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Risk assessment of a liquid storage terminal: comparison of Brazilian and Dutch methodologies

Edmilson P. Silva, Fernanda A. Lima, Isabela M. P. Souza, André P. Soares,Giovani S. Dellamea

SMS/LMA/LI-DPI-DTEN-LOG, Petrobras, Brazil.
E-mail: edmilson.silva@petrobras.com.br, fernanda.a.lima.prestserv@petrobras.com.br, isabela.moreira@petrobras.com.br, andrepinhel@petrobras.com.br, dellamea@petrobras.com.br

Benchmark studies are important for evaluating the efficiency of a company's practices, as well as for assessing modifications that can be adopted or adapted to improve internal processes and results. This study aimed to evaluate the Brazilian methodology for risk assessment of petroleum product storage terminals. The assessment was carried out by comparing Brazilian risk results with those from the Netherlands, as presented in Report 620001002 from the National Institute for Public Health and the Environment (RIVM) by Lenoble et al. (2011). To ensure a consistent basis for risk assessment, the fictitious storage depot described by Lenoble et al. (2011) was used. Brazilian risk calculations were performed according to the primary standard for evaluating risks from hazardous installations, issued in 2014 by the environmental agency of the state of São Paulo (CETESB), i.e., P.4261 - Risk of Accident of Technological Origin - Method for Decision Making and Reference Terms - CETESB (2011).

Keywords: risk assessment, storage depot, flammable liquids, Brazilian guidelines, Cetesb

1. Introduction

In Brazil, the main standard for evaluating risks in hazardous installations is P4.261/11 CETESB (2011), which was approved in April 2014 and is available at the following link: `https://cetesb.sp.gov.br/wp-content/uploads/2013/11/P4261-revisada.pdf`. This standard was developed based on international references, particularly British and Dutch publications such as the Green Book TNO (1992), the Yellow Book van de Bosch and Duijm (2005), and the Purple Book Uijt de Haag and Ale (2005)/BEVI Manual RIVM (2009).

P4.261/11 has been widely recognized as a reference by most state environmental agencies in Brazil, as well as by the federal environmental agency IBAMA – the Brazilian Institute for the Environment and Renewable Natural Resources. This study conducted a benchmark analysis to compare the risk assessment methodologies and criteria used in Brazil and in the Netherlands for a liquid petroleum product storage terminal. To ensure greater consistency between the results from the Netherlands and Brazil, the Dutch risk assessment was updated using Safeti software version 9.0, replacing the previously employed version 6.54. For the Brazilian risk calculations, only the methodological aspects and criteria specific to Brazil have been adjusted. Details regarding the site and the methodologies used by the European countries are available in Lenoble et al. (2011), while all assumptions required for the Brazilian assessment are outlined in Part II of the P4.261/11 Standard.

2. Hypothetical flammable liquid storage depot

The study used the same fictitious flammable liquid storage depot and surrounding context (population and ignition sources) described by Lenoble et al. (2011)(see Figs. 1 and 2).

At the depot, products are delivered via a pipeline into each of the seven tanks, which are organized within two bunded areas. The products are stored and subsequently transferred to tank trucks. Additional details about the installation are provided below, as referenced in Lenoble et al. (2011).

