Methodology for Risk Analysis of an Ammonia Tank Refueling Process in a Uranium Hexafluoride Facility using Bayesian Networks

Vitor S. Medeiros
Brazilian Navy Technological Center at São Paulo, Brazil

Marcelo R. Martins
Risk Assessment Laboratory – LabRisco
University of São Paulo, Brazil

1. INTRODUCTION

The nuclear fuel cycle is composed by many processes, from mining to deposition of used fuel. One of these processes is the uranium hexafluoride production which is the gas used in the enrichment step.

In a uranium hexafluoride production facility many chemical substances are used in order to convert from the compound known as "yellow cake" to uranium hexafluoride gas. One of them is the ammonia, a toxic and flammable compound, usually storage as a pressurized liquid.

So, this paper presents a proposed methodology for risk assessment in an ammonia tank refueling process in this type of installation. In order to evaluate the applicability of the proposed methodology, it is used in a case study of a real system.

2. OBJECTIVES

This paper aims to propose a practical and applicable methodology for assessing the risk for people (individual and societal risks) posed by an ammonia tank refueling process in a uranium hexafluoride facility. For this purpose, the paper proposes the use of techniques and models based on its strengths against other traditional ones.

3. PROPOSED METHODOLOGY

This paper proposes a methodology that combines techniques in order to obtain an applicable and useful sequence to the evaluation of risk in the kind of site that the study is focus on.

The sequence proposed to this methodology is composed by five steps: familiarization, evaluation of probability of occurrence, consequence estimation, risk estimation and risk control options definition.

3.1 Familiarization

In this step, all the main features of the system should be identified to guarantee that the following analysis can be representative and adequate for the system. It is important that the analyst knows all the characteristics of the system, in order to create a realistic simulation.

3.2 Evaluation of Probability of Occurrence

For the estimation of occurrence probability of an event, it is proposed to use the Bayesian Networks technique. This technique was chosen because of its advantages against traditional ones, like fault tree and event tree analysis. As this advantages, it could be included the possibility of considering the dependency between components, the possibility to consider many states for each node (not only success or failure) and the possibility to consider the chronology of events.

3.3 Consequence Estimation

For the estimation of all possible consequences caused by a leakage, this paper proposes the use of the following models:

3.3.1 Pool Formation

For modeling a pool formation, its dispersion and evaporation this paper recommends to use the model PVAP, described by Witlox [1]. This model was selected due to its adequacy of the case studied, its quality in model interactions of the pool with soil and air, its vaporization and dispersion.

3.3.2 Cloud Dispersion

For modeling cloud dispersion, it is proposed to use the model UDM [2]. It is a proprietary model, from Det Norske Veritas Germanischer Lloyd (DNVGL), that models both heavy and buoyant plumes, with or without jets in any direction, in any condition of release. Furthermore, if the chemical releases in both phases liquid and gas, this model equates the vaporization phenomenon of liquid droplets in the plume before its deposition in the ground. Moreover, this model has the capability to simulate the transition from heavy to buoyant plume, avoiding the linking between two different models for each part of the dispersion.

3.3.3 Overpressure

In case of an explosion, this paper proposes that overpressure should be modeled using Multi-Energy model, described in TNO [3]. This model considers the burn of the cloud in its stoichiometric condition, with semispherical geometry, with center and ignition point at ground level. The model is more realistic than other ones, like the ones that use an equivalent load of TNT, very conservative.

3.3.4 Radiation

If a fire occurs, the radiation from flame could cause negative effects in people, objects and systems. There are three main kinds of fire: jet fire, pool fire and fireball. This paper suggests models to model the intensity of radiation emitted for each of the types of fire:

3.3.4.1 Jet fire

For estimate the radiation emitted from a jet fire it is proposed the model presented by Chamberlain in 1987 [4], which is a semi-empirical model that considers the flame like a solid cone with uniform emissive power. However, this model is only applicable for jets with no more than 45° of inclination to the vertical and consisting only of steam. In case of different ways of release, there should be used the model JSFH-Cook – for liquid or multi-phase releases – or JSFH-Johnson – for horizontal jets or jets with more than 45° of inclination to the vertical, both described by Oke [5].

3.3.4.2 Pool fire

For modeling a pool fire, this paper proposes the use of POLF model, developed by Witlox [6], which combines empirical models that consider the flame like a cylindrical emissive surface, in case of no wind, or an elliptical emissive surface, in case of the presence of wind.

3.3.4.3 Fireball

For modeling a fireball, it is proposed the use of the DNV model, described by Oke [7], which is a combination of two empirical models – HSE and TNO – as an explanation of being more conservative.

3.4 Risk Estimation

The calculation of the risk is carried out by the combination of the probability of occurrence of each scenario with the respective consequence, and adding all of the risks, in order to obtain an individual risk for a person located at a specific distance from the release, and a societal risk to the group of people that is around the location of the release.

3.5 *Risk Control and Options Definition*

The obtained results in all analysis should be compared with international standards in order to evaluate the risk tolerability. So, if the risk values obtained are not tolerable, risk reduction measures should be proposed in order to reduce the probability of occurrence of undesirable events or the consequences of these possible events.

