

A RISK– BASED DESIGN OF AMMONIA REFRIGERATION SYSTEMS IN FOOD MANUFACTURING PLANTS

P.S. BISCOTTI[†], M.A. REINHEIMER^{†‡} and N.J. SCENNA^{†‡}

[†] CAIMI –Centro de Aplicaciones Informáticas y Modelado en Ingeniería-UTN, FRRO – Universidad Tecnológica Nacional, Facultad Regional Rosario, Rosario – Argentina

[‡] CONICET –Consejo Nacional de Investigaciones Científicas y Técnicas

Email: pbiscotti@frro.utn.edu.ar, mareinheimer@santafe-conicet.gov.ar, nscenna@frro.utn.edu.ar

Abstract— This paper presents a risk-based design procedure of ammonia based refrigeration processes taking into account the allocation of the manufacturing plant and the surrounding environment vulnerability at early stages of process design. In addition, the proposed design framework allows the integration of a process simulator with vulnerability assessment packages. As a case study, the design of the refrigeration system for a surimi manufacturing plant is presented.

Keywords— Ammonia refrigeration; risk-based design; design software.

I. INTRODUCTION

Industrial refrigeration systems use ammonia for many reasons. However, it is known that ammonia releases may cause severe damage due to its toxicity and potential ignition in air mixtures. Accidental ammonia releases in food facilities are well documented (see for example, Berry, 2009 and Gathright, 2010).

Release consequences can be food contamination and/or surrounding damages (product, equipment, operators, population and environment). Food ammonia contamination causes are commonly identified and evaluated using Hazard Analysis and Critical Control Point (HACCP). Our objective is to take into account hazardous events at early steps of the design task, moving towards an inherent safe design philosophy. We will here consider only equipment, operator, population and environment vulnerability. A software system and a procedure for risk-based design will be presented.

The paper is organized as follows. Section 2 briefly describes the proposed methodology and the design tool, named CEIBO (Ponzzone *et al* 2015, 2017). In Section 3 the design method is applied to a specific case study: the conceptual design of an ammonia refrigeration facility for a surimi processing plant. According to the design procedure, a preliminary layout will be adopted and vulnerability analysis will be made to evaluate if layout or process modifications are necessary to achieve the final design. Finally, in Section 4 conclusions are presented.

II. A RISK-BASED DESIGN PROCEDURE FOR AMMONIA REFRIGERATION SYSTEMS IN FOOD INDUSTRIES

Our design method takes into account inherent safety design principles and project constrains. Inherently safer design philosophy is a proactive approach for process design taking into account hazard/risk management (see

Kletz, 1991). The general principles of inherent safety design are: substitution, intensification, attenuation, simplification, error tolerance and limitation of effects. However, several constrains must be handled. So, a trade off among desirable choices and practical constraints always appears.

In order to implement risk-based design procedures, it is important to handle adequate computer tools. In fact, an important difficulty reported in the literature is the lack of compatibility among computer aided design packages and risk analysis assessment software. For example, process simulator outputs are very “hard” to be fed to risk and vulnerability assessment software. Moreover, two key points are quality and quantity of necessary data to perform risk assessment, which generally are not at hand at early stages of conceptual design.

Figure 1 shows the proposed risk-based design methodology. As can be appreciated, firstly, a preliminary risk analysis is made, and a basic structure (the process flowsheet) is adopted considering design objectives and raw materials. This flowsheet is achieved after making the synthesis, simulation and optimization steps as usual. From mass and energy balances, equipment units are designed or adopted and also basic control strategies are proposed. For all these steps, principles of safe design are considered. Indeed, hazard identification analysis (HAZOP, check lists, others) are applied as usual.

Taking into account identified hazards it is possible to design (or adopt) piping and isometric diagrams and the control system and safety devices (active, passive and Instrumented Safety Systems). Safety system must be designed according to process operation conditions, existing regulations and identified dangerous events. After this step, a preliminary layout is proposed taking into account all process information and specific heuristics for layout design. According to our procedure, the actual design is evaluated considering hazardous events and environmental vulnerability. Consequences associated to potential releases are assessed. In addition, safety distances are calculated.

If safety distances are satisfactory, the preliminary layout becomes the definitive one. If not, adequate layout modifications must be done.