- Bund A: The larger bund contains a 40000 m^3

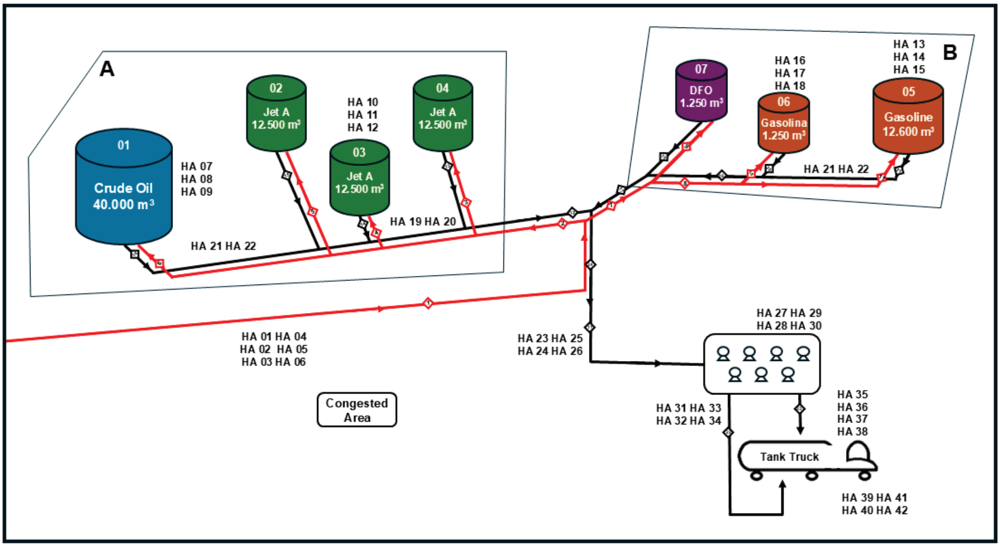

Fig. 1. Layout of the flammable liquid storage depot.

floating roof crude oil tank (tank 1) and three 12500 m^3 fixed roof Jet A tanks (2, 3 and 4);

- Bund B: The smaller bund houses a 12600 m^3 floating roof gasoline tank (tank 5), a 1250 m^3 internal floating roof gasoline tank (tank 6) and a 1250 m^3 fixed roof domestic fuel tank (tank 7);
- Pipeline: Enters the site from the west (left side of the diagram) and splits into two branches near the bunds. Another pipeline of the same dimensions connects the storage tanks to the pump and loading areas;
- Tank cars: Can be stationed in the southern part of the facility, a congested area;
- Pump area: Seven centrifugal, non-canned, pumps are used to transfer products to tank trucks at a flow rate of 120 m^3/h.

3. Surroundings of the Depot

In the vicinity of the depot, a hypothetical populated area has been defined and is depicted in Fig. 2. Potential ignition sources include the population itself and the roads surrounding the facility.

The population estimates utilized in each methodology are presented in Table 1.

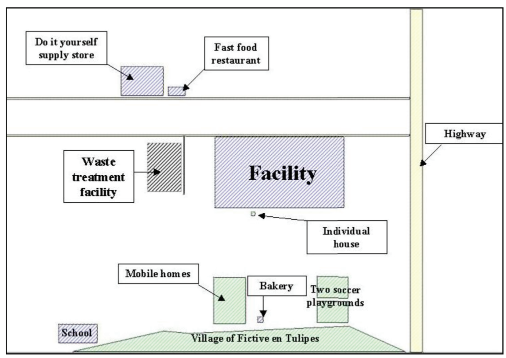

Fig. 2. Population in the surroundings of the depot by Lenoble et al. (2011).

4. Risk Assessment Premises

4.1. *Representative substances*

To undergo a risk assessment, the flash point and boiling point must meet the criteria outlined in Table 2. According to the standard, only substances classified as levels 3 or 4 are subject to detailed risk assessments. Consequently, domestic fuel oil, categorized as level 1, was excluded from the QRA due to its lower risk. Conversely, Jet A1, with a flash point approximately equal to 37.8°C and a boiling point exceeding this value,

Table 1. Estimated population for each methodology.

Object	INERIS	RIVM (Day / Night)	CETESB (Day / Night)
Waste treatment facility	7	7 / 0	7 / 0
Fast food restaurant	15	15 / 0	15 / 0
Do It Yourself supply store	150	150 / 0	150 / 0
Soccer fields	44	44 / 0	44 / 0
Bakery	10	10 / 0	10 / 0
Mobile homes	25	15 / 30	21 / 30
School	150	150 / 30	150 / 30
Fictive en Tulipes	214	107 / 214	149,8 / 214
Individual house of Bob	1	1 / 1	0,7 / 1
Highway(4 ways with traffic jams)	1200/km	0 / 0	1500 Vehicles/Hour

was included in the QRA as it satisfies the criteria for further analysis.

The representative substances for each petroleum product, as defined by CETESB, are n-decane for crude oil, n-hexane for gasoline, and n-nonane for Jet A1.

In this case, the Brazilian methodology differs significantly from the Dutch methodology.

In the original work, the operational factors of gasoline and petroleum—covering lines, pumps, and loading—were grouped. Consequently, in this study, n-hexane was conservatively used as a representative substance for both products.

Table 2. Classification of flammable substances by CETESB (2011).

