applied.

KEYWORDS

Risk, Safety, Working fluid, Heat pump, Refrigerator, Freezer, Halogenated hydrocarbon, Ammonia, Propane, Propene

INTRODUCTION

Halogenated hydrocarbons such as chlorofluorocarbons (CFC, HCFC, and HFC) have been used as working fluids (refrigerants) in heat pumps and in refrigerating machinery to absorb and transfer heat energy. Halogenated hydrocarbons are excellent from a thermodynamic standpoint. In addition, they have an

advantage: they are relatively harmless with regard to toxicity and flammability. This is one reason for the wide use of this material. In fact, halogenated hydrocarbons replaced ammonia, which is toxic, in most applications except in big industrial applications (process cooling). Recently, halogenated hydrocarbons and related chemicals have been banned in Europe because they destroy the ozone layer in the stratosphere and contribute to the greenhouse effect. Instead, in heat pumps and refrigeration systems, natural working fluids such as ammonia, propane or propene are reintroduced. These “natural” gases are environmentally friendly (their contribution to ozone destruction and climate change is negligible) but they are toxic (ammonia) or flammable (hydrocarbons, ammonia to a lesser extent). The question arises as to whether environmental benefits outweigh safety.

In many countries, the use of heat pumps is endorsed and subsidised because they help to conserve fossil fuels. Heat from the ground, air or aquifers is absorbed and transferred to heat the rooms. With heat pumps using either toxic or flammable working fluids on the increase, it is interesting to know if the risk of intoxication, fire, and explosion for homeowners, installers and maintenance staff is relevant and how this risk compares to a conventional heating system using natural gas.

In supermarkets refrigerators and freezers help to protect the quality of food. The refrigeration systems either consist of a central unit in a machine room connected to freezers/refrigerators in the shopping area. Alternatively, the individual freezers and refrigerators in the shopping area are equipped with small units. In supermarkets, the use of a central unit is more economical, but it is not known if the central or the decentralised system is riskier when natural working fluids are used.

METHODS

Scope of the Analysis

The following four systems were included in the quantitative risk analysis (Wolfer et. al., 1999):

- A heat pump in a single-family house with 1 to 2 kg refrigerant. Refrigerants under consideration: ammonia, propane, R 134a.
- This system was compared with a central heating system with natural gas in a single-family house (the risk of such a system is accepted by the public).
- A central cooling system in a supermarket with 20 to 40 kg refrigerants. Refrigerants under consideration: ammonia, propene, R 404A.
- Decentralised cooling and freezer units in a supermarket with approximately 200 g refrigerant. Refrigerants under consideration: ammonia, propane, R 404A

System Definition

The environment for the quantitative risk analysis was defined as follows:

Heat pump in single-family house

- Site: Heat pump in a separate room in the basement: area 15 m², height 2,2 m.
- Ventilation: ventilation of the pump housing with an air exchange rate of 15/h. The ventilation runs continuously when the condenser is running. When the condenser is not running, the ventilation starts when a safety pressure switch indicates a pressure below a certain limit (SNV, 1998 & 2000).
- Maintenance, servicing measures involving the opening of the cooling system (every two years).
- Environment: Single-family house with 500 m³ living space.
- It is assumed that release frequency is independent of the refrigerant.

Central cooling system in a supermarket

- Site: Machine room in the basement, area 40 m², height 3 m.
- Ventilation: ventilation of the room at max. 370 m³/h (SNV, 1998 & 2000). Ventilation is activated and controlled via room temperature and gas detectors.
- Gas detection: Two separate gas detectors. An alarm sounds in the control centre and starts the ventilator.
- Installation, operation, maintenance, and service: two cases are considered.
 - 1) Low standard operational procedures corresponding to a safety level when dealing with halogenated hydrocarbons (non-toxic, inflammable). Normal care, s. Figure 2.
 - 2) High standard operational procedures corresponding to a safety level when dealing with machinery filled with liquefied toxic or flammable gases under pressure (extra care, s. Figure 2).
- Environment: Corridor, length 7 m x 30 m, height 3 m bordering on the machine room. On average, five people are present in this area. Two staircases to the sales area of 1500 m² with 500 customers, on average.