The modified design is then iteratively evaluated. If safety distances are satisfactory, the current layout becomes the definitive one. If not, adequate layout modi-

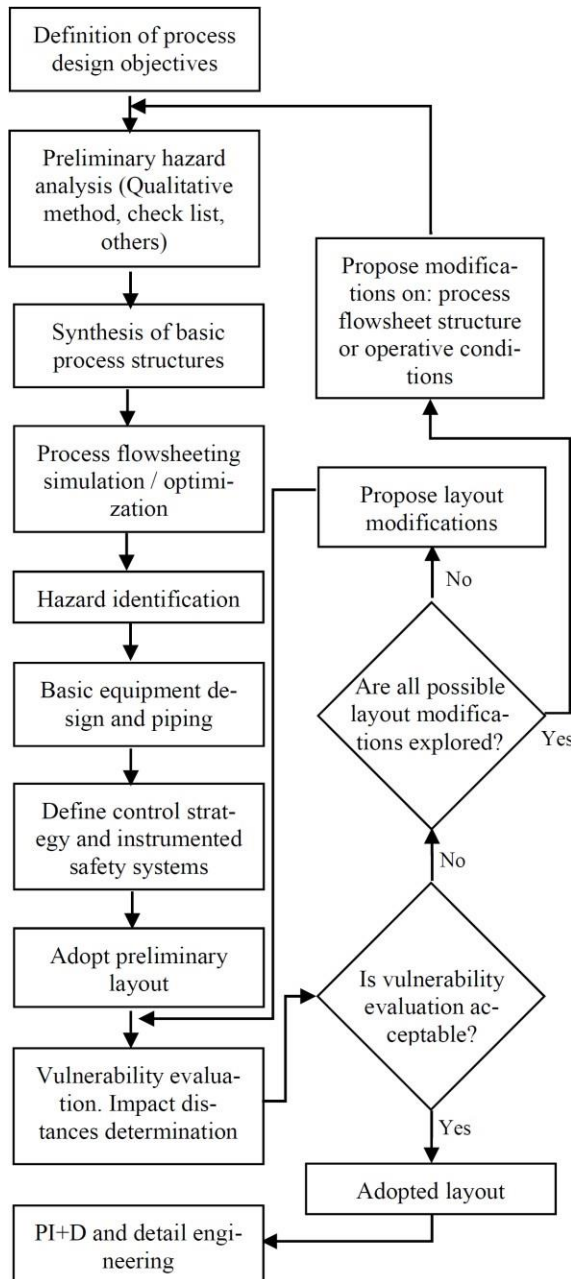


Fig. 1: Methodology for risk-based design.

fycations must be done. In case to achieve a given number of iterations (alternatives or feasible layout modifications), changes in flowsheet structure or process operating conditions (such as pressures and temperatures) must be proposed, starting once again the iteration loop as is indicated in Fig 1.

Here we use an own prototype (a design software system) which was built to support the proposed design task. Although this approach and the prototype software can be used in a general context, we focus on the specific case of ammonia based refrigeration systems.

The software system (CEIBO) couples a process simulator (HYSYS) with specific models for vulnerability/risk assessment. HYSYS is used to solve mass and energy balances and to size equipment units. CEIBO also allows to represent the layout in order to calculate safe

distances (Ponzone *et al.* 2015, 2017).

III. STUDY CASE: SURIMI MANUFACTURING PROCESS. DESIGN OF A SAFE REFRIGERATION SYSTEM

The procedure in Figure 1 is implemented step by step for the design of the refrigeration system of a surimi manufacturing plant.

The term surimi refers to myofibrillar protein extracted from minced and water-washed fish tissue that is stored frozen. The worldwide surimi industry activity is increasing nowadays to produce new value-added food products enabling the market expansion.

A. Process Flowsheet Simulation and optimization. Basic equipment design

The basic steps in the manufacturing process of frozen surimi are (Park and Lin, 2005):

1. Holding fish, sorting by size and cleaning.
2. Fish meat separation (heading, gutting, deboning and mincing).
3. Preliminary washing (to remove the blood and adherent particles)
4. Leaching process (minced meat acquires gel-forming capability)
5. Refined, dewatered and mixed with cryoprotectants (sugar, sorbitol, polyphosphate) for long-term frozen storage

The process requires refrigeration utilities at many process stages, like whole fish reception and storage, freezing and frozen surimi storage, as well as for conditioning cold water utility streams used in the leaching stage. These processes are operated generally in a semi-continuous mode (8-hour day). However, the refrigeration system must be continuously available; and it must account for load variations, which depend on demand (production orders) and atmospheric conditions.