Level [1]	Flash Point[ºC] and Boiling Point [ºC]
4	FP$\leq$ 37.8 and BP $\leq$37.8
3	FP$\leq$ 37.8 and BP $>$ 37.8
2	$37.8 < FP \leq 60$
1	FP$>$ 60

1: 4-Highly flammable gas/liquid; 3 - Easily flammable liquid, 2 - Flammable liquid; 1- Slightly flammable liquid

4.2. *Hazards identification*

Using a systematic approach to hazard identification, various scenarios with the potential to cause accidents were identified, and their impacts evaluated. Both major and minor leak scenarios were considered. These scenarios are summarized in Table 3 and illustrated in Figure 1.

4.3. *Vulnerability*

Thermal radiation vulnerability was determined using the probit equation proposed by Tsao and Perry (Eq. 1). For pool fire and jet fire scenarios, the exposure time limit is set at 20 seconds.

$$Pr = -36.38 + 2.56 \ln[I^{4/3}t] \tag{1}$$

Additionally, for thermal radiation levels (jet fire and pool fire) exceeding $35kW/m^2$, a fatality likelihood of 100% is assumed. The protective effect of clothing is accounted for by applying a reduction factor of 0.2. This factor diverges from the Dutch methodology.

In flash fire scenarios, it is assumed that within the flame envelope (the area defined by the reach of the lower flammability limit), the probability of fatality is 100%. The modeling of vapor cloud explosion effects was conducted using the multi-energy model, with an unconfined explosion strength of 10 and an unconfined explosion efficiency of 10%. These premises result in distance values similar to those predicted by the TNT model. Overpressure levels of 0.1 bar

Table 3. Accidental scenarios used to simulate consequences and assess risks.

Scenario	Area	Description
1/2/3	Pipelines	Large/Medium/Small release of gasoline/crude oil in the section of the pipeline between the plant's boundary and Tanks 01, 05 and 04
4/5/6	Pipelines	Large/Medium/Small release of Jet A1 in the section of the pipeline between the plant's boundary and Tanks 02, 03, and 04.
7/8/9	Bund A	Tank (TQ-01) - Catastrophic rupture/ 10 min leakage/leak
10/11/12	Bund A	Tanks (TQ-02/03/04) - Catastrophic rupture/10 min leakage/leak
13/14/15	Bund B	Tank (TQ-05) - Catastrophic rupture/ 10 min leakage/leak
16/17/18	Bund B	Tank (TQ-06) - Catastrophic rupture/ 10 min leakage/leak
27/28	Pump	Large/Small release of Jet A1 due to pump rupture/leakage
29/30	Pump	Large/Small release of gasoline/crude oil due to pump rupture/leakage
35/36	Loading	Large/Small release of Jet A1 due to loading arm rupture/leak
37/38	Loading	Large/Small release of gasoline/crude oil due to loading arm rupture/leak
39/40	Loading	Rupture/leak in the tank truck storage vessel (Jet A1)
41/42	Loading	Leak/rupture in the tank truck storage vessel (gasoline/crude oil)

and 0.3 bar were considered. Unlike the Dutch methodology, probabilities of 0.25 and 0.75 for unprotected individuals were assumed, as outlined in CETESB (2011).

4.4. *Calculation of Consequences*

The calculation of consequences was performed using Phast software, developed by DNV and widely recognized for its application in risk analysis and safety scenario modeling.

The hazard distance results obtained using the Dutch methodology with SAFETI version 9.0, as calculated by the authors, were very similar to those derived from the CETESB methodology. This similarity can be attributed to the fact that CETESB's assumptions are largely based on Dutch standards, with the exception of Tank 01, where CETESB models crude oil using n-decane.

When comparing the hazard distances from SAFETI version 6.54, as presented by Lenoble et al. (2011), with those calculated by the authors using version 9.0, no consistent pattern was observed. In some cases, version 6.54 resulted in greater distances, while in others, it produced smaller distances.

The most significant difference was observed for Tank 01, particularly in the flash fire effect, as detailed in Table 4.

4.5. *Failure Frequencies and ignition probabilities*

4.5.1. *Event Trees*

Figure 3 presents the event tree for flammable liquid release in installations and pipelines, as established by CETESB (2011).

