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Risk Assessment of Steam Pipelines in Industrial Areas

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A framework is presented to evaluate external risk from steam pipelines. Though water is not labeled as such, it can be a dangerous substance. The standard QRA approach, scenario definition followed by calculation of effects, damage and risk is also well suited for steam pipelines. However some modeling modifications need to be made due to the heat transfer by convection instead of radiation. To evaluate the need for extra safeguarding a risk matrix approach is illustrated with some examples.

1. Introduction

In industrial areas chemical plants tend to integrate their material- and energy balance. A surplus of heat, e.g. from the incineration of industrial and domestic waste, is not wasted anymore but transported to and used by a client e.g. a neighbouring company or a district heating system. High pressure steam is a classical much used medium to transport energy. So more and more steam networks emerge among plants in the form of pipelines, underground and overhead, onsite and offsite over public areas. The application of steam for heating is of course a classical one. The New York steam network was constructed in the beginning of the 20th century.

Water as a dangerous substance

Though often overlooked and not labelled as a hazardous material, water under specific conditions is a dangerous substance. The hazard may arise from solutes (e.g. methane, carbonmonoxide or hydrogensulfide from rocks), temperature (e.g. hot water systems for heating) and pressure (e.g. exploding boiler vessels). **Errore. L'origine riferimento non è stata trovata.** shows the well known tow-truck disappearing in the explosion crater of a ruptured 20 inch steam pipeline, measuring over 10 x 10 m and over 5 m depth. One person was killed (though by heart attack, not by steam contact), 40 people were injured, damage was assessed in millions. The cause of the rupture was condensation-induced waterhammer (State of new York, 2008). So it is clear from historical experience that also steamlines impose a risk on their surroundings.

Risk management

High pressure cross country steam lines belong to Group I pipelines (NEN 3650-standards-series). For these pipelines a pipeline integrity management system (PIMS) needs to be in place. Risk-identification and evaluation are an integral part of the PIMS.

The pipeline operator, the asset owner, the producer of the steam and the customer need insight in the threats to the integrity and continuity of their steamlines for their business case. But above that the amount of damage that may be done to third parties (material damage as well as health damage) by a steam line rupture needs to be known, at least from a liability perspective. Other stakeholders involved are the common public, authorities for land use planning and emergency services. Considering the risk of damage, should there be restrictions on land use along steamlines like for gas transmission lines? Can we put portacabiins for workers right beside a steamline? Should we cross other infrastructure (e.g. road, rail) overhead or underground?

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Figure 1Tow-truck in crater (State of New York, 2008)

The answer to these kind of questions requires insight in the possible extent of damage from a steam pipeline rupture. Some simple effect models are presented here. Combined with scenario frequencies these data make an input to risk evaluation e.g. in the form of a risk matrix.

2. Causes of steam pipeline rupture

Table 1 shows some cause categories for pipeline ruptures. Pipeline operators need to have lines of defence (LOD) in place to prevent a loss of containment (LOC) by any one of these causes. Condensation-induced waterhammer is by far the most devastating cause of steam pipeline rupture (Kirsner 2010). To prevent this phenomenon the control of the amount and the temperature of condensate in the system is crucial.

Table 1Some identified causes for pipeline rupture

Cause category	Description
Erosion/corrosion internal	Waterquality off spec
	Particles in medium
Corrosion external	Isolation wet
Operation	Negative pressures (shutdown)
	Waterhammer, several types (startup)
	Overpressure (process control error)
External impact	Collision (car, train, crane, excavator)
	Wind turbine
	Gas pipeline rupture jet fire
	Base destabilization by earthworks
	Base destabilization by overload (ice,wind, snow)

This overview is not limitative. The risk identification process is site specific, part of the PIMS and makes the list as complete as possible.

3. Consequences of steam pipeline rupture

The consequences of a steam pipeline rupture are health damage and material damage. For illustrative purposes we consider a typical steamline of 20 inches diameter, 330 °C and 40 bar working pressure.
Table 2 shows an overview of physical effects and possible damage.

Table 2 Physical effects and type of damage

Effect	Type of damage	Indication of distance (m)
Shock wave lineburst	Façade damage, glass breakage, ear drum rupture	façade damage: 5 glass breakage: 50
Oxygen depletion	Loss of consciousness	5
Hot steam jet	skin burns, glass breakage	3rd deg. skin burns 10-30 2nd deg. skin burns 20-60 glass breakage 20
Noise	Hearing damage	< 5
Impulse by jet	Load on impacted walls, fall of person	15
Fragments	Damage to hit objects and persons	30->100
Explosion crater	(underground lines) soil structure change in sandy soils influences load bearing capacity	5
Erosion crater	(underground lines) Soil ejected may destabilize nearby foundations and the hot jet may affect parallel or crossing infrastructure	15

Almost all of the effects cause the damage mentioned within the first 5-15 m. Fragments ejected may travel more than 100 m depending on velocity, angle, shape and mass. They may cause damage locally, but the probability of being hit decreases sharply with distance. The external health risk is dominated by the risk of skin burn. This risk cannot be calculated by the well known models for flame radiation incorporated in most risk analysis software. The main heat transfer mechanism in this case is not radiation, but convection. The appendix describes a simple model suited for risk evaluation. A typical result is shown in Figure 2 for 2nd and 3rd degree skin burns. The sub maximum around 30 m and the following decline is due to steam condensation in the jet. The vertical cutoff is due to a threshold criterium for skin damage of 45 °C.