The plant here analyzed processes 42 tn/day of fresh fish, in order to produce 10 tn/day of frozen surimi. The cold storage of the fresh fish must be maintained at 0°C. During the freezing stage, the product temperature is reduced from 2 °C to -30 °. The product must be maintained at -25 °C.

According to our inherent safe design methodology, the first step is the adoption of the refrigerant. In several works carbon dioxide, sulfur dioxide and methyl chloride have been analyzed as alternative, friendly refrigerants. However, the refrigeration industry adopts ammonia as the most convenient refrigerant (Fairchild and Baxter, 1995). Nowadays, ammonia refrigeration systems are still the backbone of the food industry. So, this refrigerant is selected.

In order to design the refrigeration system, we must accomplish:

1. Calculation of materials flowrates given a product rate.
2. Statement of the cold and freezer storage conditions (raw materials and products).
3. Calculation of the thermal loads.
4. Definition of the storage chamber dimensions (cold

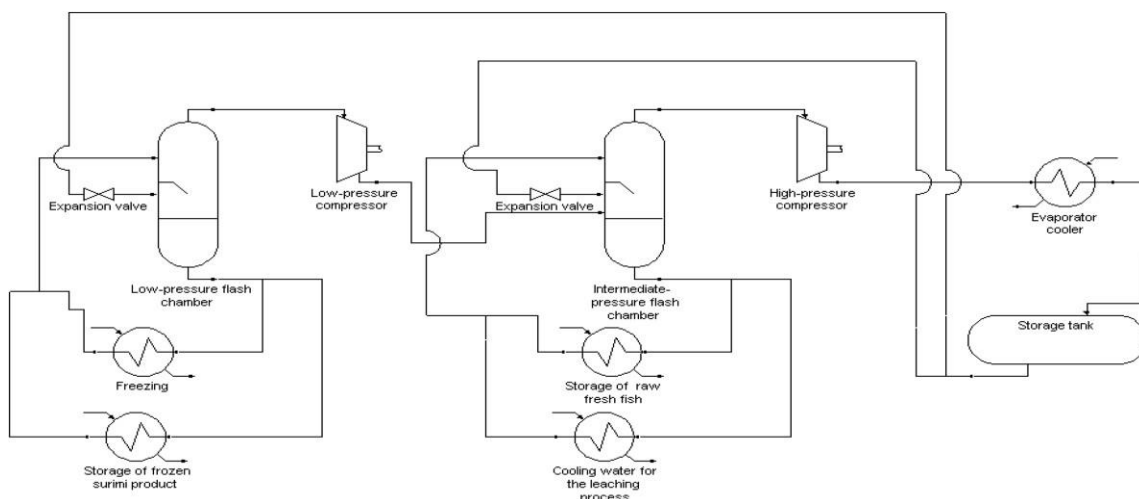


Fig. 2: Simplified refrigeration cycle flowsheet.

- and freezer).
5. Adoption of the Refrigeration System structure.
6. Calculation of the ammonia flow rate and inventory to satisfy the required demand.

Cold and freezer storage dimensions are adopted using typical guidelines and heuristics (Kolbe and Kramer, 1993) as well as total installed capacity necessary to satisfy the calculated demand. It must be remarked that the principal objective of this work is to introduce a risk-based design methodology, and not to deeply analyze each design step of the full process.

Here a conventional closed loop ammonia refrigeration system is adopted. A two stages compression system is selected in order to improve energy efficiency.

The schematic flowsheet is shown in Fig. 2. The ammonia system is operated at three design levels of saturated temperatures and pressures: -35°C (93.7 kPa), 10°C (291.8 kPa) and 35°C (1,351 kPa). Compressors adiabatic efficiencies are assumed (75%). An ammonia purge stream is introduced as well as a make-up feed in order to replace losses.