Decentralised cooling and freezing units in a supermarket

- Number: 50 units
- Site: Supermarket sales area (see above).

Risk Analysis

Risk is a function of the possible extent of damage in an incident and the frequency with which this can occur. In this study, damage to people (death and injury), and damage to buildings are analysed. The risk is presented as individual and societal risk (Taylor, 1994).

Individual risk corresponds to the probability that a person (e.g. the house owner or the installer) is injured or killed as the result of an accident. Individual risk is used to answer the question if the house owner and his family runs a relevant risk if he or she decides to install a heat pump filled with propane or ammonia. In addition, it is also important to know if this risk is acceptable to the pump installer and maintenance staff.

Societal risk is represented as a cumulative frequency consequence curve. The frequency consequence curves are compared with societal risk criteria used in Switzerland (SAEFL, 1996b) to answer the question if the risk of natural refrigerants in a supermarket is acceptable to the public or not.

Risk Criteria

Table 1 shows individual risks in Switzerland.

TABLE 1 INDIVIDUAL RISKS IN SWITZERLAND PER 100 000 MAN-YEARS

Cause	Individual risk per 100 000 man years
Alcohol (80 g/day)	680
Smoking	410
Mountain climbing	70
Car travel	10
Pedestrian	3
Fire	0,5
Drowning	0,5
Electricity	0,4
Lightening strike	0,05
Snake bite	0,001

While the greatest risks in Table 1 are considered as “voluntary risks”, the risks at the bottom of the list are of a more “imposed risk” nature. The borderline between these is located at about $1 \cdot 10^{-5}$ per year. New technical risks should certainly be considerably less than this value. In comparison, the lowest mortality rate in Switzerland is that of girls aged about 10 at around $1.5 \cdot 10^{-4}$.

Thus, for this study the risk criterion of death and injury to be acceptable (or negligible) for people is proposed to be at 10^{-6} and 10^{-5} , respectively. Individual risks 100-times higher than these limits are considered not acceptable.

Societal risk criteria have been defined in Switzerland in the framework of the “Ordinance on Protection against Major Accidents” (OMA, 1991). However, these criteria only cover accidents that may cause serious damage, i.e., for example, those with more than 10 fatalities. For this study the risk criteria of the OMA (SAEFL 1996b) were extrapolated into the domain of no serious damage, i.e. below 10 fatalities or 100 injuries.

Models and Data

This study is based on earlier work carried out by Basler & Hofmann and others (SAEFL, 1996a & 1999). Most data for the risk analysis come from the following sources: Berghmans (1994), TNO (1996 & 1997), Calor Gas (1998), Kataoka (1998), and SAEFL (1999). Leakage, gas diffusion and distribution, and consequence analysis was described by Clodic (1997 & 1999), in the “Yellow”, and in the “Green Book” (Committee 1992a & 1992b).

RESULTS

Heat Pump in Single-family House

The individual risks for the house owner and the installer are shown in Figure 1. Keep in mind that the numerical values are only valid for the system investigated and cannot be transferred to other systems, i.e. other equipment in another environment.