4. Evaluation of steam pipeline risk

The rupture frequency of above ground pipelines used in QRA's for land use planning is in the order of 10^{-7}/m/yr (RIVM 2015). For steam pipelines no other specific failure database is publicly available. When the distance to 3rd degree burns is roughly taken as an indication for potential lethality this amounts to an individual risk of 10^{-6}/yr or higher up to 10-20 m. For comparison: underground gas pipelines have lower rupture frequencies (typical for a 20 inch gas transmission pipeline is a rupture frequency of $2.9.10^{-9}$/m.yr (Gielisse et. al., 2008), but larger effect distances (for a 20 inch line typically about 270 m) resulting in an individual risk below 10^{-6} per year.

The question is whether a steam pipeline adds significantly to the risk by other sources and whether extra safeguarding is needed.

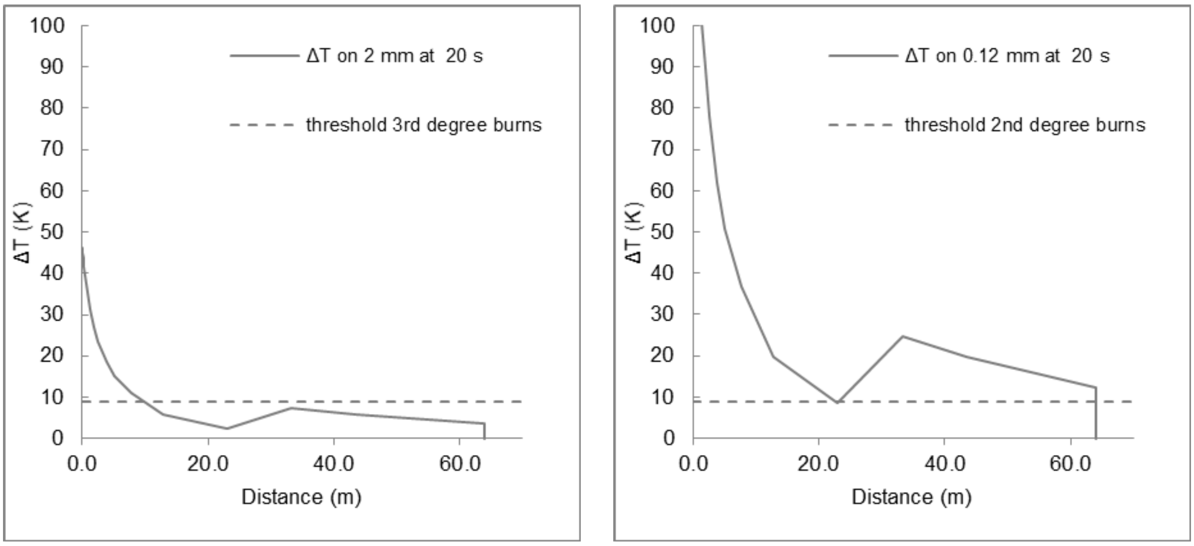

Figure 2 Predictions of distance to 3rd degree skin burns (left) and 2nd degree skin burns (right)

Office buildings, portacabins for workers and other building objects in industrial areas are exposed to many risk sources e.g. transport of hazardous materials, chemical storage and plants. To make a fair comparison it is useful to use a risk matrix like the one in Figure 3. Impact and probability are combined in a score with the following meaning:

I	No extra safeguarding needed for the pipeline, nor the building
II	Extra safeguarding may be considered if the costs are reasonable
III	Extra safeguarding needed if one wants to avoid a significant increase in risk

It is important to emphasize that the starting point is the existing risk level i.e. the location and robustness of the building structures as well as the industrial standards for design (best available techniques).

	Probability compared to other risk sources		
STEAM PIPELINE RUPTURE	Significantly smaller	About equal	Significantly larger
impact smaller	I	I	II
impact equal	I	II	III
impact larger	II	III	III

Figure 3 Risk matrix to evaluate added risk by a steam pipeline in industrial area

Some application examples are:

- Do we need extra safeguarding to route a steam pipeline right beside a transformer building? Impact is equal or smaller (loss of voltage for at least several hours, in case of a gas explosion this may be longer). Probability is at a level that is already there (building beside a pipeline trench), resulting score is I. So extra safeguarding is not needed unless simple and not too costly measures eliminate the extra risk. When there is space enough, it is always sensible to keep some distance between a risk source and a vulnerable object.
- Do we need extra safeguarding to route a steam pipeline right beside an office building? A gas explosion from some storage tanks a few hundreds of meters away is much more devastating but has a smaller probability. So we create a significantly larger probability by the steam line routing, the impact is much smaller, but not negligible (façade damage, windows break, people may suffer skin burns), resulting score is II. Extra protection of the steam line section along the building or a steam jet deflection structure may be considered if costs are reasonable.
- Should we prefer an underground or above ground passage of a railway track? This depends on the damage that may be done to the track by the undermining due to the erosion by the steam jet. The downtime for repair of a deformed track may be much longer than the downtime due to leakage from a overhead pipebridge. Condensate collection from a low lying passage may be a point of attention. So suppose an underground passage adds to the impact. From the matrix one can see that if we choose this option, we need to consider extra safeguarding to reduce the probability of rupture e.g. more wall thickness or a form of casing. A sturdy casing also prevents erosion.

5. Conclusion

The standard QRA approach (scenario definition followed by effect-, damage- and risk-calculation is equally well suited to evaluate the risk from steam pipelines. Some modifications in the effect-modeling need to be made.

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Appendix A simple model for prediction of distance for skin burns

The heat transfer model is described as add-on to a conventional turbulent jet model. This may be taken from a software package like Phast (DNV GL), Effects (TNO) or Hegadas (Shell). An overview of jet models is found in TNO 2005. The outflow after pipeline rupture is steeply transient, so some averaging needs to be done sensibly. The model output contains the following variables as a function of distance:

- Height of jet axis
- Concentration on axis
- Vapor temperature on axis
- Liquid fraction in the jet
- Velocity on the plume axis
- Cloud density

For simplicity and to be conservative we take the jet axis properties as representative.

Additional calculations:

$$\mathrm{Re} = \frac{\rho v d}{\eta} \tag{1}$$

$$\mathrm{Pr} = \frac{\eta C_p}{\lambda} \tag{2}$$

r	Density steamjet	Kg/m^3
V	Velocity	m/s
d	Diameter body in flow	m
η	Dynamic viscosity steam	Pas
Cp	Heat capacity steam jet	J/kgK
λ	Heat conductivity steam jet	W/mK

To calculate the heat transfer coëfficiënt α_u on the steam side in W/m^{2}K a non dimensional Nusselt relation is used:

$$Nu = \frac{\alpha_u d}{\lambda} = 0.027\,\mathrm{Re}^{0.805}\,\mathrm{Pr}^{\frac{1}{3}} \tag{3}$$

(For the distances considered here the flow is turbulent Re~10^6)

The heat penetration in a body for short exposure times is described by the heat penetration theory in semi-infinite media. The average heat transfer coëfficiënt on the body side is

$$\alpha_i = 2\sqrt{\frac{\lambda \rho C_p}{\pi t}} \tag{4}$$

$\mathbf{a}_i$	Heat transfer coëfficiënt body side	W/m^2K
ρ	Density of the body	Kg/m^3
t	Contact time	S
C_p	Heat capacity body	J/kgK
λ	Heat conductivity body	W/mK

The product $\lambda\rho C_p$ for a human body is $2.47.10^6$ J^2s/m^4K^2 (Ministry VROM 2005)

Total heat transfer coëfficiënt U:

$$U = \frac{1}{\dfrac{1}{\alpha_i} + \dfrac{1}{\alpha_u}} \text{ W/m}^2\text{K} \tag{5}$$

When condensation occurs (liquid fraction in jet >0), heat transfer is simply described with a constant surface temperature of the skin surface equal to the steam temperature (no heat resistance on the steam side). The heat transfer coëfficiënt is equal to α_i.
The heat flux into the body is

$$q = U(T_s - T_B) \text{ W/m}^2 \tag{6}$$

Where

T_s	Average steam temperature	K
T_B	Body center temperature	K

Temperature rise in a body as a function of time t and penetration depth x when a body is exposed to a heat flux q is (Ministry VROM 2005):

$$\Delta T(t,x) = \frac{2q\sqrt{t}}{\sqrt{\lambda\rho c}} ierfc(\frac{x}{\sqrt{4at}}) \tag{7}$$

Where

$$ierfc(y) = \int_y^{\infty} \left(\frac{2}{\sqrt{\pi}} \int_p^{\infty} e^{-t^2} dt \right) dp \tag{8}$$

The relation of penetration depth, temperature rise and degree of skin burn is (Ministry VROM 2005):

Degree of skin burn	**Depth to ΔT=9 K**
First	<0.12 mm
Second	< 2 mm
Third	> 2 mm

A skin surface temperature of at least 45°C is roughly a threshold value for serious skin burns (Ministry VROM 2005).
The effect criterium adequate for a quantitative risk analysis may thus be stated as: does the heat flux calculated lead to a temperature rise of 9 °C on a depth of 2 mm? Up to that distance 3rd degree skin burns are possible. Analogous to common risk calculations for external safety an exposure time of 20 seconds to unprotected skin is set. There may be considerations for a shorter time as direct steam contact is required and thus shorter distances are involved compared to heat transfer by radiation.