This process is simulated / optimized using HYSYS. After process streams (flow rates, compositions, pressures, temperatures) and thermal loads are calculated, we evaluate the ammonia inventory at different conditions, in order to design or adopt process equipment, tanks and others auxiliary systems. Regarding ammonia refrigeration systems, several key points must be addressed. In general, ammonia releases can occur during transportation, charge or discharge, storage or during process operation. Accidental release from storage vessels can result from improper design and installation (including improperly designed relief valves), thermal expansion or contraction, corrosion, overfilling, or external damage. Specific guidelines such as Process Safety Management (PSM) (Standard, 29 CFR 1910.119), must be considered.

B. Preliminary layout

The preliminary layout of the surimi manufacturing plant (Fig. 3) is proposed following general heuristics and

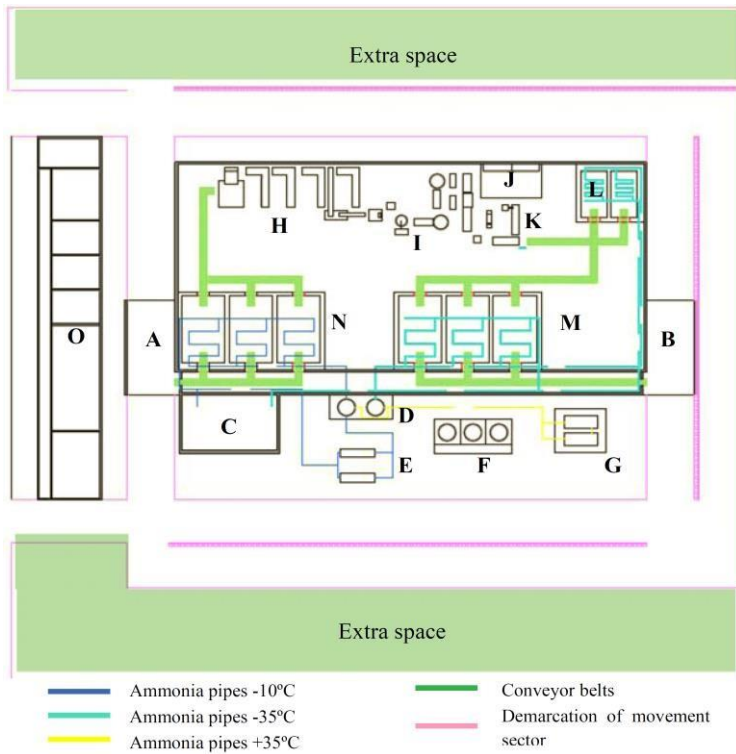
specifications used in surimi manufacturing industry (Canpolar Inc., 1988). In general, from the safety viewpoint, plant layout is largely constrained by the need to maintain minimum safe separation distances between facilities. Adequate separation is often done by grouping facilities of similar hazards together. However, space among facilities is always limited and more separation gives more capital and operating costs due to the usage of more land and piping, among others (Jung, 2010).

Process simulation (HYSYS) data can be used by CEIBO to draw the preliminary layout according to user input data. So, all “geographical” data are stored in CEIBO and process data in HYSYS.

C. Hazard identification and impact distance calculation

In CEIBO, following the AIChE -Guidelines for Chemical Process Quantitative Risk Analysis- (CCPS, 2000), several generic event trees are codified. Figure 4 shows possible scenarios associated with ammonia leakages. In our case, the amount of ammonia released is one of the main variables for evaluation of leakage consequences, as well as its aggregation state. Holdup, pressure and temperature determine the strength of the release. In general, in ammonia - air mixtures fire and/or explosion hazard may occur (confined or unconfined vapor cloud explosion -VCE / UVCE-). Ammonia vapor cloud can also diffuse and depending on the atmospheric ammonia concentration, dangerous levels can be overcome at long distances.

Ramabrahmam *et al.* (1996) and Gangopadhyay and Das (2008) analyzed specific incident/accident data related to ammonia refrigeration systems. They concluded from existing empiric data that valve and pipe leakages and seal blow outs are the most frequent incidents. Storage vessels leakages are uncommon and unconfined vapor cloud explosion and catastrophic ruptures are highly unlikely. Regarding release mechanisms, pipe cracking is more probable than punched holes. Release rates are more likely from 1 mm to 2 mm holes being larger holes more unlikely.



where:

- A. Dumpsite for fresh products
- B. Loading sector of frozen products
- C. Compressor room
- D. Ammonia storage vessels at -35°C and -10°C
- E. Heat exchangers for conditioning washing water stream
- F. Evaporative cooled condenser (+35°C)
- G. Horizontal liquid ammonia vessels at (+35°C)
- H. Heading, gutting and preliminary washing and deboning stages
- I. Leaching stage
- J. Laboratory
- K. Packaging sector
- L. Freezer
- M. Freezer storage at -25 °C
- N. Cold storage at 0 °C
- O. Administrative offices

Fig. 3: Preliminary layout for a surimi manufacturing process.