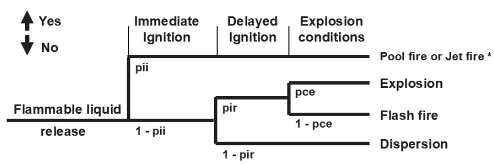

Fig. 3. Event tree for flammable liquid release.
**Jet fire is not applicable to instantaneous rupture of installations and pipeline releases.*

The failure frequency can be estimated using historical records from databases or bibliographic references, provided they are relevant to the case

Table 4. Hazard distances for Tank 01.

Simulation	Effect	Rupture (TQ01)		10 min. Leakage (TQ01)		Leak (TQ01)	
		D5	F1.5	D5	F1.5	D5	F1.5
RIVM SAFETI 6.54	Flash fire [LFL]	90	180	230	470	5	5
	Jet fire [9,8kW/m2]	x	x	290	320	15,00	15,00
	Pool fire [9,8kW/m2]	130	120	130	120	30	25
	VCE [0,1bar]	x	240	310	630	x	x
RIVM SAFETI 9.0	Flash fire [LFL]	202,80	262,24	209,85	471,84	x	9,39
	Jet fire [9,8kW/m2]	x	x	257,83	311,49	12,69	14,26
	Pool fire [9,8kW/m2]	126,30	110,45	105,57	91,33	33,06	24,93
	VCE [0,1bar]	251,05	254,87	234,44	485,46	x	x
CETESB SAFETI 9.0	Flash fire [LFL]	37,10	35,19	23,55	31,97	x	x
	Jet fire [9,8kW/m2]	x	x	34,77	41,27	1,29	1,46
	Pool fire [9,8kW/m2]	126,35	110,47	105,46	91,40	28,49	23,38
	VCE [0,1bar]	19,20	12,37	14,27	14,33	x	x

under study CETESB (2011). In this analysis, the frequencies were estimated based on the Manual Bevi Risk Assessments RIVM (2009) for equipment and the CONCAWE database CONCAWE (Conservation of Clean Air and Water in Europe) (2015) for pipelines.

The probability of immediate ignition depends on the characteristics of the product and the release rate or leaked mass, as shown in Table 6. The probability of explosion is 0.4.

5. Risk Assessment

5.1. *Individual Risk*

Individual risk refers to the projected annual frequency at which a person located near the analyzed facilities may experience specific types of harm, most commonly fatalities, resulting from potential accidents in these installations.

5.1.1. *Individual Risk Criteria*

The individual risk criteria defined by CETESB (2011) is presented in Figure 4.

As shown in Figure 4(a), the iso-risk contour of 1.0×10^{-6}/year, fully contained within the project boundaries, indicates residual risk that must be managed, classifying this risk as tolerable. In contrast, if the iso-risk contours corresponding to 1.0×10^{-5}/year are contained within the project limits, but the 1.0×10^{-6}/year contour extends beyond the boundaries, as depicted in Figure 4(b), the risk falls into the ”risk to be

Table 5. Failure frequencies.

Area / Product	Release type	Freq. [oc/year]
Pipeline Gasoline/Crude Oil	Rupture	5,72E-05
	Hole 20% ND	8,20E-05
	Hole 5% ND	9,60E-05
Pipeline JET A1	Rupture	4,50E-05
	Hole 20% ND	6,45E-05
	Hole 5% ND	7,55E-05
Tank	Catastrophic rupture	5,00E-06
	10 min.	5,00E-06
	Leak	1,00E-04
Loading Arm Gasoline/Crude Oil	Rupture	1,57E-04
	Hole 10%ND	1,57E-03
Loading Arm JET A1	Rupture	1,23E-04
	Hole 10%ND	1,23E-03
Road Tank Gasoline/Crude Oil	Rupture Total	1,10E-05
	Largest Connection	5,50E-07
Road Tank JET A1	Rupture Total	8,68E-06
	Largest Connection	4,34E-07
Pump Gasoline/Crude Oil	Rupture	5,96E-05
	Hole 10%ND	2,62E-03
Pump JET A1	Rupture	4,69E-05
	Hole 10%ND	2,06E-03

Table 6. Ignition probabilities.