4. CASE STUDY

The proposed methodology was applied in a case study, in order to evaluate its applicability and usefulness. So, the sequence presented on methodology will be followed in this section.

4.1 *Familiarization*

The ammonia storage system – focus of the study – is compound of a pressurized tank, a compressor, a buffer tank, an absorber tank, pipes (5 meters used to transfer liquid ammonia, 10 meters used to transfer gaseous ammonia, and 2 meters after each pressure relief valve), 1 block valve, 15 globe valves, 3 pressure relief valves, an evaporator and 2 flexible hoses. All these components are over a bund, which has 26.4 square meters of area, and a capacity for all liquid ammonia. A schematic representation of the system is shown in Figure 1.

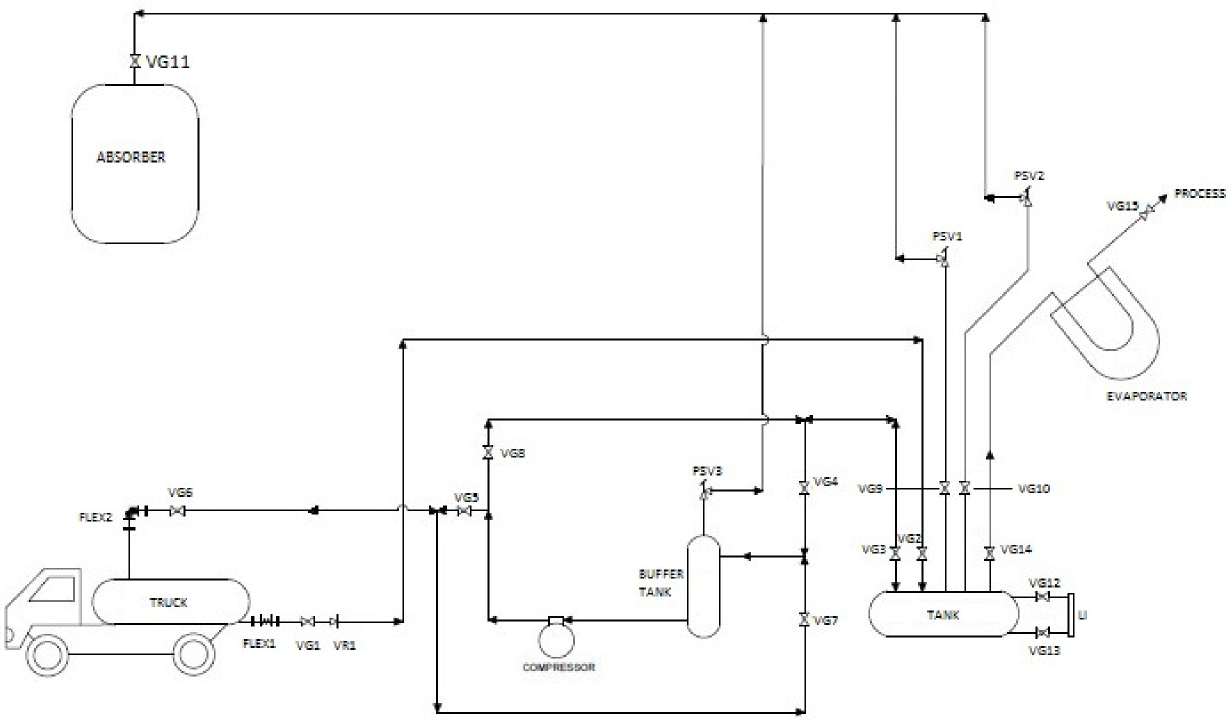

Figure 1 - System analyzed

For this study, it was not considered the line used to distribute ammonia to process, its valves and evaporator. A possible leakage at the truck was not considered too. Due to the solubilization of ammonia in the absorber tank, it was not consider a leakage in there.

During normal operation, ammonia is stored pressurized at between 600 and 1350 kPa, varying according to the ambient temperature, in order to maintain the product in liquid phase.

The refueling process starts with the truck in correct position (next to the tank) and both flexible connectors connected. If the truck is more pressurized than tank, transferring of liquid ammonia will begin by opening valves VG1 and VG2, until pressure is equal in truck and tank. At this moment, or if the pressure inside the truck is equal or below pressure inside the tank, gaseous pipe will be aligned to compression system by opening valves VG3, VG4, VG5 and VG6, so the ammonia inside the truck will be compressed until get a slightly higher pressure than in the tank, in order to restart the liquid ammonia transfer to tank, keeping this gap of pressure until the end of the process. At that time, the compressor is turned off and the alignment of pipes is inverted in order to transfer gaseous ammonia from truck to tank, by closing valves VG4 and VG5 and opening valves VG7 and VG8.

4.2 *Evaluation of Probability of Occurrence*

At this step, a Bayesian Network representing the system was built in order to obtain the probabilities to occur and ammonia leakage during the process of refueling the tank. The Network is shown in Figure 2.