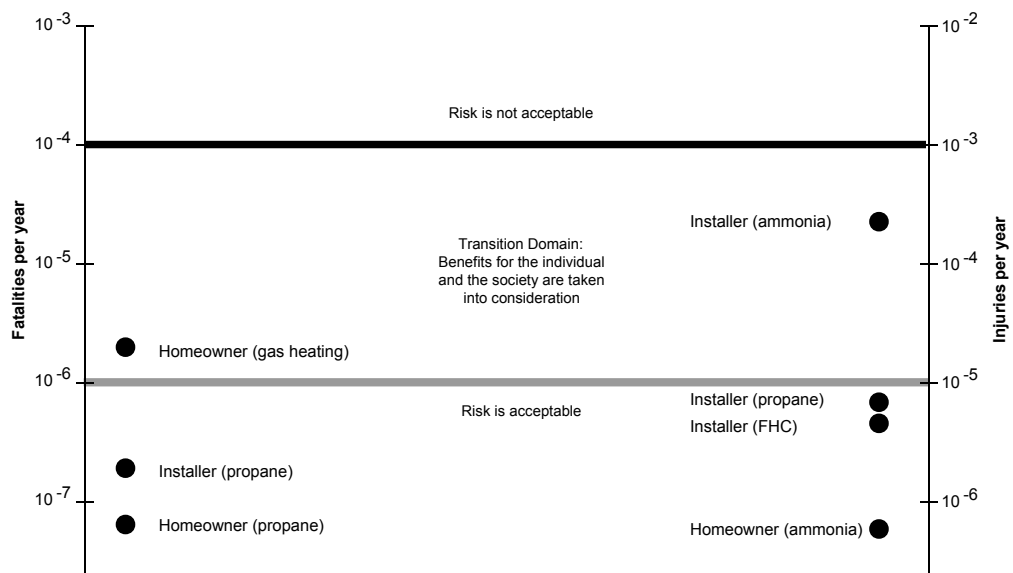


Figure 1: Individual risk of different working fluids in a heat pump compared to gas central heating (single family home). The results on the left-hand side of the graph relate to the left-hand scale, those on the right-hand relate to the right-hand scale. Risks below the lower line are acceptable; risks above the upper line are

not acceptable. Risks in the “transition domain” must be evaluated considering individual, economic, and environmental benefits.

Central Cooling System in a Supermarket

The societal risk for the employees and patrons in a supermarket are shown in Figure 2. The curves marked “normal care” in the legend are based on the release frequency that is today normal for FHC systems (statistical values). The other three curves marked “extra care” assume a safety standard in manufacture, installation, operation and maintenance of the system that is comparable to ammonia systems in ice rinks (generic values). Risks below the bottom line are acceptable; risks above the extrapolated acceptability line are not acceptable in accordance with SAEFL (1996b). Risks in the “transition domain” must be evaluated including individual, economic, and environmental benefits. A “damage value” (SAEFL, 1996b) of 0 represents 1 fatality or 10 people injured, a value of -0.3 represents 1 person injured, a value of $+0.3$ represents ten fatalities or 100 people injured.

Note that the results shown are only valid for the system investigated and cannot be transferred to other systems, i.e. other equipment in another environment.

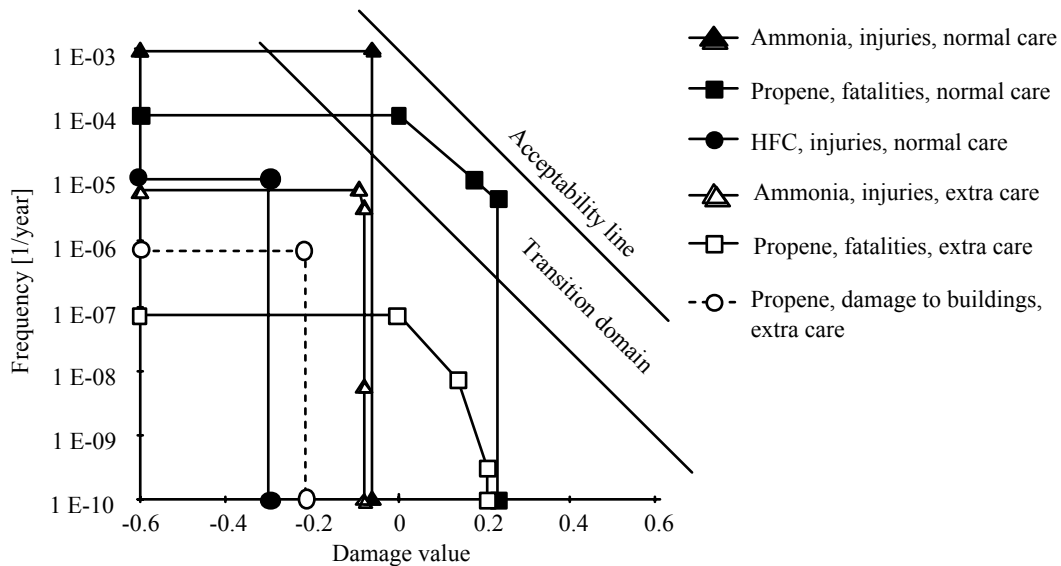


Figure 2: Societal risk of central cooling systems in a supermarket. Damage values of 0 and 0.3 correspond to 1 and 10 fatalities or 10 and 100 injured people, respectively.