Product	Leaked mass (kg)	Mass rate(kg/s)	Ign. Prob.
Gasoline Crude Oil	< 1000	< 10	0.2
	1000-10000	10-100	0.5
	> 10000	> 100	0.7
Jet A1	Any	Any	0.065

reduced" category, requiring the implementation of mitigation measures. Furthermore, if the 1.0×10^{-5}/year iso-risk contour is entirely or partially outside the project limits, as shown in Figure 4(c), the risk is deemed intolerable, suggesting that the project is not feasible.

5.1.2. *Individual Risk Results*

Figure 5 compares RIVM individual risk results obtained using version 9.0 of Safeti with the original results reported by Lenoble et al. (2011), based on version 6.54 of Safeti. The comparison

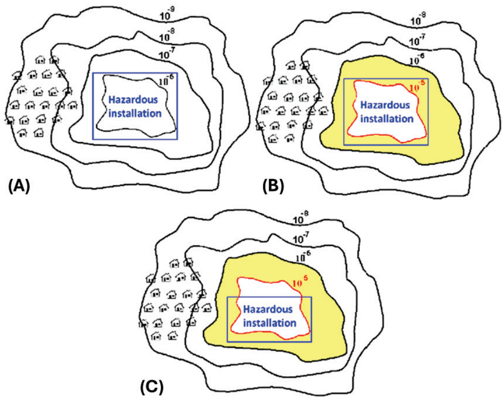

Fig. 4. CETESB (2011)'s individual risk assessment method for installations.

reveals a significant difference in the extent of the 1.0×10^{-6}/year risk contour (red curve) around tank 01. In version 9.0, this contour extends approximately 250 meters from the tank's center, whereas in version 6.54, it reaches only about 160 meters.

These discrepancies can be attributed to variations in the calculated distances of the flash fire from the catastrophic rupture scenario of tank 01, which are notably greater in the Safeti 9.0 simulation compared to the original results (see Table 4 for details).

Additionally, in the pump and loading areas, the newer results show the emergence of risk frequencies higher than 1.0×10^{-5}/year, which were not observed in the original study. In these areas, no significant differences were observed between the original results and the new simulation. Thus, a possible explanation may lie in variations in the distances associated with other levels of pool fire radiation (e.g., 19.45 kW/m² or 35 kW/m²). However, a more detailed analysis is not feasible, as these ranges were not reported in the original work.

The individual risk results, calculated using the Brazilian methodology, are depicted in Figure 6.

The main differences between the Brazilian and Dutch results are associated with the representative product used for crude oil in the tanks and the probability of immediate ignition

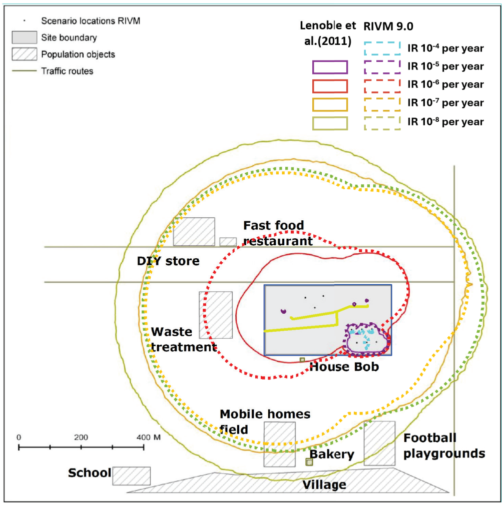

Fig. 5. Comparison of Individual Risk Results: RIVM SAFETI 9.0 versus Original Study.

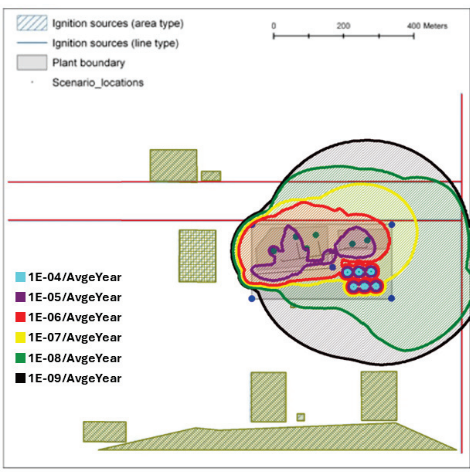

Fig. 6. Individual risk results calculated using the Brazilian methodology

for crude oil and gasoline. The use of n-decane in the tank simulations significantly reduces the 1.0×10^{-6}/year iso-risk curve, as it results in considerably smaller flash fire distances compared to n-hexane.