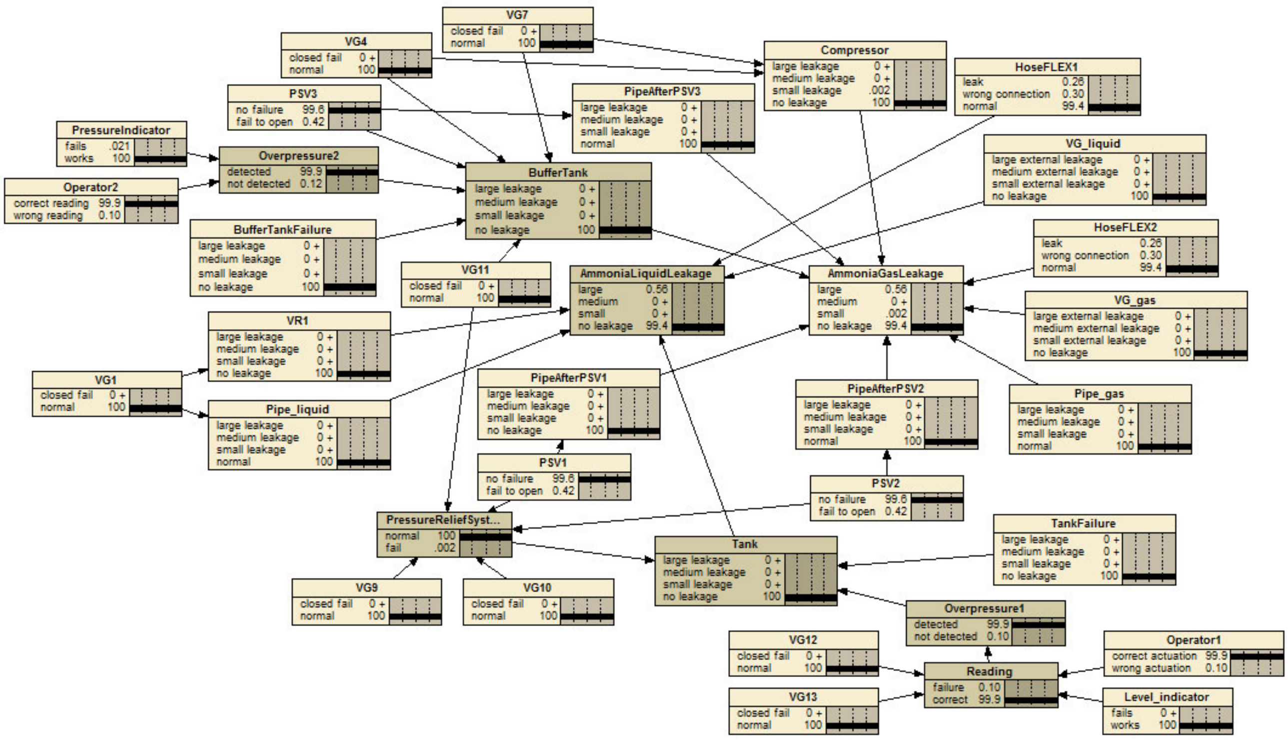

Figure 2 - Bayesian Network

This network considers 6 different possible ways of leakage of ammonia (large, medium or small release of liquid or gas ammonia). The large release was considered being a full rupture of a pipe, or a hole with equivalent size (2") of the pipe diameter. Medium release was considered being a hole in pipes or tank with 0.5" diameter. And small release was considered being a hole in pipes or tank with 0.1" diameter.

For the probabilities' calculation, data from DNV [8], RIAC [9] and USNRC [10] databases were used.

The mission time considered for the system was 24 hours, which represents 6 operations of tank refueling with 4 hours of duration each per year. It is considered that every year the system is verified, so the mission time is limited to one year of use of the system.

4.3 *Consequence Estimation*

The consequence of a possible leakage of ammonia, considering the models presented in Section 3, was evaluated using the software Phast Risk version 6.7.

For modeling consequences, it was necessary to input weather data in the software. It was considered four weather conditions, being “Summer day” and “Winter day” considered with 21% of probability of occurrence during the year each, and “Summer night” and “Winter night” with 29% of probability of occurrence during the year. This data is presented in Table 1.

Table 1 – Weather Data

Weather Data	Summer day	Summer night	Winter day	Winter night
Temperature	24,7 °C	19,9 °C	20,5 °C	15,2 °C
Humidity	63,3%	78,9%	75,5%	71%
Wind velocity	2,2 m/s	1,53 m/s	1,94 m/s	1,16 m/s
Atmospheric stability	D	E	D	G

4.3.1 Pool Formation

In case of a liquid release, an ammonia pool is formed. The model calculated the rate of formation of the pool for each possible release, obtaining the time of 5.9 seconds to reach the maximum radius of the pool for a large leakage, 51.1 seconds for a medium leakage, and 699.6 seconds for a small leakage. The pool was compound by approximately 75% of total inventory of ammonia in a large leakage, 67% in a medium release, and 41% in a small release. The pool has the same area of the bund in large and medium releases cases, and has a maximum of 0.87 meters of diameter in the case of small release.

4.3.2 Cloud Dispersion

The model used determined distances for concentration’s levels. So, it is used to determine the toxic consequences for people and the possibility of occurrence of a flash fire.

For toxic consequences, it was set the ERPG dose, which considers three levels of doses: ERPG-1, which is the level where is expected no adverse effect for people who is exposed up to one hour, ERPG-2, which is the level where is expect no irreversible adverse effect for people who is exposed up to one hour, and ERPG-3, which is the level where is expect no death for people who is exposed up to one hour. For ammonia, these values are 25 ppm (ERPG-1), 150 ppm (ERPG-2) and 750 ppm (ERPG-3).