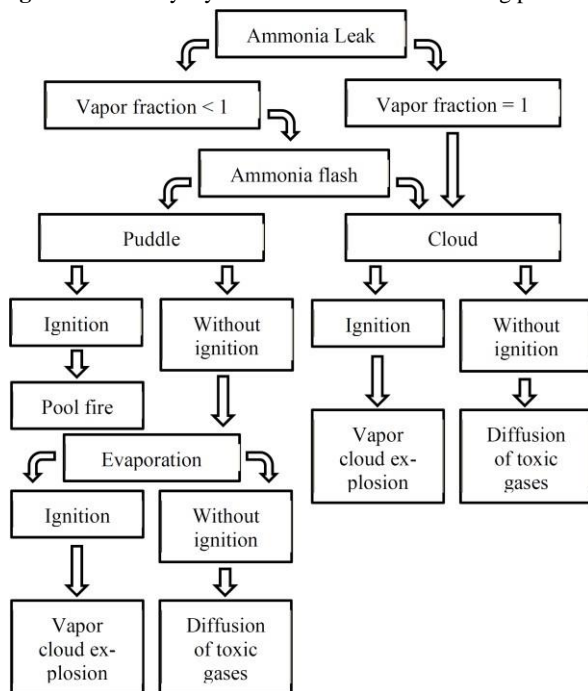


Fig. 4: Event tree of ammonia leakage.

Safety distances are of major concern in land planning and the placement of industries near urban areas. Quantification of safety distances is often done by consequence analysis or risk assessment approaches; or both simultaneously, adopting the greater of safety distances so calculated. In consequence analysis the worst-case is generally adopted as reference scenario, and frequencies are not used. Contrarily, in risk based approaches, both the consequences and the frequencies are used.

It is known that both methods give very different safety distances in many cases. In particular, when very high inventories are involved and very high consequences / very low frequencies are expected.

Some land-using planning criteria or legislation adopt LC1 (lethal concentrations which causes mortality of 1% of the exposed population) as a criterion for safety distance calculation while others use IDLH (Immediately Dangerous to Life and Health Limit). For Risk-based criteria, in general the adopted target is 10^{-06} (death per year) for safety distances calculation, for a single new risk source. In many countries a combination of risk levels and frequencies are used as a criterion for safety distances calculation.

Yu *et al.* (2009) analyzed safety distance assessment for chemical industries in an industrial park in China. In their work they adopted a consequence based approach combined with different frequencies values. They introduced four safety levels, taking into account four frequencies intervals and four consequences levels. For example, for relatively probable and frequent events (10^{-04} to 10^{-02}) they associated the consequence indicator “irreversible health effect” or mortality of 1% of the exposed population (which is the criterion to assess the safety distances); and for improbable or remote events (frequencies lesser than 10^{-05}) the mortality level they associated is 75% of the exposed population.

In our case, the “consequence approach” is attractive due to its ease of implementation at the first step of the design procedure. However, it is also important to consider events frequencies. This can be done if a risk target is adopted. Here we choose as a target for each single event a risk of 10^{-08} -death per year- (for safety distances

assessment). So, according to this criterion, for each

event frequency it the corresponding criterion for safe distance calculation (indicator) can be determined. For example, for relatively high frequency events ($F=10^{-3}$), safety distances are calculated (according to the risk definition) considering a death probability of 10^{-5} . For low frequency events ($F=10^{-8}$), the critical distance we consider corresponds to the one for which the associated death probability is 1; and for medium frequency events ($F=10^{-5}$), the criterion for safety distance assessment is a probability of 10^{-3} .