Decentralised cooling and freezing units in a supermarket

The societal risk for employees and patrons in a supermarket are shown in Figure 3. Note that the results shown apply only for the system investigated.

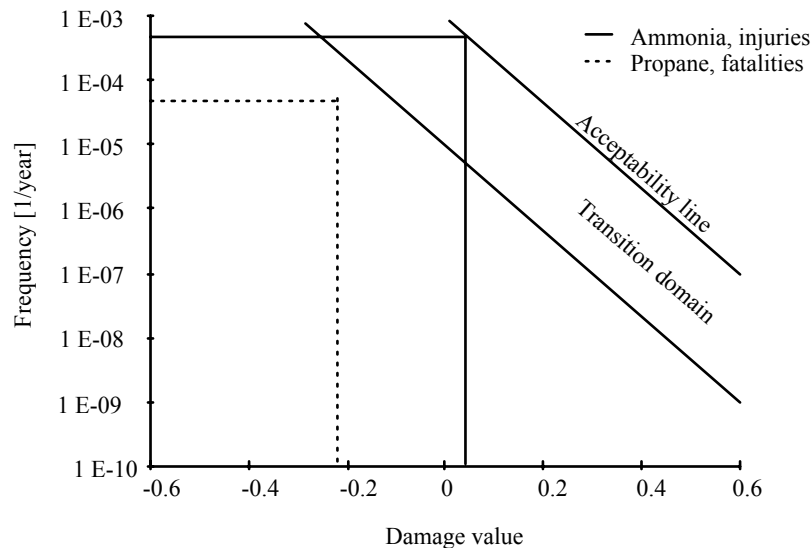


Figure 3: Societal risk of 50 decentralised cooling and freezing units in a supermarket. Damage values of 0 and 0.3 correspond to 1 and 10 fatalities or 10 and 100 injured people, respectively.

DISCUSSION

- When discussing the results it must be considered that simplified generic risk models have been used. Nevertheless, we feel competent enough to make the following statements:
- The individual risk for the people living in a single-family house is negligible when heat pumps with ammonia or propane are installed, the heat pump is state-of-the-art, and the capacity is less than 1 kg of refrigerant. Heating with natural gas is riskier. The results presented here cannot be extrapolated to systems with a capacity of more than 1 kg.
- However, the individual risk for the installer is relatively high as compared to halogenated hydrocarbons if he or she is not properly trained and does not take extra care when dealing with ammonia-containing heat pumps. The risk of a propane system is comparable to one filled with halogenated hydrocarbons.
- The risk of central refrigerator/freezer systems in supermarkets, which contain ammonia or propene and have a refrigerant capacity of approximately 20 kg, is acceptable to shoppers if the system is professionally installed, operated, and maintained, and if in case of an accidental release the refrigerant cannot flow directly into the sales area. If the machine room is adjacent to the sales area or another area with a large number of people, additional safety measures must be implemented (e.g. wide separation of machine room from sales area, pressure release vents, sprinklers).
- Decentralised cooling and freezing units in the sales area using propane or ammonia as a refrigerant could pose unacceptable risks under certain circumstances. This must be examined with a detailed analysis based on the case in hand.
- In short, natural working fluids are a win-win-solution: Environmental benefits and acceptable risks if handling and safety measures meet a high standard. This includes professional manufacture, installation, maintenance, and operation.

REFERENCES

- Berghmans, J. (1994). *Working Fluid Safety*. Annex 20, Report No. HPP-AN20-1, IEA Heat Pump Programme, ISBN 90-73741-10-6, IAE Heat Pump Centre, Sittard, The Netherlands.
- Calor Gas (1998). *Risk Assessment of Flammable Refrigerants*. CEN/TC 182/WG 5, Part N40. Secretariat CEN/TC, Deutsches Institut für Normung e.V., Kamekestr. 8, D-50672 Köln, Germany.