The distances for these doses are presented from Table 2 to Table 7, for each leakage scenario. In these tables it is possible to notice that distances from scenarios at night and during the winter are higher than the other ones. It happens due to atmospheric stability in these cases, which causes less dilution of the plume.

A flash fire is also considered by the model. For the possibility of a flash fire it is considered the dispersion of the cloud until half of the lower flammable limit (LFL), which represents 8 % of concentration for ammonia. For risk calculations it is considered that inside the cloud the probability of death is 1, and outside it the probability is 0.

The distances where this concentration is reached are presented in Table 8.

Table 2 – Distances for equivalent toxic dose for a large liquid release

Toxic Dose	Summer day	Summer night	Winter day	Winter night
ERPG-1	2617 m	3783.7 m	2785.4 m	10479 m
ERPG-2	1255.1 m	1476.3 m	1377.9 m	2368.7 m
ERPG-3	562.4 m	601.7 m	573.7 m	847.9 m

Table 3 – Distances for equivalent toxic dose for a large gas release

Toxic Dose	Summer day	Summer night	Winter day	Winter night
ERPG-1	1411.6 m	1063.4 m	1264.2 m	1156 m
ERPG-2	613.9 m	527.2 m	574.2 m	405.1 m
ERPG-3	295.5 m	243.8 m	267.4 m	203.9 m

Table 4 – Distances for equivalent toxic dose for a medium liquid release

Toxic Dose	Summer day	Summer night	Winter day	Winter night
ERPG-1	1296.9 m	2129 m	1356.8 m	11854 m
ERPG-2	503.6 m	649.1 m	522 m	1999.9 m
ERPG-3	280.2 m	305.4 m	289.9 m	412.3 m

Table 5 – Distances for equivalent toxic dose for a medium gas release

Toxic Dose	Summer day	Summer night	Winter day	Winter night
ERPG-1	644.8 m	687.2 m	642.6 m	421.8 m
ERPG-2	280.7 m	276.7 m	278.6 m	232.7 m
ERPG-3	157.3 m	134.5 m	149 m	108 m

Table 6 – Distances for equivalent toxic dose for a small liquid release

Toxic Dose	Summer day	Summer night	Winter day	Winter night
ERPG-1	501.2 m	875.3 m	527.8 m	5194.2 m
ERPG-2	181.7 m	275.3 m	191 m	1139.5 m
ERPG-3	84.7 m	95.1 m	89.5 m	121.4 m

Table 7 – Distances for equivalent toxic dose for a small gas release

Toxic Dose	Summer day	Summer night	Winter day	Winter night
ERPG-1	96.3 m	172.8 m	103.5 m	174.6 m
ERPG-2	31.6 m	58.2 m	36.2 m	76.8 m
ERPG-3	12.1 m	16.6 m	12.9 m	24.4 m

Table 8 – Maximum distances of occurrence of a flash fire

Scenario	Summer day	Summer night	Winter day	Winter night
Large liquid release	17.7 m	17.9 m	17.4 m	19.2 m
Large gas release	7.7 m	7.8 m	7.7 m	7.8 m
Medium liquid release	4.7 m	4.7 m	4.7 m	4.7 m
Medium gas release	2 m	2 m	2 m	2 m
Small liquid release	2.2 m	2.2 m	2.2 m	2.3 m
Small gas release	0.4 m	0.4 m	0.4 m	0.4 m

4.3.3 Overpressure

The Multi-Energy model was used with an unconfined factor of 2, which means an area with low confinement. The model do not obtained any explosion; consequently, there was no overpressure effect estimated.

4.3.4 Radiation

For radiation consequences, reference values were used in order to measure the effects for people inside the affected area. The values adopted have the following effects, described by MANNAM [11]:

- 4 kW/m^2: Tolerable limit for people in emergency escape;
- 12.5 kW/m^2: 1% probability of death;
- 37.5 kW/m^2: 100% probability of death.

4.3.4.1 Jet fire

Modeling a possible jet fire, the obtained results for the reference values of radiation are presented from Table 9 to Table 14, for each leakage case. As it can be seen, the value of 37.5 kW/m^2 of radiation is not reached for any of the analyzed scenarios. This happens due to the characteristic of ammonia to have a low flame emissive power. So, although a jet fire occurs, the emitted radiation will be relatively low.