For safe distances assessment, the release frequencies are combined with wind direction frequencies (wind rose). Here, it is assumed an equally distributed frequency distribution (12 sectors, 30° each one, $P_{wind} = 0.0833$ for each one). The probit equation is used to evaluate death probabilities, which depends on the dose and exposure time. For toxic gases, the probit function is defined as follow:

$$Pr = a + b \cdot \ln(C^n \cdot t) \quad (1)$$

where Pr is the probit, C is the toxic concentration in the air being inhaled (ppm), t is the exposure time (in minutes); and a, b and n are probit constants (for ammonia $a = -35.9$, $b = 1.85$ and $n = 2$; Lees, 2005).

Table 1 summarizes the used parameters to perform tank leakages simulations to estimate impact distances.

DEGADIS model is used to simulate atmospheric dispersion (Havens and Spicer, 1985; Ramabrahmam *et al.*, 1996). Thus, ammonia concentrations are calculated to estimate death probabilities associated with each hazardous event. Even we have evaluated different releases in several points of the plant, here for limited space and because it is the most representative (dominant) event, only potential storage tank releases will be shown.

According to our safety distance calculation criterion above mentioned, we assess ammonia concentrations as a function of distance for three different potential releases (holes diameters) of the storage tank (point G in Fig 3). In Table 2 the release frequencies, representative holes diameters and calculated safe distances, are indicated.

Table 1. Parameters.

<i>Atmospheric parameters</i>	
Mean wind speed [m/s]	1
Surface roughness	Open land
Mean ambient temperature [$^\circ\text{C}$]	25
Stability	B
Relative humidity [%]	75
<i>Storage horizontal vessel parameters</i>	
Diameter [m]	1.5
Length [m]	3.85
Volume [m^3]	6.8
Aggregate state of the content	Liquid
Temperature [$^\circ\text{C}$]	35
Liquid ammonia mass [kg]	3500
Fill percentage [%]	88

Table 2. Safe distances.

Hole diameter	Release frequency	Wind frequency	Corresp. death frequency	Safety distance (m)
4"	5.0E-07	0.0833	2.4E-01	394
1"	1.0E-05	0.0833	1.2E-02	360
0.25"	1.0E-03	0.0833	1.2E-04	150

The adopted safe distance is the highest value for each analyzed hazardous event. From data shown in Table 2 the safe distance in this case is 394 m.

As it can be seen in Fig 5 (continuous line), there are two small urban zones near the plant in which an impact is produced according to the actual design (zones A and B).

D. Layout or process modifications

Therefore, according to the design procedure (Fig. 1), layout modifications must be done. The first alternative is to rearrange or relocate the whole plant moving it along the free land area. After evaluations of different alternatives using the same methodology above explained, in Figure 5 (dotted line) it is presented a new plant placement for which near urban areas are practically not affected.

Regarding safe distances, evaluated for other release events (pipes for example -not shown-), it is concluded that the most important impact is related to administrative offices (O in Fig. 3) and inside the plant. Therefore, contingency and /or emergency plans are always necessary to organize the evacuation in case of being necessary. The evacuation distances and emergency plans can be easily determined at this step of the process design using CEIBO.

It must be remarked that for safe distances calculation we have not considered any active or passive protection system. It is clear that we can improve the process design and to reduce the risk. For example, adequate devices for early leak detection or diffusion mitigation, such as ammonia sensors, sprinkler systems or shut-off valves, among others (due to normative prescriptions or design decisions).

IV. CONCLUSIONS

In this work, a design methodology is proposed and implemented in order to achieve a risk-based plant design. It is shown that in our case study it is possible to estimate (during early design steps) impact distances due to hazardous events; hence providing crucial information that can be used to improve inherent plant safety. This methodology is easy to implement if an adequate software is at hand. Here, a software prototype (CEIBO) which integrates a process simulator with risk assessment packages is used.

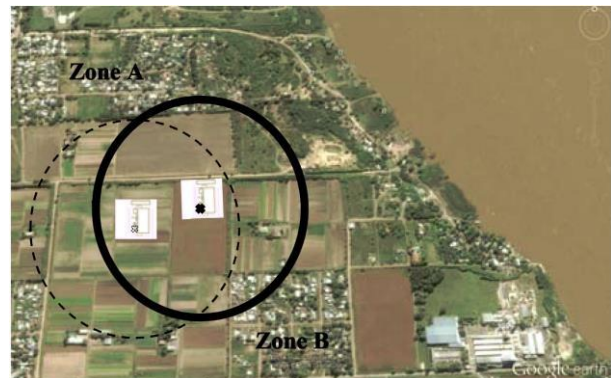


Fig. 5: Impact zone due to the event ammonia release.