The probability of immediate ignition for crude oil and gasoline can be up to ten times higher, contributing to the emergence of the 1.0×10^{-5}/year iso-risk curve in the gasoline and crude oil tank area. This assumption also leads to increased risk levels in the pump and loading areas.

5.2. *Societal risk*

Societal risk refers to the population exposed to the physical effects generated by various accident scenarios CCPS (1999). The number of fatalities (N) for each scenario is determined based on the population distribution within the area of interest and the probability of fatalities caused by the physical effects of the scenario.

5.2.1. *Societal Risk Criteria*

The tolerability limit values for societal risk proposed by CETESB (2011) are illustrated in Figure 7.

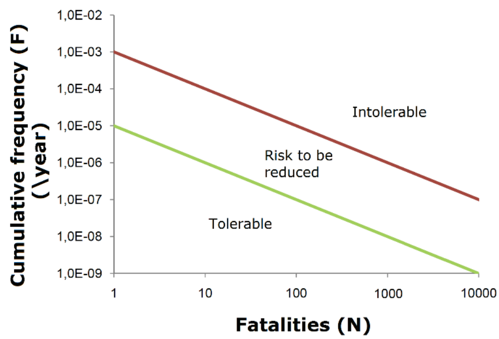

Fig. 7. CETESB (2011)'s societal risk criteria.

The societal risk criterion defines three regions where risk results must be evaluated: tolerable, "risk to be reduced", and intolerable. These regions are interpreted as follows:

(i) If the FN curve is entirely within the tolerable risk region, it indicates the presence of residual risk, which must be managed through a Risk Management Program.

(ii) If the FN curve is entirely or partially within the "risk to be reduced" region, measures must be implemented to reduce the risk.

(iii) If the FN curve is entirely or partially within the intolerable risk region, pipeline operation is unfeasible without the implementation of mitigation measures. These measures should aim to shift the FN curve entirely into the "risk to be reduced" region or, preferably, into the tolerable risk region.

5.2.2. *Societal Risk Results*

The comparison between the F-N curves, considering the RIVM simulation with Safeti 9.0 and the original results, is presented in Figure 8. It is evident that the original study reports a greater number of fatalities.

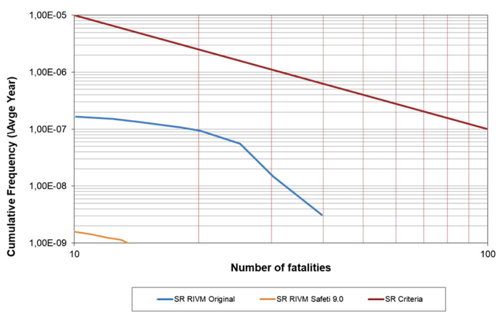

Fig. 8. Comparison of Societal Risk Results: RIVM SAFETI 9.0 versus Original Study.

A possible explanation for this difference is that the 0.1 bar blast radius for the 10-minute release from Tank 01 in the original study is significantly larger than that obtained with the new simulation. As a result, a greater number of individuals are exposed to the explosion effects.

In the case of societal risk using the Brazilian methodology, only a single point on the F-N curve was generated, corresponding to a frequency of 8.73×10^{-9} and one fatality. This outcome occurs because only Bob's individual house is affected by the accidental scenarios of the installation.

6. Conclusion

RIVM individual risk results with version 9.0 reveals a significant difference in the extent of the 1.0×10^{-6}/year around tank 01 when compared with the original results. In the pump and loading areas the newer resulted in risk frequencies higher than 1.0×10^{-5}/year, not observed in the original study.

The use of n-decane in the tank simulations by Brazilian methodology significantly reduces the 1.0×10^{-6}/year iso-risk curve.

RIVM simulation with Safeti 6.54 produces a greater number of fatalities. A possible explanation for this difference is that the 0.1 bar blast radius for the 10-minute release from Tank 01 in the original study is significantly larger than that obtained with the new simulation.

Societal risk using the Brazilian methodology produced only a single point on the F-N curve, corresponding to a frequency of 8.73×10^{-9} and one fatality.

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