Table 9 – Distances for radiation due to a jet fire for a large liquid release

Radiation level	Summer day	Summer night	Winter day	Winter night
4 kW/m^2	126.8 m	134.9 m	129.6 m	140.4 m
12.5 kW/m^2	109.8 m	117.3 m	112.5 m	122.3 m
37.5 kW/m^2	Not reached	Not reached	Not reached	Not reached

Table 10 – Distances for radiation due to a jet fire for a large gas release

Radiation level	Summer day	Summer night	Winter day	Winter night
4 kW/m^2	38.3 m	40.9 m	39.2 m	42.8 m
12.5 kW/m^2	33.3 m	35.6 m	34.2 m	37.1 m
37.5 kW/m^2	Not reached	Not reached	Not reached	Not reached

Table 11 – Distances for radiation due to a jet fire for a medium liquid release

Radiation level	Summer day	Summer night	Winter day	Winter night
4 kW/m^2	41.8 m	44.5 m	42.7 m	46.1 m
12.5 kW/m^2	36 m	38.3 m	36.8 m	39.6 m
37.5 kW/m^2	Not reached	Not reached	Not reached	Not reached

Table 12 – Distances for radiation due to a jet fire for a medium gas release

Radiation level	Summer day	Summer night	Winter day	Winter night
4 kW/m^2	9.8 m	10.5 m	10 m	10.9 m
12.5 kW/m^2	Not reached	Not reached	Not reached	Not reached
37.5 kW/m^2	Not reached	Not reached	Not reached	Not reached

Table 13 – Distances for radiation due to a jet fire for a small liquid release

Radiation level	Summer day	Summer night	Winter day	Winter night
4 kW/m^2	9.7 m	10.4 m	10 m	10.9 m
12.5 kW/m^2	Not reached	Not reached	Not reached	Not reached
37.5 kW/m^2	Not reached	Not reached	Not reached	Not reached

Table 14 – Distances for radiation due to a jet fire for a small gas release

Radiation level	Summer day	Summer night	Winter day	Winter night
4 kW/m^2	Not reached	Not reached	Not reached	Not reached
12.5 kW/m^2	Not reached	Not reached	Not reached	Not reached
37.5 kW/m^2	Not reached	Not reached	Not reached	Not reached

4.3.4.2 Pool fire

In case of occurrence of a liquid leakage, the pool formed shown in section 4.3.1 can catch fire. It could happen immediately or after a period of time. The specified model calculates distances from the pool to reference values of radiation for early and late pool fire and, for this case study, the distances are the same for the two possible fires. These values are presented from Table 15 to Table 17. As in jet fire, the value of 37.5 kW/m^2 is not reached for any of the scenarios of pool fire due to the ammonia characteristics.

4.3.4.3 Fireball

According to the model used, for the analyzed scenarios, no fireball occurred. So, there wasn't any radiation level estimated.

Table 15 – Distances for radiation due to a pool fire for a large liquid release

Radiation level	Summer day	Summer night	Winter day	Winter night
4 kW/m^2	8.3 m	8.1 m	8.2 m	7.9 m
12.5 kW/m^2	3.9 m	3.9 m	3.9 m	3.9 m
37.5 kW/m^2	Not reached	Not reached	Not reached	Not reached

Table 16 – Distances for radiation due to a jet fire for a medium liquid release

Radiation level	Summer day	Summer night	Winter day	Winter night
4 kW/m^2	8.3 m	8.1 m	8.2 m	7.9 m
12.5 kW/m^2	3.9 m	3.9 m	3.9 m	3.9 m
37.5 kW/m^2	Not reached	Not reached	Not reached	Not reached

Table 17 – Distances for radiation due to a jet fire for a small liquid release

Radiation level	Summer day	Summer night	Winter day	Winter night
4 kW/m^2	4.6 m	4.6 m	4.6 m	4.6 m
12.5 kW/m^2	3.9 m	3.9 m	3.9 m	3.9 m
37.5 kW/m^2	Not reached	Not reached	Not reached	Not reached

4.4 Risk Estimation

For the risk calculation, it was necessary to specify the data about wind direction. The data (presented in Table 18) was obtained from a weather station located in Iperó city, São Paulo state, Brazil.

Table 18 – Wind directions probabilities

Direction	*Summer day*	*Summer night*	*Winter day*	*Winter night*
N	11.42 %	2.76 %	8.2 %	2 %
NNE	11.57 %	2.98 %	10.4 %	1.7 %
NE	4.95 %	1.38 %	4.7 %	1.1 %
NEE	2.80 %	1.06 %	3.2 %	1.4 %
E	2.66 %	1.26 %	3.8 %	1.4 %
ESE	6.05 %	2.78 %	7.7 %	1.9 %
SE	11.49 %	17.59 %	11.5 %	13 %
SES	12.08 %	27.14 %	11 %	22.9 %
S	9.72 %	17.38 %	8.6 %	20.8 %
SSW	3.58 %	12.38 %	5.1 %	17.7 %
SW	2.32 %	5.32 %	2.7 %	3.5 %
SWW	2.39 %	1.95 %	3.5 %	3.8 %
W	2.34 %	1.38 %	3.4 %	4.1 %
WNW	3.76 %	1.51 %	4.2 %	2 %
NW	6.36 %	1.41 %	6.6 %	1.4 %
NWN	6.32 %	1.72 %	5.4 %	1.2 %

Considering these probabilities, and combining the consequences calculated with the probabilities of occurrence of possible scenarios, the isocurves of risk shown in Figure 3 were obtained. In the figure are shown the curves of isorisk from 10^{-3} to 10^{-9} per year.

As acceptation criteria was considered the one presented in CETESB [12], where is defined that an individual risk higher than 10^{-5} is considered unacceptable, one between 10^{-5} and 10^{-6} is at ALARP zone, and one lesser than 10^{-6} is considered tolerable for people located around the site. For workers, the ALARP zone was considered being between 10^{-4} and 10^{-5} per year, as defined by CCPS [13].