As the case study, the design of the refrigeration system for a surimi manufacturing plant is presented. Hazardous events consequences and impact distances are assessed at the earlier design stages in order to improve process safety performance, tending to an inherent safe design philosophy. In fact, a trade off among layout design and the incorporation of new safety devices to achieve a given risk level is highlighted at a very early stage of the design task.

ACKNOWLEDGMENTS

We acknowledge CONICET and the Universidad Tecnológica Nacional (UTN-FRRo) for their financial support.

REFERENCES

- Berry, C., *Ammonia refrigeration systems: process safety management is vital to employee safety*, Hazard Alert, N.C. Department of Labor (NCDOL) (2009).
- Canpolar Inc., Development of Process Controls for Surimi Production. Part I. *Canadian Industry Report of Fisheries and Aquatic Sciences* (1988).
- CCPS, *Guidelines for Chemical Process Quantitative Risk Analysis*, Centre for Chemical Process Safety, The American Institute of Chemical Engineering, New York (2000).
- Fairchild, P.D. and V.D. Baxter, "Ammonia usage in vapor compression for refrigeration and air-conditioning in the United States," *IEA Annex 22 Workshop on Compression Systems with Natural Working Fluids Applications* (1995).
- Gangopadhyay, R.K. and S.K. Das, "Ammonia Leakage from Refrigeration Plant and the Management Practice," *Process Safety Progress*, **27**, 15-20 (2008).
- Gathright, A. "Ammonia leak at Coors Plant triggers evacuations," *7 News: Denver News*, <http://www.thedenverchannel.com/news/24228769/detail.html> Retrieved on Oct 27 (2010).
- Havens, J.A. and T.O. Spicer, *Development of an atmospheric dispersion model for heavier-than-air gas mixtures*, I., U.S. Coast Guard (1985).
- Jung, S., *Facility siting and layout optimization based on process safety*. PhD Thesis, Texas A&M University (2010).
- Kletz, T.A., *Plant design for safety – A user friendly approach* (2nd ed.), Taylor and Francis (1991).
- Kolbe, E. and D. Kramer, "Planning seafood cold storage," *Marine Advisory Bulletin*, **46**, University of Alaska Fairbanks (1993).
- Lees, F.P., *Loss prevention in the process industries: hazard identification, assessment and control*, Third edition, Ed. S. Mannan, Elsevier Butterworth-Heinemann (2005).
- Park, J.W. and T.M.J. Lin, "Surimi: Manufacturing and Evaluation," *Surimi and Surimi Seafood*, 2nd Edn., CRC Press, Florida, 33-106 (2005).
- Ponzzone, D., S. Viscusso, P. Biscotti, N. Rodriguez, S. Godoy and N. Scenna, "CEIBO: Un sistema informático para el diseño inherentemente seguro de procesos," *CLICAP 2015*, San Rafael, Mendoza (2015).
- Ponzzone, D., P. Biscotti and N. Scenna, "CEIBO: Un sistema informático para el diseño, basado en riesgo, de procesos industriales," *46JAIIO*, Córdoba, Argentina (2017)
- Ramabrahmam, B., B. Sreenivasulu and M. Mallikarjunan, "Model on-site emergency plan. Case study: Toxic gas release from an ammonia storage terminal," *Ecological Chemistry and Engineering*, **19**, 297–314 (1996).
- Standard 29 CFR 1910.119, *Process safety management of highly hazardous chemicals*. OSHA. <https://www.wbdg.org/ccb/OSHA/29cfr1910.pdf>
- Yu, Q., Y. Zhang, X. Wang, W.C. Ma and L.M. Chen, "Safety distance assessment of industrial toxic releases based on frequency and consequence: A case study in Shanghai, China," *Journal of Hazardous Materials*, **168**, 955-961 (2009).

Received: October 23, 2017.

Sent to Subject Editor: January 31, 2018.

Accepted: August 8, 2018

Recommended by Subject Editor: Marcelo Seckler