Clodic, D. (1997). *Diffusion of Flammables in Rooms Due to Leaks From Portable Air-conditioners or Refrigerators Working With Propane or Isobutane*. 12 pages, CEN/TC 182/WG 5, N2. Secretariat CEN/TC, Deutsches Institut für Normung e.V., Kamekestr. 8, D-50672 Köln, Germany.

Clodic, D. (1999). *Commentaires français sur le document CEN/TC 182/WG5 N30 relatifs au „risk assessment“ présenté lors de la réunion du Groupe de travail CEN/TC 182/WG 5 à Berlin le 22 septembre 1998*. CEN/TC 182/WG 5, N43. Secretariat CEN/TC, Deutsches Institut für Normung e.V., Kamekestr. 8, D-50672 Köln, Germany.

Committee (1992a). *"Methods for the determination of possible damage"*. Committee for the Prevention of Disasters, CPR16E, (Green Book), The Hague, The Netherlands

Committee (1992b). *"Methods for the calculation of physical effects"*. Committee for the Prevention of Disasters, CPR14E, (Yellow Book), The Hague, The Netherlands

Kataoka, O. (1998). Comments on (1) Most Dangerous Life Stage of Equipment and (2) Ignition Sources. CEN/TC 182/WG 5, N38. Secretariat CEN/TC, Deutsches Institut für Normung e.V., Kamekestr. 8, D-50672 Köln, Germany.

OMA (1991). *Swiss Ordinance on Protection against Major Accidents (Ordinance on Major Accidents, OMA)*, SR 814.012, (in English, French or German) February 27, 1991 (Updated July 1994).

SAEFL (1996a). *Case Study of a Risk Study for a LPG Storage Vessel, Ordinance on Major Accidents*. (In French or German), Swiss Agency for the Environment, Forests and Landscape (SAEFL), Berne.

SAEFL (1996b). *Evaluation Criteria for the Ordinance on Major Accidents, OMA. Evaluation of the Extent of Damage, Evaluation of the Acceptability of Risk, Guidelines for Establishments with Substances, products or Special Wastes*. (In French or German), Swiss Agency for the Environment, Forests and Landscape (SAEFL), Berne, 1996.

SAEFL (1999). *Case Study of a Risk Study for an Ammonia-Based Cooling Process in a Public Ice Rink*. (in French or German). Swiss Agency for the Environment, Forests and Landscape (SAEFL), Berne, 1999 (draft edition).

SNV (1998). Schweizerische Normenvereinigung: *Kälteanlagen - Anforderungen in Bezug auf den Aufstellungsort*. SN 253130, Switzerland.

SNV (2000). Schweizerische Normenvereinigung: *Kälteanlagen - Anforderungen in Bezug auf den Aufstellungsort*. Änderung 2000. SN 253130/A2, Switzerland.

Taylor, J.R (1994). *Risk Analysis for Process Plant, Pipelines and Transport*. E&FN Spon, London, U.K.

TNO (1996). TNO-MEP-R 96/477, *Risk Assessment of Typical Cooling and Heating Systems Using Natural Working Fluids*. Part: Propane Residential Heat Pump.

TNO (1997). *Risk Assessment of Typical Cooling and Heating Systems Using Natural Working Fluids*. TNO-Reports in CEN/TC 182/WG 5, Parts N6, N7, N8, and N9. Secretariat CEN/TC, Deutsches Institut für Normung e.V., Kamekestr. 8, D-50672 Köln, Germany.

Wolfert, M., Seitz, E. and Seiler, H. (1999). *Ammoniak und Kohlenwasserstoffe als Kältemittel: Risikoanalyse, Produkthaftpflicht und Strafrecht*. Bundesamt für Energie, Forschungsprogramm Umgebungs- und Abwärme, Wärme-Kraft-Kopplung (UAW). Schlussbericht. This report is available in the internet (in German): http://www.bhz.ch/fragen/2001/05/Kaeltemittel_RA_SB.pdf.

ACKNOWLEDGEMENT

This work was prepared for the Swiss Federal Office of Energy (SFOE) and supported by both the SFOE and the Swiss Agency for the Environment, Forests and Landscape (SAEFL).