Figure 3 - Isocurves of risk from 10^{-3} to 10^{-9} per year

Additionally, it was created F-N curves for societal risk of population around the area of the installation. These curves, one combining all risks and other showing risks for each weather condition, are presented, respectively, in Figure 4 and Figure 5. The population considered in this study is compounded by people located in other industries around the site and a group of 110 workers of the plant during the day and 35 during the night.

It is possible to note that, even in worst condition, the societal risk is not in the intolerable area of the graph.

4.5 Risk Control Options Definition

Considering that the obtained results are at ALARP region of criteria, some control measures should be suggested in order to reduce the risk. One of them is to reduce the mission time of the components by reducing maintenance interval of time, which would cause a reduction in the probability of occurrence of ammonia leakages.

Another one is to refuel the tank with restrictions in people access to the area, in order to have less people exposed to the effects of a possible leakage.

Consider reducing the inventory may also be an alternative to reduce the risk, since it is considered that all inventory is released in case of a leakage.

As example, it was considered half of the population of the site (55 workers during the day and 18 workers during the night) and created new F-N curves. These curves are shown in Figure 6 and Figure 7.

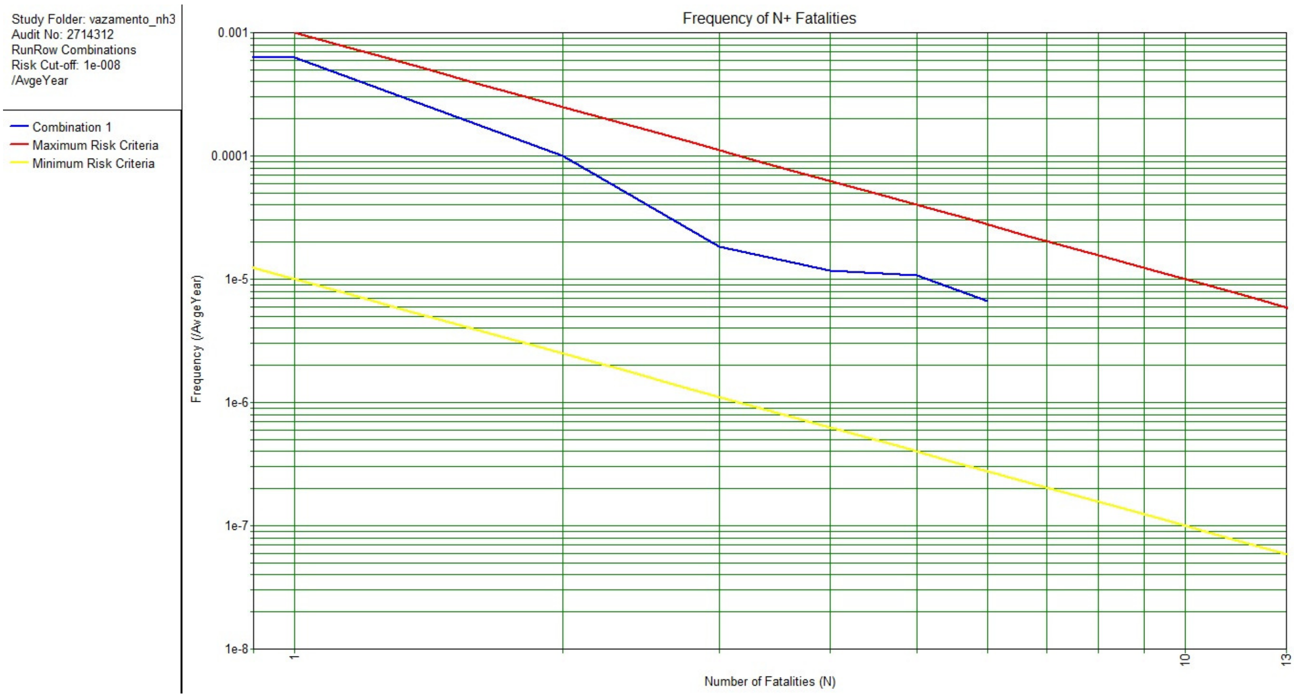

Figure 4 - Combined F-N

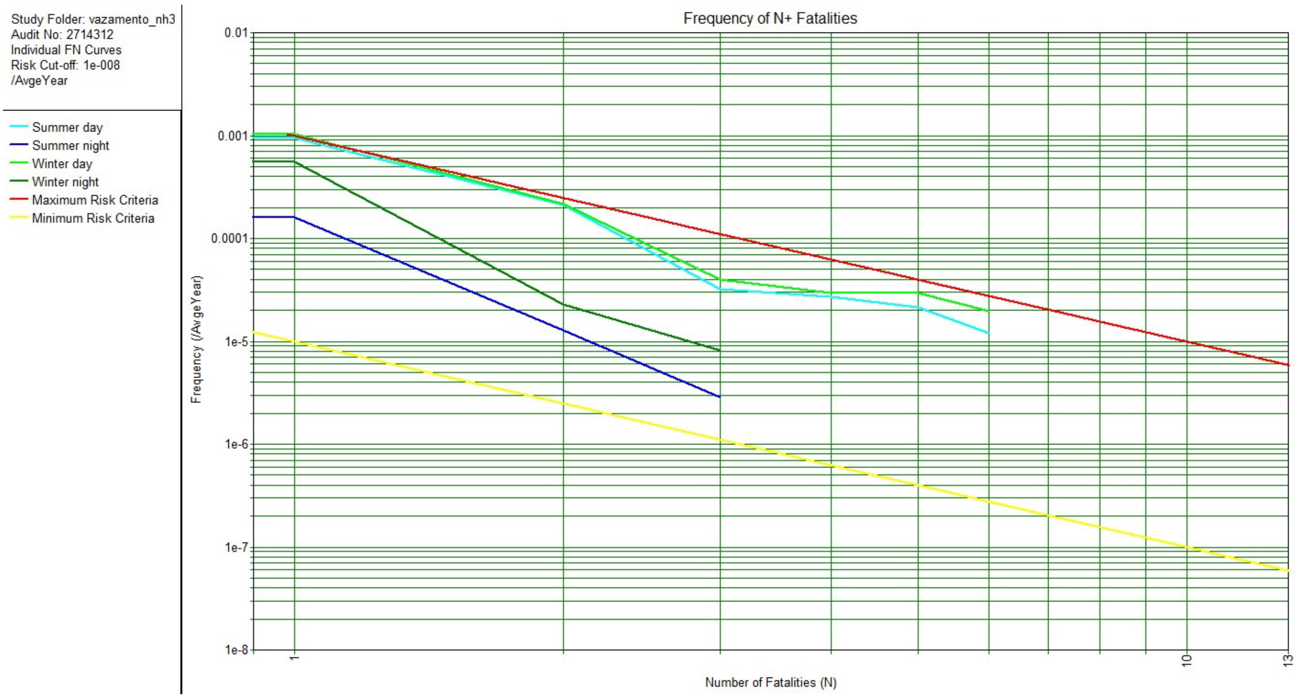

Figure 5 - F-N curves for all weather conditions

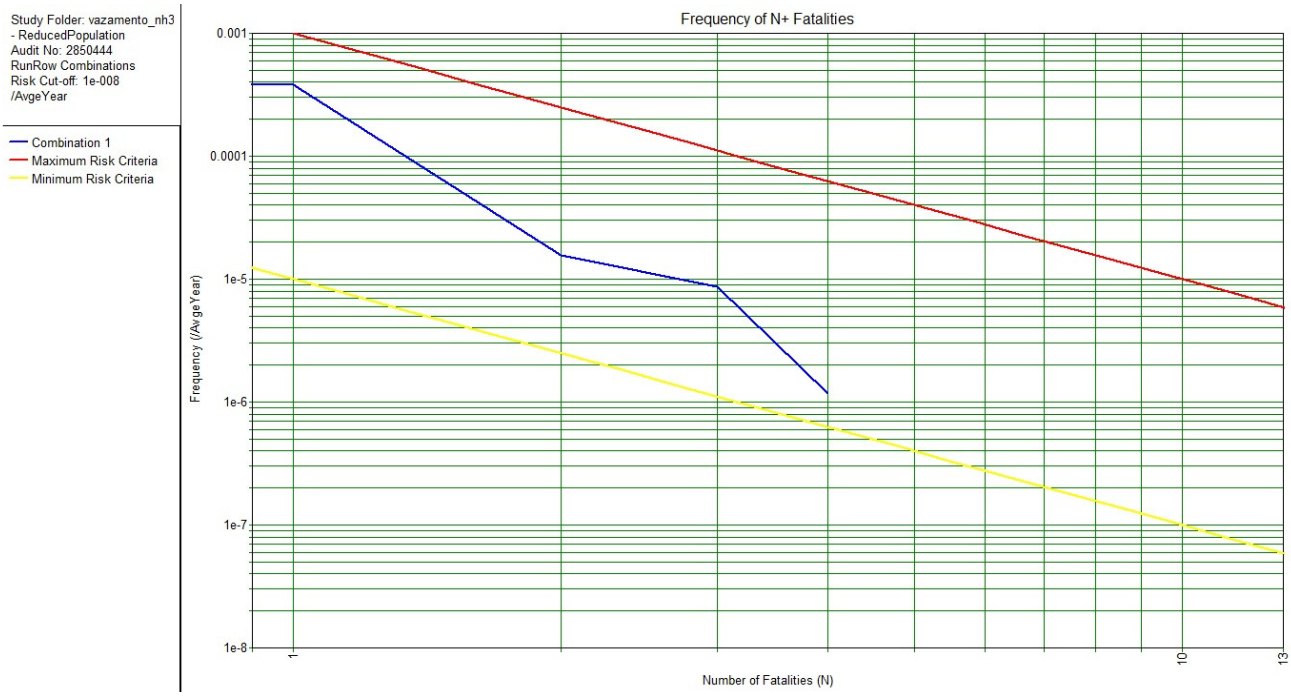

Figure 6 - Combined F-N considering the reduced population

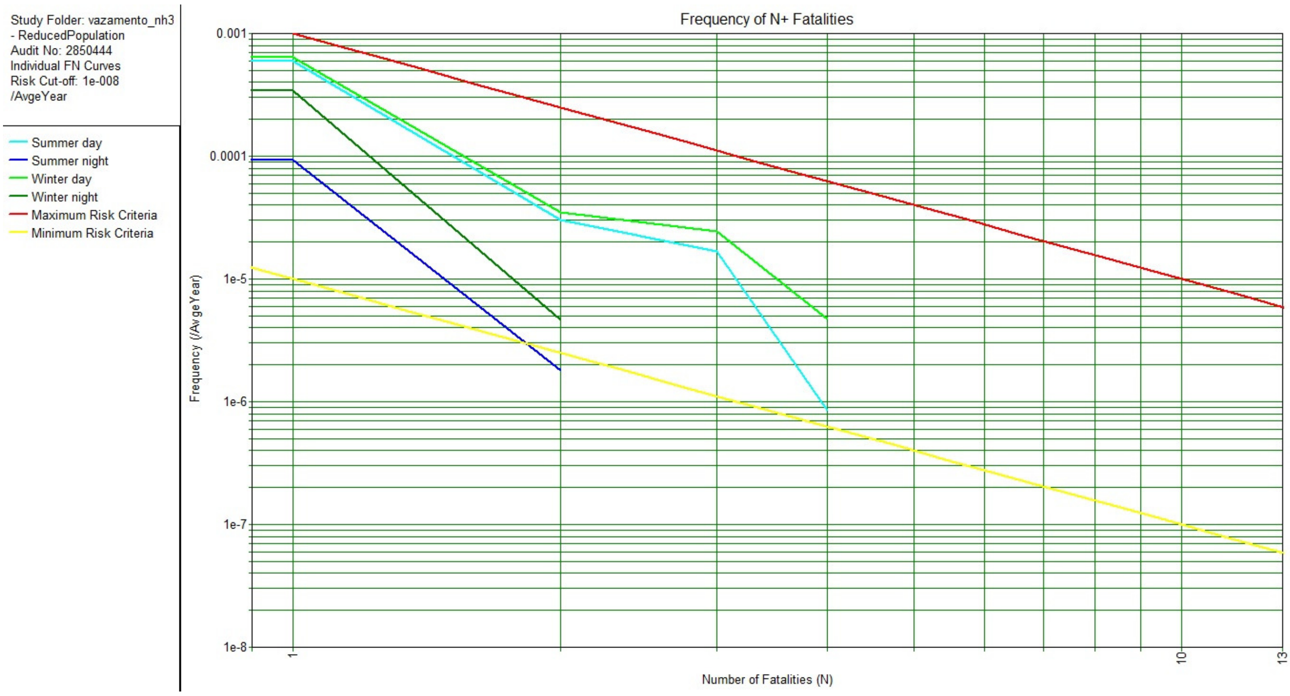

Figure 7 - F-N curves for all weather conditions considering the reduced population

As it can be seen, the proposed reduction of the population would considerably reduce the risk of the refueling process of the ammonia tank.

5. CONCLUSIONS

It is possible to conclude, based on obtained results, that the proposed methodology is applicable in this kind of process for installations like this. Its application is recommended during the design phase of the system, in order to have more flexibility to make changes in the plant.

Furthermore, analyzing the case study, it is possible to conclude that the process of refueling a tank of ammonia in a uranium hexafluoride facility does not represent an unacceptable risk for people located around the site or for workers, based on criteria adopted.

6. REFERENCES

[1] WITLOX, H. "PVAP Theory Document". DNV Report (2006).
[2] HARPER, H. "UDM Theory Document". DNV Report (2009).
[3] THE NETHERLANDS ORGANIZATION (TNO). *Methods for the calculation of physical effects (Yellow Book).* Netherlands (2005).
[4] CHAMBERLAIN, G. A. "Developments in design methods for predicting thermal radiation from flares". *Chemical Engineering Research & Design,* p. 299 (1987).
[5] OKE, A. O. "JFSH (Jet fire) Theory Document". DNV Report (2005).
[6] WITLOX, H. "POLF (Pool Fire) Theory Document". DNV Report (2005).
[7] OKE, A. O. "BLEVE (Fireball) Theory Document". DNV Report (2004).
[8] DET NORSKE VERITAS (DNV). *Failure Frequency Guidance: Process Equipment Leak Frequency Data for Use in QRA*. Norway (2013).
[9] RELIABILITY INFORMATION ANALYSIS CENTER (RIAC). *Non Electronic Parts Reliability Data.* United States. (2011).
[10] U. S. NUCLEAR REGULATORY COMISSION (USNRC). "Handbook of Human-Reliability Analysis with Emphasis on Nuclear Power Plants Applications", NUREG/CR-1278. (1983).
[11] MANNAN, S. *Lees Loss Prevention in the Process Industries*. Elsevier, Oxford, United Kingdom (2005).
[12] COMPANHIA AMBIENTAL DO ESTADO DE SÃO PAULO (CETESB). "Risco de Acidente de Origem Tecnológica – Métodos para Decisão e Termo de Referência". Norma Técnica P4.261 (2011).
[13] CENTER FOR CHEMICAL PROCESS SAFETY. *Guidelines for Developing Quantitative Safety Risk Criteria*. John Wiley & Sons, Hoboken, USA (2009).